Arduino Controlled Automatic Capacitor Bank for Power Quality Improvement in Household Scale

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Abstract— The use of inductive loads on a household scale, especially in electricity customers with a power of 1300 VA, often leads to low power factor values (cos φ) which degrades power quality. This study aims to design and build an Arduino-based automatic capacitor bank system capable of dynamically improving power quality in 1300 VA household electrical installations. The system integrates an Arduino Nano microcontroller with a PZEM-004T sensor to monitor electrical parameters—such as voltage, current, and cos φ—in real time and automatically controls capacitor switching through relays to provide the most suitable compensation. Experimental results show that the system successfully increased the power factor from an average of 0.75 to 0.97 under varying load conditions. In addition, the implementation reduced reactive power by up to 65% and demonstrated potential savings in electricity bills of approximately 8–12% for household consumers. These findings indicate that the proposed system not only improves power factor close to ideal conditions (cos φ ≈ 1) but also enhances overall energy efficiency and provides tangible economic benefits for household users.

Keywords— Arduino Nano Microcontroller; Capacitor Bank; Efficiency Energy; Electrical Automation System; Power Factor Optimization.

I. INTRODUCTION

The quality of electrical power in the household sector, especially for customers with 1300 VA power, is a crucial issue that is often overlooked [1]. One of the main benchmarks of power quality is the value of the power factor (cos φ)[2]. The majority of modern household appliances such as air conditioners, water pumps, and refrigerators have inductive load characteristics, which causes the power factor value to be low (often below the PLN standard of 0.85) [3]. This indicates high use of reactive power—energy that does not produce real work but still puts a strain on the power grid and consumer bills [4]. As a result, there is a decrease in power quality, energy inefficiency, and potential cost waste[5].

To solve this problem, the most effective technical solution is the installation of a capacitor bank that serves as a local reactive power supplier to offset the inductive load [6]. Thus, the power grid no longer needs to supply a large amount of reactive power, so that the total current decreases, power losses can be suppressed, and the power quality can be improved by raising the value of the power factor close to the ideal number (cos φ ≈ 1) [7].

Although the use of capacitor banks is not a new idea, pre-existing systems are generally manual. The user has to statically activate the capacitor, which is ineffective for household environments where the electrical load is very dynamic and variable throughout the day. These limitations are the gaps for innovation [8].

Recent studies have investigated various approaches to automatic power factor repair, with most focusing on large-scale or commercial applications [9]. Research on industrial-scale capacitor banks has shown improvements in power quality through controller-based systems, but these designs are generally tailored to three-phase or high-capacity installations rather than single-phase residential loads. Previous systems, typically benchmarked in megavars (Mvar), were optimized for high-power industrial use and therefore lack adaptability to the rapidly changing patterns of smaller residential loads [10]. This limitation reduces their real-time responsiveness and often leads to suboptimal performance in residential contexts. To address this gap, the present research targets single-phase residential customers (1300 VA) by implementing a system that integrates real-time monitoring using the PZEM-004T sensor with adaptive capacitor switching to respond effectively to load dynamics.

This research developed an Arduino-controlled Automatic Capacitor Bank system as an adaptive solution to improve power quality on a household scale. The system uses an Arduino Nano microcontroller as the main processing unit integrated with the PZEM-004T sensor to monitor electrical parameters (voltage, current, and cos φ) in real-time. Based on the measured data, the system will intelligently activate the relay to connect capacitors with capacitance values that best suit the current load needs.

The effectiveness of the system will be evaluated by comparing the electrical conditions before and after installation, as well as analyzing its economic impact in the form of potential reduction in electricity bill costs [11]. In this research, the loads used in the households that are the research samples are not classified in detail, but the intended loads consist of resistive and inductive loads that are commonly found in household appliances. The results of the research are expected to provide technical evidence regarding practical, automated, and affordable energy-saving solutions for the wider community.

II. METHOD

A. System Architecture Design

The hardware architecture of this system is designed with a modular approach that groups functionality into three main

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components that interact with each other: the sensor module, the main control unit, and the actuator device [12]. This structure is designed to logically separate functions, thus facilitating the process of designing, developing, and testing systems for 1300 VA household scale [13].

1) Sensor Module (Data Acquisition)

This module functions as a data acquisition subsystem that is in charge of measuring the electrical parameters of the household grid in real-time. Accurate data is a crucial input for the control algorithm.

The hardware used PZEM-004T sensor was used in this study. This sensor was chosen for its ability to measure voltage (V), current (I), active power (P), energy (E), and power factor (cos φ) simultaneously [14]. PZEM-004T has sufficient accuracy for power factor repair applications, is reliable, and is easy to integrate with microcontrollers [15]. The data obtained is then sent to the main control unit for processing.

