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IoT-Based Automatic Power Factor Correction with Real-Time Carbon Footprint Estimation

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Abstract: ***IoT-based Automatic Power Factor Correction (APFC) system with real-time carbon footprint estimation aimed at improving electrical efficiency and promoting sustainable energy usage. The system uses the Raspberry Pi Pico W microcontroller to continuously monitor voltage and current through Potential Transformers (PT), Current Transformers (CT), and a Zero-Crossing Detector (ZCD) to calculate the real-time power factor of an electrical load. Based on the measured power factor, the controller automatically switches capacitor banks using relay modules to compensate for lagging power factor and maintain it close to unity, thereby reducing reactive power, minimizing energy losses, and avoiding utility penalties. To quantify environmental impact, the system calculates CO_2 savings in real-time by correlating the reduction in energy losses. The measured parameters, including power factor, real power, and estimated CO_2 savings, are displayed on an LCD and transmitted to the ThingSpeak IoT cloud platform for remote monitoring and data logging. The system was initially validated through simulation using MATLAB and Simulink, followed by successful hardware implementation and testing. The obtained results demonstrate effective power factor correction and reliable real-time monitoring. This low-cost and scalable system provides a practical solution for smart power management and supports global sustainability efforts aligned with the United Nations Sustainable Development Goals, particularly SDG 7 – Affordable and Clean Energy and SDG 13 – Climate Action.***

Keywords: Automatic Power Factor Correction (APFC), Internet of Things (IoT), Carbon Footprint Estimation, Capacitor Bank Switching, Power Factor Monitoring, ThingSpeak Dashboard, Energy Efficiency, Smart Energy Management.

I. INTRODUCTION

The increasing global demand for electrical energy has intensified the need for efficiency improvements in power systems. In AC systems dominated by inductive loads such as induction motors and transformers, low lagging power factor (PF) is a major issue that leads to increased current flow, higher (I^2R) losses, voltage drops, reduced system capacity, and financial penalties. Conventional Automatic Power Factor Correction (APFC) systems improve PF by switching capacitor banks based on reactive power demand; however, they lack advanced features such as remote monitoring, real-time analytics, and environmental impact assessment. With the emergence of IoT technologies, power management systems can now incorporate real-time data acquisition, remote control, cloud integration, and sustainability tracking.

This project proposes an IoT-based APFC system using Raspberry Pi Pico W that not only corrects power factor to near-unity but also estimates and displays the real-time reduction in CO_2 emissions achieved through improved efficiency. The objectives include automatic PF correction, reduction of energy losses and penalties, real-time carbon footprint estimation, and promotion of environmental awareness. The report covers the system background and objectives, literature review, detailed system design and implementation, MATLAB/Simulink simulation and performance validation, and concludes with key findings and future enhancement possibilities.

II. SYSTEM DESIGN AND METHODOLOGY OF APFC SYSTEM

A. System Architecture and Hardware Implementation

The proposed IoT-based Automatic Power Factor Correction (APFC) system integrates conventional reactive power compensation techniques with modern IoT capabilities to create a cost-effective, scalable, and intelligent solution for power quality improvement and environmental monitoring. The design approach focuses on continuous sensing of electrical parameters, intelligent decision-making, automated capacitor switching, and real-time data communication to both local and cloud interfaces. The system operates on the principle of reactive power compensation by detecting low power factor conditions and switching appropriate capacitor banks to maintain near-unity power factor. As illustrated in Figure 1, the architecture consists of sensing, processing, actuation, and communication subsystems working together to ensure efficient power factor correction while quantifying environmental impact.

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The sensing subsystem uses Potential Transformers (PT) and Current Transformers (CT) to safely measure line voltage and current with galvanic isolation. Signal conditioning circuits scale and filter these signals before processing. Zero Crossing Detectors convert sinusoidal waveforms into square pulses, and an XOR logic circuit determines the phase difference between voltage and current, enabling accurate power factor computation.

The Raspberry Pi Pico W serves as the central controller due to its computational efficiency, cost-effectiveness, and built-in WiFi connectivity. It performs real-time calculations of electrical parameters, executes the control algorithm, manages IoT communication, and computes carbon savings. The actuation subsystem includes multiple capacitor banks arranged in binary weighted configuration and controlled using relay driver circuits, enabling precise reactive power compensation through staged switching.

