

# An Edge AI-Driven IOT Framework for Automatic Power Factor Correction in Smart Industrial Power Systems


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## Abstract

Power factor correction remains a significant challenge in modern industrial power systems due to the presence of highly inductive and fluctuating loads. Poor power factor results in increased energy losses, reduced system efficiency, and higher operational costs. Conventional correction methods based on mechanical or thyristor switching provide limited intelligence and slower adaptability to dynamic load variations. This paper presents the design and hardware implementation of an Edge AI-driven IoT framework for automatic power factor correction in smart industrial environments. The proposed system utilizes voltage and current sensing modules integrated with an ESP8266 controller to continuously monitor electrical parameters. Edge Artificial Intelligence enables real-time local decision-making for optimal capacitor bank switching to compensate reactive power effectively. IoT connectivity allows remote monitoring and data visualization through cloud platforms. The developed system maintains near-unity power factor, minimizes harmonics, and optimizes current consumption under varying load conditions. Experimental results demonstrate improved power quality, faster response time, and enhanced energy efficiency compared to conventional APFC systems.

## Keywords

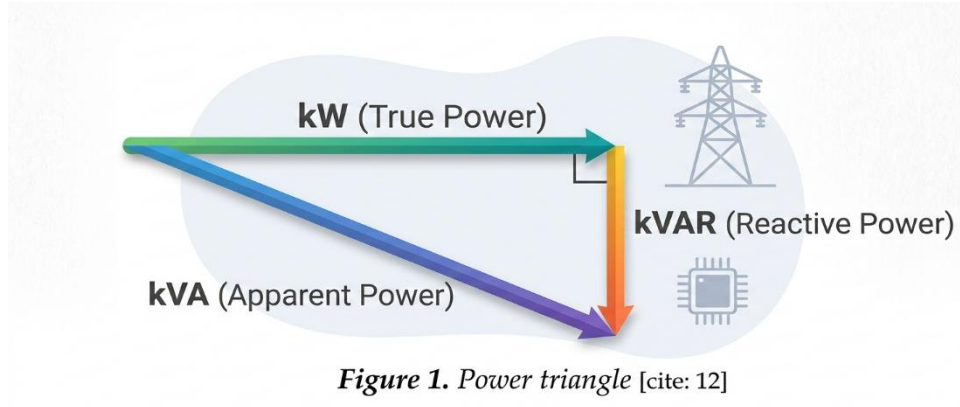
Power Factor Correction, Edge Artificial Intelligence, Internet of Things (IoT), Smart Industrial Power Systems, Reactive Power Compensation, TinyML.

## 1. Introduction

Power factor represents the relationship between active power and apparent power consumed in an electrical system. Maintaining a high power factor is essential for efficient utilization of electrical energy in industrial power networks. Most industrial loads such as induction motors, transformers, welding machines, and compressors are inductive in nature, which results in a lagging power factor. A low power factor increases transmission losses, causes voltage instability, and leads to additional penalty charges imposed by power utilities. Therefore, maintaining the power factor within permissible limits is necessary to ensure efficient and economical operation of industrial systems.

Automatic Power Factor Correction (APFC) units are widely employed to improve energy transmission efficiency by compensating reactive power using capacitor banks. Conventional APFC systems mainly rely on contactor or thyristor-

based switching techniques for connecting and disconnecting capacitor banks



**Figure 1.** Power triangle [cite: 12]

With the advancement of smart power systems, integration of Internet of Things (IoT) and Edge Artificial Intelligence (Edge AI) technologies enables real-time monitoring and intelligent control of electrical parameters. Edge AI allows local processing and fast decision-making without dependency on cloud latency, ensuring rapid response for power factor correction. IoT connectivity further enables remote supervision, data logging, and performance analysis through cloud-based dashboards.

