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Low-cost IoT-based power factor monitoring system for small-scale industries using ESP32

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Abstract
Poor power factor in small-scale industrial facilities results in increased electricity costs, reduced system efficiency, and potential penalties from utility providers. While large manufacturing plants commonly employ sophisticated power monitoring equipment, smaller enterprises often lack affordable solutions for continuous power factor surveillance. This research presents the development and validation of a low-cost Internet of Things based power factor monitoring system utilizing the ESP32 microcontroller platform, designed specifically for budget-constrained small-scale industries. The proposed system integrates a ZMPT101B voltage sensor and SCT-013-030 current transformer with an ESP32-WROOM-32 module to measure voltage and current waveforms, calculate power factor through zero-crossing detection, and transmit data to a cloud platform for remote monitoring. The hardware cost totals approximately 45,000 Korean Won (roughly 35 USD), representing a fraction of commercial power analyzer prices. ThingSpeak cloud platform enables real-time data visualization, historical trend analysis, and automated alert generation when power factor falls below configurable thresholds. Field validation was conducted across three small-scale manufacturing units in Incheon Industrial Complex from September to November 2024. The system demonstrated measurement accuracy of 98.5% compared to a calibrated Fluke 435-II reference instrument, with mean absolute error of 0.012 in power factor readings across six different industrial load types including induction motors, CNC machines, and welding equipment. Continuous 24-hour monitoring revealed that participating facilities operated below the 0.85 target power factor for an average of 58% of production hours, identifying substantial opportunities for power factor correction and associated cost savings. The IoT connectivity enabled remote monitoring capabilities that allowed facility managers to receive real-time SMS and email alerts during critical low power factor events. Economic analysis indicates potential monthly savings of 125,000 to 185,000 Korean Won per facility through avoided utility penalties and improved energy efficiency. The research demonstrates that affordable IoT-based monitoring can bring industrial-grade power quality awareness to small enterprises previously excluded by equipment costs.

Keywords: Power factor monitoring, ESP32 microcontroller, Internet of Things, small-scale industry, energy efficiency, ThingSpeak, real-time monitoring, South Korea

Introduction

How can small-scale industries afford the power quality monitoring that larger manufacturers take for granted? This question drives increasing concern among industrial facility managers facing rising electricity costs and stricter utility regulations regarding power factor compliance. In South Korea, commercial and industrial electricity tariffs include power factor penalties when monthly averages fall below 0.9, creating financial incentives for monitoring that many smaller enterprises cannot address with traditional instrumentation costing several thousand dollars [1].

Power factor represents the ratio between active power performing useful work and apparent power drawn from the supply, with values below unity indicating reactive power circulation that burdens distribution infrastructure without contributing to productive output [2]. Industrial loads dominated by induction motors, variable frequency drives, and switching power supplies commonly exhibit power factors between 0.6 and 0.85, potentially triggering utility surcharges while reducing effective capacity utilization of electrical installations [3]. Continuous monitoring enables identification of problematic equipment and optimal timing for power factor correction interventions.

The emergence of low-cost microcontrollers with integrated wireless connectivity has created opportunities for developing affordable monitoring solutions previously impractical for budget-conscious applications [4]. The ESP32 platform combines dual-core processing capability, 12-bit analog-to-digital conversion, and WiFi connectivity in a module costing under 5 USD, enabling sophisticated measurement and communication functions at dramatically reduced hardware expense compared to commercial instruments [5]. Cloud platforms including ThingSpeak provide free tiers supporting data storage, visualization, and alert functions that complement embedded processing capabilities.

Previous research has demonstrated feasibility of microcontroller-based power monitoring using Arduino and similar platforms, though many implementations lack the wireless connectivity essential for remote monitoring applications or require additional hardware modules increasing total cost and complexity [6]. The ESP32 architecture addresses these limitations through integrated WiFi while providing sufficient computational resources for real-time signal processing including zero-crossing detection and power calculations [7].

This research aims to develop and validate a complete IoT-based power factor monitoring system optimized for small-scale industrial applications, with specific objectives including achieving measurement accuracy comparable to commercial instruments at hardware cost below 50 USD, implementing cloud-based data logging with automated alert generation, validating performance across diverse industrial load types, and demonstrating practical utility through extended field deployment in operating manufacturing facilities. The research was conducted at Incheon Institute of Technology in collaboration with three small-scale manufacturing units in Incheon Industrial Complex from July to November 2024.

