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Internet of Things and edge computing-based parallel vector power factor compensator

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ABSTRACT

This article presents the design and implementation of an Internet of Things (IoT) and edge computing-based system for real-time monitoring and compensation of power factor in electrical installations using low-cost hardware. The proposed edge computing monitoring device (ECMD) integrates voltage and current sensors with an ATmega328P microcontroller and a Jetson Nano platform for local signal processing. The system estimates voltage, current, phase angle, power factor, and active, reactive, and apparent power, while a Node-RED graphical interface provides real-time visualization of the measured parameters. In addition to monitoring, a proportional-integral-derivative (PID) based control strategy generates pulse width modulation (PWM) signals to regulate the capacitive compensation stage through insulated gate bipolar transistors (IGBTs), enabling dynamic correction of inductive loads. Experimental validation was performed using a Fluke 434 Series II power quality analyzer. Under the evaluated inductive-load condition, the reference analyzer measured a power factor of 0.260, while the ECMD exhibited a difference of approximately 0.08. The results demonstrate that low-cost hardware platforms are viable for real-time power factor monitoring and compensation in edge computing environments, providing a scalable and cost-effective approach for energy management applications.

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1. INTRODUCTION

Currently, alternating current (AC) systems are indispensable in both daily life and industrial applications within the electrical field. With the advent of edge computing, new opportunities have emerged to enhance the efficiency and effectiveness of energy management in these systems. One of the primary advantages of edge computing is its ability to handle critical data locally and in real-time, making it ideal for environments where rapid decision-making is crucial, such as in companies that require precise power factor calculations.

Unlike traditional systems that rely on centralized data processing, edge computing allows the analysis and processing of electrical data directly at the source. This localized approach is particularly beneficial for monitoring critical parameters in industrial facilities, such as voltage, current, and power factors. By processing data at the edge, companies can achieve faster response times, reduce network latency,

and improve reliability. Those parameters are crucial for optimizing energy use and avoiding penalties for poor power factors.

Edge computing's ability to perform on-site calculations and provide real-time insights into power factors enables proactive adjustments and optimization without continuous cloud connectivity. These characteristics help maintain power factors within ideal ranges and ensure excellent stability and efficiency in electrical systems. Edge computing empowers companies to manage their energy consumption by leveraging advanced, localized data analytics, thereby improving operational efficiency and reducing costs.

Developing a parallel vector power factor compensator based on edge computing provides a localized approach to improving energy efficiency and power management in electrical systems. This project aims to address the challenge of low power factor, which can lead to significant energy and resource wastage. By integrating edge computing, the compensator optimizes power factor in real time and safeguards sensitive data through localized processing, thereby reducing the risk of data breaches associated with cloud-based systems. This approach reduces operational costs, improves energy efficiency, and enhances the system's security, contributing to overall reliability and sustainability in power management. Combining improved power factor and data security supports environmental sustainability by minimizing greenhouse gas emissions and reducing the environmental impact of electricity generation.

In industrial AC systems, most electrical loads are inductive in nature, causing a phase displacement between voltage and current that negatively impacts energy efficiency and power quality, leading to energy losses in the form of heat, reduced equipment lifespan, and overloading of electrical networks. Furthermore, the apparent power (the product of voltage and current) can exceed the real power due to this phase shift, which results in economic penalties imposed by utility providers. A low power factor increases the demand for reactive power to ensure proper device operation, thereby generating higher transmission and distribution losses and contributing to environmental impact through the emissions associated with electricity generation.

In the current context of technology, monitoring and efficient management of electrical systems are essential to ensure performance, safety, and sustainability. With the increasing demand for electrical devices and systems, from industrial to residential environments, precise measurement and real-time analysis of parameters such as voltage and current have become crucial to optimizing energy consumption and detecting potential issues. However, traditional monitoring methods present significant limitations, especially when providing a quick and efficient response.

