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Development of a Real-Time IoT-Based Monitoring System for 3-Phase Industrial Machines

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ABSTRACT

This study addresses the urgent need for timely and accurate information regarding manufacturing resources by developing a cost-effective, real-time Internet of Things (IoT)-based monitoring system for 3-phase industrial machines, such as milling, turning, and grinding equipment. The primary objective is to enhance operational efficiency, minimize downtime, and support manufacturing digitalization. The methodology employed a mixed-methods approach and utilizes a hybrid microcontroller architecture, featuring low-cost SCT-013 current sensors and ZMPT-101B voltage sensors for data capture. An Arduino Mega performs high-speed data acquisition and complex measurement calculations, while an ESP32 module handles dedicated wireless communication and transmission. The system monitors crucial electrical parameters, including phase voltage, current, active and reactive power, and energy cost, while explicitly classifying the machine state (ON/OFF/STANDBY). A MySQL database ensures reliable data storage, and a Nextion display and web interface provide real-time visualization and user control. Rigorous quantitative testing validated the implementation: the fidelity of data transfer to the database was confirmed to be 100%. Sensor readings were successfully validated against a reference AC Clamp Meter. The system efficiently supports early anomaly detection using residual analysis. However, the end-to-end system latency was measured between 5 and 6 seconds consistently. This prototype delivers an effective and reliable solution for industrial online monitoring, providing a robust, data-driven foundation for future predictive maintenance and energy efficiency strategies.

Keywords: *Real-Time Monitoring, Internet of Things, 3-Phase Industrial Machine, Digital Manufacturing, Condition Monitoring*

1. INTRODUCTION

Electricity is a critical resource supporting modern life and various socio-economic aspects, making the efficient management and monitoring of energy consumption essential (Arifianto & Prasetyani, 2022; Azizi & Arinal, 2023). The reliance on fossil fuels for electricity generation necessitates conservation efforts, as consumption levels, particularly in the household sector, continue to increase (Ciancetta et al., 2021; Hadi et al., 2022; Sandiari et al., 2024). Consequently, real-time monitoring of energy consumption is considered the foundational step toward achieving greater energy savings (Shadiq & Mangani, 2021). The rapid proliferation of the Internet of Things (IoT) provides the technological infrastructure needed for remote, real-time oversight and control of physical devices (Jokanan et al., 2022; Soori et al., 2023; Sandiari et al., 2024; Aiman et al., 2025).

In traditional power installations, whether residential or industrial, energy use is often measured exclusively at a centralized single point, typically the kWh meter (Hadi et al., 2022; Sandira et al., 2023). This approach yields aggregate consumption data but fails to provide the granular, individual energy usage details necessary for effective efficiency management or accurate cost analysis for specific pieces of equipment (Shadiq & Mangani, 2021; Hantoro, 2023). For industrial environments, especially those utilizing 3-phase machinery, this lack of detailed information is compounded by the critical need to maintain power stability and detect anomalies promptly. Loss of a phase or voltage asymmetry can severely damage 3-phase equipment, underscoring the necessity for comprehensive condition monitoring (Dharmawan et al., 2022; Bachri et al., 2025). Therefore, industrial digitalization efforts increasingly require intelligent systems capable of providing precise and timely information regarding resource utilization, machine health, and energy cost analysis to minimize downtime and enhance productivity (Arifianto & Prasetyani, 2022; Xu et al., 2024; Singh et al., 2025).

State of the Art

Previous research has widely explored IoT-based power monitoring systems, primarily focusing on single-phase loads in domestic settings (Shadiq & Mangani, 2021; Hermanto & Agustini, 2022; Jokanan et al., 2022). Many prototypes employed low-cost microcontrollers like NodeMCU ESP8266 or ESP32, integrating sensors such as the PZEM-004T or the ACS-712 (Hadi et al., 2022; Hermanto & Agustini, 2022; Laksana et al., 2024; Rahman et al., 2024; Hendrawati et al., 2025). Platforms like Blynk are frequently leveraged for visualization and remote control capabilities, enabling users to monitor voltage, current, power, and estimated costs via mobile apps or web interfaces (Shadiq & Mangani, 2021). For instance, studies monitoring household load consumption reported measurement efficiencies consistently high, with reported measurement errors ranging from typically below 5% for various parameters (Hadi et al., 2022). Some research utilizing the ACS-712 reported errors up to 9.93% for current sensing, while other systems using PZEM-004T reported errors around 6.6% or slightly higher (Jokanan et al., 2022; Sandira et al., 2023).