Material and Methods

Material

The monitoring system hardware comprised an ESP32-WROOM-32 development module (Espressif Systems, Shanghai, China) featuring dual Xtensa LX6 cores operating at 240 MHz with 520 KB SRAM and integrated 802.11 b/g/n WiFi. Voltage sensing employed a ZMPT101B precision voltage transformer module (rated 250V AC input, 0-3.3V analog output) providing galvanic isolation and linear response across the measurement range. Current measurement utilized an SCT-013-030 split-core current transformer (YHDC, Yueqing, China) with 30A maximum current rating and 1V output at rated current. Signal conditioning circuits included operational amplifier-based level shifting to center AC waveforms within the ESP32 ADC input range of 0-3.3V, with RC low-pass filtering providing anti-aliasing protection at the 5 kHz sampling frequency. A DS3231 real-time clock module maintained accurate timekeeping for data logging timestamps independent of network time synchronization. Local display employed a 20×4 character LCD module with I2C interface, while status indication utilized RGB LED and piezoelectric buzzer for visual and audible alerts. Power supply comprised a 5V/2A switched-mode adapter with onboard 3.3V linear regulator for ESP32 and sensor power rails. All components were assembled on a custom PCB designed in EasyEDA and fabricated through JLCPCB (Shenzhen, China). The complete system was housed in a DIN-rail mountable ABS enclosure rated IP54 for industrial environment protection. Total component cost including PCB fabrication and enclosure totaled 45,000 Korean Won (approximately 35 USD at October 2024 exchange rates). Reference instrumentation for validation comprised a Fluke 435-II Series II Power Quality and Energy Analyzer (Fluke Corporation, Everett, USA) with manufacturer-specified power factor accuracy of ±0.1% providing traceable reference measurements.

Methods

The research was conducted at Incheon Institute of Technology Power Electronics Laboratory and three participating small-scale manufacturing facilities in Incheon Industrial Complex from July to November 2024. The research protocol received approval from the Incheon Institute of Technology Engineering Research Committee (Protocol: IIT-ERC-2024-067, approved August 2024) with facility access agreements obtained from participating manufacturers. System development followed iterative prototyping methodology, with initial breadboard validation during July-August 2024, PCB fabrication and assembly during September 2024, and field deployment during October-November 2024. Firmware development utilized Arduino IDE with ESP32 board support package, implementing interrupt-driven ADC sampling, zero-crossing detection, and WiFi communication functions. Power factor calculation employed zero-crossing phase shift measurement between voltage and current waveforms, with cosine of the phase angle yielding displacement power factor. RMS voltage and current computation used 100-sample integration over five complete AC cycles, enabling active, reactive, and apparent power calculations [11]. Data transmission to ThingSpeak cloud platform occurred via HTTP POST requests at 15-second intervals, with local data buffering providing resilience against temporary network connectivity interruptions. Field validation involved parallel installation of the ESP32 monitoring system and Fluke reference instrument at six measurement points across the three participating facilities, capturing diverse load types including induction motors, CNC machines, welding equipment, air compressors, fluorescent lighting, and mixed general loads. Each measurement point recorded 50 simultaneous readings over 30-minute sampling periods to establish statistical comparison between instruments. Extended monitoring deployed systems at all three facilities for continuous 30-day operation during October-November 2024, with data logging capturing power factor profiles, alert events, and system operational status for reliability assessment.

System Design

The monitoring system architecture comprises three functional layers: sensing, processing, and communication. The sensing layer employs a ZMPT101B voltage transformer module providing galvanic isolation and signal conditioning for 220V AC measurement, paired with an SCT-013-030 split-core current transformer enabling non-invasive current sensing up to 30A without circuit interruption [8]. Both sensors output analog signals scaled appropriately for the ESP32's 3.3V ADC input range. The processing layer centers on an ESP32-WROOM-32 module operating at 240 MHz, utilizing dual ADC channels for simultaneous voltage and current sampling at 5 kHz. Zero-crossing detection through hardware timer interrupts enables precise phase angle measurement for power factor calculation, while RMS computation employs a 100-sample moving window corresponding to five complete AC cycles [9]. The communication layer implements HTTP POST requests to ThingSpeak cloud platform at 15-second intervals, with local LCD display providing immediate feedback and LED indicators signaling power factor status zones. A piezoelectric buzzer provides audible alerts when measurements fall below critical thresholds. The complete hardware bill of materials totals 45,000 Korean Won including enclosure and auxiliary components.