The main contributions of this work are summarized as follows: (i) the design and implementation of a low-cost and scalable edge computing monitoring device (ECMD) that integrates voltage and current sensing modules, local signal processing, a Jetson Nano platform, and a Node-RED-based graphical interface for real-time power factor monitoring without cloud dependency; (ii) the development of a power factor compensation strategy based on proportional-integral-derivative (PID) control and pulse width modulation (PWM) modulation for capacitor bank activation, enabling dynamic correction of inductive loads; (iii) the experimental validation of the proposed system using a Fluke 434 Series II power quality analyzer, demonstrating the capability of the ECMD to estimate voltage, current, active power, reactive power, apparent power, phase angle, and power factor; and (iv) the integration of Internet of Things (IoT) and edge computing technologies into a cost-effective architecture designed to reduce communication latency, improve local data processing, and support energy management applications in industrial and commercial electrical installations.

Power theory is fundamental to understanding the relationships between voltages, currents, delivered power, and losses in power systems. Traditional theories often fail when addressing real-world complexities, such as poly-phase systems with non-sinusoidal waveforms, direct current (DC) components, and voltage/current imbalances. To tackle these challenges, Malengret and Gaunt [1] introduces a novel formulation that caters to these complexities, providing a comprehensive framework for poly-phase systems with periodic non-sinusoidal waveforms and unequal wire impedances. Power factor correction (PFC) is essential for improving power quality. Metwaly *et al.* [2], a method using hysteresis band current control (HBCC) is presented, employing a dual-loop control system to ensure supply currents are in phase with supply voltages. This approach includes an inner loop generating PWM signals and an outer loop determining the reference current magnitude.

The integration of IoT technologies into energy monitoring systems has led to significant advancements. Mudaliar and Sivakumar [3] an IoT-based real-time energy monitoring system for a switchgear industry using Raspberry Pi is discussed, facilitating energy conservation efforts through daily consumption pattern insights [4], [5] further explore smart energy meters and monitoring devices, emphasizing real-time data acquisition and control of electrical devices to reduce costs and enhance grid stability. Additionally, Romero *et al.* [6] presents an edge computing system for building energy monitoring, focusing on data security and detailed power measurements. A detailed comparison is presented in Table 1.

Automatic PFC (APFC) systems are crucial for maintaining power quality. Mane *et al*. [7], an Arduino UNO microcontroller-based APFC system is proposed, using power factor transducers and capacitor banks to compensate for reactive power. Abdelhady *et al*. [8] introduces a multi-step capacitor bank system with detuned filters to improve power factors and mitigate harmonics.

Edge and fog computing applications in energy monitoring and control are increasingly important. Forcan and Maksimović [9], an IoT-based architecture for intelligent grid monitoring is introduced, detailing how edge computing can facilitate real-time data processing and decision-making. Sha *et al*. [10], edge-centric IoT architectures are discussed, enhancing data processing and decision-making capabilities in industrial settings. Moreover, previous studies [11]-[14] demonstrate the applicability of edge computing to distributed resource management, emphasizing local processing, reduced latency, and efficient allocation of computational resources. Although these studies address different application domains, their findings support the use of edge architectures for time-sensitive and resource-constrained systems.

Recent studies have explored edge and fog computing frameworks for improving latency and resource management. For instance, Xiao and Krunz [15] demonstrates the potential of adaptive fog architectures for maintaining service performance under latency constraints. Furthermore, de Simona-Vasilica and Bara [16] proposes an adaptive approach for direct load optimization and control using an IoT architecture, contrasting it with a classic direct load control (DLC) approach. By implementing day-ahead scheduling to minimize electricity costs through programmable appliance management, this adaptive system addresses real-time uncertainties, such as consumer temperature comfort, by introducing additional load control mechanisms.

Recent advancements in intelligent edge computing frameworks have emerged as a solution to offload artificial intelligence (AI) tasks from servers. Zhu *et al*. [17] proposes a heterogeneous architecture that enhances the energy efficiency of various computing resources through a novel scheduling algorithm for different AI tasks. Performance evaluations demonstrate the energy efficiency of intelligent edge computing in industrial IoT (IIoT) applications.

