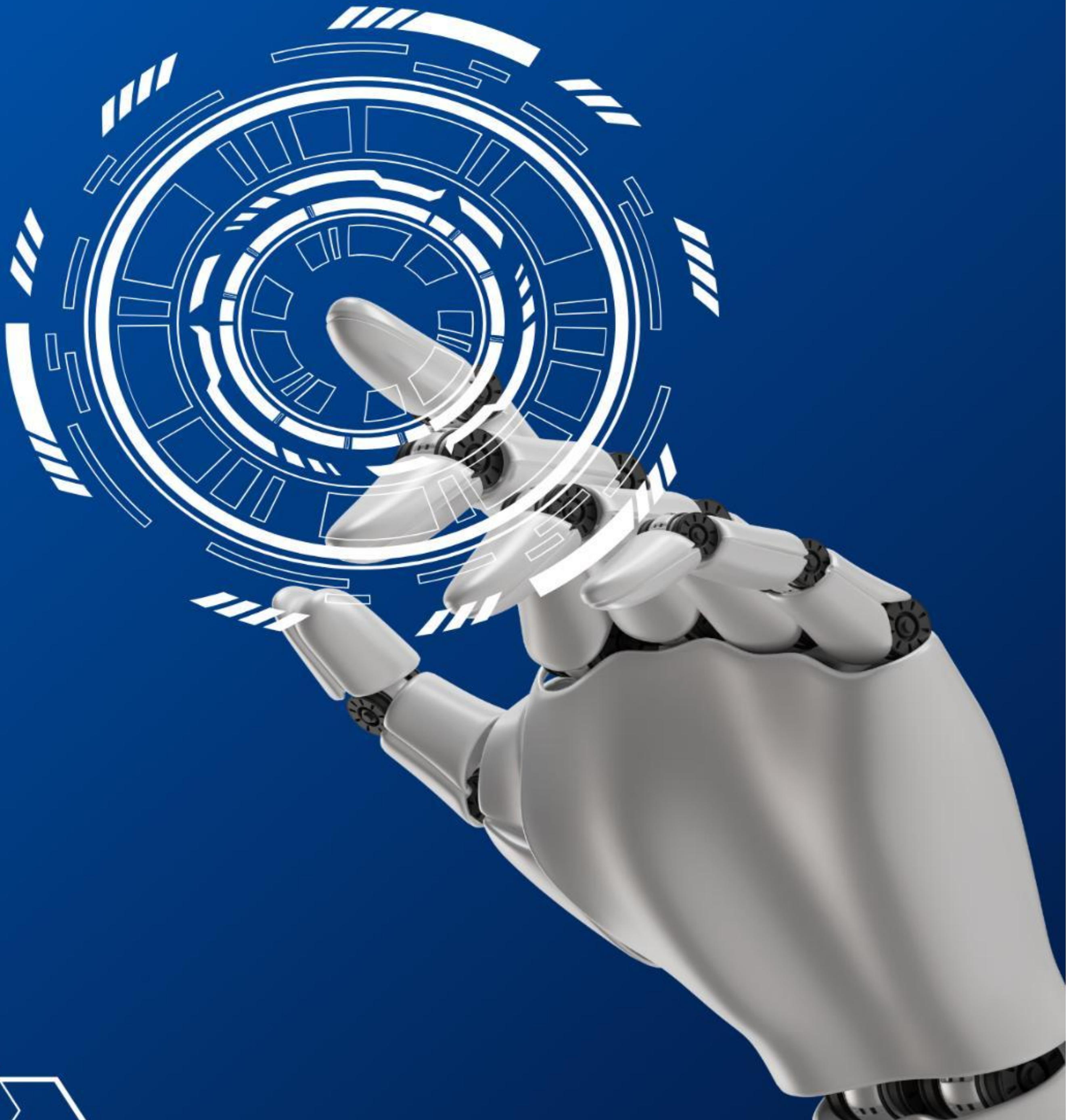
EISSN: XXXX - XXXX PISSN: XXXX - XXXX

Vol 1 No 1, Feb 2026

Journal of
ELECTRICAL ENGINEERING AND INFORMATICS



LPPM STTN LAMPUNG

Journal of Electrical Engineering and Informatics (JEEI)
Vol. 1, No. 1, February (2026), pp. i-iii | p-ISSN: xxxx-xxxx, e-ISSN: xxxx-xxxx
doi: https://doi.org/xxx.xxx

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Tabel of Content

Journal of Electrical Engineering and Informatics (JEEI)

Vol. 1, No. 1, February (2026), pp. 1-9 | p-ISSN: xxxx-xxxx, e-ISSN: xxxx-xxxx
doi: https://doi.org/xxx.xxx

