Literature Review of Microcontroller-Based Automatic Power Factor Correction Systems and The Internet of Things

Gugut Hedi Afandi[1], Aji Brahma Nugroho[1], Iswahyudi[1]
[1]Department of Electrical Engineering, Faculty of Engineering, Universitas Muhammadiyah Jember, Jember, Indonesia
Jl. Karimata No. 49, Sumbersari, Jember 68121, East Java, Indonesia
e-mail: guguthediafandi@gmail.com

***Abstrak*— Faktor daya rendah pada sistem kelistrikan industri maupun rumah tangga menyebabkan pemborosan energi, peningkatan arus beban, dan kerugian finansial akibat denda penyedia listrik. Tinjauan literatur sistematis ini bertujuan menganalisis perkembangan, komponen, metode kontrol, dan capaian performa sistem Automatic Power Factor Correction (APFC) berbasis mikrokontroler dan Internet of Things (IoT) yang dipublikasikan pada periode 2021–2026. Pencarian dilakukan melalui empat basis data ilmiah, yaitu Sage Journal, Scopus, Taylor & Francis, dan IEEE Xplore, menghasilkan 108 artikel awal yang kemudian disaring menggunakan protokol PRISMA hingga diperoleh 10 artikel akhir. Hasil analisis menunjukkan bahwa ESP32 dan NodeMCU merupakan mikrokontroler yang paling umum digunakan, sensor PZEM-004T sebagai alat ukur daya, serta protokol MQTT sebagai medium komunikasi yang efisien untuk pemantauan real-time. Perbaikan faktor daya yang dicapai berkisar antara 0,60–0,99 setelah koreksi diterapkan. Integrasi IoT terbukti meningkatkan kemampuan pemantauan dan kendali jarak jauh secara signifikan.**

Kata kunci: ***Daya Reaktif, Internet of Things, Koreksi Faktor Daya, Mikrokontroler, Pemantauan Real-Time***

Abstract—Low power factors in industrial and household electrical systems cause energy waste, increased load flow, and financial losses due to fines for electricity providers. This systematic literature review aims to analyze the development, components, control methods, and performance achievements of microcontroller-based Automatic Power Factor Correction (APFC) systems and the Internet of Things (IoT) published in the period 2021–2026. The search was conducted through four scientific databases, namely Sage Journal, Scopus, Taylor & Francis, and IEEE Xplore, resulting in 108 initial articles that were then filtered using the PRISMA protocol until the final 10 articles were obtained. The results of the analysis show that the ESP32 and NodeMCU are the most commonly used microcontrollers, the PZEM-004T sensor as a power measuring tool, and the MQTT protocol as an efficient communication medium for real-time monitoring. The power factor improvement achieved ranges from 0.60–0.99 after the correction is applied. IoT integration has been shown to significantly improve remote monitoring and control capabilities.

Keywords: ***: Internet of Things, Microcontrollers, Power Factor Correction, Reactive Power, Real-Time Monitoring***

I. INTRODUCTION

The quality of electrical power is one of the fundamental parameters in modern electric power systems that directly impacts the operational efficiency, lifespan of equipment, and industrial and commercial operational costs [1]. One of the main problems in power quality is the low power factor caused by inductive loads such as electric motors, transformers, and power electronic equipment that inevitably exist in modern distribution systems [2].

Poorly managed reactive power causes various systemic losses, including increased current in the distribution network, which leads to energy waste in the form of heat, decreased effective capacity of distribution systems, overloading of transformers and distribution conductors, and the imposition of power factor fines by electricity supply companies to industrial consumers [3]. Surveys conducted in various industrial sectors show that the average power factor of industrial loads in Indonesia ranges from 0.6 to 0.75, far below the ideal value recommended by PLN, which is 0.85 or more [4].

The conventional solution to the reactive power compensation problem is the installation of a manually operated bank capacitor based on a schedule or load estimate. This approach has a fundamental weakness that is the inability to adapt to dynamic and unpredictable load changes, and requires intensive human intervention [5]. The development of power electronics technology and digital control systems has opened up opportunities for the development of Automatic Power Factor Correction (APFC), which is able to respond to load changes in real-time with high precision [6].

The development of power electronics technology and embedded systems has encouraged the use of microcontrollers in automatic reactive power compensation systems [7]. The microcontroller acts as a control center that is able to measure electrical parameters, process data, and control the capacitor switching process in real-time. The use of microcontrollers provides high flexibility in system development because it can be integrated with various sensors, communication modules, as well as control algorithms that are more adaptive and efficient [8]. In addition, the application of semiconductor-based switching devices such as Solid State Relay (SSR), TRIAC, and SCR has also improved system performance through a faster switching process, minimal transient interference, and has a longer operational life than conventional electromechanical relays [9].