Intelligent algorithms are pivotal in optimizing power quality and innovative energy systems. Singh *et al*. [18], a power quality algorithm that enhances data logging and analysis through cloud integration is proposed. Moreover, recent studies [19], [20] explored IoT-driven smart energy systems and meters for energy monitoring, emphasizing improved data accuracy and automated management. These systems incorporate multi-protocol communication capabilities to support real-time monitoring and proactive energy control across various applications. Efforts to reduce energy consumption and costs are discussed in [21], where a neural network-based energy modeling approach optimizes edge server energy consumption. Furthermore, studies [22], [23] propose approaches for reducing energy consumption in industrial and edge computing environments through efficient data offloading and optimized edge-server placement.

Edge computing has also been applied to industrial signal processing and fault diagnosis [24], [25], demonstrating the feasibility of local data acquisition and real-time processing in resource-constrained environments. These capabilities support the use of edge architectures for time-sensitive electrical monitoring applications. Security and privacy are also relevant considerations in edge computing environments. Studies [26], [27] highlight data protection and privacy challenges associated with distributed edge architectures, supporting the use of local processing to reduce dependence on centralized cloud infrastructures.

In IIoT systems, edge computing enables local data processing, reduced latency, and timely decision-making. For instance, Ren *et al*. [28] demonstrates the use of edge-based IIoT architectures for real-time sensor monitoring and local data analysis, supporting their applicability to time-sensitive industrial monitoring systems. Edge computing has also been applied to electrical load forecasting, where distributed learning approaches enable local data processing while reducing the need for centralized data transmission [29]. Recent edge computing approaches for industrial IoT have also focused on distributed processing and efficient resource utilization, further supporting the feasibility of responsive local computing architectures in industrial environments [30].

Table 1. Comparison of IoT-based energy monitoring systems

Reference	System description	Technology	Purpose	Key benefits
[3]	Real-time energy monitoring system for switchgear industry	IoT	Energy conservation	Provides daily consumption patterns to optimize energy use
[4]	Smart energy meter for real-time data monitoring	Raspberry Pi	Control of electrical devices	Reduces costs and improves grid stability
[5]	Smart real-time energy monitoring device	IoT	Control of electrical devices	Focused on cost reduction and grid stability
[6]	Building energy monitoring system based on edge computing	IoT		Enhances data security and provides detailed power measurements
	Smart energy meter for real-time data monitoring	Raspberry Pi	Control of electrical devices	Reduces costs and improves grid stability

2. EDGE COMPUTING BASED POWER FACTOR COMPENSATOR SYSTEM

Figure 1 illustrates the general design of the proposed monitoring and control system (E. C. M. D.). The system is structured in three essential stages: the power supply line that feeds the inductive loads, the measurement sensors (current and voltage), and the peripheral computing monitoring device (E. C. M. D.).