Analysis of Transformer Oil Maintenance Management in Electrical Power Distribution Systems

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Article History: *Received: January, 25th 2026; Accepted: February, 5th 2026; Published: February, 28th 2026*

ABSTRACT

Maintenance management is a critical technical and managerial approach to ensuring the reliability and sustainability of electrical power distribution systems, particularly through effective transformer oil maintenance. Transformer oil performs dual functions as an electrical insulating medium and a cooling agent; therefore, its degradation can significantly reduce transformer performance and operational reliability. This study analyzes the implementation of transformer oil maintenance management in distribution transformers within an electrical power distribution system using a field research approach with a descriptive–evaluative design. Data were collected through structured interviews, direct field observations, and a review of technical maintenance documents. The analysis focuses on the physical, chemical, and electrical characteristics of transformer oil, as well as the maintenance strategies applied, including preventive maintenance, corrective actions, and scheduled oil replacement. The results indicate that a structured transformer oil maintenance management framework contributes to maintaining transformer reliability, supporting continuous system operation, minimizing operational risks, and extending the economic service life of distribution transformers. These findings underscore the importance of condition-oriented maintenance management as an integral component of asset management in electrical power distribution systems.

Keywords: *transformer oil; maintenance management; distribution transformer; power distribution system; condition-based maintenance*

INTRODUCTION

Transformer oil is a critical component in electrical power systems, serving dual functions as an insulating medium and a cooling agent in power and distribution transformers. It is commonly produced from mineral oil derived from petroleum refining processes, although synthetic and alternative liquids are used in specific applications. The primary role of transformer oil is to electrically isolate energized components while simultaneously dissipating heat generated during transformer operation, thereby maintaining safe operating temperatures and ensuring system reliability (Jin et al., 2022; Saodah et al., 2024).

In practical operation, transformer oil plays a vital role in preventing insulation failures such as flashover, sparkover, and short circuits, which may lead to severe equipment damage and power supply interruptions (Ghani et al., 2019). The performance of transformer oil is therefore closely linked to the overall reliability of power transmission and distribution systems. Degradation of transformer oil properties—caused by thermal stress, oxidation, moisture ingress, and contamination by solid particles—can significantly reduce its dielectric strength and cooling capability, accelerating transformer aging and increasing the risk of operational failure (Ogirimah et al., 2025; Rouabeh et al., 2019).

As transformers age, continuous exposure to electrical, thermal, and environmental stresses leads to gradual deterioration of the physical, chemical, and electrical characteristics of transformer oil. These changes necessitate systematic monitoring and maintenance to ensure that the oil continues to meet operational requirements (Bryakin et al., 2022). Without proper maintenance management, degraded transformer oil can compromise insulation performance and reduce the operational lifespan of power and distribution transformers (Mavrikakis & Siderakis, 2025).

Accordingly, transformer oil maintenance management has become an essential element of asset management in electrical power systems. Effective maintenance management encompasses condition monitoring, preventive maintenance, corrective actions, and scheduled oil replacement or reconditioning based on test results and operational conditions (Bustamante et al., 2019). Such a structured approach is widely recognized as an effective means to enhance transformer reliability, maintain service continuity, and reduce unexpected maintenance costs, particularly when diagnostics such as dissolved gas analysis, oil quality assessment, and health-index–based evaluation are systematically integrated into decision-making (Badawi et al., 2022; Levin & Yahya, 2020; Rêma et al., 2024).

Despite extensive studies on transformer oil diagnostics and condition monitoring, most existing research focuses on laboratory-based oil analysis, on-line sensor technologies, or high-voltage power transformers at transmission levels (Badar et al., 2021; N'cho et al., 2016). Limited attention has been given to the integration of transformer oil condition parameters with practical maintenance management implementation at the distribution level, particularly in real operational environments (Audax et al., 2025; Pambudi et al., 2025). This study addresses this gap by analyzing transformer oil maintenance management as an integrated technical–managerial framework, combining oil condition evaluation with preventive, corrective, and scheduled maintenance practices in a distribution power system. The contribution of this research lies in providing empirical evidence on how condition-oriented transformer oil maintenance management supports operational reliability and asset sustainability in distribution transformers.

RESEARCH METHODS

This study employed a field research approach with a descriptive–evaluative design to analyze the implementation of transformer oil maintenance management in distribution transformers within an electrical power distribution system. This approach is commonly applied in maintenance studies of power equipment to capture actual operational practices and evaluate them against established technical and managerial standards (A2.34, 2017; Jalbert et al., 2015).