2) Main Control Unit (System Brain)

The main control unit becomes the center of data processing and decision-making. It is this component that makes the system work automatically and adaptively [16]. The hardware used is Arduino Nano. The Arduino Nano is in charge of running a pre-programmed control algorithm to analyze the data from the sensor and determine the necessary repair actions [17]. These microcontrollers were chosen because of their compact size, efficient power consumption, and wide compatibility with a wide range of additional modules [18].

3) Actuator Device (Repairing Executor)

An actuator device is a component that performs physical actions to repair the power factor based on commands from the control unit. A circuit of five DC relays connected to a capacitor bank with different capacitance values. The relay functions as an electronic switch. Based on the results of the Arduino Nano analysis, the relay will be dynamically active to connect the most appropriate combination of capacitors into the power grid. This process aims to compensate for the reactive power of the load and raise the power factor value close to ideal.

4) User Interface (Monitoring)

To make it easier to monitor system performance, a visual interface is added. The hardware used is LCD (Liquid Crystal Display) 4x20. This screen displays important information in real-time, such as voltage values, current, power factor, instantaneous power, and the status of the relay that is active. This allows users to monitor the effectiveness of power quality improvements directly [19].

B. How the System Works

How the system works can be explained as follows:

1) Input Sensor to microcontroller

The PZEM004T sensor measures the voltage, current, frequency, and power factor values of the electrical system. These measured values are then transmitted to the microcontroller for processing. Based on this data, the system can determine the appropriate actions to optimize power quality.

2) Input Mode to microcontroller

The operating mode of the system can be selected using a switch. This switch allows the user to choose between the measurement mode and the capacitor bank mode. By selecting the appropriate mode, the system can either monitor electrical parameters or actively manage reactive power compensation.

3) Data processed in microcontroller

Both signals are sent to the Arduino Nano, which serves as the microcontroller, for processing according to the selected operating mode. In capacitor bank mode, the system utilizes the sensor data to automatically control the activation of the capacitors. The activation is determined based on the load current, with each capacitor switching at every multiple of two amperes. This allows the system to dynamically compensate for reactive power. Meanwhile, in measurement mode, the sensor data is only displayed on the interface. No automatic control or switching of capacitors occurs in this mode. Therefore, the system provides both monitoring and automation functions depending on the user's selection.

4) Automate Relay

In the capacitor bank mode, a relay is used to connect the capacitor to the home electrical grid in an automatic way adjusting the load using the current parameters. However, in the automatic system measurement mode the relay is not used.

5) Display Data in LCD

After the current is processed by the arduino nano, in the next capacitors bank mode, arduino nano commands the digital pin which is used as the output to turn on the relay whose function is to connect capacitors of a certain size according to the calculation to the 1300 VA household installation as a consumer and the results of the process are displayed using a 20x4 I2C LCD, while in the measurement mode after the data is processed, the data will be displayed to the LCD as an output. Based on how the tool works, it can be explained more easily in the following Figure 1.