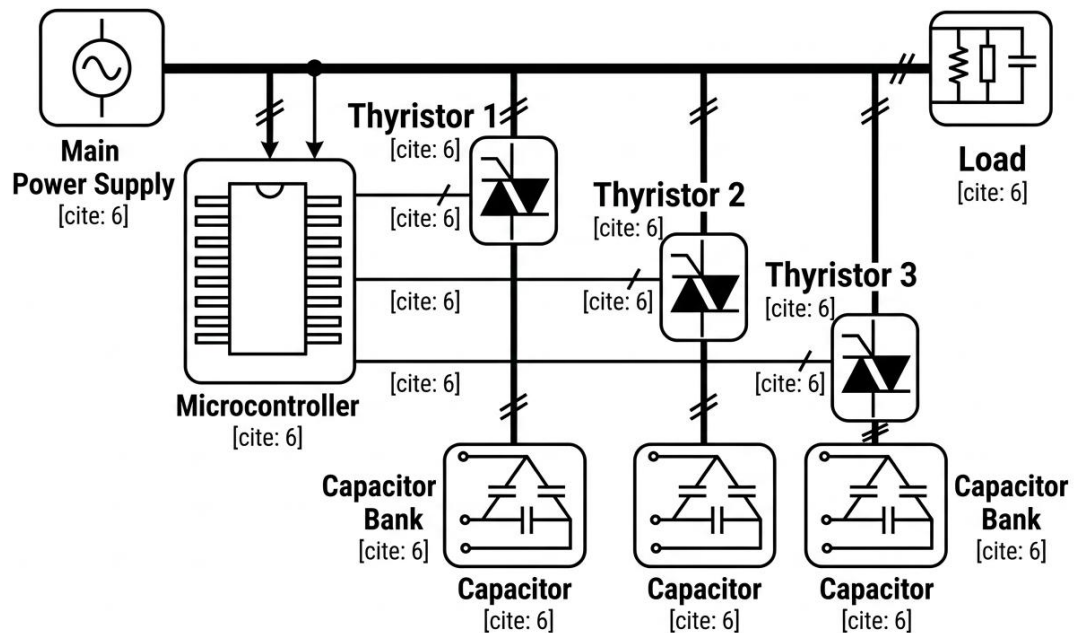
The proposed system introduces an Edge AI-driven IoT framework for automatic power factor correction in smart industrial power systems. The system continuously monitors voltage, current, and power factor using sensing modules interfaced with an ESP8266 controller. Based on real-time analysis and AI prediction, capacitor banks are automatically switched to maintain near-unity power factor. The APFC unit is connected in parallel with the industrial power supply, providing dynamic compensation and improved power quality under fluctuating load conditions.

## 2. Edge AI-Based Automatic Power Factor Correction Unit

In conventional Automatic Power Factor Correction (APFC) systems, thyristor switching devices such as Silicon Controlled Rectifiers (SCR) or TRIACs are commonly used for rapid and reliable capacitor bank control. These semiconductor devices act as electronic switches between the capacitor banks and the industrial load circuit, enabling fast compensation of reactive power. Instead of connecting all capacitor banks simultaneously, selective switching is performed depending on the required reactive power demand.[10]

In a practical APFC system, multiple capacitor banks with different ratings are installed to provide step-wise compensation. When the power factor decreases significantly due to heavy inductive loading, additional capacitor stages are connected to

the system. Conversely, when the power factor approaches unity, unnecessary capacitor banks are disconnected to avoid



overcompensation..

**Figure 2.** Single line diagram of APFC unit

The proposed system enhances conventional thyristor-based correction by incorporating an Edge AI-enabled controller along with IoT monitoring capability. Current Transformer (CT) and voltage sensing circuits continuously measure electrical parameters such as voltage, current, and reactive power. These measured signals are processed by the ESP8266 microcontroller, which evaluates the real-time power factor condition.

Based on Edge AI prediction, control signals are generated to activate relay or solid-state switching modules that connect the appropriate capacitor banks to the load circuit. This intelligent decision-making mechanism enables faster response compared to traditional rule-based APFC panels.

To minimize switching transients and harmonic disturbances, capacitor switching is performed near the zero-crossing point of the AC waveform. Zero-crossing switching ensures that capacitor connection occurs when instantaneous voltage is nearly zero, thereby reducing inrush current, voltage spikes, and waveform distortion.

The implemented switching module offers several advantages including fast response time, silent operation, reduced mechanical wear, improved operational life, thermal protection, and enhanced system reliability. Protection circuits such as RC snubber networks are incorporated to limit dv/dt stress and protect switching components from overvoltage conditions.

By integrating Edge AI intelligence with IoT-enabled monitoring, the proposed APFC unit provides adaptive, efficient, and real-time reactive power compensation suitable for modern smart industrial power systems.

