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Power Factor Correction of Solar Integrated Single-Phase System with Remote Monitoring through IoT

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KEYWORDS

Power Factor Correction, Solar Integrated System, Single-Phase Power System, Internet of Things (IoT), ESP32 Microcontroller, Reactive Power Compensation, Capacitor Bank, Smart Energy Management, Remote Monitoring, Power Quality Improvement

ABSTRACT

Real-time voltage, current, and power factor monitoring enable this PFC system to integrate solar energy into the grid. It monitors these parameters remotely via an internet connection and can view system data locally on a 16x2 lcd display and remotely via a web or mobile app. A PFC system's ESP32 controls a relay that turns on/off a capacitor bank based on power factor. If the power factor is below one, the capacitor bank activates to compensate for inductive load reactives. This variable-load PFC system can handle resistive and inductive loads. A battery-backed solar panel improves energy efficiency and reliability during grid instability. This intelligent method for smart power factor correction for residential and small commercial applications monitors power factor and reduces reactive power losses at a lower cost than traditional methods. This paper describes the IoT integrated single-phase PFC system development and construction. This solar-integrated PFC system uses an ESP32 to monitor and control real-time voltage, current, and power factor readings from the solar source and the grid. The power factor reading determines when to activate a capacitor bank via relay to compensate for inductive load reactive power. ESP32 can monitor and control resistive and inductive loads and has variable load capabilities. The system can be monitored locally via a 16x2 LCD display and remotely via a web or mobile app. A battery-backed solar panel improves energy efficiency and grid reliability.

1. INTRODUCTION

Electricity usage is rapidly growing, while renewable energy is increasingly being utilized. These factors are creating a new set of problems for modern power grids. A large number of these problems include power factor issues; reactive power loss; and inefficient use of energy. Issues related to power factor and reactive power are particularly acute in single-phase residential and small commercial installations that utilize inductive loads such as motors, transformers, fans, and other household devices. The inductive nature of most residential and commercial devices creates a lagging power factor that results in additional energy losses associated with the transmission lines; reduces the capacity of the distribution system; increases the cost of electricity; and requires frequent changes to manual switching mechanisms to optimize energy usage [1], [2]. Power factor correction (PFC) is one of the key means by which to correct these types of power quality issues. PFC is used to minimize reactive power requirements and maintain a near unitary power factor. Most traditional power factor correction (PFC) techniques employ fixed capacitor banks, or manual switching schemes, that are generally less than optimal in varying load conditions, and typically require routine manual intervention [3]. As a result of advancements in the field of embedded systems and communications technology, fully automated and intelligent power factor correction systems have become a viable solution to address the above mentioned shortcomings [4]. In addition to the need for improved automation and intelligence in power factor correction systems, the integration of solar photovoltaic (PV) systems into low-voltage distribution networks has become increasingly popular due to the environmental impacts of fossil fuels; rising costs of fossil fuels; and favorable government incentives for the adoption of renewable energy. While solar PV provides a clean and renewable source of energy, the intermittency of solar PV and its interaction with grid connected loads can exacerbate power quality issues related to voltage fluctuations, and reactive power imbalances [5], [6]. Therefore, coordinating solar generation and load side compensation is critical to ensuring the stability and efficiency of single phase systems. Modern developments in microcontrollers have made possible the continuous real-time monitoring and control of electrical parameters. High-performance microcontrollers like the ESP32 are capable of processing complex information quickly; consume little power; and possess built-in wireless connectivity, making them ideal for smart energy management applications [7]. Based on real-time monitoring of voltage and current waveforms, the microcontroller can determine the instantaneous power factor and activate the proper capacitor bank(s) to compensate for reactive power demands [8]. The Internet of Things (IoT) has also dramatically impacted the way energy monitoring and control systems operate. IoT enables platforms for seamless data transmission to cloud servers allowing for remote monitoring, data logging, predictive maintenance, and user friendly visualizations via web or mobile applications [9], [10]. Incorporating IoT into power factor correction systems, will significantly enhance transparency, operational efficiency, and fault detection; while reducing the necessity of on-site supervision. For solar-integrated systems, remote monitoring is particularly important since it will enable users and utilities to monitor their systems' performance; solar contributions; load behaviors; and compensation effectiveness in real-time. IoT based solutions also enable pro-active decision making by utilizing historical data analytics and notifications for abnormal operating conditions [11]. This type of functionality is especially valuable for distributed energy systems installed in remote or rural areas. Relay-controlled capacitor banks employing automatic power factor correction have been demonstrated to be a cost-effective and reliable method for correcting power factor in low- to medium-power applications. The incorporation of intelligent switching logic ensures that only the necessary quantity of reactive power compensation is provided, thereby precluding over-compensation and resonance [12]. Furthermore, these systems are able to accommodate both resistive and inductive loads, making them versatile in regards to real world operating conditions. Although several different PFC techniques exist, few of the available PFC systems incorporate renewable energy sources or provide the ability for real-time remote monitoring. Furthermore, traditional PFC systems are limited in terms of scalability, accessibility of data, and user interaction, all of which are desirable characteristics of modern smart-grid environments [13]. This demonstrates the need for a comprehensive solution that incorporates solar energy utilization; automatic power factor correction; and IoT-based monitoring within a singular framework. This project proposes to meet this challenge by designing a solar-integrated single-phase power factor correction system incorporating IoT-based remote monitoring. The system continuously monitors electrical parameters; automatically compensates for reactive power using capacitor banks; and provides real-time data access via cloud connectivity [14]. On-site visibility is enhanced by local display units; whereas, wireless communication enables access to the system remotely. The proposed system's objective is to improve overall power quality; reduce energy losses; increase system efficiency; and promote the effective utilization of renewable energy sources [15]. Utilizing the latest advancements in embedded controllers and IoT technologies, the proposed system will contribute towards the design of smart; efficient; and sustainable electrical power systems applicable for residential and small commercial applications.