The study was conducted on distribution transformers operated by PT. Persada Lampung Nusantara, Bandar Lampung, focusing on oil maintenance practices applied during normal operating conditions. The observation covered several in-service distribution transformers with different service ages, monitored over a defined maintenance period based on available maintenance records and field inspection schedules. This approach enabled the evaluation of transformer oil condition and maintenance decision-making processes as implemented in actual operational practice.

The object of the study was the transformer oil maintenance system applied to distribution transformers operated by the company under investigation. The analysis focused on transformer oil condition and maintenance practices, including preventive maintenance, corrective actions, and scheduled oil replacement or reconditioning during normal operation.

The observed parameters comprised the physical, chemical, and electrical characteristics of transformer oil, as documented in maintenance records and technical reports, together with the maintenance management practices implemented by the operator. These parameters reflect widely accepted indicators for assessing transformer oil condition and are consistent with international recommendations for transformer oil evaluation and maintenance (Koch et al., 2018).

Data were collected using multiple complementary techniques to ensure the validity and completeness of information related to transformer oil maintenance practices. These techniques were selected to capture both documented maintenance procedures and actual field implementation. The data collection techniques included:

1) Structured interviews with personnel directly involved in transformer maintenance activities to obtain information on maintenance procedures, schedules, and decision-making practices related to transformer oil;

2) Direct field observations of transformer operating conditions and oil maintenance activities to verify the consistency between documented procedures and actual practices; and
3) Document and literature review, covering technical manuals, maintenance reports, standards, and scientific publications related to transformer oil and maintenance management.

The data analysis was conducted using a descriptive qualitative approach, whereby field data obtained from interviews and observations were systematically examined and interpreted. The findings were then evaluated by comparing existing maintenance practices with internationally recognized principles of transformer oil maintenance and condition-based maintenance strategies. This analytical approach enables an assessment of the extent to which transformer oil maintenance management supports transformer reliability, operational continuity, and asset sustainability in electrical power distribution systems, and it has been widely adopted in transformer maintenance studies (Tenbohlen et al., 2016).

Operationally, the transformer oil maintenance management process evaluated in this study follows a sequential framework comprising oil condition monitoring, comparison with standard threshold values, maintenance decision-making, and implementation of appropriate actions. Oil test results are used as the primary input for determining preventive maintenance, corrective actions, or scheduled oil replacement. This condition-oriented approach reflects practical maintenance management implementation rather than laboratory-based experimentation.

RESULTS AND DISCUSSION

Research Result

This section presents factual findings obtained from field observations, maintenance records, and transformer oil test documentation related to the implementation of transformer oil maintenance management in distribution transformers.

Transformer Oil Characteristics

The results indicate that the transformer oil used in distribution transformers exhibits physical, chemical, and electrical characteristics that serve as primary indicators of operational suitability. These characteristics are directly associated with the oil's function as an insulating medium and a cooling agent during transformer operation.

The observed physical parameters include clarity, specific gravity, viscosity, flash point, and pour point. These parameters describe the oil's flow behavior, heat transfer capability, and safe operating temperature range. Electrical parameters, on the other hand, reflect the oil's ability to withstand electrical stress and maintain insulation performance under operating conditions.

Standard Values and Characteristics of Transformer Oil

The results of transformer oil evaluation were compared with relevant technical standards, as summarized in Table 1.

Table 1. Standard Values and Characteristics of Transformer Oil

Characteristics	**ASTM Standard**	**Value**
Dielectric strength	D-1816	> 28 kV (1.02 mm)
Specific gravity	D-1298	825–890 kg/m^3
Viscosity	D-445	3–16 cSt (40°C)
Pour point	D-97-66	−30°C
Water content	D-1533	3–15 ppm
Flash point	D-92-7	145°C
Fire point	D-92-78	> 150°C
Impulse strength	D-3300	145 kV
Resistivity	D-1167	3–10 GΩ·m

Table 1 presents the threshold values used as reference criteria for assessing transformer oil condition. Dielectric strength, expressed in kilovolts (kV), indicates the oil's insulating capability, while viscosity, expressed in centistokes (cSt), reflects its flow characteristics. Water content, expressed in parts per million (ppm), serves as an indicator of moisture contamination, whereas flash point and fire point represent the oil's thermal safety limits during operation.

The values presented in Table 1 are used solely as reference criteria for evaluating transformer oil condition in this study and form the basis for maintenance-related decision-making.

Electrical Properties of Transformer Oil

The observed electrical properties of transformer oil include breakdown voltage, impulse strength, resistivity, dielectric dissipation factor, and permittivity. Breakdown voltage represents the maximum voltage the oil can withstand before insulation failure occurs, while resistivity indicates the level of oil purity with respect to conductive contaminants.