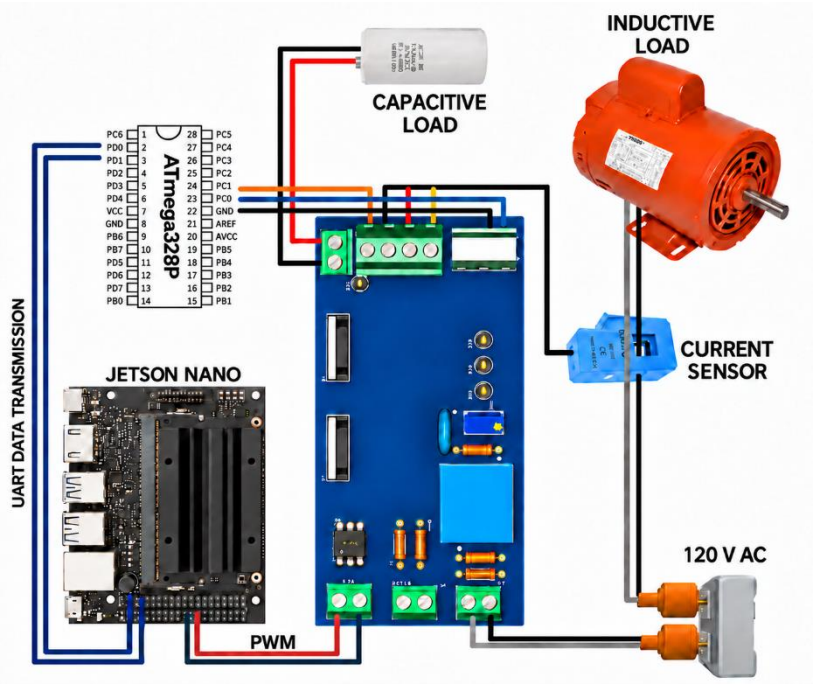


Figure 1. Proposed edge computing monitoring system

Jetson Nano is integrated for complex calculations and robust peripheral computing server functionality. Its powerful graphics processing unit (GPU) enables real-time processing of large datasets, which is essential for implementing advanced analytics and machine learning applications to optimize energy use. Jetson Nano's compatibility with various communication protocols ensures high-speed data transmission and seamless integration with the microcontroller and other system devices. The characteristics of these components establish a versatile platform that effectively meets the requirements of the E. C. M. D., offering rigorous data acquisition and intelligent processing capabilities.

The essential sensors for voltage and current measurement are also detailed in the figure. For voltage measurement, the ZMPT101B is used, a potential transformer sensor commonly used to measure AC voltages. When a 127 VAC signal is applied, this sensor acts as a potential transformer, conditioning the high-voltage signal to a lower, proportional voltage level compatible with the microcontroller's analog inputs. For current measurement, the SCT-013, a non-invasive current sensor capable of measuring up to 30 A, is used.

2.1. Analog coupling

Using a 5 V supply (Vcc), resistance values can be calculated to achieve a 2.5 V offset in a sinusoidal signal with a 5 V peak-to-peak amplitude. Using the voltage divider formula and assuming $R_1 = 10\ k\Omega$, the calculation for R_2 becomes:

$$R_2 = \frac{V_{out}}{(V_{cc} - V_{out})R_1} = \frac{2.5V}{(5V - 2.5V)10k\Omega} \quad (1)$$

By selecting standard values $R_1 = 10\ k\Omega$ and $R_2 = 10\ k\Omega$, the sinusoidal signal is shifted by a 2.5 V DC offset, resulting in an approximate voltage range of 0 V to 5 V, which is compatible with the microcontroller analog input range. Figure 2 illustrates the analog signal-conditioning circuit used to attenuate the sensor outputs and apply the 2.5 V DC offset required for compatibility with the ATmega328P analog inputs.

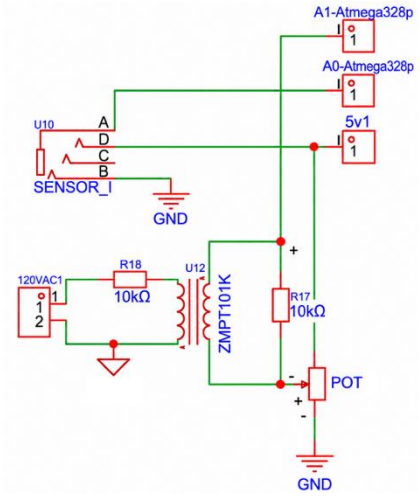


Figure 2. Electronic schematic of signal coupling (signal attenuation and offset)

2.2. Digital signal processing

Prior to the experimental measurements, the voltage and current acquisition channels were calibrated by comparing the ECMD readings with those obtained using the Fluke 434 Series II power quality analyzer as the reference instrument. Small correction adjustments were subsequently implemented in software to minimize the differences between the ECMD measurements and the reference values. This calibration procedure was applied to improve the accuracy of the acquired voltage and current signals before calculating the electrical parameters. Once the calibrated signals are acquired, they are processed using Arduino Code and C++. Voltage and current signals were acquired sequentially by the ATmega328P ADC using 400-sample acquisition windows. A 30 ms interval was configured between consecutive acquisitions in the implemented program. The primary function of this code is to adjust the offset to 0 v and elevate the voltage and current value to the real one. After getting the actual values, it uses the function $atan2()$ to calculate the angle shift between both signals, which calculates the arctangent of the two variables y and x. $atan2()$ takes two arguments and returns an angle from $-\pi$ to π, allowing it to determine the angle's quadrant correctly. Figure 3 shows the graph of the angular displacement function calculation.