II. System Configuration

This paper proposes an architecture that includes both a Solar Integrated Single Phase Power Factor Correction (PFC) System and IoT-based Monitoring and Control System as illustrated in Figure 1. An ESP32 Microcontroller controls all aspects of the system including acquisition of the electrical parameters and making decision based upon those parameters. Real time voltage and current signals from voltage and current sensors are fed into the ESP32 Microcontroller to calculate the required reactive power of the connected load. In addition to the Single phase PFC System, this system also incorporates a Solar Photovoltaic (PV) Panel and Battery Backup to increase the reliability and overall efficiency of the system. The PV Panel generates power for the control circuitry and a DC-DC Buck Converter is used to regulate the voltage to the required level to safely operate the Microcontroller, Sensors, Display, Relay Modules etc. To improve the power factor of the inductive loads, a relay controlled Capacitor Bank is utilized. When the required power factor is reached, the relay switches in or out of the capacitor bank to provide the required compensation for each inductive load to achieve a near unity power factor. The User Interface is provided by a 16x2 LCD with I2C interface which will provide the users with local displays of the values of the voltage, current, and power factors. The remote monitoring capability is supported by the ESP32 Microcontroller's built-in IoT connectivity that enables the system data to be sent to the Cloud Platform for real time viewing and analysis through web or mobile applications. The integrated architecture enables improved power quality, reduction of reactive power losses, and efficient use of solar energy in residential and small commercial single phase systems.