The dielectric dissipation factor reflects energy losses within the oil during transformer operation, and permittivity represents the oil's ability to store electrostatic energy. These parameters collectively provide an overview of the electrical condition of transformer oil throughout its service life.

Comparison of Transformer Oil Conditions Based on Service Status

A comparison of transformer oil conditions based on service status is presented in Table 2, which categorizes oil into aged oil, reactor oil, and new oil.

Table 2. Acceptable Limits of Transformer Oil Properties

Oil Properties	**Aged Oil**	**Reactor Oil**	**New Oil**
Acid content	1 mg KOH/g oil	0.03 mg KOH/g	0.03 mg KOH/g
Breakdown voltage	80 kV/cm	120 kV/cm	120 kV/cm
Water content	0.05 %	0.0 %	0.0 %
Impurity level	1.1 %	0.0 %	0.0 %
Viscosity	30 mP	19.24 mP	18.45 mP

Color	Reddish brown	Yellow	Light yellow
Odor	Strong odor	Odorless	Odorless

Table 2 summarizes the observed variation in transformer oil properties according to service condition and serves as a descriptive comparison of oil characteristics based on operational status.

Implementation of Transformer Oil Maintenance Management

The results show that transformer oil maintenance management at PT. Persada Lampung Nusantara includes preventive maintenance, corrective maintenance, and scheduled oil replacement. Preventive maintenance is carried out to reduce the likelihood of operational disturbances, while corrective actions are implemented when oil condition degradation is identified.

Scheduled oil replacement is performed in accordance with established maintenance intervals. The maintenance data obtained from these activities serve as a basis for controlling transformer oil condition and supporting the continuous operation of distribution transformers.

DISCUSSIONS

The results obtained in this study indicate that transformer oil condition parameters, including dielectric strength, moisture content, viscosity, and acidity, are directly associated with maintenance decision-making in distribution transformers. These findings support the principle that transformer oil diagnostics serve not only as technical indicators but also as managerial inputs in maintenance management systems.

Interpretation of Results

The results demonstrate that the physical, chemical, and electrical characteristics of transformer oil constitute key indicators for assessing the operational suitability of distribution transformers. Parameters such as dielectric strength, viscosity, water content, and resistivity provide direct evidence of the oil's ability to function effectively as an insulating and cooling medium. Adequate dielectric strength indicates sufficient insulation performance under electrical stress, while acceptable viscosity values support efficient heat transfer during normal transformer operation.

Scientific and Theoretical Explanation

From a scientific perspective, changes in transformer oil properties are closely associated with thermal aging, oxidation processes, moisture ingress, and contamination by degradation by-products from solid insulation materials. These mechanisms lead to reductions in dielectric strength and resistivity, as well as increases in acidity and viscosity over time. Previous studies have shown that even small increases in moisture content can significantly accelerate insulation aging and reduce transformer reliability (Tenbohlen et al., 2016). Therefore, continuous monitoring of oil condition parameters is essential to maintain insulation integrity and thermal performance.

Comparison with Previous Studies

Consistent with previous studies by Jalbert et al. (2015) and Wang et al. (2019), this research confirms that systematic evaluation of transformer oil parameters supports condition-based maintenance strategies and reduces the risk of unexpected transformer failures. Unlike earlier studies that primarily emphasize diagnostic techniques, the present study extends existing knowledge by demonstrating how oil condition assessment is operationally integrated into routine maintenance management practices at the distribution level.

Practical and Theoretical Implications

Practically, the results indicate that the application of systematic transformer oil maintenance management—encompassing preventive maintenance, corrective actions, and scheduled oil replacement—contributes to maintaining transformer reliability and ensuring continuity of power distribution services. These practices align with internationally recognized guidelines for transformer oil maintenance and condition assessment (A2.34, 2017). From a theoretical standpoint, this study adds empirical evidence to the body of knowledge on the relationship between transformer oil characteristics and maintenance management practices, particularly within the context of distribution transformer asset management.

Study Limitations

This study is limited to a single operational environment and a restricted number of distribution transformers, which may affect the generalizability of the findings. In addition, the analysis relies on existing maintenance records and field observations without incorporating advanced diagnostic techniques such as dissolved gas analysis or long-term laboratory testing. Future studies are recommended to involve extended monitoring periods, multiple operational sites, and comprehensive diagnostic methods to enhance the robustness and applicability of the results.