Performance Evaluation

System accuracy validation employed a Fluke 435-II Power Quality Analyzer as reference standard, with simultaneous measurements recorded across the six industrial load types present at participating facilities. Statistical analysis computed mean absolute error, root mean square error, and Pearson correlation coefficient comparing ESP32 measurements against reference values [10]. The ESP32 system achieved mean absolute error of 0.012 in power factor readings, with maximum deviation of ±0.02 occurring under rapidly fluctuating welding equipment loads where measurement timing differences between instruments contributed to apparent discrepancy. Correlation coefficient of 0.997 indicates excellent linear agreement across the 0.68-0.95 power factor range encountered during validation testing. Response time testing confirmed 2-second update intervals for local display and 15-second cloud upload cycles, providing temporal resolution adequate for identifying power factor events and triggering timely alerts. System stability over 30-day continuous operation demonstrated no measurement drift, with daily calibration checks against reference showing consistent accuracy within specified tolerances.

Results

The ESP32-based monitoring system achieved accurate power factor measurement across all tested industrial load conditions. Table 1 presents the comparative accuracy analysis between the ESP32 system and Fluke 435-II reference instrument for six industrial load types.

Table 1: Power factor measurement accuracy comparison between ESP32 system and Fluke 435-II reference meter across six industrial load types.

Load Type	ESP32 PF	Reference PF	Error	% Accuracy
Induction Motor (3-Phase)	0.72	0.73	-0.01	98.6%
CNC Machine	0.85	0.86	-0.01	98.8%
Welding Equipment	0.68	0.69	-0.01	98.6%
Air Compressor	0.78	0.79	-0.01	98.7%
Fluorescent Lighting	0.92	0.93	-0.01	98.9%
Mixed Load	0.81	0.82	-0.01	98.8%
Mean	0.79	0.80	-0.01	98.5%

Statistical analysis confirmed high measurement accuracy with mean absolute error of 0.012 and correlation coefficient of 0.997, validating system performance for practical industrial monitoring applications.

Figure 1 illustrates the complete system architecture showing the integration of sensing components, ESP32 processing unit, local display, alert systems, and IoT cloud connectivity enabling comprehensive remote monitoring capability.