However, the specific application of cost-effective, real-time monitoring for multi-phase industrial machines presents distinct challenges compared to household single-phase monitoring (Dharmawan et al., 2022). Solutions in the industrial sector often rely on sophisticated, expensive, or highly specific protocols, implementing systems such as Programmable Logic Controllers (PLCs), Node-RED, Grafana, and specialized communication standards like LoRaWAN or Modbus (Arifianto & Prasetyani, 2022; Reinard et al., 2023; Aiman et al., 2025). These high-end systems typically integrate industrial-grade devices for comprehensive monitoring of power quality parameters across multiple phases (Viciana et al., 2023; Kotsilitis et al., 2024; Prasetyo et al., 2024). While recent work addresses three-phase monitoring (e.g., using RS-485 communication or specialized power quality meters), there remains a gap in providing an easily deployable, hybrid IoT solution utilizing widely available, low-cost sensors and microcontrollers capable of performing the complex data analysis required for digital manufacturing environments (Kotsilitis et al., 2024; Prasetyo et al., 2024; Aiman et al., 2025).

Novelty, Contribution, and Solution

This research aims to bridge the gap by designing and implementing a system tailored for real-time, granular monitoring of 3-phase industrial machines, such as milling, turning, and grinding equipment. The novelty lies in utilizing a hybrid architecture, combining the high processing speed of an Arduino Mega for data acquisition with the dedicated wireless capabilities of an ESP32 module, while relying on cost-effective sensors like SCT-013 and ZMPT-101B.

The main contribution of this system is the capability to provide comprehensive and accurate real-time measurement of crucial industrial electrical parameters (phase voltage, current, active and reactive power, and energy cost). Crucially, the system supports early anomaly detection and automatically classifies the machine operational state (ON/OFF/STANDBY). By reliably transferring this data to a secure database for visualization via a web interface, this solution directly supports digital manufacturing objectives by enabling proactive maintenance strategies and optimizing operational efficiency, thereby minimizing machine downtime.

2. SCOPE

The scope of this research is specifically defined by the components utilized, the target application domain, the electrical parameters measured, and the inherent system limitations. This system aims to support the digitalization of manufacturing operations and enhance operational efficiency.

1. Problem Coverage

The proposed system focuses exclusively on the real-time condition and energy monitoring of three-phase industrial machines. The target machines are conventional equipment typically found in manufacturing environments, such as milling, turning, and grinding machines. The primary goal is to obtain granular data on electrical consumption and machine status to minimize operational downtime.

2. Research Limitations

The constraints and boundaries of this system are defined as follows:

1) Hardware and Architecture
The system employs a hybrid microcontroller architecture designed for low cost and accessibility, utilizing the Arduino Mega for complex, high-speed data acquisition and measurement computation, paired with an ESP32 module strictly for dedicated wireless communication and data transmission.
2) Sensing Technology
Sensing capabilities are restricted to readily available, low-cost components: SCT-013 non-invasive current sensors and ZMPT-101B voltage sensors. This approach inherently necessitates meticulous calibration to compensate for typical nonlinearity issues observed in low-cost sensors.
3) Measured Parameters
The core parameters monitored are Phase Voltage (R, S, T), Current (R, S, T), Active Power, Reactive Power, Apparent Power, Frequency, Energy consumption (kWh), and calculated energy cost. The system is not scoped to measure detailed high-order harmonics or provide high-precision Power Factor

measurements typical of commercial industrial Power Quality Analyzers (PQAs) (Prasetyo et al., 2024).

4) Data Persistence and Access
Data is stored in a MySQL database and initially visualized via a Nextion local display and a basic web interface. The system does not currently feature a full enterprise-level dashboard required for seamless data exchange with platforms like Enterprise Resource Planning (ERP) or Manufacturing Execution Systems (MES).

5) Performance Constraints
Under tested conditions, the end-to-end system latency should limit its application in high-speed control loops requiring a number of delay standards.