CONCLUSION

This study concludes that transformer oil maintenance management plays a critical role in maintaining the reliability and operational continuity of distribution transformers in electrical power distribution systems. The physical, chemical, and electrical characteristics of transformer oil are essential indicators for evaluating its effectiveness as an insulating and cooling medium during transformer operation.

The findings demonstrate that the implementation of structured maintenance strategies, including preventive maintenance, corrective actions, and scheduled oil replacement, supports the mitigation of operational risks and contributes to extending the economic service life of distribution transformers. Effective management of transformer oil condition enables more reliable asset operation and enhances the overall performance of power distribution systems.

This research provides practical insights into the application of transformer oil maintenance management at the distribution level and reinforces the importance of condition-oriented maintenance as an integral component of transformer asset management. However, the scope of this study is limited to a specific operational setting and a restricted observation period. Future studies are recommended to involve longer monitoring durations, a broader range of transformer units, and more comprehensive diagnostic methods to strengthen the generalizability and depth of the findings.

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Journal of Electrical Engineering and Informatics (JEEI)
Vol. 1, No. 1, February (2026), pp. 10-20 | p-ISSN: xxxx-xxxx, e-ISSN: xxxx-xxxx
doi: https://doi.org/xxx.xxx

Effect of Capacitor Capacitance on the Power Factor Performance of Single-Phase Induction Motors

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Article History: _Received: January, 25th 2026; Accepted: February, 16th 2026; Published: February, 28th 2026_

ABSTRACT

This study experimentally investigates the effect of capacitor capacitance variation on the power factor and operating characteristics of a single-phase induction motor under no-load conditions. Single-phase induction motors are widely used in residential and light industrial applications; however, their inductive nature often results in a low power factor and increased current consumption. To address this issue, capacitive compensation was applied by installing capacitors with different capacitance values _(4 μF, 6 μF, 12 μF, and 18 μF)_ in the auxiliary winding circuit. The experimental setup was implemented in a controlled laboratory environment, and key parameters including power factor, stator current, electrical power consumption, starting voltage, and rotational speed were measured for each capacitance value. The results show that capacitor capacitance significantly influences motor performance. A capacitance of _4 μF_ provides the most favorable operating condition, yielding the highest power factor while maintaining relatively low current and power consumption. Increasing the capacitance beyond this value leads to excessive leading compensation, which is associated with higher current draw, increased power consumption, and reduced rotational speed. These findings indicate that appropriate capacitor selection is critical for achieving effective power factor improvement without compromising energy efficiency. The outcomes of this study provide practical guidance for capacitor sizing in single-phase induction motor applications and contribute to a better understanding of reactive power compensation under no-load operating conditions.

Keywords: _capacitor capacitance; power factor; reactive power compensation; single-phase induction motor; stator current_

INTRODUCTION

Single-phase induction motors are extensively employed in residential, commercial, and light industrial applications, including ventilation units, water pumps, and small cooling devices. Their widespread use is primarily attributed to their structural simplicity, low cost, and modest maintenance requirements relative to other motor types, and to their dominant share in the global stock of low-power electric drives (Coutinho et al., 2023; Iegorov et al., 2021). In many household and rural installations where only single-phase supply is available, these machines remain indispensable, so even incremental performance improvements can yield meaningful energy savings at scale (Karpe et al., 2019; Parihar et al., 2018).

Despite these advantages, single-phase induction motors inherently exhibit important operational drawbacks, most notably low starting torque and a relatively poor power factor arising from the inductive nature of the stator windings and the pulsating air-gap field. A low power factor increases current demand and copper losses, reduces overall efficiency, and can impose additional stress on distribution networks, motivating continued efforts toward power factor improvement and loss reduction in such drives (Kaplun et al., 2022).

Capacitor-assisted configurations are widely adopted to mitigate these limitations. By introducing a phase displacement between the main and auxiliary winding currents, the series capacitor establishes a quasi-rotating magnetic field that enhances starting capability and can improve the steady-state power factor (Anagreh & Al-Ibbini, 2023; Dawood & Ali, 2022). However, the effectiveness of this approach is highly sensitive to the selected capacitance value. Undersized capacitance leads to insufficient phase shift and weak starting torque, whereas oversized capacitance can cause overcompensation, increased reactive current, higher losses, and reduced efficiency or overheating risk (Muteba, 2021).