On the other hand, the development of Internet of Things (IoT) technology has expanded the capabilities of monitoring and control systems in electrical installations [10]. IoT integration allows electrical parameter data to be monitored remotely, stored in real-time, and analyzed to support the efficiency and reliability of power systems [11]. Various communication and cloud monitoring platforms can be used in IoT implementation, both based on mobile applications, web servers, cloud dashboards, and instant messaging platforms. With this technology, the reactive power compensation system not only functions automatically, but is also able to provide more flexible, responsive, and integrated monitoring and control access [12].

This literature review aims to provide a comprehensive overview of the state-of-the-art technology of automatic reactive power compensation. This study is expected to be a valuable reference for researchers, academics, and practitioners who want to develop similar systems, as well as identify research gaps that still need to be explored.

II. RESEARCH METHODS

This literature review was carried out following the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) protocol, which is an international standard for systematic review reporting. The article selection process includes four main stages: identification, screening, eligibility, and inclusion.

A. Search Strategy

The literature search was conducted through four international scientific databases, namely Sage Journal (n=11), Scopus (n=47), Taylor & francis (n=25), and IEEE Xplore (n=25), resulting in a total of 108 articles identified. The keywords used in the search are as follows:

Table 1. Keywords and Boolean

Sage Journal	(("power factor correction" OR APFC OR "reactive power compensation") AND (microcontroller OR monitoring OR automation OR IoT))
Scopus	(("power factor correction" OR APFC OR "reactive power compensation") AND (microcontroller OR monitoring OR automation OR IoT))
Taylor & Francis	(("power factor correction" OR APFC OR "reactive power compensation") AND (microcontroller OR monitoring OR automation OR IoT))
IEEE Xplore	(("power factor correction" OR APFC OR "reactive power compensation") AND (microcontroller OR monitoring OR automation OR IoT))

B. Inclusion and Exclusion Criteria

The inclusion criteria set include: a) articles published in indexed international journals or proceedings; b) discuss the design or implementation of microcontroller-and/or IoT-based APFC systems; c) present the results of measurable experimental or simulation tests, such as power factor values, power efficiency, and system response; d) issued between 2021 and 2026; and e) written in English or Bahasa Indonesia. Meanwhile, the exclusion criteria include: a) review articles without experimental data; b) articles that focus on manual or conventional power factor correction without automation; c) issued before 2021 or after 2026; and d) articles that are not relevant to the topic of automatic power factor correction.

C. PRISMA Selection Process

Of the 108 articles identified, 4 articles were removed due to duplication, leaving 104 articles for title and abstract screening. After the first stage of screening, 82 articles were excluded because they did not meet the relevance criteria, leaving 22 articles for full-text screening. Of the 22 articles, 12 were again excluded after a feasibility evaluation, and finally, 10 articles were designated as sources used in this literature review analysis.

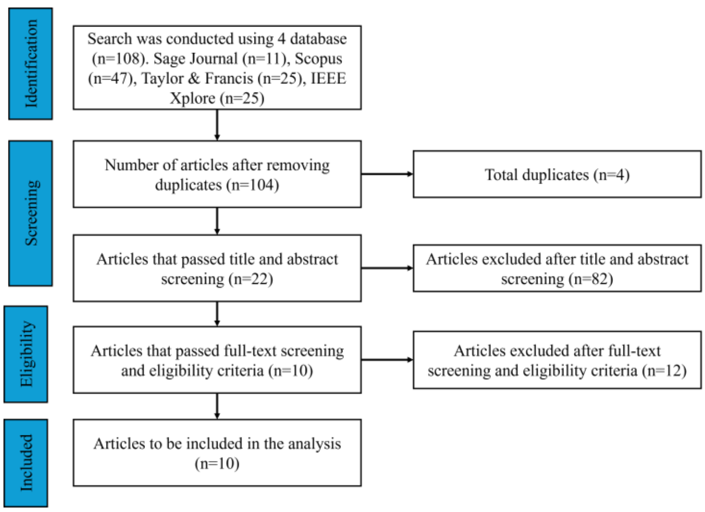

Figure 1. PRISMA Flow Diagram.

.

III. RESULT AND DISCUSSION

A. Profile of Analyzed Articles

The ten articles analyzed in depth in this literature review cover various aspects of APFC systems, ranging from IoT implementations for monitoring, artificial intelligence-based controllers, power converter topologies, to reactive compensation systems for distribution networks and PV systems. Table 1 summarizes the full profiles of the ten articles.