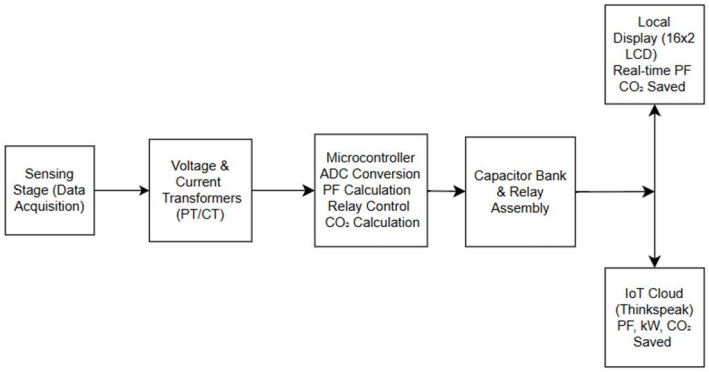


Fig. 1 Complete system architecture of IoT-based APFC with carbon footprint estimation

The operational sequence begins with continuous monitoring of voltage and current signals, followed by phase difference calculation and power factor evaluation. Based on predefined threshold values, suitable capacitor banks are activated to improve power factor, and correction effectiveness is verified through continuous feedback measurement.

B. Software Development and Environmental Impact Assessment

Software implementation is developed using MicroPython due to its simplicity and extensive library support. Program modules include sensor data acquisition, signal filtering, power factor calculation, relay control with debounce protection, LCD display handling, WiFi connectivity, and cloud communication. Integration with the ThingSpeak IoT platform enables transmission of real-time parameters such as power factor, active power, reactive power, and carbon savings for remote monitoring and historical analysis.

An environmental impact assessment module calculates the amount of CO_2 emissions prevented due to power factor correction using the relation:

$$CO_{2\ saved} = \frac{EF \times \sqrt{3}\,V \times (I_1 pf_1 - I_2 pf_2) \times t}{1000}$$

Where V is Line-to-line voltage (Volts), I_1 & I_2 is Load current before and after power factor correction (Amperes), pf_1 & pf_2 denotes Power factor before and after correction, t represents Operating time (hours) and EF denotes Emission factor = 0.8 kg/kWh. Real-time display of CO_2 savings on LCD and IoT dashboards highlights sustainability benefits alongside economic advantages.

The integrated architecture combines conventional APFC principles with intelligent control, IoT connectivity, and environmental monitoring. Reliable operation, efficient power factor improvement, and practical implementation feasibility make the system suitable for modern industrial and commercial applications focused on energy efficiency and sustainability.

III. SIMULATION AND RESULTS

A. Simulation Setup, Architecture and Working Methodology

Simulation and IoT visualization results validate the proposed IoT-based Automatic Power Factor Correction (APFC) system integrated with real-time carbon footprint estimation. MATLAB/Simulink with Power-GUI configuration was used to model the system due to its high accuracy in electrical network analysis and transient behavior evaluation.

The simulation verifies real-time power factor computation, automatic capacitor bank switching, and estimation of carbon dioxide emission savings. Integration with the ThingSpeak platform enables cloud-based monitoring and confirms the feasibility of remote visualization. The simulated environment models a single-phase APFC system operating under varying inductive load conditions ranging from 5 kW to 14 kW. The system includes an AC voltage source (230 V, 50 Hz), PT and CT sensors for voltage and current measurement, Zero Crossing Detectors (ZCD) for waveform conversion, XOR logic for phase difference detection, a controller subsystem representing Raspberry Pi Pico logic, relay-controlled capacitor banks (C1–C4), and a ThingSpeak interface for IoT communication