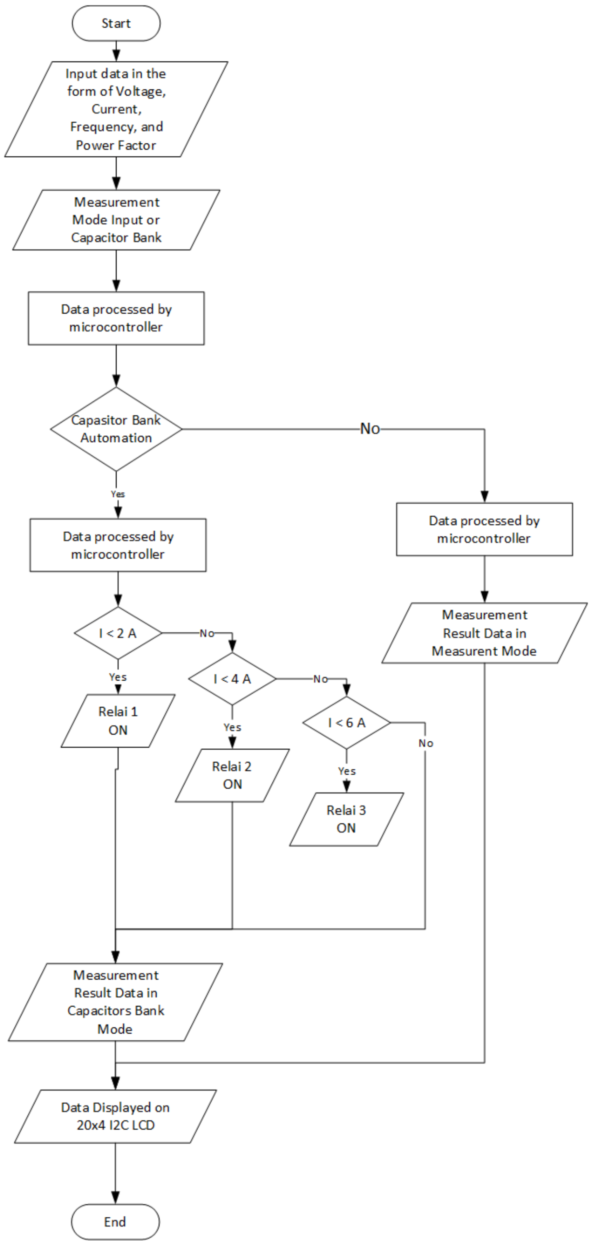

Figure 1. Flowchart System Works

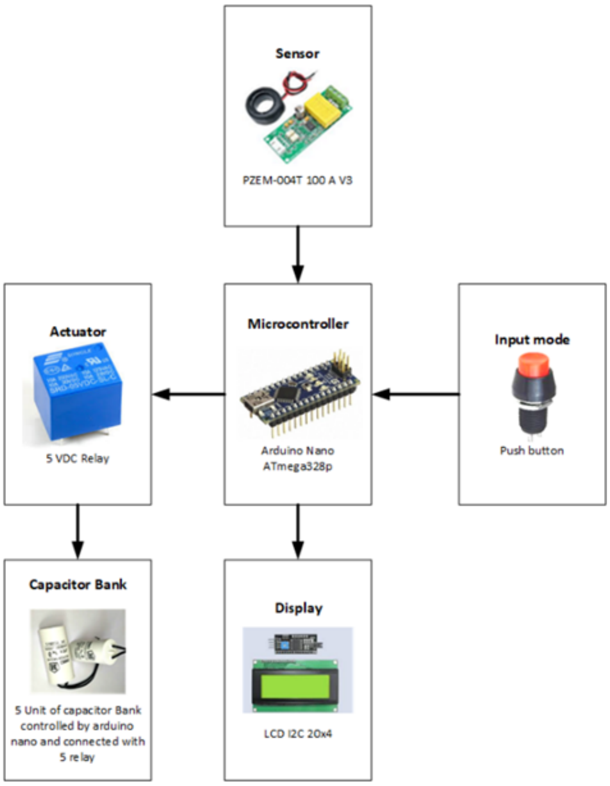

Figure 2. System Works

The operation of the device can be more easily understood from the working principal diagram shown in Figure 2.

C. How is the calculation of the required capacitors.

In this study, the value of capacitor capacity needs installed in household electrical installations with a power of 1300 VA also requires calculations so that the capacitor does not overcharge and will later become a separate capacitive load [20]. The calculation is carried out in several stages [21].

1) Classify the load.

Classify the load into power groups with the current value as a reference, in this case the current that is the reference is 2 Amperes.

2) Calculating the tan value.

Calculating the tan value of the power factor value (cos φ), it can be done with equation (1):

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

The symbol tan represents the tangent value, while $\cos^{-1}\phi$ refers to the phase angle obtained from the inverse cosine of the power factor (ϕ).

3) Calculating reactive power.

Calculating reactive power can be done with equation (2):

$$Q = V \text{ x } I \text{ x} \sin\phi \quad (2)$$

The symbol Q represents the reactive power measured in volt-ampere reactive (VAR). The symbol V denotes the voltage in volts, while I refers to the current in amperes. The term sin φ indicates the reactive power angle, which describes the relationship between reactive power and the phase difference in the electrical system. Calculating reactive power can also be done with equation (3):

$$Q = P \text{ x} \tan\phi \quad (3)$$

The symbol Q represents reactive power, measured in volt-ampere reactive (VAR), while P denotes active power, expressed in watts (W). The term tan φ refers to the tangent of the phase angle (φ), describing the ratio between reactive power and active power in the electrical system.

4) Calculate the reaktive power compensation.

From the reactive power data, it can then be used to calculate the power compensation. Calculating the ratio of the amount of reactive power compensation can be done with equation (4):

$$Qc = Q_0 - Q_1 \quad (4)$$

The symbol Qc denotes the reactive power compensation, measured in volt-ampere reactive (VAR). The term Q_0 represents the reactive power before the intervention, while Q_1 indicates the reactive power after the intervention, both expressed in volt-ampere reactive (VAR).