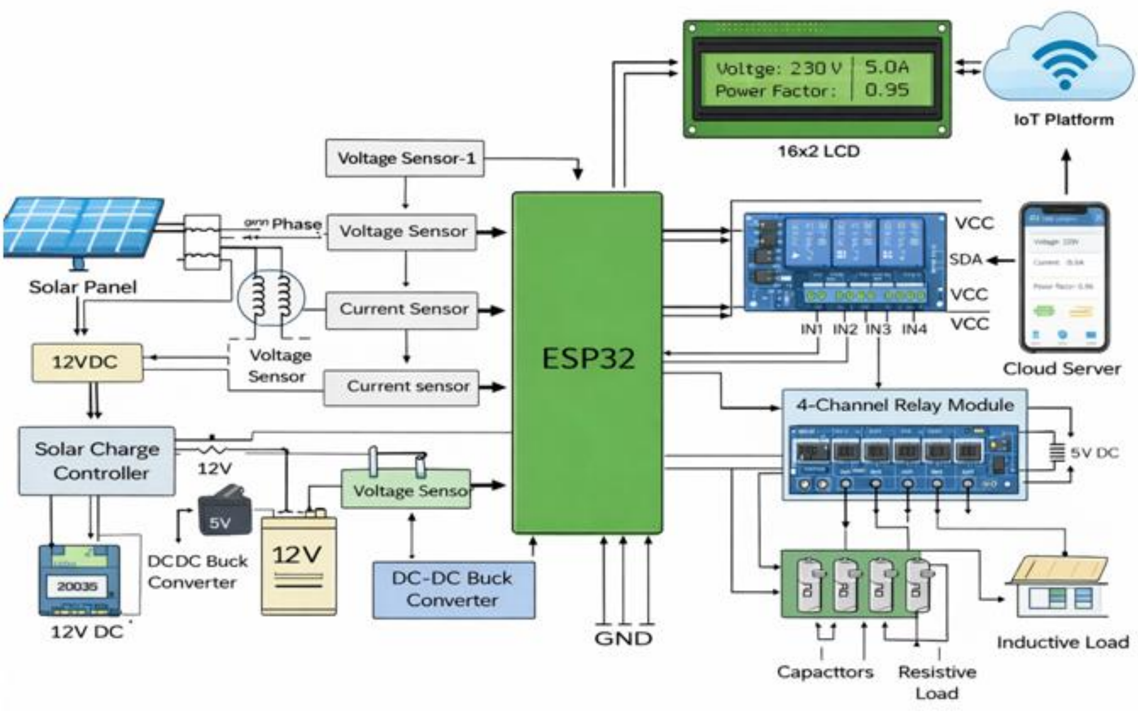

Fig.1 proposed system configuration

III. Modeling and Designing of proposed Configuration System

A. ESP 32

a. Modeling and Designing of ESP 32

ESP32 is at the center of an integrated single-phase PFC (Power Factor Correction) system using solar power. To model it, ESP32 works with several other parts to sense, calculate, and regulate many different variables within the system. Voltmeter sensor modules are interfaced with both the AC power line and solar/battery source to read voltage, while the ACS712 or CT current sensors read the load current. Analog outputs from the current and voltage sensors are sent to the ESP32's Analog Digital Converter (ADC) inputs to be converted into digital values for use by the ESP32. The ESP32's GPIO ports are used to communicate with a relay module to turn capacitor banks on/off to provide reactive power compensation as illustrated in Fig. 2. The ESP32 communicates with a 16 x 2 LCD display using the I2C protocol to display the measured voltage, current, and power factor values locally. The ESP32 has a built-in WiFi module to connect the system to the Internet to send the real-time measurement data to a cloud platform or a mobile application. This configuration allows the ESP32 to serve as the central processing unit (CPU) of the system, providing all of the necessary functions (sensing, calculation, control, communication) required for the operation of the system in one compact package.

b. Working and Operation of ESP32

In operation, the ESP32 continuously reads analog signals from the voltage and current sensors to monitor the real-time electrical parameters of the AC supply, solar panel, and battery. Using these inputs, it calculates the RMS voltage, RMS current, active power (P), reactive power (Q), apparent power (S), and power factor (PF) using standard formulas:

$$P = V_{rms} \cdot I_{rms} \cdot \cos\phi \quad (1)$$

$$Q = V_{rms} \cdot I_{rms} \cdot \sin\phi \quad (2)$$

$$PF = \frac{P}{S} \quad (3)$$

The ESP32 will activate the relay module to insert the capacitor bank in the circuit as soon as it detects that the power factor is lower than a pre-set limit. As long as the power factor continues to be lower than the pre-set limit or when the power factor goes above zero (or begins to lead), the ESP32 will remove the capacitors from the circuit and restore balance. In addition, the ESP32 continually sends the most recent voltage, current and power factor values to an LCD and to a remote server through Wi-Fi where they can be viewed on a computer or mobile device. The entire reactive power management is made possible through continuous automation by the ESP32; and the single-phase system runs smoothly and efficiently under all operating conditions; and the solar energy can be used intelligently and effectively in the single-phase system.