6) Methodology
The research and development process adhered strictly to the Waterfall methodology (Identification of Requirements, Design, Development, and Testing) (Prasetyo et al., 2024).

3. Planned Results and Outcomes

The anticipated outputs of this research, successfully demonstrated by the prototype, include:

1) Real-Time Status Classification
The ability to accurately classify the operational state of the 3-phase machines in real-time as ON, OFF, or STANDBY.

2) Anomaly Detection Foundation
Providing a robust foundation for early anomaly detection through continuous monitoring of electrical parameters and supporting the use of residual analysis for performance assessment.

3) Proof of Concept for Digital Manufacturing
Validating a reliable, low-cost proof-of-concept for industrial online condition and energy monitoring, which supports proactive maintenance strategies.

4) Comparative Accuracy
Demonstrating that the system’s measurement accuracy is acceptable for the defined parameters, when compared with laboratory equipment.

3. MATERIALS AND METHODS

The study employed an applied research and development methodology, utilizing a mixed-methods approach to define requirements, build the prototype, and validate its industrial performance. This approach was essential to ensure the functionality, reliability, and accuracy required for industrial applications (Hendrawati et al., 2025).

3.1 Research Approach and Development Model

The research approach should establish clear requirements and empirically validate the system's performance. This effort is followed by a specific development model selection to guide the construction process. The following sections provide a detailed explanation of these foundational frameworks.

1. Mixed-Methods Approach

The research was divided into distinct phases to gather comprehensive data:

1) Qualitative Research
This initial phase focused on identifying necessary system features and establishing technical specifications. Data was collected primarily through interviews and discussions with practitioners and academic instructors to define critical operating limits and required monitoring parameters (Shadiq & Mangani, 2021; Arifianto & Prasetyani, 2022).

2) Quantitative Research
This subsequent phase focused on the rigorous empirical testing and evaluation of the system, validating its performance against predefined technical goals. This involved specifically measuring sensor accuracy, data reliability, and real-time latency when deployed on 3-phase machines in a workshop setting (Noyjeen & Noipitak, 2021; Chanda & Gudipalli, 2024). The process included comparing sensor readings against reference meters or laboratory equipment to ensure measurement accuracy and assessing key performance indicators (KPIs) like production rate and resource utilization (Ciancetta et al., 2021; Koyuncuoğlu, 2024).

2. Waterfall Development Model

The overall system engineering adhered strictly to the Waterfall Model, chosen for its systematic and sequential nature, which is highly suitable for complex hardware-software integration projects like this Internet of Things (IoT) solution. This model consists of five key phases: Requirements Analysis, System Design and Architecture, Implementation, Testing and Integration, and Evaluation and Reporting. Each phase progresses in a linear order, allowing the team to thoroughly complete, verify, and document one stage before moving on to the next. This disciplined approach helps maintain clarity, traceability, and consistency throughout the development lifecycle (Prasetyo et al., 2024; Rahman et al., 2024).

3.2 Development Stages (Waterfall Model)

The research and development process was segmented into five key phases as in the Waterfall Model. The following sections provide a detailed explanation of these development stages.

1. Requirement Analysis

This stage established the foundational specifications based on identified industrial needs.

1) Problem Context
The fundamental challenge addressed was the lack of timely, accurate, and consistent information regarding manufacturing resources during production execution.

2) Key Parameters
They defined the electrical variables essential for comprehensive condition and energy monitoring:

Voltage (R, S, T), Current (R, S, T), Active Power, Reactive Power, Total Power, and the explicit Machine Status (ON, STANDBY, OFF).

3) Hardware Selection
This research uses accessible, low-cost components, including the SCT-013 current sensors, ZMPT-101B voltage sensors, Arduino Mega, and ESP32 microcontroller.

2. System Design and Architecture

This phase translated the functional requirements into a comprehensive, working architecture.