Recent research has therefore focused on optimizing the interaction between winding design and capacitive compensation to enhance efficiency, torque, and power factor in single-phase and related induction motor topologies (Chasiotis & Karnavas, 2020). Several works have demonstrated performance improvements using analytical models, finite-element analysis, or power-electronic replacements for fixed capacitors, yet most investigations emphasize loaded operation, variable-speed control, or design optimization rather than systematic experimental characterization of unloaded machines (Almani et al., 2021; Kurt & Fenercioglu, 2025). Experimental studies specifically addressing the influence of capacitor value on key performance indicators such as power factor, stator current, starting voltage, and rotational speed under no-load conditions remain comparatively limited and report differing trends depending on motor design and operating regime (Alsharida et al., 2021; Al-Yoonus & Alyozbaky, 2021).

Accordingly, the present study experimentally examines the effect of capacitor capacitance variation on the power factor and principal operating parameters of an unloaded single-phase induction motor. The evaluated quantities include power factor, stator current, electrical power consumption, starting voltage, and rotational speed. The findings are expected to provide practical guidance for capacitor selection that improves power factor while avoiding unnecessary increases in current and energy consumption in single-phase induction motor applications.

RESEARCH METHODS

This study employs an experimental research design to investigate the effect of capacitor capacitance variation on the power factor of a single-phase induction motor. The experimental approach was selected to directly observe changes in motor operating characteristics resulting from different capacitor values under controlled laboratory conditions (Resketi et al., 2023).

Experimental Setup and Location

The experiment was conducted at the Electrical Engineering Laboratory over a seven-week period from April to May 2024. All measurements were performed under controlled environmental conditions to minimize external disturbances and ensure measurement consistency.

Test Object

The test object was a capacitor-start single-phase induction motor with the following specifications: nominal voltage of *230 V*, frequency of *50 Hz*, rated power of *1/3 HP*, rated current of *1.4 A*, and nominal power factor of 0.87.

All experiments were performed under no-load conditions, ensuring that the observed variations in electrical parameters were solely attributable to changes in capacitor capacitance (Sharma et al., 2016).

Research Variables

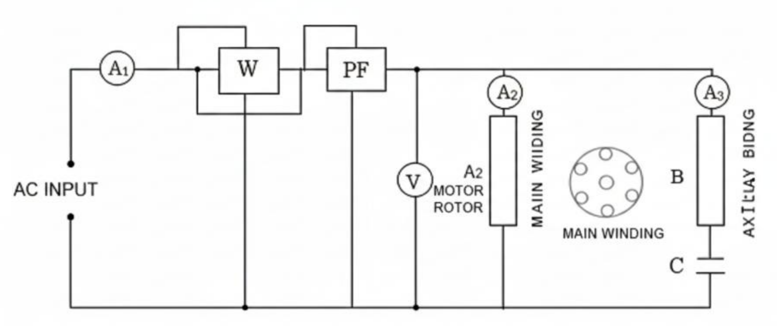
In order to ensure clarity and reproducibility of the experimental analysis, the variables considered in this study are defined and classified as follows.

1) Independent variable: capacitor capacitance (*4 μF, 6 μF, 12 μF, and 18 μF*).
2) Dependent variables: power factor ($\cos \varphi$), total stator current, electrical power consumption, starting voltage, and rotational speed (*RPM*).
3) Controlled variables: supply voltage (100 *V* during testing), supply frequency (*50 Hz*), motor configuration, and no-load operating condition.

Instruments and Materials

The experimental setup utilized standard electrical measurement instruments, including a wattmeter, voltmeter, ammeter, power factor meter, digital tachometer, variable power supply, and digital multimeter (Negahdari et al., 2019). Capacitors with different capacitance values were installed sequentially according to the experimental configuration shown in Figure 1.

Figure 1. Experimental setup of the single-phase induction motor test under no-load conditions.



All instruments were operated in accordance with the manufacturers' specifications to ensure measurement reliability.

Experimental Procedure

To systematically evaluate the effect of capacitor capacitance variation on motor performance, the experimental procedure was conducted through the following sequential steps.

1) Assembling the test circuit according to the configuration shown in Figure 1.
2) Conducting an initial test without a capacitor to establish baseline operating conditions.
3) Installing capacitors with capacitance values of *4 μF, 6 μF, 12 μF, and 18 μF* sequentially in the auxiliary winding circuit.
4) Energizing the motor and recording electrical parameters, including supply voltage, stator current, electrical power, power factor, and rotational speed.
5) Repeating measurements for each capacitance value under identical operating conditions.

All measurements were taken after the motor reached a steady-state condition to avoid transient effects during startup.

Data Analysis

The experimental data were organized in tabular and graphical forms to illustrate the relationship between capacitor capacitance and motor operating parameters. A descriptive–comparative analysis was employed to evaluate changes in power factor, current, power consumption, starting voltage, and rotational speed across different capacitance values (Kumar et al., 2014). The capacitor value that yielded the highest power factor with relatively low current and power consumption was identified as the most effective capacitance under no-load conditions.