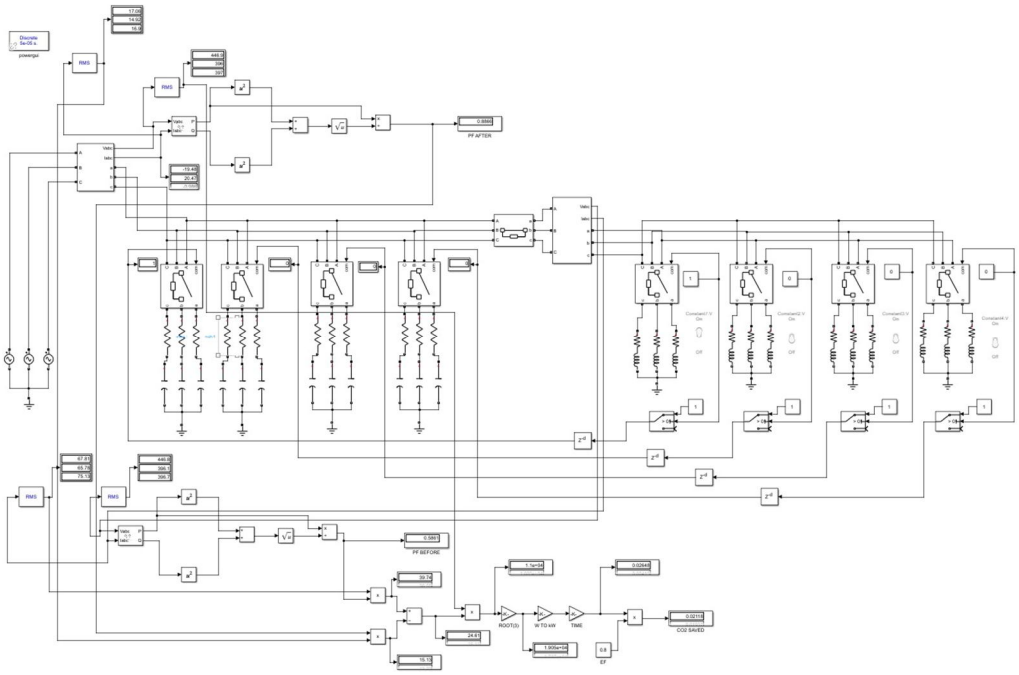


Fig. 3 Simulink model of the APFC relay showing integrated measurement, control, and capacitor bank switching logic.

Voltage and current signals are first sensed through PT and CT modules. Zero Crossing Detectors convert sinusoidal signals into square pulses, and XOR logic measures the phase difference (Δt). The phase angle is calculated using:

$$\phi = \Delta t \times f \times 360^0$$

Power factor is computed using:

$$PF = cos(\phi)$$

When the power factor falls below 0.95, capacitor banks are switched sequentially until PF approaches unity.
Environmental impact estimation is implemented using:

$$CO_{2\,saved} = \frac{EF \times \sqrt{3}\,V \times (I_1 pf_1 - I_2 pf_2) \times t}{1000}$$

Where V is Line-to-line voltage (Volts), I_1 & I_2 is Load current before and after power factor correction (Amperes), pf_1 & pf_2 denotes Power factor before and after correction, t represents Operating time (hours) and EF denotes Emission factor = 0.8 kg/kWh

B. Simulation Results, Performance Analysis and IoT Visualization

Performance evaluation was conducted under two operating scenarios. Before correction, inductive loads exhibited lagging power factors ranging from 0.70 to 0.94 with higher reactive power and line current.

After automatic capacitor bank switching, the power factor improved between 0.82 and 0.97, resulting in reduced reactive power demand, lower line current, and measurable CO_2 savings. Table I presents the variation of load power, corresponding power factor before correction, improved power factor after automatic switching, and estimated CO_2 savings.

TABLE I
LOAD POWER, POWER FACTOR IMPROVEMENT, AND CO2 SAVINGS

Load Power (Inductive)	Power Factor (Before)	Improved Power Factor	CO_2 Saved (Kg/S)
50 KW	0.5884	0.8866	0.02118
51 KW	0.5869	0.9156	0.00225
52 KW	0. 5855	0.9445	0.02332
53 KW	0. 5841	0.9598	0.02414

IoT visualization through ThingSpeak demonstrates real-time monitoring capability. The dashboard displays power factor values before and after correction along with calculated CO_2 savings.