B. Solar and battery integrated with Grid Power Supply

The ESP32 microprocessor controls the system as an intelligent processor that handles the sensing of all parameters, the calculation of all parameters, the control of the system, and also provides wireless connectivity to enable the Internet-of-Things (IoT) interface. As depicted in Fig. 2, the system draws power from two sources, i.e., the Alternating Current (AC) grid and the Solar-Battery Backup System. The Power Supply Section is composed of a 12V DC Battery, a 12V Solar Panel and a Solar Charge Controller which prevents the battery from being overcharged and regulates the rate at which the battery is charged by the solar panel. The DC-DC Buck Converter then reduces the 12V DC to 5V or 3.3V to provide DC power to the ESP32, sensors, and relay modules. The ESP32 is interfaced with Voltage Sensors connected to both the AC Grid and Solar/Battery and with a Current Sensor to measure the current flowing through the Load. The ESP32 reads the input signal from the ADC Pins to compute the RMS Value of the Voltage, RMS Value of the Current, Active Power (P), Reactive Power (Q), Apparent Power (S) and Power Factor (PF) using standard equations. Depending upon the computed value of the power factor, the ESP32 automatically switches on/off the relay module to connect/disconnect the Capacitor Banks to compensate for the reactive power and maintain the Power Factor close to unity. For the purpose of monitoring, the ESP32 communicates with a local 16x2 LCD Display and sends the real time data wirelessly to a cloud server or mobile application to allow remote monitoring of the system. The system can draw power from the grid during periods of low solar availability or use the Solar-Battery Backup System when the grid is unstable. The integrated design of the proposed system enables continuous, efficient, and intelligent Power Factor Correction; seamless integration of solar energy into the system; and remote monitoring and control capability through IoT technology.

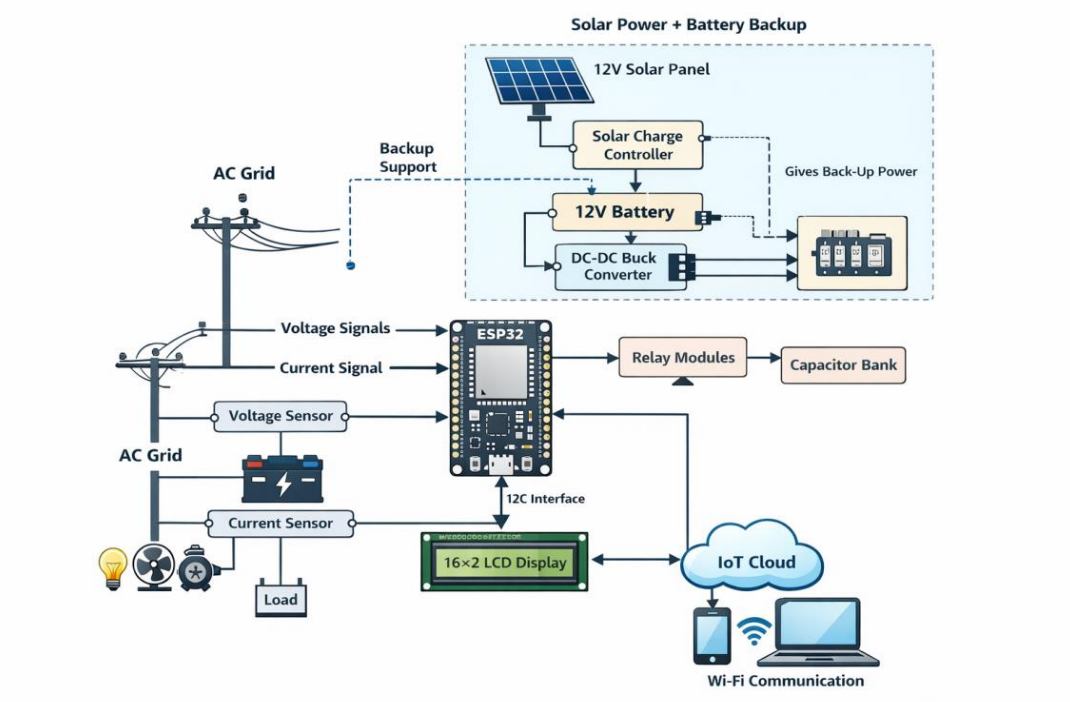

Fig.2 Solar power system schematic with ESP32

C. Voltage and Current Sensing, Monitoring, and Control

In the proposed solar integrated single phase PFC system the measurement and control of electrical parameters rely heavily on the use of voltage and current sensing modules. The first voltage sensor module (Voltage Sensor Module – 1) is located across the ac supply to enable safe measurement of the ac grid voltage. The voltage sensor module converts the high ac mains voltage to a low level voltage which is compatible with the analog input of the esp32 microcontroller so that the microcontroller can compute the rms voltage, instantaneous power and the overall power factor. The second voltage sensor module (Voltage Sensor Module – 2) is attached to the dc side of the solar panel and the battery to ensure that all the energy generated by the solar panel is utilized efficiently and that there is proper integration of the solar energy into the grid. The current sensor module (acs712 or a current transformer) is used to measure the current supplied to the load from the grid and the solar and battery source as illustrated in Figure.3. The esp32 constantly monitors the data from the above mentioned sensors and calculates the real time electrical parameters of the system i.e., voltage, current, power and power factor. Based on these calculated values the esp32 can automatically control the relay driven capacitor bank to counteract the reactive power losses due to inductive loads. Additionally the computed electrical parameters are displayed on a 16×2 lcd display and the computed electrical parameters are transmitted to a cloud platform using the internet of things (iot), hence enabling remote monitoring, remote analysis and remote diagnostics. The combination of sensing, computing and control in this system enables improved power quality, increased efficiency of the utilization of the solar generated energy and reliable operation of the system at varying loads.