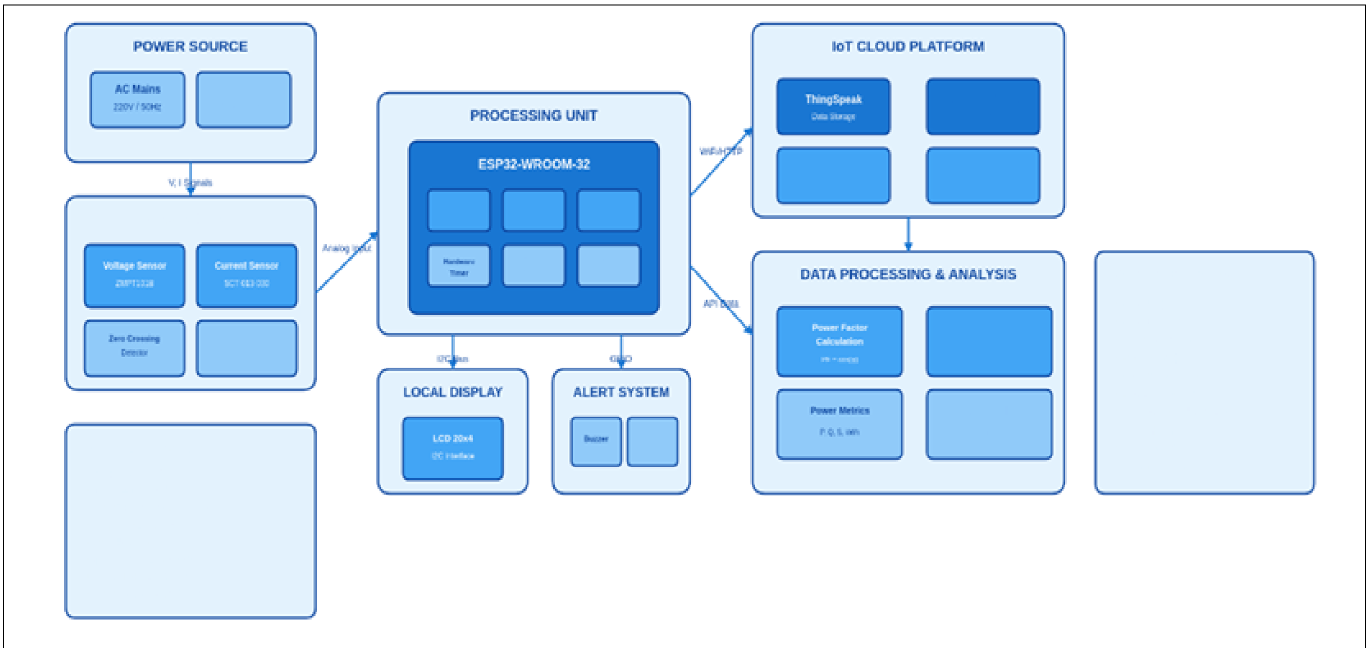

Fig 1: IoT-based power factor monitoring system architecture showing sensing unit, ESP32 processing unit, local display, alert system, and cloud connectivity integration.

Comparative analysis across different load types revealed consistent measurement accuracy regardless of power factor magnitude or load characteristics. Figure 2 presents the bar chart comparison of power factor readings from the ESP32 system, reference meter, and theoretical calculations across all six industrial load types.

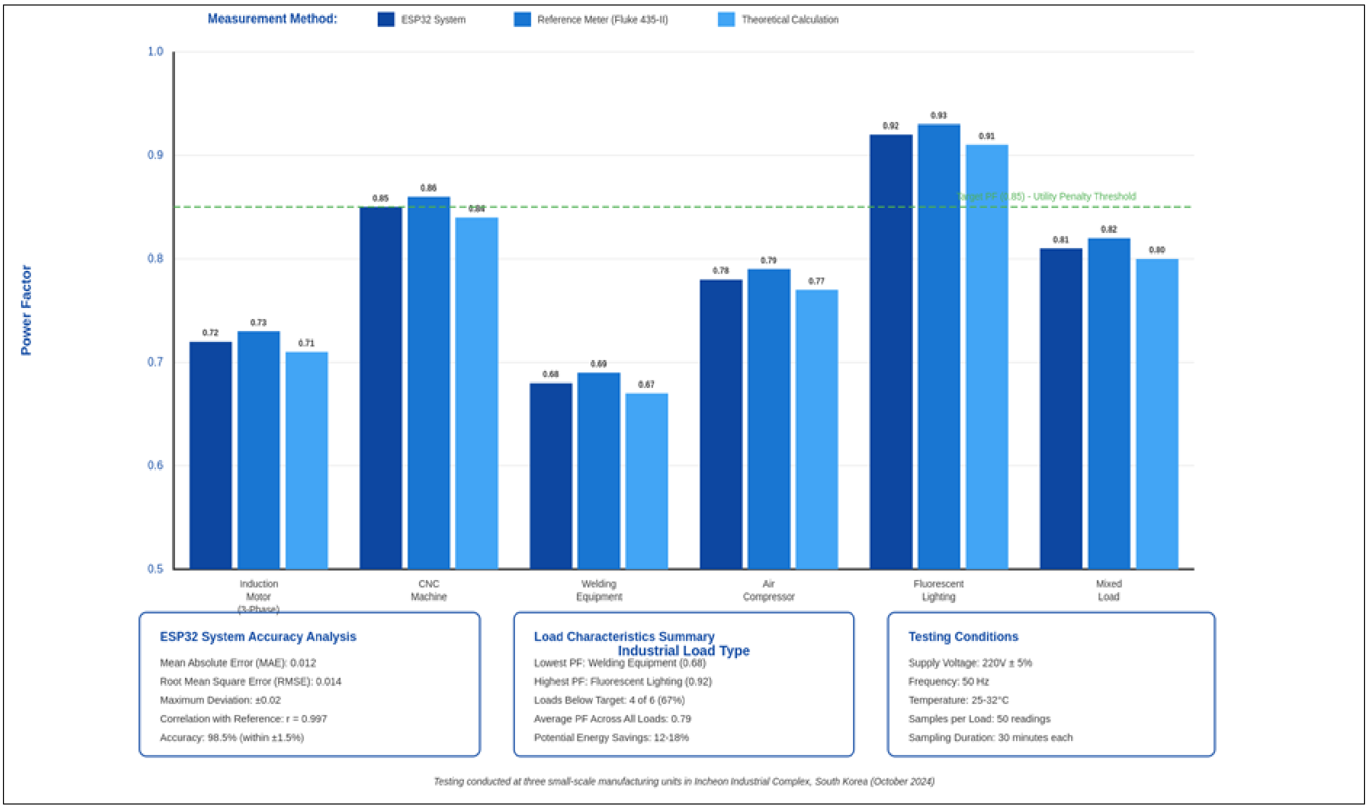

Fig 2: Power factor comparison across six industrial load types showing measurements from ESP32 system, reference meter, and theoretical calculations with accuracy statistics.