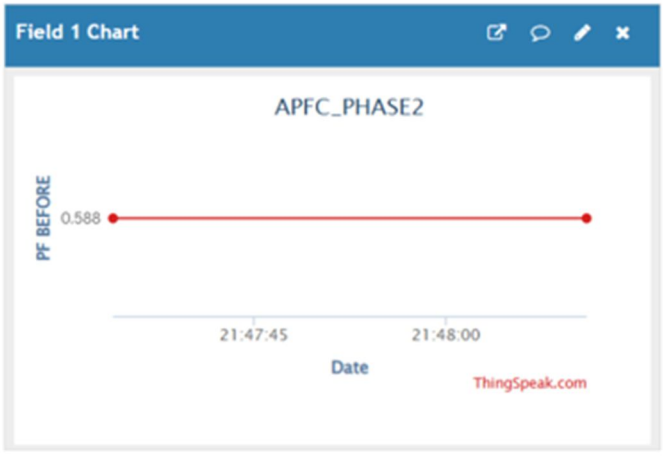


Fig. 4 Power factor monitoring on ThingSpeak dashboard before correction

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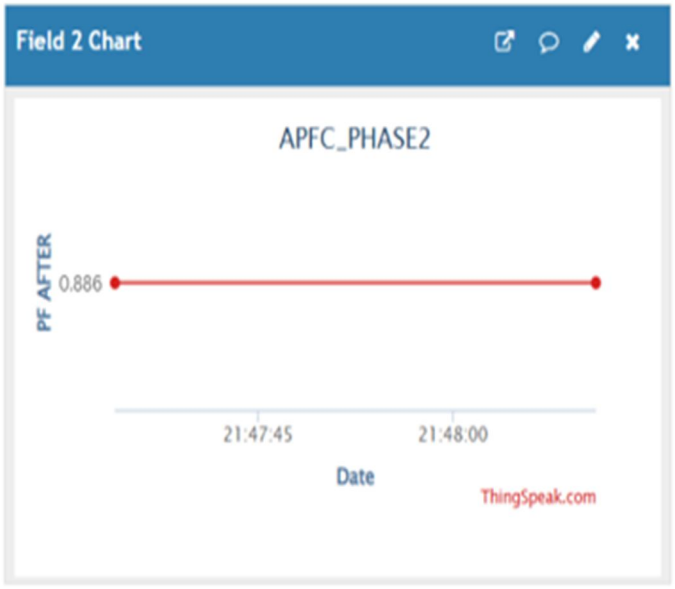


Fig. 5 Updated power factor displayed on ThingSpeak after correction

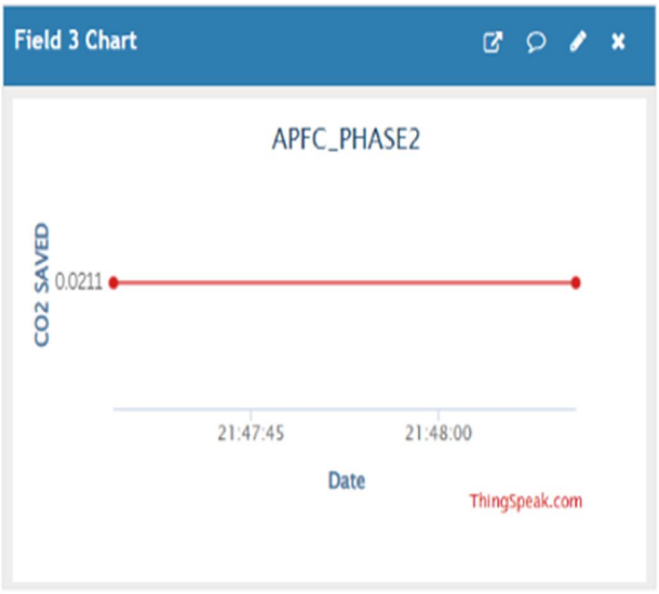


Fig. 6 CO2 savings visualization on ThingSpeak corresponding to PF improvemen

Simulation results confirm effective power factor correction across varying load levels, reduction in reactive power and current, and accurate estimation of carbon emission savings. Real-time IoT integration ensures reliable monitoring, data logging, and visualization, demonstrating the suitability of the proposed system for smart energy management and sustainable power utilization.

IV. SYSTEM OPERATION AND WORKING PRINCIPLE

The operational workflow of the proposed IoT-based Automatic Power Factor Correction (APFC) system consists of four major stages: signal acquisition, digital conversion, computational processing, and corrective action with IoT logging. The complete hardware prototype is shown in Figure 7.