1) Architecture
A hybrid microcontroller architecture was designed, utilizing the Arduino Mega for high-speed sensor data acquisition and complex measurement calculations, and the ESP32 module as the dedicated wireless communication module to transmit data. The complete representation is shown in Figure 1.
2) Data Flow and Integration
The design mandated seamless dual-way connectivity and interoperability among the machine, workshop floor, and enterprise layers. The data acquisition device, built using Arduino Mega, converts raw readings into encoded form for transmission to a server.
3) Data Management
A MySQL database was selected for reliable data storage. This storage is critical, as it serves as the repository for traceability and for generating data-based reports to support energy efficiency and productivity analysis.
4) Logic Control
The core software design included developing specific logic to automatically classify the motor's operational status (ON/OFF/STANDBY) by comparing continuous V and I sensor values against predefined set point parameters defined by the administrator.

Figure 1 illustrates the underlying architecture that translates the system's functional requirements into a comprehensive, working design during the System Design and Architecture phase of the research. This foundational design utilizes a hybrid microcontroller architecture, combining the computational strength of the Arduino Mega for high-speed sensor data acquisition, measurement calculations, and logic control, with the ESP32 module acting as the dedicated wireless communication module to transmit data. The system begins by receiving raw Voltage and Current (V & I) data through the cost-effective ZMPT-101B and SCT-013 sensors, processing this data locally, and subsequently sending it to the remote server and MySQL database. This design mandates seamless dual-way connectivity and interoperability among the machine, the workshop floor, and the enterprise layer for real-time monitoring and analysis.

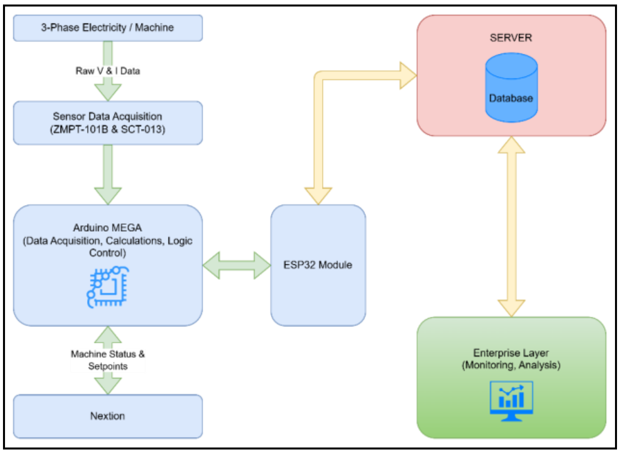

Figure 1. System Architecture

3. Implementation

This phase integrates complex hardware and software components, designed to work together to provide continuous, real-time data.

1) Mechanical Design and Hardware Components
The physical realization of the system involved housing all electronic components within an acrylic box. Safety was prioritized, with the four corners of the box featuring radius corners created using 3D printing to prevent injury to the user. Figure 2 presents the 3D visualization of the enclosure and the internal layout of the IoT-based machine monitoring module.

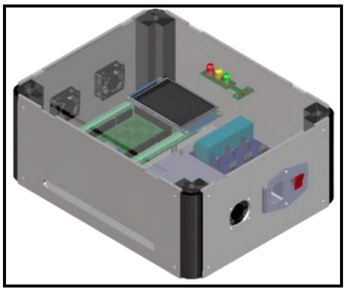
Figure 2. Design of IoT-Based Monitoring Module

The realized result of making the acrylic box and installing the components inside is shown in Figure 3.


Figure 3. Realization of IoT-Based Monitoring Module

The arrangement of the electrical and electronic components can be observed in Figure 4. The core electrical and control components are:

(1) Current Sensor (SCT-013): Used to measure AC current ranging from 0 to 100 Amperes. Crucially, this sensor requires signal conditioning circuitry before its data can be processed by the microcontroller.
(2) Voltage Sensor (ZMPT-101B): Capable of measuring AC voltage up to 500 Volts. Like the current sensor, it requires additional circuitry for signal conditioning.
(3) Microcontrollers: The system employs a dual-microcontroller setup to manage complex tasks. An Arduino Mega functions as the main control unit. It is responsible for reading and processing raw data from the sensors, managing local peripherals (Keypad, LED Traffic, Nextion Display), and providing the initial processed data to the ESP32. A NodeMCU ESP32 functions as the communication module. It is selected for its integrated WiFi and Bluetooth capabilities, strong dual-core processor, small size, and cost-effectiveness. Its sole purpose is to receive processed data from the Arduino Mega and transmit it wirelessly to the database.
(4) User Interface (HMI): A Nextion Enhanced 2.8" Display serves as the Human-Machine Interface. It allows the operator to set parameters (upper and lower limits for current and voltage for R, S, and T phases) and select the monitored machine type (milling, grinding, or lathe). This display replaced the initial LCD I2C 20x4 due to challenges in data placement and visualization with the older component.
(5) Data Backup and Storage: An SD Card 1 GB module is integrated with the Arduino Mega. It is essential for storing parameter settings and acting as a temporary backup storage for sensor data if the ESP32's WiFi connection is interrupted. When the connection is restored, the data stored on the SD card is prioritized for transmission before new actual data is sent.
(6) Status Indication: An LED traffic component (Red, Yellow, Green) indicates the machine status (ON, OFF, STANDBY, or blinking for error), determined by comparing sensor values against preset limits.