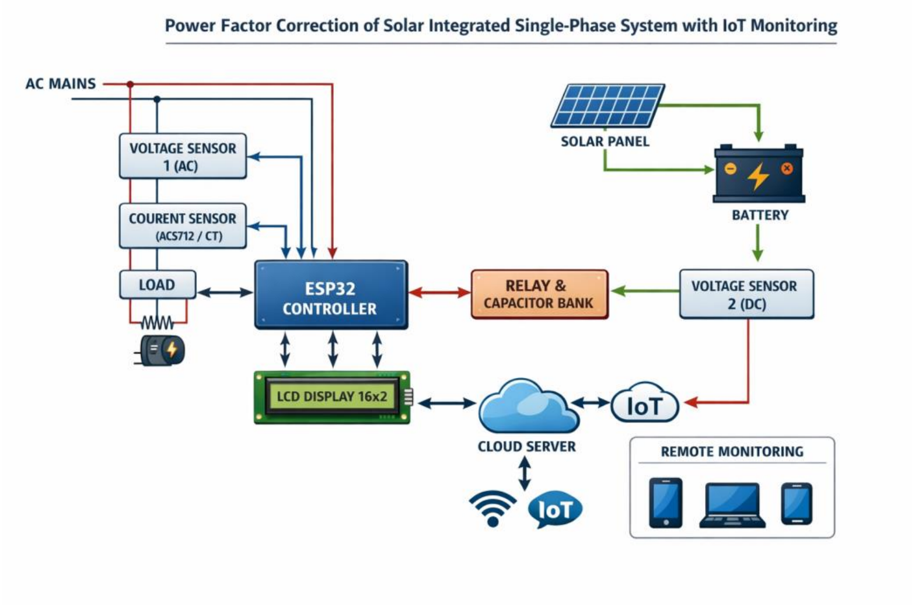

Fig.3 designing of power sensor unit

D. 16×2 LCD Display with I²C Interface

The 16 × 2 Liquid Crystal Display (LCD) shows users' real time electrical parameters, for example; voltage, current, energy consumption and a user's remaining prepaid balance, as can be seen in Figure.4. The I²C interface makes use of only two wires (SDA and SCL) that communicate between the ESP32, thus reducing the number of pins required to interface the display and simplifying the overall wiring of the system. The values are periodically updated on the display with the calculated data.

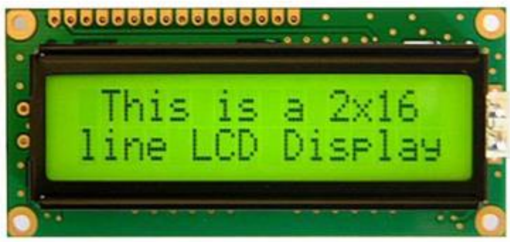

Fig.4 16×2 LCD Display

8. 4-Channel Relay Module

The relay module enables switching and control of multiple electrical loads as shown in Figure.5. The ESP32 controls each relay based on prepaid balance and peak load conditions. When the total power exceeds the preset threshold P_{max} , low-priority loads are disconnected:

Fig.5 Relay Module

$If\ P > P_{max} \Rightarrow$ Load shedding initiated

Similarly, when the prepaid balance reaches zero, the relay controlling the main load is turned OFF automatically.