Table 2. Article in Analysis

Author & Year	Title	Hardware	Platform IoT	Result
Surya & Kustija (2023)	Dashboard for Industrial Load Control and Remote Power Factor Correction Based on Adafruit's MQTT	NodeMCU ESP32, PZEM-004T, Relay 220V, Capacitor Bank	Adafruit MQTT (IoT)	Real-time monitoring of current, voltage, power, power factor; delay 0.5–2 seconds; PF correction approaches unity
Shubbar et al. (2021)	Cloud-Based Automated Power Factor Correction and Power Monitoring	Raspberry Pi (private cloud), NodeMCU, PZEM-004T, Neural Network	ThingSpeak (Cloud)	Cloud & neural network based APFC system design; Support multi-home correction in one device
Martínez & Rendón (2023)	Power Factor Correction Using an ESP32 Embedded in an Interleaved Boost Converter	ESP32, Interleaved Boost Converter, Sliding Mode Control (SMC)	Not IoT-based	PF approaches unity; Stable output voltage 400 Vdc; overshoot 7% at start-up; Ripple Input Low Current
Lamo et al. (2022)	Academic Use of Rapid Prototyping in Digitally Controlled Power Factor Correctors	TI LAUNCHXL-F28379D, PLECS® Rapid Prototyping, Bridgeless Totem-pole PFC	Not IoT-based	Digital PFC THD 7% (simulation); output 400 Vdc; Faster development time with rapid prototyping
Nirmala & Venkatesan (2022)	Inverter Current Control for Reactive Power Compensation in Solar Grid System using Self-Tuned Fuzzy Logic Controller	SFLC-MPPT, LUO Converter, Hysteresis Current Controller, PLL	Not IoT-based	THD 1.87% with LCL filter; automatic reactive power compensation; PF unity in grid-connected PV systems
Guarnizo et al. (2023)	MPSO-based PID Control Design for Power Factor Correction in an AC-DC Boost Converter	DSP C2000 F28069M (TI), MATLAB/Simulink, Konverter Boost AC-DC 100 W, Kontrol MPSO-PID	Not IoT-based	PF = 0.9968 at full load; PF > 0.98 to 20% load; better than conventional PID (CMAT); Lower THD
Wagle et al. (2024)	Optimal Power Flow Based Coordinated Reactive and Active Power Control to Mitigate Voltage Violations in Smart Inverter Enriched Distribution Network	OpenDSS, Pyomo, Solver Knitro, Smart Inverter (SI), Unbalanced three-phase CIM model	Smart Inverter with communication infrastructure (not IoT eksplisit)	Lower network loss (1.49 kW); less reactive power (8.93 kVAR); awakened voltage; more efficient than combined VVC+VWC
Sonawane & Umarikar (2023)	Voltage and Reactive Power Regulation With Synchronverter-Based Control of PV-STATCOM	PV 10 kVA, VSC IGBT 2-level, Filter LCL, RTDS, DSP TMS320F28377s, Synchronverter (VSG)	Not IoT-based	PCC voltage regulation is stable; the frequency deviation is smaller than conventional STATCOM; weak tissue resistance (SCR=2.7); Passed IEEE 1547 LVRT test
Zhang et al. (2022)	Research on Reactive Power Compensation Based on Magnetic Saturation Controllable Reactor	MSCR (Magnetic Saturation Controllable Reactor), Thyristor, Algorithmic genetics	Not IoT-based	Static dynamic reactive compensation; Design optimization reduces material costs by 11.2%
Zhou et al. (2026)	High-proportion Reactive Power Compensation Control for D-HVT-BESS via Optimal Zero-sequence Current Injection	D-HVT-BESS (Cascaded H-bridge), Zero-sequence Current Injection, QPR Controller	Not IoT-based	Elimination of zero-crossing SORC; system efficiency >95.6%; SOC balance between phases ±0.4%

B. Hardware Component Analysis

1. Microcontrollers and Primary Processors

Analysis of the reviewed articles shows the trend of using ESP32 and NodeMCU as the main microcontrollers in IoT-based APFC systems. Surya and Kustija (2023) chose NodeMCU ESP32 because of its integrated Wi-Fi and Bluetooth capabilities, low power consumption, and compatibility with the Adafruit MQTT platform [13]. Martínez and Rendón (2023) also utilized ESP32 for direct control of boost converters with 12-bit ADC and a sampling rate of 6 kSPS [14].

Shubbar et al. (2021) used a combination of Raspberry Pi as a private cloud server and NodeMCU as a data transmission node [15]. Guarnizo et al. (2023) memilih Digital Signal The F28069M C2000 processor (DSP) from Texas Instruments features 12-bit ADC, suitable for real-time PID control computing on a 100 W power converter [16]. For larger-scale reactive compensation, Wagle et al. (2024) used the Knitro numerical solver in a Pyomo/Python environment, while Sonawane and Umarikar (2023) used the TMS320F28377s DSP in RTDS-based CHIL assays [17].

2. Power Measurement Sensor

The PZEM-004T sensor is used as an electrical energy measurement sensor because it is able to measure electrical parameters such as voltage, current, power, energy, and frequency and supports serial communication with microcontrollers for IoT-based monitoring needs [18].