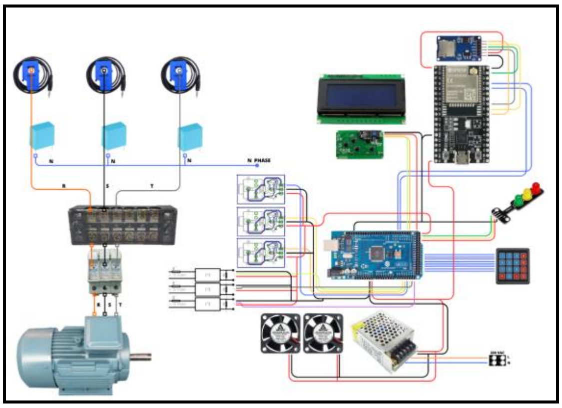

Figure 4. Wiring Diagram

2) Software, Communication, and Data Management
The software implementation connects the physical world to the digital platform:

(1) Microcontroller Programming: Both Arduino Mega and ESP32 were programmed using the Arduino IDE software, employing C language with dedicated libraries for sensors, Nextion, and WiFi. The Arduino Mega program focuses on sensor reading and data processing, while the ESP32 program handles communication with the web server. Figure 5 shows the machine selection page on the Nextion display that is used in the module.

Figure 5. Machine Selection on Nextion

One of the machine's voltage monitoring displays on the Nextion can be seen below in Figure 6.

Figure 6. Voltage Monitoring on Nextion

(2) Microcontroller Communication: Data transfer between the two microcontrollers is achieved using serial communication (TX/RX pins). Maintaining the same baud rate is critical to ensure a smooth exchange of data. The Arduino Mega successfully sends 18 distinct data points to

the ESP32, including R, S, and T measurements for voltage, current, power (apparent, active, and reactive), machine status, and machine selection.

(3) Database and Server Configuration:
A MySQL database is used for storing all collected sensor data in structured tables. The system uses a Virtual Private Server (VPS) running Ubuntu 24.04 LTS, enabling the website to be accessed from any location at any time. There were several server setup tools used in this research. PuTTY was used as a free SSH client to access and install essential web services like Apache2 (web server), MySQL (database), and PHP (server-side scripting). WinSCP was then used to transfer the website files from the local development computer to the server.

(4) Web Interface (Website): The front-end interface was programmed using HTML and JavaScript in Visual Studio Code. The system features a login page with two roles: Admin and User. Admin users have expanded access, including the ability to change set values and access the Export Data Page to download reports (PDF, CSV, Excel) as shown in Figure 7.

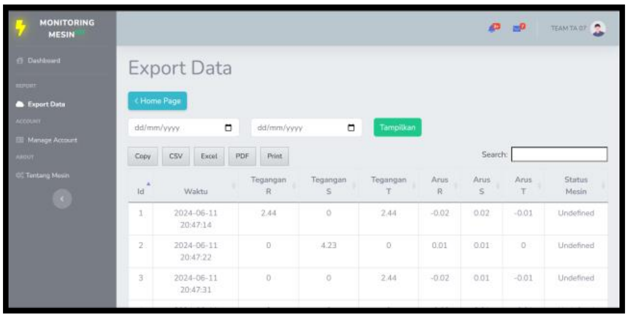

Figure 7. Export Data Page

The dashboard provides real-time indicators for total current, total voltage, total power, total energy used, total electricity cost, machine status, set values, and dynamic usage graphs as seen in Figure 8. The website data is updated automatically every second, followed by committing changes to the database.