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

Calculating the current passing through the capacitor (Ic)can be done with equation (5):

$$I_c = \frac{Q_c}{V} \quad (5)$$

The symbol $I_C$represents the current flowing through the capacitor, measured in amperes (A). The symbol Q_C denotes the reactive power compensation, expressed in volt-ampere reactive (VAR). The symbol V indicates the nominal system voltage, measured in volts (V).

6) Capacitive reactance (X_C).

Capacitive reactance (X_C) used to determine what size capacitor is used to fix the power factor with the capacitor bank. Calculating the value of capacitive reactance can be done with equation (6):

$$X_C = \frac{V}{I_C} \quad (6)$$

The symbol X_C denotes the capacitive reactance, measured in ohms (Ω). The symbol V represents the system voltage, expressed in volts (V). The symbol I_C indicates the current passing through the capacitor, measured in amperes (A).

7) Calculate the value of the required capacitor.

After finding the value of capacitive reactance, further calculations are required to calculate the value of the required capacitor, which can be calculated with equation (7):

$$X_C = \frac{1}{2\pi FC} \quad (7)$$

The symbol X_C represents the capacitive reactance, measured in ohms (Ω). The symbol F denotes the frequency of the system, expressed in hertz (Hz). The symbol C refers to the capacitance of the capacitor, measured in farads (F).

8) Converting the amount of capacitor value.

Converting the amount of capacitor value is necessary because in the Indonesian market the amount of capacitor value is generally marketed with a micro farad (μF) standard unit. Calculating these conversions can be done with equation (8):

$$C(\mu F) = C(F) \text{ x } 10^{-6} \quad (8)$$

The symbol C (μF) represents the capacitance value expressed in microfarads (μF), while C (F) denotes the capacitance value expressed in farads (F). The term 10^6 serves as the multiplier factor used for converting microfarads to farads.

D. Analyze the performance of the capacitor bank automation system.

To analyze the performance of the capacitor bank automation system, the researcher performed a series of careful calculations [22]. The first step is to use real-time electrical data (such as voltage, current, and power factors) that has been collected [23]. By comparing pre- and post-installation data, we can quantitatively measure the impact of the system. Various mathematical equation are applied to evaluate its effectiveness, such as how well the power factor is successfully repair close to the ideal value of 1. In addition, we also calculate energy efficiency and potential electricity cost savings. This process will generate concrete data that shows that this solution is not only technically effective, but also economically beneficial for consumers [24]. To analyze the work results of the capacitor bank automation system that has been made before, it can be done in several calculation stages.

1) Increase Results on Power Factor Testing.

To calculate the results of increase in the power factor test in percentage (%) with equation (9):

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

The symbol Cos φ_0 denotes the power factor before the intervention, while Cos φ_1 represents the power factor after the intervention.

2) Results of Reducing in Testing Electrical Power Consumption.

To calculate the results of increase in the power factor test in percentage (%) with equation (10):

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

The symbol P_0 refers to the electrical power consumption before the intervention, while P_1 indicates the electrical power consumption after the intervention.

3) Results of Reducing in Customer issued electricity cost

To analyze the results of customer issued electricity cost in percentage (%) with equation (11):

$$\text{Electricity Cost}(\%) = \frac{IDR_0 - IDR_1}{IDR_1} \text{ x } 100\% \quad (11)$$

The symbol IDR_0 denotes the customer's electricity cost before the intervention, while IDR_1 represents the customer's electricity cost after the intervention.

E. Implementation

The implementation stage represents the physical realization of the planned system architecture, where the PZEM-004T sensor module, Arduino Nano control unit, and DC relay actuator are integrated into a functional unit. The integration process includes circuit connections, wiring, component installation, and uploading of program code to the microcontroller. This code executes the control algorithm for processing sensor data and operating the relay to repair the power factor. A functionality test is then performed to ensure accurate sensor readings and actuator response prior to field installation.

The selection of a household with a 1300 VA power capacity as the experimental subject was based on technical considerations and population representativeness. Typical households within this power category generally exhibit diverse yet small-scale load characteristics, such as the use of common household electrical and electronic appliances, making them suitable to reflect the real conditions of most PLN R1 customers. In terms of efficiency and safety, this power category also enables the implementation of experiments at a relatively low cost without the need for large-scale industrial equipment. Therefore, the selection of a 1300 VA household customer is considered both representative and relevant for testing the effectiveness of power factor repairing solutions at the residential consumer level.