RESULTS AND DISCUSSION

Research Result

Motor Performance without Capacitor

The initial experimental condition was conducted to evaluate the baseline behavior of the single-phase induction motor in the absence of capacitive assistance. This test was intended to confirm the necessity of a phase-shifting element for initiating motor rotation and to establish a reference condition for subsequent comparisons.

Table 1. Experimental Results of the Single-Phase Induction Motor without Capacitor
Test conditions:
Stator resistance $R_u = 16.6\ \Omega$
Auxiliary winding resistance $R_b = 55.1\ \Omega$

No.	Capacitor (μF)	Supply Voltage (V)	Total Current (A)	Main Winding Current (A)	Auxiliary Winding Current (A)	Power (W)	Power Factor	Speed (RPM)	Remarks
1	-	100	-	-	-	-	-	-	Motor did not rotate

Note: As reported in the *Results* section, the motor was unable to rotate in the absence of a capacitor, even when a supply voltage of *100 V* was applied. Consequently, current, power, power factor, and rotational speed could not be measured.

As shown in Table 1, the motor did not rotate when supplied with a voltage of *100 V* without capacitor installation. Under this condition, no measurable values of stator current, electrical power, power factor, or rotational speed were obtained. This result confirms that, without an auxiliary phase-shifting component, a single-phase induction motor is unable to generate the rotating magnetic field required for operation.

Motor Performance with Capacitor Installation

Following the baseline test, the motor was evaluated with capacitor installation to examine the effect of different capacitance values on its operating characteristics. Capacitors with capacitance values of *4 μF, 6 μF, 12 μF,* and *18 μF* were installed sequentially under identical test conditions.

Table 2. Experimental Results of the Single-Phase Induction Motor with Capacitor Installation
Test conditions:
Stator resistance $R_u = 16.6$
auxiliary winding resistance $R_b = 55.1$

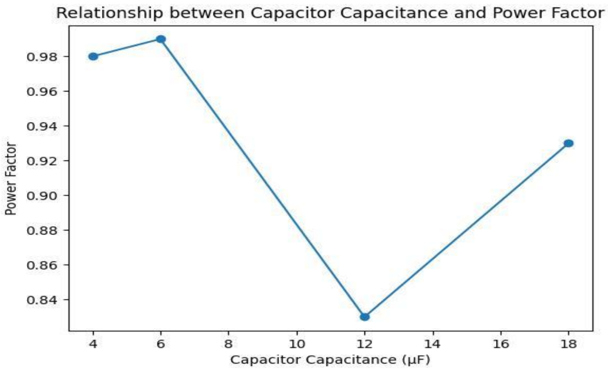
No.	Capacitor (μF)	Starting Voltage (V)	Supply Voltage (V)	Total Current (A)	Main Winding Current (A)	Auxiliary Winding Current (A)	Power (W)	Power Factor	Speed (RPM)	Operating Condition
1	4	90	100	0.32	0.20	0.10	30	0.98	2978	Lagging
2	6	75	100	0.35	0.05	0.30	34	0.99	2973	Leading
3	12	50	100	0.94	0.35	0.65	75	0.83	2950	Leading
4	18	42	100	1.55	0.82	0.78	145	0.93	2912	Leading

The data presented in Table 2 indicate that capacitor installation enabled the motor to operate and reach rotational speeds close to synchronous speed. However, variations in capacitance resulted in noticeable differences in power factor, stator current, electrical power consumption, starting voltage, and rotational speed. These results demonstrate that capacitor capacitance plays a critical role in determining the electrical and mechanical performance of the motor.

Effect of Capacitor Capacitance on Power Factor

To further illustrate the influence of capacitor capacitance on motor performance, the relationship between capacitance and power factor is examined graphically to emphasize changes in phase characteristics.

Figure 2. Relationship between Capacitor Capacitance and Power Factor



As illustrated in Figure 2, the power factor is strongly affected by capacitor capacitance. A lagging power factor is observed at a capacitance of *4 μF*, while higher capacitance values *(6 μF, 12 μF, and 18 μF)* shift the operating condition toward a leading power factor. The highest power factor values occur at *4 μF* and *6 μF*, followed by a reduction at higher capacitance levels.

Effect of Capacitor Capacitance on Starting Voltage

The effect of capacitor capacitance on the starting voltage of the motor is analyzed to assess how capacitance influences the voltage required to initiate motor operation.