In advanced reactive converter systems, separate current transformer and voltage dividers (VD) are used for high-precision real-time control. Guarnizo et al. (2023) used a shunt resistor as a current sensor to measure the inductor current (iL) and the input/output voltage of the converter. Sonawane and Umarikar (2023) used DSP-integrated ADCs with conditioned signals from PV-STATCOM inverter voltage and current [16].

3. Converter Actuators and Topologies

Electromechanical relays (EMRs) are becoming the most commonly used actuators for compensating capacitor switching in IoT-based research. Surya and Kustija (2023) used 4 220 V AC relays with capacitors of 15, 45, 60, and 75 VAR. Shubbar et al. (2021) noted that SSR is a superior alternative but has not been widely implemented.

For power converter applications, Guarnizo et al. (2023) used PWM-controlled MOSFETs on a 100 W boost converter with a switching frequency of 50 kHz, while Sonawane and Umarikar (2023) used a 6-pulse (2-level, 10 kHz) IGBT VSC with LCL filter for the PV-STATCOM interface to the network [19]. Wagle et al. (2024) utilize smart inverters as distributed actuators that can adjust the active and reactive power simultaneously based on the optimal set point of the OPF solver [17].

C. Control Method Analysis

The control methods used in the APFC systems reviewed show considerable diversity, from simple methods based on direct computing to advanced artificial intelligence and optimization approaches.

The direct computational control method was used by Surya and Kustija (2023) and Shubbar et al. (2021), in which the value of the power factor is compared to the setpoint then the corresponding capacitor is activated [13,15]. Sliding Mode Control (SMC) by Martínez and Rendón (2023) offers high resistance to interference, achieving PF close to unity with a settling time of ~70 ms [14]. SFLC (Self-Tuned Fuzzy Logic Controller) by Nirmala and Venkatesan (2022) yields a THD of 1.87% with LCL filters [20].

Guarnizo et al. (2023) introduced the first use of MPSO (Multi-Particle Swarm Optimization) for offline PID tuning on an AC-DC boost converter-based PFC [16]. MPSO modifies the classic PSO algorithm by using multiple independent swarms to avoid premature convergence to local solutions. The optimal PID parameters obtained (Kp=0.504; To=3000; $Kd=4.1\times10^{-6}$; $Kn=4.8\times10^{6}$) yields PF = 0.9968 at full load and PF > 0.98 at 20% load, exceeding the performance of conventionally tuned controllers.

Wagle et al. (2024) used an Optimal Power Flow (OPF) approach based on the unbalanced three-phase Current Injection Method (CIM) model to obtain the optimal set point of active and reactive power from each smart inverter in the distribution network [17]. OPF was solved as a quasi-dynamic optimization problem with a resolution of 5 minutes for one day, using Pyomo and Knitro solvers. The results were compared with the Volt-Var Control (VVC), Volt-Watt Control (VWC), and VVC+VWC combinations. The OPF method has been proven to result in lower tissue losses and less reactive power requirements.

Sonawane and Umarikar (2023) propose a synchronverter controller for PV-STATCOM that mimics the physical characteristics of a synchronous machine through swing equations. The synchronverter integrates an active power loop (APL), DC voltage loop (DCVL), reactive power loop (RPL), PCC voltage control loop (VCL), and voltage droop loop (VDL) [19]. This approach provides virtual inertia that reduces frequency deviation and improves dynamic stability, especially in weak network conditions (SCR=2.7) where conventional STATCOM exhibits oscillatory responses.

D. IoT System Analysis and Communication Protocols

1. Protocol MQTT

MQTT is the most widely adopted IoT communication protocol. Surya and Kustija (2023) leveraged Adafruit IO with MQTT brokers, enabling real-time monitoring and control. MQTT uses a minimum header overhead of 2 bytes and supports TLS/SSL encryption on port 8883 [13].

2. Platform Monitoring IoT

Adafruit IO and ThingSpeak are platforms used by two IoT-based studies. The research of Guarnizo et al., Wagle et al., Sonawane & Umarikar did not integrate IoT platforms, relying on direct measurements via oscilloscopes, software simulations (OpenDSS/PSCAD), or DSP interfaces. The use of Telegram Bot as a monitoring platform has not been found in the entire article reviewed, although it offers the advantages of easy access, end-to-end encryption, and automatic push notifications [16-17, 19].

Telegram Bot has several advantages that support the implementation of an IoT-based monitoring system. First, Telegram provides an open API that makes it easy to integrate with microcontrollers and IoT platforms without requiring additional licensing fees [21]. Second, users do not need to register again because the system can directly utilize the Telegram account they already have. Third, Telegram provides a communication security mechanism through an encryption system that supports data protection during the transmission process. Fourth, Telegram Bot is able to provide automatic push notifications in real-time so that system condition information can be received by users quickly and efficiently. With these characteristics, Telegram Bot has the potential to be an alternative monitoring platform that is simple, economical, and easy to implement on the Automatic Power Factor Correction (APFC) system [22].