The use of a single household sample in this study is intended as a preliminary investigation or technical feasibility test (proof-of-concept) for the application of capacitors in improving power factor and electrical energy efficiency. Data collection follows a quantitative methodology through direct measurement on 1300 VA household electrical installations. Measurements are conducted over two phases: pre-intervention and post-intervention, each lasting two months. The pre-intervention phase establishes baseline data on power factor and energy consumption, while the post-intervention phase evaluates the performance of the automatic capacitor bank system. Comparative analysis of both phases confirms the system's effectiveness in improving power factor and reducing energy use, while also identifying possible errors and limitations. Although the use of a single sample is not sufficient to generalize the results to the entire R1 customer population, this approach remains appropriate when the research focuses on demonstrating the technical functionality and measurement procedure. To enhance the validity of the findings, measurements were conducted repeatedly before and after the installation of the capacitor under various random time conditions, accompanied by comprehensive documentation of load profiles and household electricity usage characteristics. Through these measures, the experimental results are expected to provide an initial overview of the effectiveness of capacitor implementation in improving power factor, which may serve as a foundation for further studies involving a larger number of samples.

III. Result and Discussion

By applying equation (1) through (8) and using a nominal voltage of 220 volts, the required capacitor bank was calculated based on the load classification established in Chapter 2. Each capacitor corresponds to a load of approximately 2 amperes or about 450 watts, serving as the reference for determining the capacity of each repairing stage. This classification ensures that capacitor sizing remains proportional to the load demand, allowing balanced reactive power repairing across different load levels. The approach also simplifies the Arduino-based automatic control system, which adjusts capacitor operation according to real-time current measurements. Overall, this systematic calculation enables the capacitor bank to achieve the target power factor efficiently while maintaining stability in household-scale electrical systems.

The calculation results presented in Table 1 provide a detailed overview of the effect of power factor repair through the installation of capacitor banks at different current loads. Prior to the intervention, the measured power factor (cos φ) was consistently 0.85 for all load conditions, corresponding to a tangent value (tan φ) of 0.62, indicating the presence of a significant inductive reactive component.

TABLE I. CAPACITOR BANK PLANNING CALCULATION TABLE

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 (I_C(Ampere))	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

TABLE III. CAPACITOR VALUES AVAILABLE ON THE MARKET

Current (Ampere)	Capacitors Value (uF)	Capacitor values available on the market (uF)
2	6.2	6
4	12.4	12
6	18.6	20

After the installation of the capacitor bank, the power factor improved to 0.95 with a corresponding tan φ of 0.33. This improvement signifies a substantial reduction in the reactive component of the load, demonstrating that the capacitors successfully compensated for a portion of the inductive reactive power drawn by the system.

From the quantitative perspective, the reactive power pre intervention decreased considerably post-intervention of the capacitor. For a load current of 2 A, reactive power decreased from 231.78 VAR to 137.39 VAR, resulting in a compensation of 94.39 VAR. Similarly, for load currents of 4 A and 6 A, the reductions were 188.79 VAR and 283.18 VAR, respectively. This trend indicates that the reactive power compensation is directly proportional to the magnitude of the load current, confirming the linear relationship between the required reactive compensation and load demand. The corresponding capacitor currents (I_C) were calculated as 0.43 A, 0.86 A, and 1.29 A for each load condition, respectively, with capacitive reactance values inversely proportional to the load (512.74 Ω, 256.37 Ω, and 170.91 Ω). These values translate to capacitor sizes of 6.2 µF, 12.4 µF, and 18.6 µF, showing that higher load currents require larger capacitances to achieve the same target power factor.

Overall, the results confirm that the use of capacitor banks effectively improves the power factor from 0.85 to 0.95, leading to a reduction in reactive power demand by approximately 40–45% across the tested load range. This not only enhances the efficiency of the electrical system by reducing losses due to reactive current but also stabilizes voltage levels and minimizes unnecessary power consumption. The proportional increase in capacitor value with load current further validates the theoretical model described in equation (1)–(8), demonstrating the practical accuracy of the design approach for low-voltage residential applications.

The data presented in Table II compares the theoretically calculated capacitor values with those available on the market for different load current levels. Based on the calculations, the required capacitance values for compensating reactive power at load currents of 2 A, 4 A, and 6 A are 6.2 µF, 12.4 µF, and 18.6 µF, respectively. However, since capacitors are produced in standardized discrete values, the closest commercially available options are 6 µF, 12 µF, and 20 µF.