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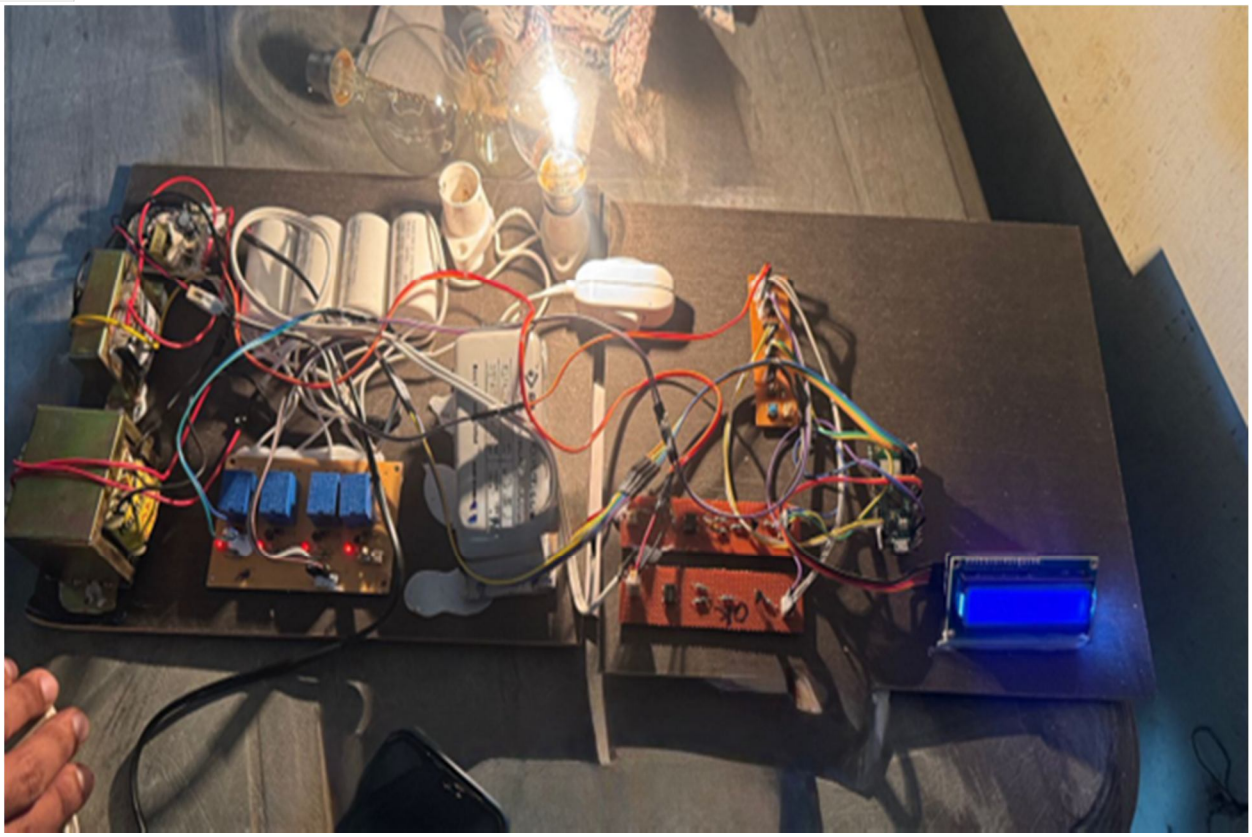


Fig. 7 Hardware of the IoT-Based Automatic Power Factor Correction System

A. Signal Acquisition

The operation of the proposed system begins with real-time sensing of electrical parameters using a Potential Transformer (PT) and a Current Transformer (CT). The PT steps down the 230 V AC supply voltage to a lower measurable level while providing electrical isolation from the main power line. Similarly, the CT senses the current flowing through the connected loads. These scaled voltage and current signals preserve the waveform characteristics required for accurate phase analysis. The analog voltage and current signals are then fed into Zero Crossing Detector (ZCD) circuits for phase comparison.

B. Digital Conversion Using Zero Crossing Detection

The Zero Crossing Detector circuits convert the sinusoidal voltage and current waveforms into digital square waves suitable for microcontroller processing. Each ZCD consists of a bridge rectifier and transistor switching arrangement that generates clean logic-level pulses. Whenever the AC waveform crosses the zero-voltage point, the output signal transitions between LOW and HIGH states. Consequently, the sinusoidal waveform is transformed into a square wave with the same frequency but with clearly defined edges that can be processed by the controller. These digital pulses are connected directly to the GPIO pins of the Raspberry Pi Pico W for precise timing analysis.

C. Phase Measurement and Decision Logic

The Raspberry Pi Pico W acts as the central controller of the system. It measures the time difference (Δt) between the rising edges of the voltage and current square waves obtained from the ZCD circuits. Using the system frequency of 50 Hz, the phase angle (ϕ) between voltage and current is calculated as

$$\phi = \Delta t \times f \times 360^{\circ}$$

The power factor is then computed using

$$PF = \cos(\phi)$$

If the calculated power factor falls below the predefined threshold value of 0.85, the controller activates the correction mechanism. This digital method enables accurate phase tracking without requiring complex analog signal processing techniques.