E. Comprehensive Comparison of APFC System

Table 3 presents a comprehensive comparison between the ten systems from the article analyzed based on hardware components, communication protocols, user interfaces, and control methods.

Table. 3 Comprehensive Comparison of APFC System from Analyzed Articles

Artikel	MCU/ Prosesor	Sensor	Actuator	Protokol IoT	Interface	Control Method
Surya & Kustija (2023)	NodeMCU ESP32	PZEM-004T	Relay EMR 220V	MQTT (Adafruit IO)	Web Dashboard	Direct computing
Shubbar et al. (2021)	Raspberry Pi + NodeMCU	PZEM-004T	Relay + Kapasitor Selector	HTTP (ThingSpeak)	Web Page	Neural Network
Martínez & Rendón (2023)	ESP32	CT + VD	MOSFET (IBC)	None	None	Sliding Mode Control
Lamo et al. (2022)	TI F28379D	CT + Shunt	MOSFET (Totem-pole)	None	PLECS/ HIL	Digital PID + Current Mode
Nirmala & Venkatesan (2022)	PIC MCU	Shunt + VD	LUO Converter + Relay	None	Hardware Lab	SFLC + Hysteresis
Guarnizo et al. (2023)	DSP C2000 F28069M (TI)	CT + Shunt Resistor	PWM → Boost Converter	None	Oscilloscope / DSP	MPSO-PID (Offline Tuning)
Wagle et al. (2024)	Pyomo/Knitro Solver (Software)	Energy Meter (simulation)	Smart Inverter (aktif+reaktif)	SI communication (implicit)	OpenDSS + Python	Three-phase CIM-based OPF
Sonawane & Umarikar (2023)	DSP TMS320F28377s	ADC voltage & current	IGBT VSC 6-pulsa (PV-STATCOM)	None	PSCAD/ RTDS + DSP	Synchronverter (VSG) + MPPT
Zhang et al. (2022)	MATLAB/ Simulink	CT + VD	MSCR + Thyristor	None	LCD/ Simulation	Adaptif Genetika
Zhou et al. (2026)	DSP Controller	CT + VD	IGBT (CHB Converter)	None	Oscilloscope	Zero-seq. Current Inj.

Various control methods have been developed to improve the performance of reactive power compensation and power quality control in electric power systems. Each method has different performance characteristics, complexity levels, and computing needs. Therefore, a comparative analysis was conducted based on the results reported in the reviewed articles to compare response time, overshoot, steady-state error (SSE), total harmonic distortion (THD), implementation complexity, and computational needs of each control method. This comparison aims to provide an overview of the advantages and limitations of each control approach.

Table 4. Comparative Performance Analysis of Control Methods

Control Method	Response Time	Overshoot	Steady-State Error	THD	Implementation Complexity	Computational Requirement
Direct Computing	0.5–2 s	N/A	Not quantified	N/A	Low	Low
Neural Network Control	N/A	N/A	2.2–5.2%	N/A	High	High
Sliding Mode Control (SMC)	~70 ms	~7%	≈0	Low	High	Moderate
Digital PID + Current Mode	~1.5 s	Low	~7%	~7%	Moderate	Moderate
SFLC + Hysteresis	Fast	Low	0.38 A	1.87%	High	Moderate
MPSO-PID	Not reported	Not reported	Very low	Not reported	Moderate–High	Moderate
CIM-Based OPF	Minutes	Not reported	Very low	Not reported	Very High	Very High
Synchronverter	Fast	Low	Low	Not reported	Moderate	High
Adaptive Genetic	>500 ms	Not reported	Low	Not reported	High	High
Zero-Sequence Current Injection	Several seconds	Not reported	ASOC ≤ ±0.4%	Not reported	Very High	Very High

DISCUSSION

The Adafruit MQTT-based system excels in ease of access to monitoring, but has limitations in the form of dependence on third-party servers and latency of 0.5–2 seconds [13]. The Raspberry Pi cloud approach offers neural network computing, but the cost and complexity are higher [15].

Advanced control systems demonstrate superior performance in response speed and fault resistance, but without IoT monitoring features [14-17, 19-20]. The MPSO-PID approach provides the unique advantage of secure offline tuning, the converter is not at risk of being damaged by unstable parameters during algorithm iterations [16]. However, the system is also not equipped with IoT and needs to be reimplemented if the converter parameters change significantly.

The OPF method by is the only approach that considers the simultaneous coordination of all inverters in a distribution network [17]. Compared to VVC and local VWC, OPF results in more even power distribution, network losses are 15.8% lower than VVC+VWC combined (1.49 kW vs 1.77 kW), and reactive power requirements are more efficient. However, this approach requires a larger communication and computing infrastructure, which is impractical for small scales.