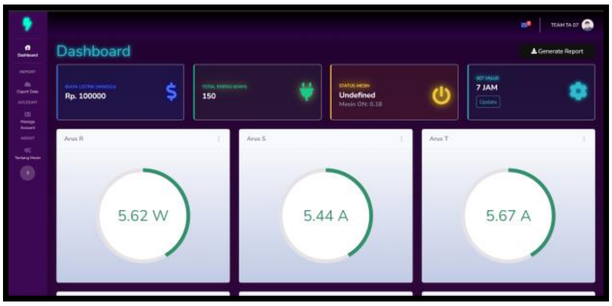

Figure 8. Dashboard with Real-Time Information and Machine Status

4. Testing and Validation

This critical phase involved the quantitative evaluation of the fully integrated prototype in a near-industrial setting, leveraging the principle of residual analysis by monitoring the deviation in continuous variables (like current and voltage) to detect abnormal behaviors or underperformance in real-time.

1) Sensor Accuracy
Calibration tests were necessary to assess the accuracy of the low-cost SCT-013 and ZMPT-101B sensors by comparing their readings against high-precision measuring instruments, ensuring the acquired data is trustworthy.

2) Performance Validation
The viability for real-time monitoring was validated by measuring two core performance indicators:
(1) Data Transfer Reliability: Testing confirmed the fidelity of the data from the ESP32 to the database, achieving 100% accuracy (data values sent were identical to those received).
(2) End-to-End Latency: The delay time, from the sensor reading, transmission via the ESP32, database storage, and final display on the web interface, was measured to be consistently between 5 and 6 seconds.

3) Advanced Performance Analysis
Beyond simple data logging, the quantitative phase supported advanced analysis, aligning with current industrial monitoring trends. Performance monitoring relies on continuously comparing actual data from the plant floor against expected outcomes or simulated data (a foundation for digital twin development). This research utilized the principle of residual analysis by monitoring the deviation (residuals) in continuous variables (like current and voltage) to detect abnormal behaviors or machine underperformance in real-time. This systematic approach is critical for diagnostics and tracing the root cause of performance deviation.

5. Evaluation and Reporting

The final phase concluded the research with documentation, objective fulfillment assessment, and dissemination of results.

1) Deliverables
Production of the final report, the scientific article, and a feasibility study to assess the technical and economic viability of scaling the system for industrial application.

2) Maintenance
In alignment with the final phase of the Waterfall model, maintenance and operational procedures were defined for the ongoing use and potential future modification of the system, including addressing any performance errors identified by the end-user.

4. DISCUSSION

The system realization followed the rigorous Waterfall methodology, culminating in a functional prototype validated through specific testing phases that quantified real-time performance and data accuracy. The resulting system is capable of providing real-time visibility and traceability of machine status, a key requirement for modern manufacturing systems.

4.1 System Realization and Monitoring Capabilities

The deployed system successfully monitors and displays critical data, including real-time values for Voltage (R, S, T), Current (R, S, T), Active Power, Reactive Power, and Total Power, as well as calculated Total Usage Cost and the machine's Operational Status.

1. Operational Status Classification

The system successfully implemented logic to classify the motor's operational state into three explicit categories: ON, OFF, or STANDBY. This logic compares continuous Voltage (V) and Current (I) readings against set parameters defined by the operator. This automatic classification provides essential context for production managers, moving beyond mere raw data presentation.

2. Web Interface and Reporting Features

The web interface, built using PHP and JavaScript, serves as the central visualization and decision-support dashboard. This interface displays real-time indicators and corresponding graphs for up to 10 continuous data points. Crucially, the administrator account is granted privileged access to data management features. The web interface allows admin users to download comprehensive monitoring data for a specified time period in formats such as Microsoft Excel (.csv or .xlsx), PDF, or print format. This functionality is essential for external analysis and integration with other management systems.

4.2 Quantitative Performance Validation

To confirm the prototype's reliability and suitability for deployment in the industrial workshop environment, three quantitative tests were performed: Sensor Calibration, Data Transfer Accuracy, and Real-Time Latency Measurement.