D. Reactive Power Compensation and IoT Logging

When a low power factor condition is detected, the Raspberry Pi Pico W sends a control signal to the relay module to initiate reactive power compensation. The relay connects a 2.5 µF capacitor bank in parallel with the inductive load. This introduces leading reactive power into the system, compensating for the lagging reactive power drawn by the load. As a result, the phase difference between voltage and current decreases and the overall power factor improves toward unity.

In addition to electrical correction, the system estimates the environmental impact by calculating the reduction in carbon dioxide emissions achieved through improved power factor.

The CO_2 savings are calculated using the following expression:

$$CO_{2\ saved} = \frac{EF \times \sqrt{3}V \times (I_1 pf_1 - I_2 pf_2) \times t}{1000}$$

Where V is Line-to-line voltage (Volts), I_1 & I_2 is Load current before and after power factor correction (Amperes), pf_1 & pf_2 denotes Power factor before and after correction, t represents Operating time (hours) and EF denotes Emission factor = 0.8 kg/kWh

All computed parameters including voltage, current, power factor, and CO_2 savings are transmitted through Wi-Fi to the ThingSpeak cloud platform. This enables real-time monitoring, historical data logging, and remote performance analysis of the system.

The proposed architecture integrates electrical measurement, digital signal processing, intelligent compensation, and environmental analytics into a unified IoT-enabled framework. Unlike conventional APFC systems, the presented design not only improves electrical efficiency but also quantifies sustainability impact in real time.

The performance of the developed hardware prototype was verified using different load configurations consisting of incandescent bulbs. The measured power factor values before and after compensation, along with the estimated CO_2 savings, are summarized in Table III.

TABLE III
HARDWARE PERFORMANCE VERIFICATION

Load Configuration (BULB + CHOKE)	Power Factor (Before)	Power Factor (After)	CO_2 Saved (Kg/hr)
60W	0.64	0.94	0.00025

100W	0.68	0.95	0.00033
160 W	0.70	0.96	0.00045
200 W	0.715	0.97	0.00060

The experimental results presented in Table III verify the effectiveness of the developed APFC hardware system under different load configurations. The measured power factor before compensation varies between 0.65 and 0.78 due to the inductive characteristics of the connected loads. After the capacitor bank is activated through the relay module, the power factor improves significantly, reaching values between 0.94 and 0.99. This improvement confirms that the proposed control strategy successfully reduces the phase difference between voltage and current by injecting leading reactive power. In addition to electrical performance improvement, the calculated CO_2 savings values indicate the potential environmental benefits achieved through enhanced power factor and improved energy utilization. IoT visualization through ThingSpeak demonstrates real-time monitoring capability. The dashboard displays power factor values before and after correction along with calculated CO_2 savings.