PV-STATCOM based on synchronverter stands out as the only approach that explicitly combines reactive compensation with frequency control through virtual inertia [19]. CHIL tests on RTDS confirmed that synchronverter controllers are much more stable than conventional STATCOM at low SCR, and successfully meet IEEE 1547 LVRT requirements. The limitations are the complexity of the controller design and the need for a high-speed DSP.

The Magnetic Saturation Controllable Reactor (MSCR) studied by Zhang et al. (2022) is a static-dynamic reactive power compensation device that works by compensating the capacitive reactive force through inductive lagging reactive power [23] The main advantage of MSCR lies in the ability to continuously adjust the reactive compensation capacity by simply adjusting the trigger angle of the thyristor, so that the system can respond dynamically to load changes. Simulations with MATLAB/Simulink showed that the magnetic flux density of the iron core reached a maximum value of 2.5 T after about 25 cycles and operated stably in the saturation zone (1.7–2.5 T), verifying the effectiveness of inductance control over DC current.

The control characteristics of the MSCR show the cosine relationship between the effective fundamental current and the trigger angle, providing good linearity for the control system. The application of the Improved Adaptive Genetic Algorithm (IAGA) for design optimization succeeded in reducing the effective material cost by 11.2% (from 189.78 yuan to 153.82 yuan) compared to the initial design, while still meeting all performance specifications. The limitation of this study is the lack of integration of remote monitoring systems and IoT interfaces, so the application of MSCR in small-medium scale industries still requires trained operators for direct monitoring.

Zhou et al. (2026) proposed a High-proportion Reactive Power Compensation Control (HPRPCC) method for Delta-connected High-voltage Transformerless Battery Energy Storage System (D-HVT-BESS) through optimized zero-sequence current injection [24]. The fundamental problem that was solved was the appearance of Second-Order Ripple Current (SORC) in the battery cell due to the delta configuration that did not have a shared bus; in low power factor conditions (|cosφ| < 0.083), the SORC experiences repeated zero-crossing at a frequency of 100 Hz which accelerates battery degradation and lowers the accuracy of State of Charge (SOC) estimates.

The main advantage of the proposed method is the ability to eliminate SORC zero-crossing completely without the addition of extra hardware, since the zero-sequence current redistributes power between the three phases so that each phase operates in the normal area (|Q/Q| ≤ K). Optimization of the amplitude and phase angle of the zero-sequence current was performed to minimize incremental losses of the system, resulting in a very small decrease in efficiency (≤ 0.4% from the initial value of 95.6‑96.1%). In addition, the absolute phase selector-based SOC balancing controller ensures that the SOC balance between phases is maintained in the range of ±0.4%. Validation on a 380 V/100 kW/50 kWh experimental prototype confirmed the effectiveness of the method in four different operating scenarios (cosφ = 0.062; −0.062; 0; 0). The limitation of this study is that it focuses on the scale of high-voltage utilities and does not include the integration of IoT monitoring, so it cannot be directly applied to small-scale microcontroller-based APFC systems.

A comprehensive analysis of the 10 articles reviewed not only maps the development of IoT-based APFC systems, but also uncovers a number of gaps that implicitly open up space for more integrative and applicable follow-up research. First, all of the articles reviewed still rely on Electromagnetic Relay (EMR) or conventional power semiconductor components as switching actuators. This condition shows that the use of Solid State Relay (SSR) with a zero-crossing switching mechanism that offers a much longer operational life and higher resilience for industrial environments, has not received attention in the context of small-scale APFC IoT systems, making it a development direction worth exploring.

Second, a review of the literature shows that all existing monitoring systems still rely on paid platforms, dedicated web interfaces, or mobile applications that require additional infrastructure. None of the articles use Telegram Bot as a medium of communication, even though the platform provides an open API at no cost, end-to-end encryption, automatic push notifications, and two-way control capabilities without the need for new system registration, characteristics that are well suited for implementation in small and medium-sized industries with limited budgets.

Third, the existing literature tends to distinguish between multi-parameter monitoring systems and automatic power factor correction systems. A fully integrated system capable of accurate measurement power parameters, performing automatic corrections, and sending notifications of abnormal conditions through an easily accessible platform, is still very rare, especially for small and medium-sized industrial segments.

Fourth, there is a striking dichotomy in the control approach: ESP32-based systems with IoT connectivity generally only apply simple controls in the form of static thresholds, while systems with intelligent algorithms such as MPSO or fuzzy logic are not equipped with IoT features. This gap indicates the need for research that bridges the two to present an adaptive compensation algorithm on the ESP32 platform that is simultaneously connected to the IoT network.