This minor deviation between the calculated and available capacitance values is considered acceptable in practical applications because the variation—ranging only from 0.2 µF to 1.4 µF does not significantly affect the overall reactive power compensation or the resulting power factor. The small difference is typically within the tolerance range of most commercially available capacitors, which commonly vary by ±5% to ±10% of their rated value.

Therefore, the selection of 6 µF, 12 µF, and 20 µF capacitors is justified as a practical adaptation of theoretical design to real-world market availability. This approach ensures that the system remains cost-effective, implementable, and technically reliable, while still achieving the intended power factor repairing and maintaining efficient performance in household-scale electrical systems.

From the capacitor value, the tool is made using the working method listed in the working method sub-chapter with the number of capacitors installed using the capacitor equation that has been calculated in table 1 with each capacitor having 1 unit with the size adjusted to what is available on the market with the provision that the value should not be too far from that calculated in table 1. The size is shown in table 2.

The selection of capacitor values of 6 µF, 12 µF, and 20 µF in the automatic capacitor bank system is based on considerations of efficiency, flexibility, and the stability of reactive power compensation at the household scale. This range of capacitance values provides a sufficiently graded and proportional step variation, allowing the system to perform power factor repair gradually without causing abrupt changes. With this configuration, the Arduino-based controller can select the most appropriate capacitor according to the actual load conditions, based on real-time measurements of current and voltage.

In addition, the selection of these values also takes into account the physical space limitations of the panel, the efficiency of relay switching, and the control capability of the Arduino, ensuring that the system remains stable, energy-efficient, and does not overload the power electronic components. Therefore, the use of capacitors ranging from 6 µF to 30 µF can be considered technically and academically appropriate, as it provides a balance between compensation accuracy, system stability, and operational efficiency in household-scale power factor repairing applications.

The data collection process for this study involves the installation of a power factor repairing system in the customer's household installation, followed by real-time measurement of electrical parameters. The PZEM-004T sensor serves as the primary tool for collecting voltage, current, and power factor data. The data obtained from the sensor will be sent to the Arduino Nano, where it is processed and displayed on a 20x4 LCD visual interface. This data collection was carried out in the pre-intervention and post-intervention periods for comparative analysis purposes.

Figure 3 illustrates the photos taken during the random weekly data collection process. The image captures the field measurement activities performed on the household electrical installation to record variations in current and power factor under actual load conditions.

Figure 3. Photos Taken During Random Weekly Data Collection

TABLE IIII. POWER FACTOR SYSTEM MEASUREMENT RESULTS

Num	Weeks	Customers with 1300 VA Power			
		Pre-intervention		Post-intervention	
		Current (Ampere)	Power Factor	Current (Ampere)	Power Factor
1	First	1.68	0.81	1.38	0.98
2	Second	2.67	0.8	2.2	0.96
3	Third	0.98	0.82	0.73	0.99
4	Fourth	1.28	0.78	1.03	0.9
5	Fifth	1.57	0.78	1.25	0.9
6	Sixth	1.08	0.8	0.87	0.94
7	Seventh	1.35	0.81	1.12	0.97
8	Eighth	1.32	0.79	1.05	0.91

TABLE IV. SYSTEM MEASUREMENT RESULTS FOR ELECTRICAL POWER CONSUMPTION

Num	Weeks	Customers with 1300 VA Power	
		Pre-Intervention (kWh)	Post-Intervention (kWh)
1	First	78	72
2	Second	79	73
3	Third	65	62
4	Fourth	93	88
5	Fifth	80	74
6	Sixth	78	73
7	Seventh	75	70
8	Eighth	66	62
Sum of kWh		614	574

TABLE V. CUSTOMER-ISSUED ELECTRICITY COSTS

Num	Months	Customers with 1300 VA Power	
		Pre-intervention (Rp)	Post-intervention (Rp)
1	First	500,589	468,806
2	Second	475,162	443,378

This process was carried out periodically to ensure that the recorded data reflected realistic and unbiased operational behavior of the system throughout the observation period. The random sampling approach was intentionally applied to minimize the influence of external factors and to obtain representative performance data across different days and load variations. Overall, Figure 3 serve as visual documentation that supports the validity and consistency of the experimental procedure used in this study.

Data collection was conducted over a period of four months, consisting of two months in the pre-intervention phase and two months in the post-intervention phase. During each phase, samples were randomly taken on a weekly basis to ensure representative measurement results. The collected data include key electrical parameters that reflect system performance before and after the intervention. A summary of these results is presented in Table 3.

For these customers, the installation of a capacitor bank had a direct impact on the amount of electrical energy consumed. Data were collected over a period of two months prior to the intervention and two months after the intervention to capture changes in energy usage. The comparison between these two phases provides a clear indication of the effectiveness of the capacitor bank in improving energy efficiency. The detailed results of this comparison are presented in Table 4.