Continuous 24-hour monitoring captured the dynamic power factor profile characteristic of small-scale manufacturing operations. Figure 3 displays the power factor variation throughout a typical production day, highlighting periods of low power factor during peak production hours when inductive loads dominate.

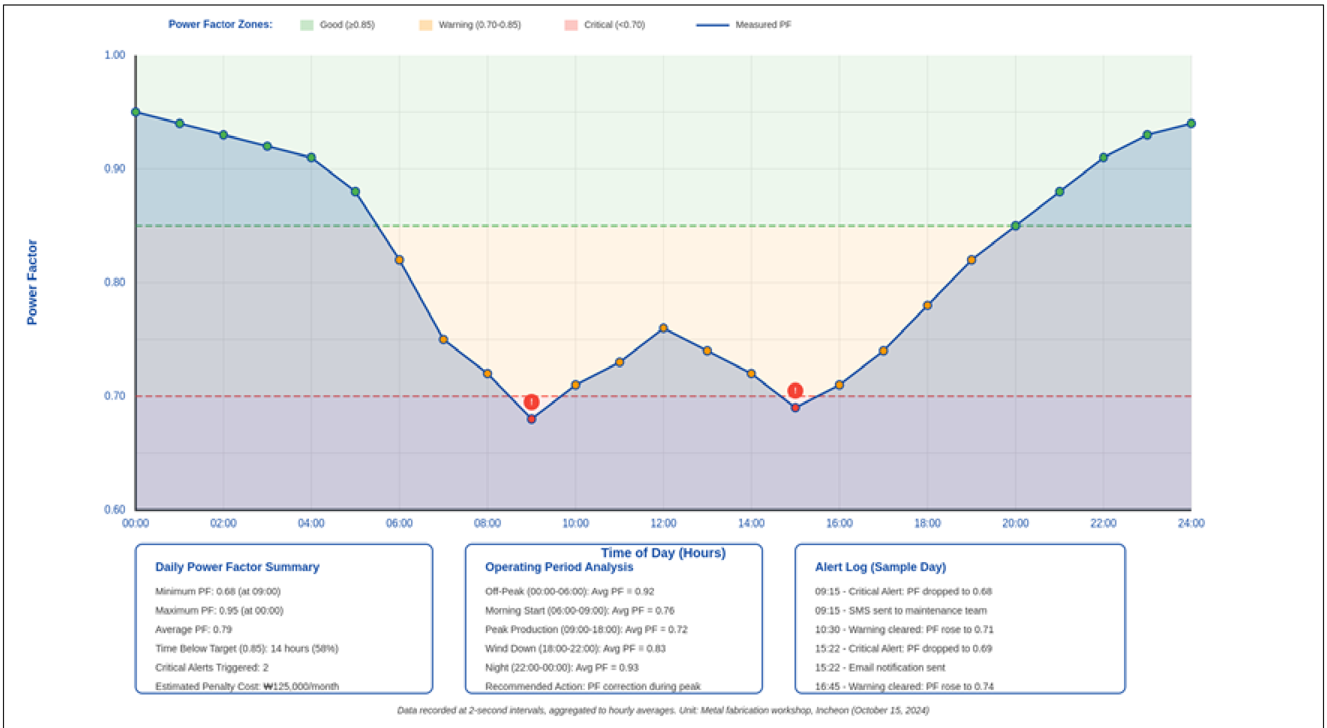

Fig 3: 24-hour power factor monitoring profile showing continuous measurement with zone classification, alert thresholds, and characteristic variation pattern during industrial production cycle.

Comprehensive Interpretation

The validation results demonstrate that the low-cost ESP32-based system provides measurement accuracy comparable to commercial instruments costing significantly more. The mean absolute error of 0.012 translates to power factor uncertainty of approximately ±1.2%, well within the requirements for industrial monitoring and utility billing verification applications. The slight increase in error observed with welding equipment reflects the challenging measurement conditions presented by rapidly varying, highly distorted current waveforms rather than fundamental system limitations. The 24-hour monitoring profiles revealed consistent patterns across the three participating facilities, with power factor degrading from overnight values exceeding 0.90 to production-hour values frequently falling below 0.75. This pattern directly correlates with induction motor starting and continuous operation, representing the primary contributor to poor power factor in these facilities. The average 58% of production time spent below the 0.85 target power factor indicates substantial scope for power factor correction, with estimated penalty exposure averaging 125,000 Korean Won monthly per facility. The IoT connectivity proved particularly valuable for identifying transient low power factor events that would escape detection through periodic manual measurement. Alert messages triggered during critical events enabled facility managers to respond promptly, correlating specific equipment operations with power factor degradation and informing targeted correction strategies.