### 3. Design Methodology

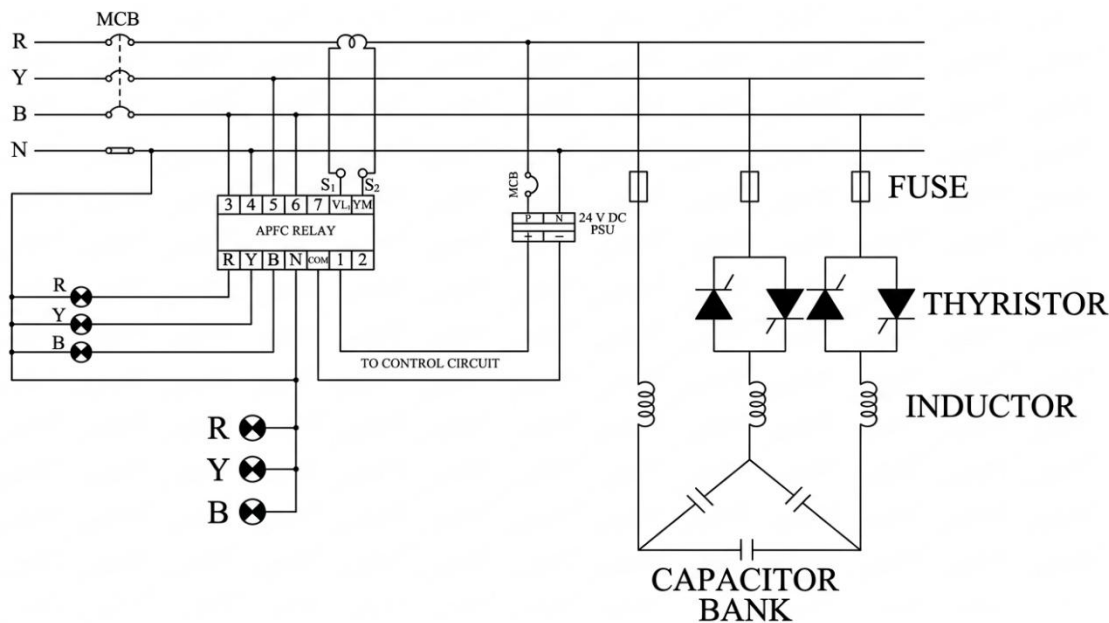
The proposed Automatic Power Factor Correction (APFC) system is designed as an integrated smart unit consisting of multiple functional modules that collectively perform real-time monitoring and reactive power compensation. The major components of the system include power supply module, sensing unit, Edge AI controller, capacitor bank switching module, harmonic filtering unit, and IoT communication interface, as illustrated in the system design architecture.[8]

The controller plays a crucial role in the power factor correction process. Voltage and current sensing modules continuously measure electrical parameters from the industrial load. The sensed signals are obtained using Current Transformers (CT)

and potential sensing circuits placed near the metering section of the electrical distribution panel. These measurements are used to calculate real power, apparent power, and power factor values in real time.

The measured analog signals are processed by the ESP8266 microcontroller integrated with an Edge AI model. The intelligent controller analyzes load variations locally and determines the required reactive power compensation level. Based on the calculated power factor value, the controller automatically connects or disconnects capacitor stages to maintain the desired power factor close to unity.

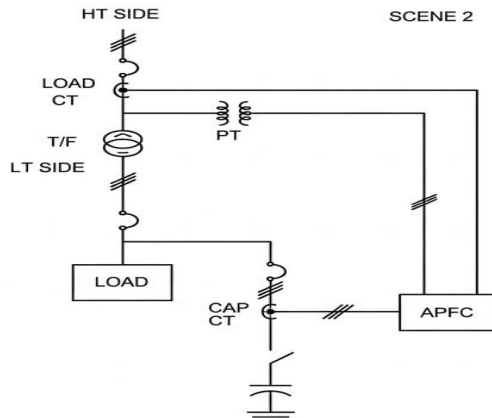
To ensure reliable operation under nonlinear industrial loads, a detuned reactor or harmonic filtering unit is incorporated in series with the capacitor bank. This arrangement limits harmonic current flow and prevents resonance conditions within the power system. The harmonic filter protects capacitors, transformers, cables, and switchgear equipment from overheating and overcurrent stress, thereby increasing system lifespan and operational stability.[14]



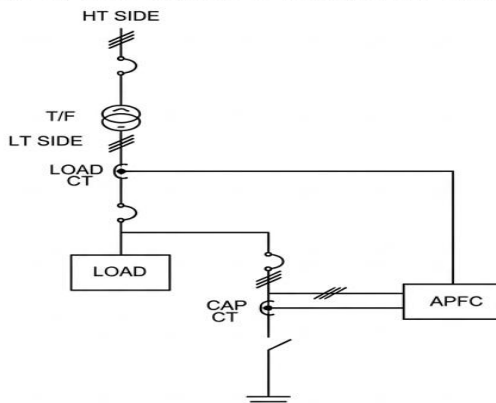
**Figure 3.** Design of thyristerised AFPC unit

Fast switching of capacitor banks is achieved using relay or solid-state switching modules controlled by the microcontroller. Multiple capacitor stages with different ratings are connected in parallel to provide step-wise reactive power compensation according to KVAR demand. The capacitor size and switching sequence are selected based on load characteristics and industrial power requirements.