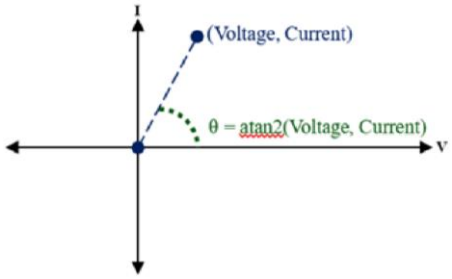


Figure 3. Angle shift calculation function

2.3. Data transmission

Figure 4 shows the electronic schematic of the data acquisition and communication system used in the proposed ECMD. The voltage and current signals are conditioned and processed by the ATmega328P microcontroller, which is connected to the Jetson Nano through Universal Asynchronous Receiver-Transmitter (UART) communication. The ATmega328P transmits the measured electrical parameters through its TX (transmit) and RX (receive) ports, enabling reliable and efficient serial communication with the Jetson Nano. This communication architecture allows the timely transfer of sensor data for local processing, visualization, and power factor analysis within the edge computing platform. The UART communication between the ATmega328P and the Jetson Nano was configured at a baud rate of 19200 bps, providing reliable serial data transmission for the monitored electrical parameters.

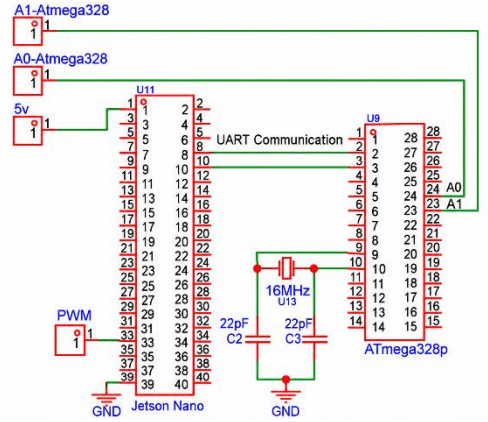


Figure 4. Electronic schematic of UART communication

2.4. PFC

PFC was implemented using a PID controller in Node-RED to regulate the PWM signal applied to the insulated gate bipolar transistors (IGBT)-based capacitive compensation stage (Figures 5 and 6). The controller was configured with a power factor setpoint of 0.90, a proportional band of 0.8, an integral time of 5 s, a derivative time of 0.5 s, an initial integral value of 0, and a derivative smoothing factor of 0.2. The PID parameters were experimentally tuned through an iterative trial-and-error procedure. The parameters were progressively adjusted while monitoring the system response until stable power-factor regulation was achieved without excessive oscillations during the compensation stage. The compensation capacitor was sized considering a 1 HP (746 W), 120 V, 60 Hz inductive load with an initial power factor of 0.74. The phase angles corresponding to the initial and target power factors were determined as:

$$\phi_1 = cos^{-1}FP_1, \phi_2 = cos^{-1}FP_2 \quad (2)$$

The required capacitive reactive power was then calculated as:

$$Q_c = P[\tan(\phi_1) - tan(\phi_2)] \quad (3)$$

where P is the active power, PF_1 and PF_2 are the initial and target power factors, respectively, and Q_c is the required capacitive reactive power. For $PF_1 = 0.74$ and a design target of $PF_2 = 0.95$, the required reactive power was approximately 432.9 VAR. The corresponding capacitance was calculated as:

$$C = \frac{Q_c}{2\pi f V^2} \quad (4)$$

where, f is the line frequency and V is the root-mean-square value (RMS) supply voltage. For $f = 60$ Hz and $V = 120\,V$, the calculated capacitance was approximately 79.7 μF; therefore, a commercial 80 μF, 250 VAC capacitor was selected. The capacitor was intentionally sized using the 0.95 design target to provide sufficient compensation margin, while the PID operating setpoint was established at 0.90 to enable stable regulation of the compensation stage.