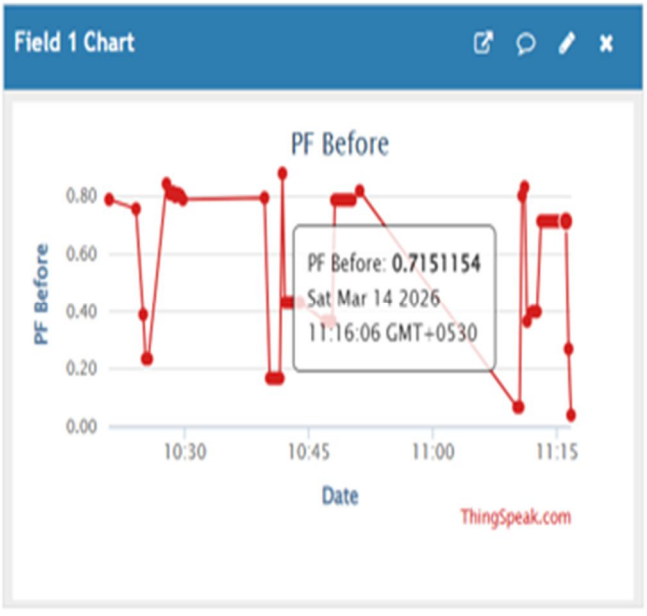


Fig. 8 Power factor monitoring on ThingSpeak dashboard before correction

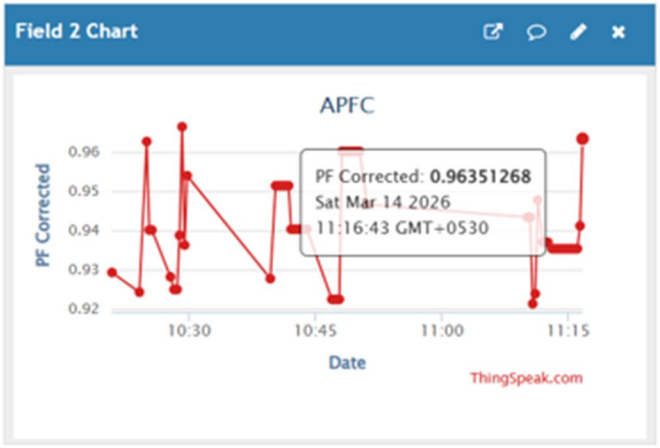


Fig. 9 Updated power factor displayed on ThingSpeak after correction

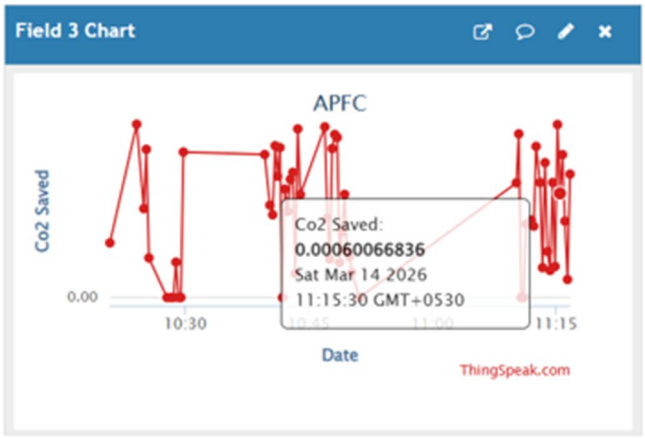


Fig. 10 CO2 savings visualization on ThingSpeak corresponding to PF improvement.

V. CONCLUSIONS

The design and implementation of an IoT-enabled Automatic Power Factor Correction (APFC) system integrated with real-time carbon footprint estimation have been presented and validated. The proposed architecture continuously monitors voltage and current signals using PT and CT modules, determines phase displacement through zero-crossing detection, and performs intelligent capacitor bank switching using a Raspberry Pi Pico W controller. Both simulation and experimental analysis confirm effective improvement of power factor from 0.70–0.94 to values approaching unity (0.95–0.99), resulting in reduced reactive power demand and lower line current. In addition to electrical performance enhancement, the integration of carbon emission estimation enables quantification of environmental benefits associated with power factor correction. The calculation of CO_2 savings and cloud-based visualization through the ThingSpeak platform demonstrate the feasibility of combining energy efficiency improvement with sustainability assessment within a unified IoT framework. The developed architecture provides a cost-effective, scalable, and intelligent solution suitable for industrial and commercial energy management applications. Future extensions may include three-phase implementation, adaptive compensation strategies, and integration with renewable energy systems to enhance compatibility with modern smart grid infrastructures. This low-cost and scalable system provides a practical solution for smart power management and supports global sustainability efforts aligned with the United Nations Sustainable Development Goals, particularly SDG 7 – Affordable and Clean Energy and SDG 13 – Climate Action.

REFERENCES

[1] M. A. H. S. Kamal, M. N. Hasan, and M. F. Hossain, “Design and implementation of IoT-based automatic power factor correction relay using Raspberry Pi,” in *IEEE 1st International Conference on Smart and Sustainable Developments in Electrical Engineering (SSDEE)*, 2025.

[2] S. Mane, R. Sapat, P. Kor, J. Shelar, R. D. Kulkarni, and J. Mundkar, "Microcontroller-based automatic power factor correction system for power quality improvement," *IEEE Xplore, Jun. 2020.*

[3] D. G. Lamar, A. Fernandez, M. Arias, M. Rodriguez, J. Sebastian, and M. M. Hernando, "A unity power factor correction preregulator with fast dynamic response based on a low-cost microcontroller," *IEEE Transactions on Power Electronics*, vol. 23, pp. 635–642, Mar. 2008.