6. Power Factor Correction with Capacitor Bank

In the proposed single-phase solar-integrated system, the capacitor bank is the primary reactive power compensator. All inductive loads, such as motors, fans, and transformers, have a negative reactive power (i.e., they take lagging reactive power) and therefore reduce the overall power factor of the system, increasing the losses on the distribution lines. Therefore, when the capacitor bank provides positive reactive power (i.e., it provides leading reactive power), the lagging reactive power provided by all the inductive loads will be neutralized and the overall power factor of the system will improve, and thus the voltage will be stabilized. The ESP32 microcontroller continuously measures the voltage, current and power factor through various types of sensors and switches the appropriate amount of capacitors through relay control to adjust the power factor so that it is as close to unity as possible. Thus, this type of adaptive adjustment allows for an efficient use of the two forms of energy; namely, the grid energy and the solar-battery energy, while also allowing for reduced line losses.

$$Q_L = V_r \cdot I_r \cdot \sin(\phi) \quad (4)$$

$$Q_c = Q_L - P \cdot \tan(\cos^{-1}(PF_{desired})) \quad (5)$$

$$C = \frac{Q_C}{2\pi f V_{rms}^2} \quad (6)$$

7. Resistive and Inductive Loads

The Load Section of the System includes Resistive Loads (such as light bulbs/heaters) and Inductive Loads (such as induction motors/fans/transformers). Resistive loads are characterized by in-phase relationships between voltage and current resulting in negligible reactive power and a nearly unity power factor. Inductive loads produce a lag relationship between the current and voltage, producing lagging reactive power. In response, the ESP32 continually monitors these electrical parameters and calculates the appropriate amount of reactive power that needs to be supplied to compensate for the lagging component. This is accomplished by controlling the activation/deactivation of the capacitor bank via relay switching. Once activated, the capacitor bank will supply leading reactive power which in turn will improve the power factor of the load, minimize energy losses, and maintain a stable voltage regardless of load changes.

For resistive loads:

$(PF \approx 1), (Q \approx 0)$

For inductive loads:

$$\left(Q_L = \sqrt{S2 - P2} = P \cdot \tan(\cos^{-1}(PF_{\text{actual}}))\right) \quad (7)$$

$$\left(PF_{\text{corrected}} = \frac{P}{\sqrt{P^2 + (Q_L - Q_C)^2}}\right) \quad (8)$$

8. Protection and Supporting Components

Protective and support systems are developed for secure, reliable operation of the system. Overcurrent protection is provided by fuses, miniature circuit breakers (MCBs), and snubbers protect relay contacts from voltage spikes due to inductive load current; excessive heat generated in switching devices, such as relays or MOSFETs, is dissipated through heat sinks that prevent thermal failure. As a result of these protective and support systems, the ESP32 can reliably control the system, rapidly switch the capacitor bank, and provide optimal power factor and stable voltage without damaging any of its operating components.

Fuse Rating:

$I_f \geq 1.25 \cdot I_{load}$

Voltage Spike due to Inductive Kickback:

$$V_{spike} = L \cdot \frac{di}{dt} \quad (9)$$

Snubber Design:

$$R_s \leq \frac{V_{relay}^2}{P_{snubber}} \quad (10)$$

$$C_s \geq \frac{I_{load} \cdot dt}{V_{spike}} \quad (11)$$

Heat Sink Design:

$$R_{th} = \frac{T_{max} - T_{ambient}}{P_{diss}} \quad (12)$$

IV. Results and Discussion

The efficiency of the proposed solar-integrated single-phase PFC (Power Factor Correction) was studied under inductive and resistive loading conditions. Under inductive loading, the initial power factor was found to be 0.48; this indicated the presence of a large reactive power component as can be seen from Figure. 6-10. The ESP32 monitored the electrical parameters and automatically controlled the relay-driven capacitor bank to eliminate the reactive power present due to the inductive load. Upon sequential activation of each capacitor bank, the power factor consistently improved. The power factor improved upon switching of the first capacitor to 0.62, then to 0.72 with the second capacitor, and finally to 0.82 with the third capacitor. The power factor was brought up to 0.99 with the fourth capacitor bank, thus achieving almost unity power factor. These results illustrate how the automatic capacitor switching strategy effectively compensates for reactive power and increases the overall system efficiency. Under resistive loading, the voltage and current remain in phase and therefore the power factor remains at unity throughout the operation. This demonstrates that the system does not over-compensate and operates appropriately based on the type of load that is being used. The solar panel served as a supplementary energy source and reduced the dependence on the grid while the battery backed operation provided for continuous operation through various grid supply fluctuations. Real-time data, including power factor, solar power contribution, and battery voltage were provided on the ThingSpeak IoT platform as shown in Figure.11. As the power factor improved, there was a consistent decrease in the battery current consumed, demonstrating efficient use of energy. Therefore, the results confirm that the proposed system successfully corrects power factor, improves power quality, and provides remote monitoring capabilities, and is applicable for residential and small commercial applications.