1. Sensor Calibration

Rigorous calibration testing was performed on the SCT-013 current sensor and the ZMPT-101B voltage sensor. The measured results displayed on the Nextion interface were compared against a reference instrument, the AC Clamp Meter 3280-10F, which has a stated basic accuracy of approximately 1.5%. The percentage error was calculated using the formula:

$$error(\%) = \left|\frac{Measured\ Value - Displayed\ Value}{Measured\ Value}\right| \times 100\% \quad (1)$$

Initial testing verified the accuracy of SCT-013 current sensors by comparing them against the reference instrument. The errors were calculated using formula (1). The results are shown in Table 1.

Table 1. Current Calibration Test Results (R Phase)

No	Displayed Current (A)	Measured Current (A)	Error (%)
1	2.35	2.41	2.49
2	2.3	2.33	1.24
3	2.31	2.39	3.32
4	2.31	2.4	3.73
5	2.3	2.36	2.49

The next test was to verify the accuracy of the low-cost ZMPT-101B voltage sensors by comparing them against the reference instrument. We use formula (1) to calculate the errors. The results are in Table 2 below.

Table 2. Voltage Calibration Test Results (R Phase)

No	Displayed Voltage (V)	Measured Voltage (V)	Error (%)
1	227.1	227.7	0.26
2	226.6	227.8	0.53
3	227.6	227.8	0.88
4	227.4	227.8	0.18
5	231.3	227.8	1.54

The current and voltage sensors' calibrations, as shown in Tables 1 and 2, demonstrated a relatively small average error in current and voltage measurements. The percentage error for current measurements ranged from a minimum of 1.24% to a maximum of 3.73%. Meanwhile, the percentage error for voltage measurements ranged from a minimum of 0.18% to a maximum of 1.54%. Based on these results, both the ZMPT-101B and SCT-013 sensors were deemed to function correctly and reliably, adhering to the IEC61000-4-7 standard, which mandates that measurement error should not exceed 5%.

This performance is consistent with findings in the literature regarding low-cost sensors, which typically show low voltage error but may exhibit greater deviation in current and power readings.

2. Data Transfer Accuracy and Reliability

A critical test verified the data fidelity across the network architecture, from the wireless transmission module (ESP32) to the database (MySQL). Data samples (in this instance, Voltage R, S, and T) sent by the ESP32 were compared against the data received and stored in the database. Test samples are presented in Table 3.

Table 3. Data Transfer Test Results

Sent by ESP32			Stored in MySQL			Val.
V_R (V)	V_S (V)	V_T (V)	V_R (V)	V_S (V)	V_T (V)	
175.24	204.67	169.7	175.24	204.67	169.7	OK
171.36	176.43	147.03	171.36	176.43	147.03	OK

152.97	163.22	133.7	152.97	163.22	133.7	OK
181.17	192.47	158.53	181.17	192.47	158.53	OK
177.09	186.99	157.22	177.09	186.99	157.22	OK
152.6	161.14	134.12	152.6	161.14	134.12	OK
152.52	159.18	133.16	152.52	159.18	133.16	OK

The comparison demonstrated that every voltage value sent by the ESP32 was identical to the value recorded in the database, confirming a 100% data transfer accuracy. This fidelity is crucial for maintaining the trustworthiness of the historical data repository.

3. Real-Time Latency Measurement

The system's real-time performance was evaluated by measuring the total end-to-end delay (latency). This measurement tracks the time interval from when the sensor reads the data until that data is successfully stored in the database and displayed on the web interface. We can also measure the timestamp interval with the previous entry.

Table 4. Web Interface Real-Time Latency Test

V_R	V_S	V_T	Time-stamp	Delay (s)	Val.
156.15	176.92	147.3	16:04:27	5	OK
159.5	178.21	150.43	16:04:32	5	OK
157.35	181.06	152.71	16:04:37	5	OK
162.38	186.71	157.7	16:04:42	6	OK
160.29	183.64	154.75	16:04:48	5	OK
158.09	176.93	145.36	16:04:53	6	OK
175.12	196.42	165.3	16:04:59	5	OK

The total measured system latency was consistently between 5 and 6 seconds. This latency is acknowledged as a technical trade-off for utilizing the chosen low-cost, open-source architecture (Arduino Mega, ESP32, MySQL, PHP). While highly optimized industrial systems using PLCs can achieve much lower latencies, typically ranging from 0.66 to 1.58 seconds, the prototype's stable 5–6 second delay is deemed acceptable for monitoring non-critical, slower-changing parameters and still fulfills the requirement for real-time information capture.