Furthermore, IoT connectivity enables transmission of real-time electrical data to cloud platforms for remote monitoring and analysis. The integration of Edge AI with IoT communication ensures intelligent, adaptive, and energy-efficient operation of the APFC system suitable for smart industrial power management applications.[6]



**Figure 4. CT and PT from HT side**



**Figure 5. CT and PT from LT side**

#### 4. Hardware Implementation

The hardware architecture of the proposed Edge AI-driven Automatic Power Factor Correction (APFC) system is illustrated in [Figure 6]. The developed prototype integrates sensing, edge intelligence, and IoT communication modules to achieve real-time reactive power compensation in smart industrial environments.

The system operates using a 230 V, 50 Hz AC industrial power supply, which represents typical industrial distribution conditions. Since embedded controllers and sensing modules require regulated DC power, a step-down power conversion unit is employed. A voltage transformer reduces the AC supply to 12 V AC, which is subsequently converted into DC using a bridge rectifier followed by filtering capacitors to remove ripple components. A regulated DC output is obtained using an SMPS or voltage regulator module to supply stable power to the controller and peripheral devices.[5]

Voltage and current parameters of the load are continuously monitored using voltage sensing circuits and current transformers (CT). These electrical signals are conditioned and provided to the ESP8266-based edge controller, which serves as the core processing unit of the system. The controller executes a deployed TensorFlow Lite TinyML model locally to predict power factor deviation and determine optimal capacitor switching requirements.

Based on the Edge AI inference results, relay driver circuits are activated to switch capacitor banks dynamically for reactive power compensation. Unlike conventional thyristor-based systems, the proposed approach enables intelligent decision-making at the edge, minimizing switching delay and improving response accuracy under fluctuating industrial loads.[7]

The ESP8266 module also provides wireless connectivity, enabling real-time monitoring and control through an IoT dashboard using the Blynk platform. Key electrical parameters such as voltage, current, power factor, and capacitor status are transmitted to the cloud for visualization and remote supervision.

The implemented hardware ensures:

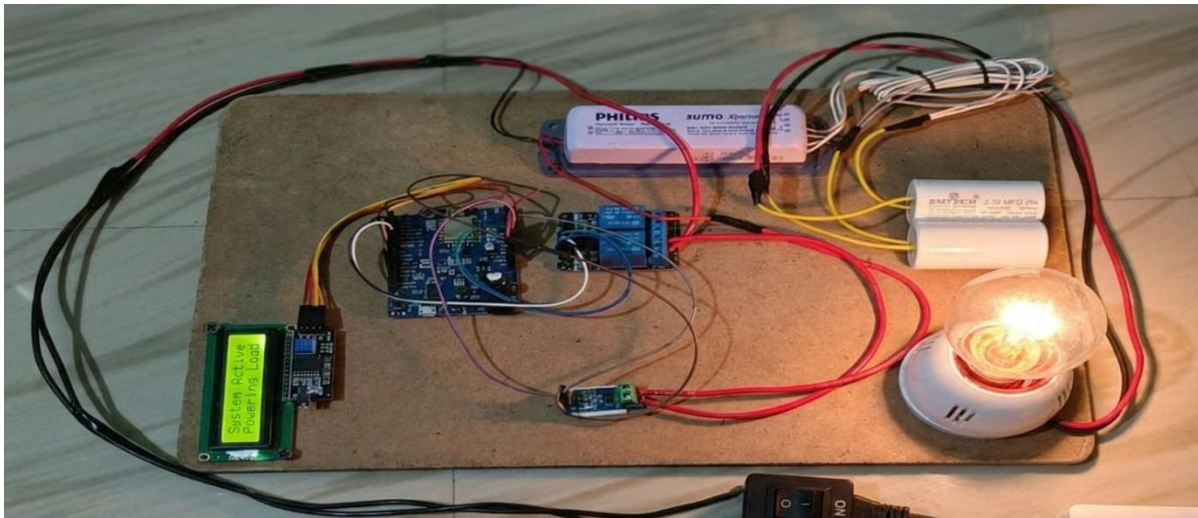
- Real-time power factor correction
- Reduced reactive power losses
- Intelligent capacitor bank switching
- Low-latency edge computation
- Remote industrial energy monitoring

Experimental validation confirms that the proposed hardware system maintains near-unity power factor while improving overall power quality and operational efficiency in smart industrial power systems.