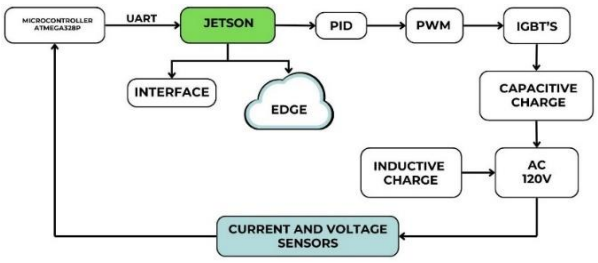


Figure 5. Power factor compensation method: capacitive charge

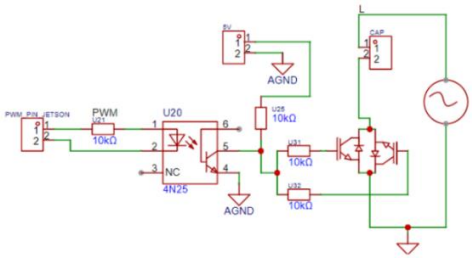


Figure 6. Protection and power control electronic diagram

2.5. Proposal interface

The proposed Node-RED interface allows users to visualize, monitor, and analyze the electrical parameters acquired and processed by the microcontroller in real time. Node-RED enables the visualization of real-time data through interactive charts. Figure 7 shows the phase relationship between the voltage (red signal) and current (blue signal). The waveforms presented at the top of Figure 7 correspond to a purely resistive load, where voltage and current remain in phase. In contrast, the waveforms shown at the bottom correspond to an inductive load, where a phase displacement between voltage and current can be clearly observed. In both plots, the horizontal axis represents time, while the vertical axis represents the instantaneous amplitudes of the voltage and current signals, allowing their phase relationship to be directly compared.

Different gauges were implemented to display the measured electrical parameters. These include indicators for active power, apparent power, reactive power, and power factor, as shown in Figure 8. The complete user interface is presented in Figure 9.

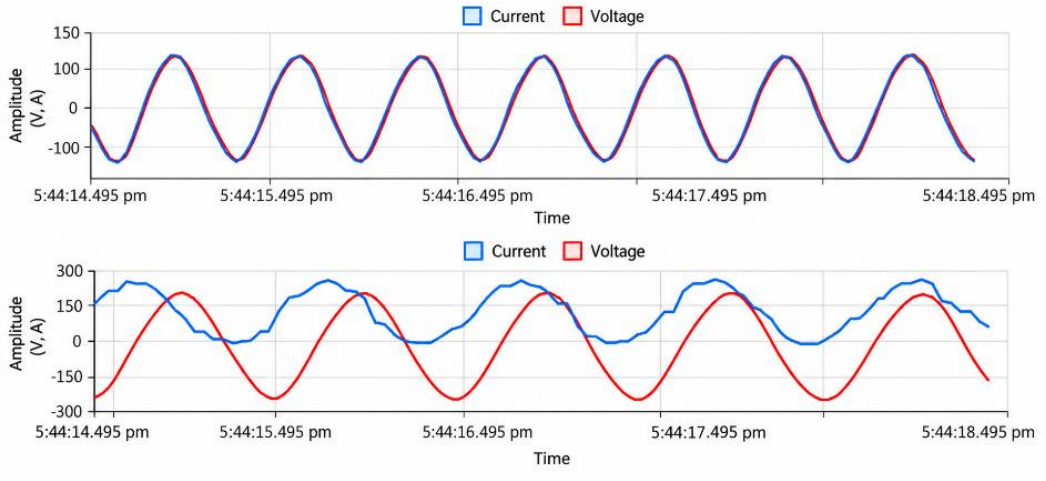


Figure 7. Voltage and current waveforms measured by the ECMD under resistive and inductive load conditions