IV. FUTURE RESEARCH DIRECTIONS

Based on the identified research gaps, several future research directions are proposed: (1) the development of Automatic Power Factor Correction (APFC) systems based on Solid State Relays (SSR) employing zero-crossing switching techniques to improve switching reliability and reduce electrical noise; (2) the implementation of Telegram Bot-based notification systems to provide real-time monitoring, fault detection, and alert services for APFC systems; (3) the integration of multi-parameter measurement capabilities, including power factor, voltage, current, active power, reactive power, and harmonic distortion, to enhance monitoring accuracy and system performance evaluation; and (4) the implementation of adaptive control algorithms on ESP32 platforms to enable intelligent and autonomous capacitor bank switching under dynamic load conditions. These research directions are expected to contribute to the development of more efficient, reliable, intelligent, and IoT-enabled APFC systems for modern power quality management.

V. CONCLUSION

This systematic literature review has analyzed 10 articles on microcontroller-based and IoT-based Automatic Power Factor Correction systems published in the period 2021-2026. Some important conclusions to be drawn from this review are: First, ESP32 and NodeMCU are the most predominant microcontrollers used in IoT-based APFC systems, supported by integrated Wi-Fi capabilities, low power consumption, and a mature development ecosystem. Secondly, the PZEM-004T became the most widely used power measurement sensor due to its ability to measure complete power parameters in a single module with a simple UART interface. Third, the MQTT protocol is proving to be the top choice for IoT communication in real-time power monitoring systems due to its low overhead, bandwidth efficiency, and data transmission reliability. Fourth, the bio-inspired MPSO algorithm for safe offline PID tuning on the PFC boost converter; OPF method based on an unbalanced three-phase network model for the coordination of smart inverters in the distribution network; and synchronverter controllers that provide virtual inertia to improve PV-STATCOM stability on weak networks.

REFERENCES

[1] F. Zheng and W. Zhang, “Long term effect of power factor correction on the industrial load: A case study,” *2017 Australasian Universities Power Engineering Conference, AUPEC 2017*, vol. 2017-November, pp. 1–5, Feb. 2018, doi: 10.1109/AUPEC.2017.8282382.

[2] K. H. Akhil, R. Asmita, N. Mishra, and P. V. Manitha, “Machine Learning Assisted Power Factor Correction using Capacitor Banks,” *2024 2nd World Conference on Communication and Computing, WCONF 2024*, 2024, doi: 10.1109/WCONF61366.2024.10692176.

[3] G. Chickering, C. Jones, and N. Blaushild, “Development of an Optimal Control Strategy of Three Phase Power Factor Correction System[تطوير اسرتاتيجية التحكم ألامثل لنظام تصحيح معامل القدرة ثالثي الطو],” *Journal of Data Science*, pp. 1–25, Jan. 2026, doi: 10.6339/26-JDS1216.

[4] A. Rodríguez and F. J. Muñoz, “Power factor correction,” *Encyclopedia of Electrical and Electronic Power Engineering: Volumes 1-3*, vol. 1, pp. 456–471, Jan. 2023, doi: 10.1016/B978-0-12-821204-2.00022-2.

[5] H. Shamshuddin, S. S. Sarnin, W. N. Wan, N. I. A. R. Muhamad, R. S. S. Abdul Kadir, and N. F. Naim, “Performance Analysis of Power Factor Correction for Inductive Load using MATLAB Simulink,” *15th IEEE Malaysia International Conference on Communications: Emerging Technologies in IoT and 5G, MICC 2021 - Proceedings*, pp. 37–42, 2021, doi: 10.1109/MICC53484.2021.9642112.

[6] M. Muthukumaran, S. Ajay, G. Kabilan, S. Sivabalan, and S. Sivasangeeth, “Smart Monitoring and Control Techniques for Power Factor Correction Systems,” *Proceedings - 3rd International Conference on Artificial Intelligence and Machine Learning Applications: Healthcare and Internet of Things, AIMLA 2025*, 2025, doi: 10.1109/AIMLA63829.2025.11041643.

[7] H. S. K. El-Goharey and W. M. Mamdouh, “On-line analysis of power quality problems in non-sinusoidal/non-linear distribution systems,” *Ain Shams Engineering Journal*, vol. 14, no. 9, p.

102266, Sep. 2023, doi: 10.1016/J.ASEJ.2023.102266.

[8] A. N. Luqman, N. S. Lestari, and I. Setiawan, “Simplified automatic VAR/Power factor compensator using fuzzy logic based on internet of things,” *J. Phys. Conf. Ser.*, vol. 1195, no. 1, p. 012016, Apr. 2019, doi: 10.1088/1742-6596/1195/1/012016.

[9] P. Singh, D. Bhule, and S. Kaarthik, “A Four Switch SiC Solid State Relay with Inrush Current Protection for High Voltage and High Power Converters,” *Proceedings of the International Conference on Power Electronics, Drives, and Energy Systems for Industrial Growth, PEDES*, no. 2024, 2024, doi: 10.1109/PEDES61459.2024.10961406.

[10] R. Venkataswamy, K. U. Rao, and P. Meena, “Development of Internet of Things Platform and Its Application in Remote Monitoring and Control of Transformer Operation,” *Lecture Notes in Networks and Systems*, vol. 80, pp. 165–183, 2020, doi: 10.1007/978-3-030-23162-0_16/FIGURES/15.