## 5. Results and Discussion

[Figure 7] illustrates the experimental results obtained from the implemented Edge AI-driven Automatic Power Factor Correction (APFC) system under varying industrial load conditions. The proposed system continuously monitors electrical parameters and performs intelligent capacitor switching using an embedded TinyML model deployed on the edge controller.

The experimental observations indicate that the system successfully maintains the power factor close to unity ( $\approx 0.99$ ) across three-phase operating conditions. The Edge AI algorithm predicts reactive power requirements in real time and automatically activates suitable capacitor banks through relay switching mechanisms. This intelligent switching significantly improves system response compared to conventional rule-based or manually controlled compensation methods.[8]



**Figure 6.** APFC System

Improvement in power factor leads to several operational advantages, including reduction in reactive power demand, minimization of transmission losses, and enhancement of overall energy efficiency. By maintaining near-unity power factor, industries can reduce electricity billing penalties associated with low power factor and excessive maximum demand charges.

Furthermore, the proposed Edge AI-based approach reduces unnecessary capacitor switching and improves system stability during fluctuating loads commonly found in industrial environments. The reduction in reactive current relieves stress on supply transformers, cables, and distribution equipment, thereby allowing additional loads to be connected without infrastructure expansion. Voltage regulation across the system is also improved due to reduced voltage drop.

Real-time monitoring through the IoT dashboard enables visualization of voltage, current, power factor, and capacitor switching status, ensuring efficient remote supervision and predictive energy management.[1]

A comparative analysis between fixed compensation, contactor-switched systems, thyristor-based APFC, and the proposed Edge AI-driven APFC system is presented in Table 1. The results demonstrate that the proposed method achieves faster response time, adaptive compensation capability, reduced switching losses, and improved automation performance.

Parameters	Contactor Based	Fixed Compensation	Thyristor Switched
Switching time	Slow(seconds)	Continuous	Very Fast(millisecons)
Maintenance	Moderate	Low	Less
Capacitor Life	Reduced	Low	Improved
Response speed	Slow	No dynamic response	Fast
Cost	Modurate	Low	High

**Table 1.** Comparison of Power Factor Correction Methods

Parameters	Before APFC	After APFC
Power Factor	0.72 – 0.80	0.96 – 0.99
Reactive Power Loss	High	Reduced
System Efficiency	Moderate	High
Energy Consumption	More	Optimized
Voltage Stability	Poor	Improved
Manual Intervention	Required	Not Required
Response Time	Slow	Fast (Real-Time)

**Table 2.** Performance Comparison

## 6. Conclusion

Low power factor in industrial power systems primarily occurs due to the widespread use of inductive loads such as induction motors, transformers, and heavy electrical machinery, which draw lagging reactive current. To improve system efficiency, reactive power compensation is required through devices capable of supplying leading current. Capacitor banks connected in parallel with the load effectively compensate reactive power and enhance the overall power factor .

In this research work, an Edge AI-driven IoT-based Automatic Power Factor Correction (APFC) system has been successfully designed and implemented to maintain near-unity power factor while optimizing energy consumption. The

proposed system integrates real-time electrical parameter sensing, intelligent decision-making using TinyML models at the edge device, and automated capacitor bank switching to achieve adaptive reactive power compensation.

The incorporation of Edge AI enables faster local processing without cloud dependency, ensuring low latency response under rapidly fluctuating industrial loads. Additionally, IoT-based monitoring allows continuous remote supervision and performance visualization through a smart dashboard interface. Harmonic effects and unnecessary switching operations are minimized through intelligent control strategies, thereby improving equipment lifespan and system stability.

Experimental results confirm that the implemented system effectively maintains the power factor close to unity and enhances operational efficiency by reducing transmission losses, voltage drops, and power factor penalties. The proposed framework is highly suitable for modern smart industries and energy-efficient manufacturing environments where dynamic load variations are common.

Overall, the developed Edge AI-enabled APFC system provides a scalable, cost-effective, and intelligent solution for next-generation smart power management applications.

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