Figure 8. Gauges used for monitoring

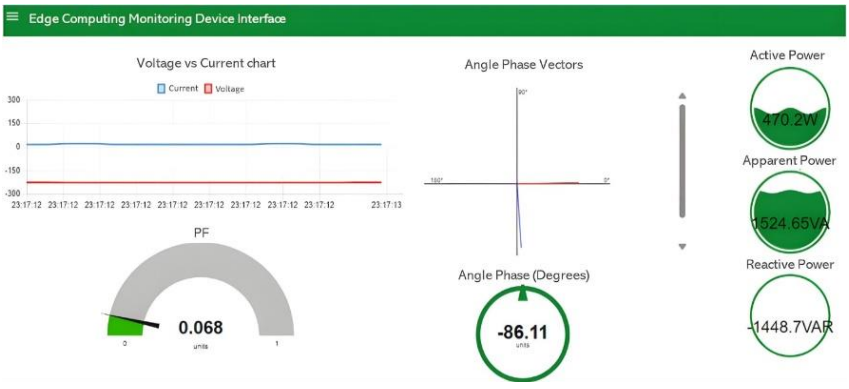


Figure 9. ECMD interface gauges

2.6. Real measurements

To validate the operation of the proposed ECMD, measurements were performed using a Fluke 434 Series II power quality analyzer. The Fluke analyzer was used as a reference instrument due to its high accuracy and capability to measure electrical power quality parameters. Figure 10 shows the phase displacement between voltage and current under inductive load conditions recorded by the Fluke 434 Series II analyzer. The recorded waveforms allow the observation of the phase shift associated with inductive loads

and provide a reference for evaluating the measurements obtained by the ECMD. The analyzer measured a power factor value of 0.260, while the ECMD reported a value with a difference of approximately 0.08 units.

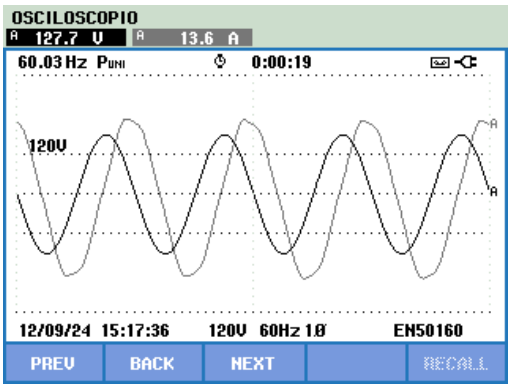


Figure 10. Voltage-current phase displacement measured using a Fluke 434 Series II power quality analyzer

Although the proposed system is based on low-cost hardware and open-source technologies, the obtained results demonstrate its capability to estimate power quality parameters and identify power factor variations in real time. These results support the feasibility of employing edge computing technologies for local monitoring and management of electrical systems while maintaining low implementation costs.

It should be noted that the reported difference of approximately 0.08 represents the measurement deviation between the ECMD and the Fluke 434 Series II under the evaluated condition and should not be interpreted as a direct power factor improvement or operational cost saving. The economic benefits of power factor compensation depend on the achieved improvement in power factor, load profile, operating time, electricity tariff structure, and utility penalties for reactive power. Therefore, a quantitative cost-saving analysis would require a longer-term evaluation under representative operating and billing conditions.

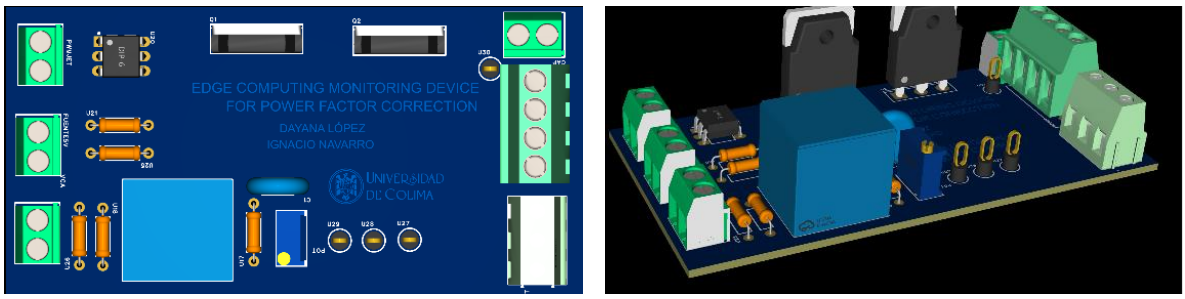
The experimental results are consistent with previous intelligent and automatic PFC studies [7], [8], which have demonstrated the feasibility of real-time electrical monitoring and reactive power compensation. Unlike conventional approaches based primarily on discrete capacitor-bank switching, the proposed ECMD integrates local edge processing with a PID/PWM-based control strategy for regulating the IGBT-driven capacitive compensation stage. This architecture enables monitoring and compensation decisions to be performed locally, reducing dependence on external cloud processing while maintaining a low-cost and modular implementation. These characteristics position the proposed system as a complementary approach to existing intelligent PFC solutions.