5. CONCLUSIONS

The development of the IoT-based 3-phase machine monitoring system was successfully completed, meeting the objectives established for enhancing efficiency and supporting the digitalisation of manufacturing operations. The integrated system is capable of monitoring all specified critical parameters of 3-phase machines, including voltage (R, S, T), current (R, S, T), total power, active power, reactive power, total usage cost, and operational condition, and presenting this information in real-time.

Key conclusions regarding the system's functionality and performance are as follows:

1) The entire data path, from sensor measurement through the microcontrollers (Arduino Mega and ESP32) to the MySQL database and finally to the user interface, was successfully implemented. Utilising a hosting service allows the system to be accessed anywhere and anytime via a user-friendly website.
2) The Nextion Display serves effectively as the Human-Machine Interface (HMI), enabling operators to easily set the upper and lower limits for current and voltage for all three phases (R, S, T) and facilitating the selection of the machine type (milling, lathe, or grinding) being monitored.
3) Calibration tests confirmed that the current (SCT-013) and voltage (ZMPT-101B) sensors operate reliably. The maximum error obtained was 3.73% for current and 1.5% for voltage. These results ensure that the system adheres to the IEC61000-4-7 standard, which requires measurement error to be no greater than 5%.
4) The data integrity across the network was confirmed with high accuracy. Data sent from the ESP32 to the database was verified to be identical, resulting in a 100% success rate. Furthermore, the data displayed on the website accurately matched the data stored in the database with 100% accuracy.
5) The time required from the moment the sensor reads the data until it is displayed on the website was consistently measured between 5 and 6 seconds. This constant interval confirms the stability of the real-time monitoring feature.

In summary, the developed system offers an effective and reliable solution for the online monitoring of industrial machines. By providing critical, accurate, and up-to-date information, the system enhances operational efficiency and enables rapid response to potential machine issues or damage, supporting better data-driven decision-making in manufacturing.

6. SUGGESTIONS

The achieved results confirm the foundational feasibility of the proposed low-cost IoMT framework, which successfully integrates the machine layer (sensors) with the workshop floor and enterprise layers (database and web interface).

The ability to classify machine status (ON/OFF/STANDBY) based on measured V and I values is essential for performance analysis. In contemporary manufacturing environments, performance is assessed not just by recording KPIs like utilization or production rate, but increasingly by comparing the actual performance to the expected performance in real-time.

The data collected by this system is structured to support future residual analysis. Residuals are deviations between expected (virtual/simulated) performance and actual data gathered from the plant floor. By continuously monitoring the residuals of continuous variables (V, I, Active Power), deviations caused by machine underperformance, component degradation, or unexpected anomalies can be identified. The high data transfer accuracy (100%) and reliable logging ensure that the data fed into any subsequent residual analysis or predictive maintenance algorithm is sound, providing a robust foundation for data-driven decision-making.

Future efforts must rapidly advance the current monitoring system to achieve predictive and prescriptive capabilities, shifting its function beyond simple monitoring toward optimization and autonomy. This transformation requires focused enhancement in three critical areas:

First, we need to integrate advanced analytics and diagnostics by using Machine Learning (ML) and Artificial Neural Networks (ANN) to analyze validated data for real-time fault prediction and classification. Second, the Real-Time Performance and Architecture must be optimized; the current 5–6 second latency is too slow for responsive industrial applications and must be reduced to align with highly optimized industrial standards (sub-2-second delays).

Finally, the modular dashboard and enterprise interoperability must evolve from the basic web interface into a complete enterprise-level dashboard. This upgraded dashboard is crucial for establishing seamless two-way communication across the enterprise, workshop, and machine layers. The modular interface must be capable of visualizing advanced diagnostic results (like ANN output) and seamlessly exchanging data with Enterprise Resource Planning (ERP) and Manufacturing Execution Systems (MES). Furthermore, exploring intuitive human-machine interfaces, such as Augmented Reality (AR), could significantly enhance usability.

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