For these customers, the use of a capacitor bank also affected the cost of electrical energy consumption. Data were collected for a period of two months before the intervention and two months after the intervention to evaluate changes in electricity expenses. This comparison highlights the economic benefits gained from improving the power factor through capacitor bank installation. The detailed electricity cost data are presented in Table 5.

Using equation (9), (10), and (11), the collected data were analyzed to assess system performance before and after the intervention. The systematic application of these equations generated quantitative results indicating variations in power factor, reactive power, and energy efficiency. The outcomes clearly demonstrate the positive impact of the capacitor bank installation on overall system improvement. The summarized results presented in Tables 6 and 7 serve as the main reference for interpreting and validating the effectiveness of the proposed method.

TABLE VI. RESULTS ANALYSIS OF POWER FACTORS AND ELECTRICAL POWER CONSUMPTION DATA

Num	Weeks	Result Cos φ Repair (%)	Results of Reducing Electric Power Consumption (%)
1	First	20.99	8.3333333
2	Second	20	8.2191781
3	Third	20.25	4.8387097
4	Fourth	15.39	5.6818182
5	Fifth	20.26	8.1081081
6	Sixth	17.5	6.8493151
7	Seventh	19.75	7.1428571
8	Eighth	15.1898	6.4516129

TABLE VII. RESULTS ANALYSIS OF CUSTOMER ISSUED ELECTRICITY COST

Num	Months	Results of Reducing Customer Issued Electricity Cost (%)
1	First	6.7795634
2	Second	7.1686011

TABLE VIII. RESULTS OF VALIDATION AND RELIABILITY TEST ANALYSIS USING SPSS SOFTWARE

Power Factor Validation Test Results	Electrical Power Consumption Validation Test Results	Customer-Issued Electricity Costs Validation Test Results
0.849	0.995	1.000
Power Factor Reliability Test Results	**Electrical Power Consumption Reliability Test Results**	**Customer-Issued Electricity Costs Reliability Test Results**
0.839	0.979	1.000

Table 8 is presented to reinforce the results of the analysis by including validity and reliability tests conducted using SPSS software. These tests are essential to ensure that the data used in the study are accurate, consistent, and suitable for further interpretation. High validity values indicate that the measurements accurately reflect the intended parameters, while high reliability values confirm consistency across repeated observations. Thus, Table 8 provides strong statistical support for the credibility of the research findings.

Cos φ Repair (%) Data shows a very significant and consistent increase in the power factor every week. The percentage of improvement is in the range of 15% to 20.99%. This value indicates that the intervention applied is very effective in improving the power quality of the system, bringing it closer to the ideal value.

The analysis is also strengthened by graphs that present data regarding power factor repairing, electrical power consumption, and electricity cost. This is shown in the figure 4.

From the graph, it can be observed that the pre-intervention power factor fluctuates between 0.78 and 0.82, indicating a consistently low and unstable performance. In contrast, post-intervention of the Arduino-controlled automatic capacitor bank, the post-intervention power factor significantly repaired, maintaining values between 0.90 and 0.99 across all weeks. This consistent improvement demonstrates that the system effectively compensates for reactive power and maintains a near-unity power factor under varying load conditions.

Overall, the graph shows a clear and stable enhancement in power factor performance following the intervention, validating the system's effectiveness in optimizing energy efficiency and reducing reactive power losses in household-scale electrical installations.

Results of Reducing Electrical Power Consumption (%) Although the percentage of improvement is smaller than the power factor, electrical power consumption also shows a positive and stable decrease in the range of 4.84% to 8.33%. This decrease proves that the improvement of the power factor directly correlates with energy efficiency, which leads to a reduction in the use of electrical power.

Results of Reducing Customer Issued Electricity Cost (%) During the two months of measurement, there was a stable decrease in electricity costs. In the first month, the savings reached 6.78% and increased slightly to 7.17% in the second month. Although only measured over two months, these figures show that the energy efficiency improvements resulting from the intervention have succeeded in significantly reducing customers' operational costs.