Fig 6: Physical kit of the project

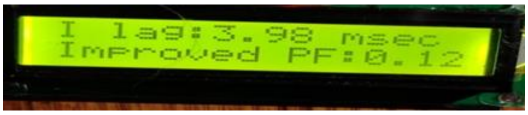

Figure 7: Improved power factor value after switching to 1 capacitor bank.

Figure 8: Total power factor after switching to 2 capacitor banks.

Fig 9: Total power factor value after switching to 3 capacitor banks.

Fig 10: improved power factor after switching to 4 capacitor banks.

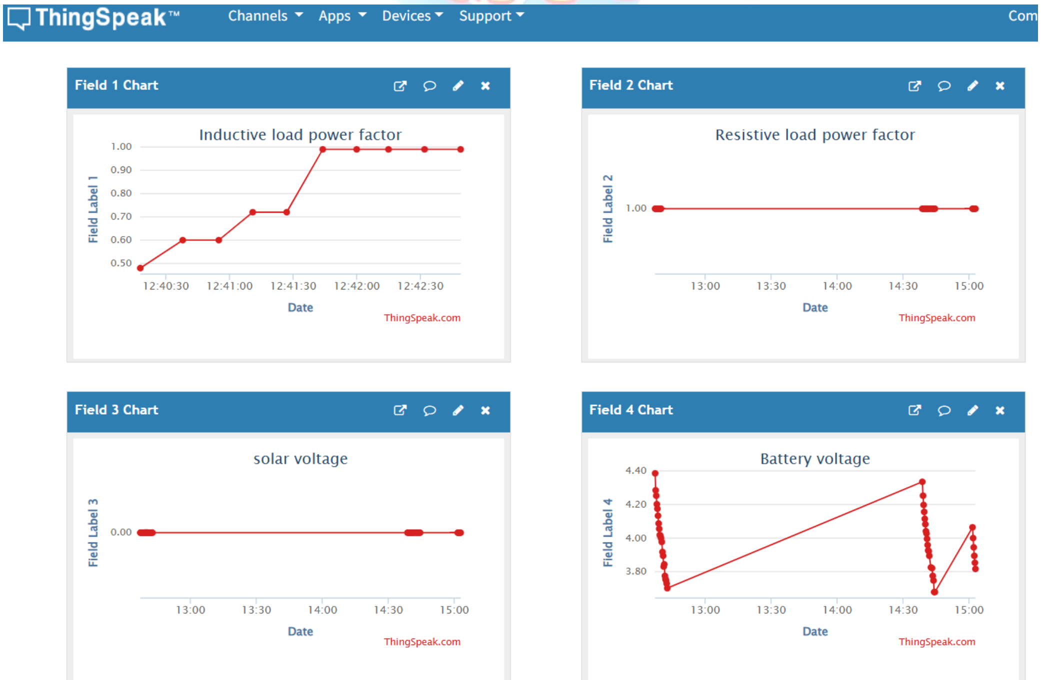

Fig. 11 Graphical results obtained in Thing speak application.

5. Conclusion

The Solar Integrated Single-Phase Power Factor Correction System with IoT Remote Monitoring was designed and implemented. This is a new solution to maintain the power factor close to one (unity) with an automatic reactive power compensation with a relay-controlled capacitor bank. This maintains power quality. The proposed system used a relay controlled capacitor bank to automatically compensate for reactive power. The proposed system also had an ESP32 Microcontroller which was able to monitor real time electrical parameters (voltage, current, power factor) and to dynamically switch the capacitor banks based upon the condition of the load. The experimental results have shown that this proposed system operates efficiently both with resistive loads and inductive loads without over compensating for reactive power, thus allowing the system to be stable and reliable. The addition of solar and battery backup reduces the dependency of the system on the grid and enhances the reliability of the system during voltage fluctuation and power interruption. The IoT monitoring platform allows for real time viewing and analysis and remote access to all the parameters of the system, and is therefore appropriate for smart energy management application. Overall, the proposed system presents a cost effective, intelligent and scalable way of providing power factor correction and is ideal for residential and small commercial installations. The study shows the potential of combining renewable energy sources with smart control and IoT technologies to provide energy efficiency and high quality power in modern electrical systems.

Conflict of interest statement

Authors declare that they do not have any conflict of interest.

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