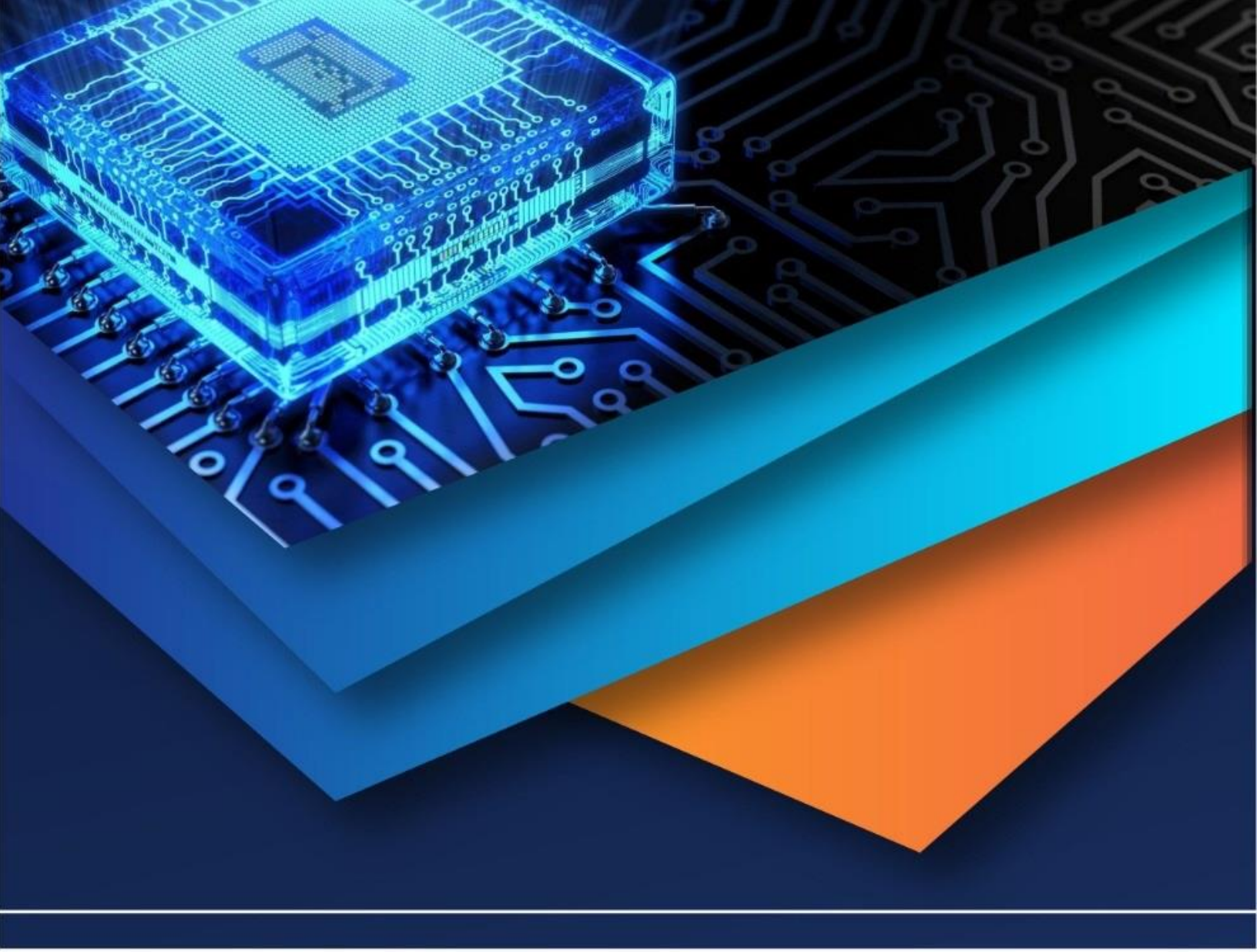
[4] M. A. Muqeet and M. Abdullah, "Implementation and analysis of automated power factor corrector unit (APFC) for an induction motor," *Journal of Information and Computational Science*, vol. 10, pp. 500–504, Feb. 2020.

[5] P. Ahmmed, S. S. Saha, A. Sunny, M. I. Hossain, and I. Jahan, "Modeling and simulation of a microcontroller-based power factor correction converter," in 2013 *International Conference on Informatics, Electronics and Vision (ICIEV), Bangladesh*, May 2013, pp. 1–4.

[6] S. Rittijun and N. Boonpirom, "Power factor correction of single-phase rectifier using fuzzy controller," in 2020 *International Conference on Power, Energy and Innovations (ICPEI), Thailand*, Oct. 2020.

[7] M. A. H. S. Kamal and M. S. Anower, "Design and implementation of numerical relay to provide current and voltage protection for electric networks using Raspberry Pi," in 2023 *International Conference on Electrical Engineering and Advanced Technology (ICEEAT)*, Nov. 2023, pp. 1–6.

[8] P. M. S. Kotresh, "Automatic power factor compensation (APFC) for industrial power use to minimize penalty," *International Journal for Research in Applied Science and Engineering Technology*, vol. 12, pp. 2688–2691, May 2024.



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