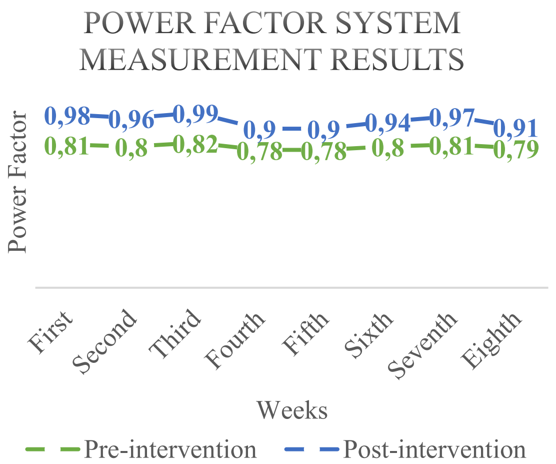

Figure 4. Power Factor System Measurement Results Graph

The validation test result for the Power Factor on the installation read by the device is 0.849. This value indicates a strong correlation between the data collected and the construct to be measured. Since 0.849 is close to 1, it indicates that the instrument or measurement used to measure the power factor has a high validity.

The reliability test result for the Power Factor on the installation read by the device is 0.839. This value indicates good internal consistency. The number 0.839, which is also close to 1, indicates that if the measurements are taken repeatedly, the results will tend to be consistent and reliable.

For Electrical Power Consumption, the validation test result is 0.995. This number is very close to 1, indicating an unusually high validity. As for Customer-Issued Electricity Costs, the validation test results reached 1,000, which indicates perfect validity. This means that the measurement instruments for both of these variables are very accurate in measuring what should be measured.

The reliability test result for Electrical Power Consumption is 0.979. This value is very close to 1, indicating very high consistency and reliability. Similarly, for Customer-Issued Electricity Costs, the reliability value is 1,000. This figure shows perfect consistency, which means that the measurement of electricity costs is very stable and reliable.

The results of this study demonstrate that the installation of a capacitor bank in household electrical installations successfully increased the power factor from 0.78–0.82 in the pre-intervention phase to 0.90–0.99 in the post-intervention phase, while also reducing both energy consumption and customer-issued electricity costs. These findings are comparable to those reported in reference [25], who applied an individual compensation method using capacitors on inductive household loads such as water pumps and refrigerators. Their study showed that power factor values improved significantly, reaching up to 0.99 and 1.0 after capacitor installation, accompanied by a decrease in apparent power consumption by as much as 14% on water pumps and 32% on refrigerators. The similarity between both studies lies in the ability of capacitor banks to provide reactive power compensation that reduces unnecessary reactive current, thereby improving power quality and overall efficiency. However, while in reference [25] focused on static and individual household loads, the present study evaluates dynamic household loads over a longer measurement period with pre- and post-intervention comparisons, thus strengthening the empirical evidence of capacitor banks as an effective solution not only for technical performance improvement but also for measurable economic savings.

During the power factor repairing process, the capacitor bank experienced an increase in body temperature. The strategy implemented by the researcher to address this issue was to avoid completely sealing the enclosure and instead allow ventilation openings for airflow. This approach was applied to manage the temperature of both the capacitors and the controller, ensuring that all components could operate under optimal thermal conditions for improved system performance. However, temperature rise remains one of the main weaknesses identified in this study, as prolonged heat exposure may reduce the lifespan and efficiency of the components. Therefore, future research is recommended to incorporate an active cooling system, such as the installation of a fan or other thermal management devices, to maintain a stable operating temperature and enhance the overall reliability of the capacitor bank system.

IV. Conclusion

The results of this study demonstrate that the implementation of an Arduino-controlled automatic capacitor bank in a household-scale electrical system effectively improves power quality and energy efficiency. The capacitor bank successfully increased the average power factor from 0.78–0.82 (pre-intervention) to 0.90–0.99 (post-intervention), representing an improvement of approximately 15–21%, while simultaneously reducing reactive power demand by around 40–45%. This improvement led to measurable benefits in energy consumption and cost efficiency, with electricity usage decreasing by 4.8–8.3% and customer-issued electricity costs dropping by 6.7–7.2% over the observation period. These findings confirm that the automatic capacitor bank system provides stable, reliable, and proportional reactive power compensation under varying household load conditions, validating both the theoretical design model and its real-world applicability. In addition to its technical effectiveness, the system design was proven practical and adaptive, utilizing commercially available capacitors of 6 μF, 12 μF, and 20 μF, which were closely aligned with theoretical calculations. The use of multiple capacitance steps enabled smoother compensation and reduced abrupt switching effects, contributing to system stability. However, one identified limitation is the temperature rise observed in the capacitor bank during operation, which may affect component longevity. As a result, future studies are encouraged to implement active cooling mechanisms, such as fan-based or thermal management systems, to further enhance reliability and maintain optimal performance. Overall, this research provides a strong foundation for the application of automated power factor correction systems in residential environments, combining both technical precision and economic benefit.

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