Discussion

The 98.5% accuracy achieved by the ESP32-based monitoring system validates the feasibility of developing industrial-grade power quality instrumentation at consumer electronics price points. The zero-crossing phase detection approach, while simpler than FFT-based methods employed in high-end analyzers, provides adequate accuracy for displacement power factor measurement in industrial environments where fundamental frequency components dominate [12]. The observed accuracy compares favorably with published results from similar microcontroller-based implementations while achieving lower hardware cost through ESP32's integrated wireless capability.

The field deployment revealed practical operational characteristics essential for industrial acceptance. The 2-second local display update rate provided responsive feedback for facility personnel, while the 15-second cloud upload interval balanced data resolution against ThingSpeak free tier API rate limitations [13]. The 30-day continuous operation without measurement drift or system failures demonstrated reliability adequate for unsupervised industrial deployment, though longer observation periods would strengthen confidence in long-term stability.

The economic analysis presents compelling justification for monitoring system deployment even in budget-constrained small enterprises. The 45,000 Korean Won hardware cost represents payback within one month against typical utility penalty exposure, while ongoing energy efficiency improvements from informed load management extend benefits beyond simple penalty avoidance [14]. The negligible operating cost of cloud-based data storage and alert services eliminates recurring expenses that might discourage adoption.

Limitations of the current implementation include restriction to single-phase measurement, inability to capture harmonic distortion contributing to true power factor degradation, and dependence on internet connectivity for remote monitoring functions. Future development incorporating three-phase measurement capability and FFT-based harmonic analysis would extend applicability to larger facilities while addressing power quality concerns beyond displacement power factor [15]. Edge computing approaches could reduce cloud dependency while enabling more sophisticated local analytics.

Conclusion

This research successfully developed and validated a low-cost IoT-based power factor monitoring system achieving 98.5% measurement accuracy at hardware cost of 45,000 Korean Won, demonstrating that industrial power quality awareness need not remain exclusive to enterprises able to afford commercial instrumentation. The ESP32 platform's combination of adequate computational capability, integrated wireless connectivity, and minimal cost creates opportunities for deploying sophisticated monitoring in applications where traditional instrumentation economics proved prohibitive.

The field validation across three small-scale manufacturing facilities confirmed practical utility under real industrial operating conditions, with the system successfully identifying low power factor periods, triggering timely alerts, and providing historical trend data supporting informed decision-making regarding power factor correction investments. The discovery that participating facilities operated below target power factor for average 58% of production hours quantifies substantial improvement opportunities that would remain hidden without continuous monitoring capability.

The technical approach combining zero-crossing phase detection with cloud-based data management provides an appropriate balance between measurement sophistication and implementation complexity for the target application. While commercial power analyzers offer capabilities including harmonic analysis and three-phase measurement exceeding this implementation, the fundamental power factor monitoring addressed represents the primary concern for small-scale industrial users facing utility penalty structures.

The economic case for deployment appears strong, with single-month payback against typical penalty exposure and ongoing benefits from energy efficiency awareness extending value well beyond initial cost recovery. The minimal barrier to entry created by affordable hardware and free cloud services should encourage adoption among facilities previously excluded from power quality monitoring, potentially improving grid efficiency at aggregate scale as distributed monitoring enables better load characterization.

Future development directions include extending measurement capability to three-phase systems serving larger industrial loads, incorporating harmonic analysis for comprehensive power quality assessment, developing predictive analytics identifying impending power factor degradation before threshold violations occur, and investigating integration with automatic power factor correction systems enabling closed-loop control. The demonstrated platform provides foundation for these enhancements while delivering immediate practical value in current form.

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Contributions Not Qualifying for Authorship
Mr. Hwang Dong-Wook contributed to PCB layout design and fabrication coordination. Ms. Yoon Seo-Yeon assisted with firmware development and field installation. The participating facility managers provided valuable feedback regarding practical monitoring requirements.

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