[11] P. P. Kulkarni, M. Patil, S. Shibi, M. Patle, and R. Kale, “Review on Online Monitoring of Electrical Machine using IOT,” *2019 International Conference on Nascent Technologies in Engineering, ICNTE 2019 - Proceedings*, Jan. 2019, doi: 10.1109/ICNTE44896.2019.8945927.

[12] E. Duraiarasu, M. Arulmozhi, and R. Karthikeyan, “Cloud-based Power Theft Detection with Automatic Notification System,” *Proceedings of the 2023 2nd International Conference on Augmented Intelligence and Sustainable Systems, ICAISS 2023*, pp. 1233–1238, 2023, doi: 10.1109/ICAISS58487.2023.10250528.

[13] I. Surya and J. Kustija, “Dashboard for Industrial Load Control and Remote Power Factor Correction Based on Adafruit’s MQTT,” *Buletin Ilmiah Sarjana Teknik Elektro*, vol. 5, no. 1, pp. 76–85, Mar. 2023, doi: 10.12928/biste.v5i1.7494.

[14] F. H. Martínez and A. V Rendón, “Power Factor Correction Using an ESP2 Embedded in an Interleaved Boost Converter,” *ARPN Journal of Engineering and Applied Sciences*, vol. 18, no. 17, pp. 2058–2065, 2023, [Online]. Available: www.arpnjournals.com

[15] M. M. Shubbar, L. A. Abdul-Rahaim, and A. A. Hamad, “Cloud-Based Automated Power Factor Correction and Power Monitoring,” *Mathematical Modelling of Engineering Problems*, vol. 8, no. 5, pp. 757–762, Oct. 2021, doi: 10.18280/mmep.080510.

[16] J. G. Guarnizo *et al.*, “MPSO-based PID control design for power factor correction in an AC-DC boost converter,” *Automatika*, vol. 64, no. 4, pp. 893–902, 2023, doi: 10.1080/00051144.2023.2225918.

[17] R. Wagle, P. Sharma, C. Sharma, and M. Amin, “Optimal power flow based coordinated reactive and active power control to mitigate voltage violations in smart inverter enriched distribution network,” *Int. J. Green Energy*, vol. 21, no. 2, pp. 359–375, 2024, doi: 10.1080/15435075.2023.2196324.

[18] M. A. Ridho, M. A. Auliq, Fitriana, Iswahyudi, and Sutikno, “Tera Ulang KWh Meter Tua Menggunakan Alat Tera Portabel Berbasis Sensor PZEM-004T (Studi Kasus di PT. PLN (Persero) ULP Klakah),” *Jurnal Teknik Elektro dan Komputasi (ELKOM)*, vol. 7, no. 1, pp. 132–139, Mar. 2025, doi: 10.32528/elkom.v7i1.22920.

[19] A. J. Sonawane and A. C. Umarikar, “Voltage and Reactive Power Regulation With Synchronverter-Based Control of PV-STATCOM,” *IEEE Access*, vol. 11, pp. 52129–52140, 2023, doi: 10.1109/ACCESS.2023.3276787.

[20] R. Nirmala and S. Venkatesan, “Inverter current control for reactive power compensation in solar grid system using Self-Tuned Fuzzy Logic Controller,” *Automatika*, vol. 63, no. 1, pp. 102–121, 2022, doi: 10.1080/00051144.2021.2009653.

[21] J. Kim, S. C. Choi, I. Y. Ahn, N. M. Sung, and J. Yun, “From WSN towards WoT: Open API Scheme Based on oneM2M Platforms,” *Sensors 2016, Vol. 16, Page 1645*, vol. 16, no. 10, p. 1645, Oct. 2016, doi: 10.3390/S16101645.

[22] R. G. Anvekar, R. M. Banakar, and R. R. Bhat, “Design alternatives for end user communication in IoT based system model,” *Proceedings - 2017 IEEE Technological Innovations in ICT for Agriculture and Rural Development, TIAR 2017*, vol. 2018-January, pp. 121–125, Jul. 2017, doi: 10.1109/TIAR.2017.8273698.

[23] Z. Keju, W. Xin, and B. He, “Research on Reactive Power Compensation Based on Magnetic Saturation Controllable Reactor,” *IEEE Access*, vol. 10, pp. 31377–31384, 2022, doi: 10.1109/ACCESS.2022.3143878.

[24] X. Zhou *et al.*, “High-proportion Reactive Power Compensation Control for Delta-connected High-voltage Transformerless Battery Energy Storage System via Optimal Zero-sequence Current Injection,” *JOURNAL OF MODERN POWER SYSTEMS AND CLEAN ENERGY*, vol. 10, no. 10, pp. 1–6, 2026, doi: 10.35833/MPCE.2025.000516.