More advanced control and energy optimization approaches based on adaptive strategies [16] and neural-network-based methods [21] have also been reported in the literature. These methods can provide greater flexibility under varying operating conditions, although they generally require additional computational resources, training procedures, or more complex tuning strategies. In contrast, the proposed PID/PWM-based ECMD prioritizes implementation simplicity, local processing, and low-cost hardware while maintaining real-time compensation capability.

The present validation focused on a direct comparison between the ECMD and the Fluke 434 Series II under the evaluated inductive-load condition. Therefore, the reported difference represents the observed measurement deviation for this experimental condition rather than a statistical error estimate. Further validation will include repeated measurements under different load conditions to determine statistical performance indicators, including measurement uncertainty and confidence intervals.

2.7. Prototype

Figure 11 shows the proposed ECMD board. Figure 11(a) presents the top view, illustrating the arrangement of the coupling, acquisition, power, and control stages and the terminal blocks for data transmission. In contrast, Figure 11(b) provides an isometric view of the assembled board, showing the spatial arrangement of its main components. The board was installed in a cabinet, as shown in Figures 12 and 13, designed for placement next to the target system's main electrical distribution panel. The main operational characteristics of the proposed ECMD are summarized in Table 2. The cabinet is designed to accommodate two capacitors, which can be replaced as needed based on the calculated reactive power. The cabinet also provides easy access for maintenance and upgrades, ensuring long-term reliability and user convenience.



(a) (b)

Figure 11. Proposed PCB board for the ECMD: (a) top view and (b) isometric view

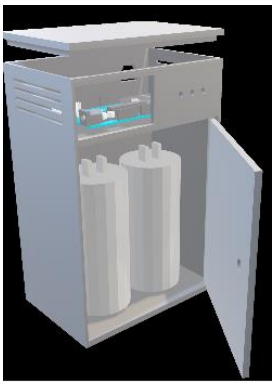


Figure 12. Design of the E.C.M.D. cabinet: 3D design



Figure 13. Design of the E.C.M.D. cabinet: 3D Print

Table 2. Main operational characteristics of the proposed ECMD

Main characteristics	
Maximum voltage	250 VCA
Maximum current	30A
Frequency	60 Hz
Data saving	Local
Connectivity	Ethernet

3. CONCLUSION

This work presented the design and implementation of an ECMD for real-time monitoring and compensation of power factor in electrical systems using low-cost hardware and open-source technologies. The proposed architecture integrates voltage and current sensing modules, local signal processing, a Jetson Nano platform, and a Node-RED-based graphical interface for real-time visualization and management of electrical parameters. Experimental validation was performed using a Fluke 434 Series II power quality analyzer. Under the evaluated inductive-load condition, the reference analyzer measured a power factor of 0.260, while the ECMD exhibited a difference of approximately 0.08. These results demonstrate the capability of the proposed system to identify phase displacement between voltage and current and to estimate power factor variations in real time using low-cost hardware. The integration of edge computing technologies enabled local data processing, reducing communication latency and improving data security by avoiding continuous cloud connectivity. In addition, the proposed architecture provides a scalable and cost-effective solution that can be adapted to different monitoring and power factor compensation applications in industrial and commercial environments. Extending the ECMD to three-phase installations would require voltage and current sensing for each phase, enabling independent estimation of each phase's electrical parameters and power factor. The compensation stage could then be adapted to provide phase-specific reactive power correction, allowing the system to address both balanced and unbalanced load conditions. Future work will focus on improving the compensation strategy to enhance dynamic response under varying load conditions, incorporating intelligent algorithms to enable predictive energy management, and extending the proposed system to three-phase electrical installations to broaden its applicability in industrial environments.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

The source code, implementation files, and experimental data supporting the proposed ECMD are openly available in the project repository. The repository includes the Node-RED flow used to implement the monitoring interface (TesisNode.json), software resources associated with the system implementation, and experimental measurement data used for system evaluation https://github.com/NachoNavarroCode/C-digo-Tesis-.

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