Figure 3. Relationship between Capacitor Capacitance and Starting Voltage

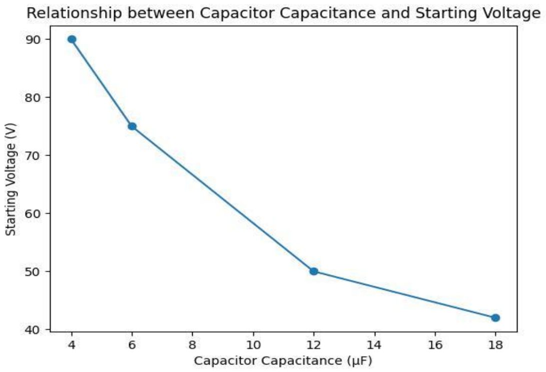
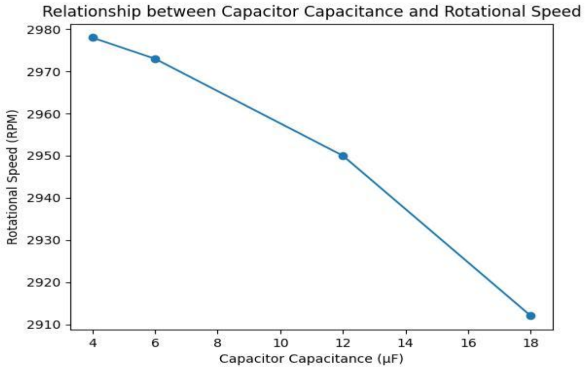


Figure 3 shows that the starting voltage decreases as capacitor capacitance increases. The highest starting voltage is observed at *4 μF*, whereas the lowest starting voltage occurs at *18 μF*. This trend indicates that larger capacitance values reduce the voltage required during motor startup.

Effect of Capacitor Capacitance on Rotational Speed

The variation in rotational speed resulting from changes in capacitor capacitance is presented to illustrate its effect on motor mechanical performance under no-load conditions.

Figure 4. Relationship between Capacitor Capacitance and Rotational Speed



As shown in Figure 4, motor rotational speed decreases gradually with increasing capacitance. The maximum speed is achieved at a capacitance of *4 μF*, while the minimum speed is recorded at *18 μF*, indicating that excessive capacitance adversely affects steady-state rotational speed.

Effect of Capacitor Capacitance on Total Stator Current

To evaluate the electrical demand imposed on the motor, the relationship between capacitor capacitance and total stator current is examined.

Figure 5. Relationship between Capacitor Capacitance and Total Stator Current

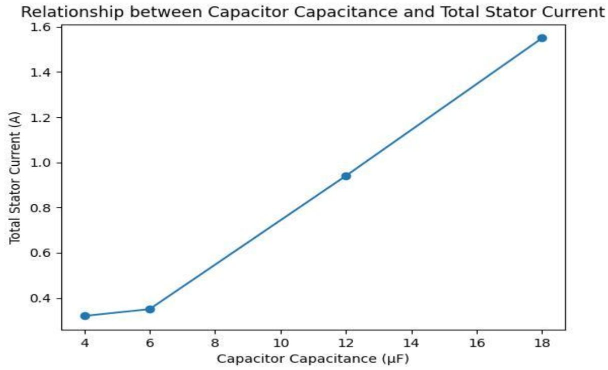
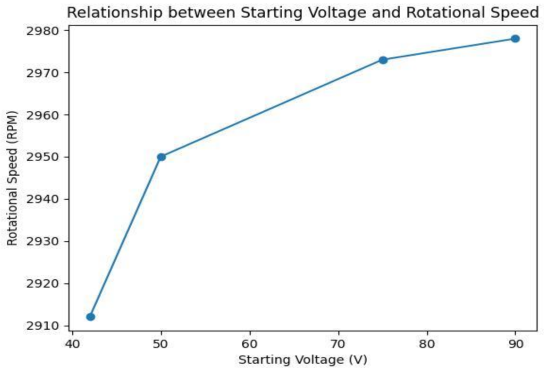


Figure 5 demonstrates that total stator current increases with increasing capacitance. The lowest current is observed at *4 μF*, while the highest current occurs at *18 μF*. This result reflects the increasing electrical load associated with higher capacitive compensation.

Relationship between Starting Voltage and Rotational Speed

The combined influence of starting voltage on motor rotational speed is examined to identify trends in motor response during startup.

Figure 6. Relationship between Starting Voltage and Rotational Speed



As illustrated in Figure 6, the relationship between starting voltage and rotational speed is non-linear. In general, higher starting voltage corresponds to higher rotational speed, although the rate of increase varies across different operating conditions.

Relationship between Stator Current and Electrical Power Consumption

Finally, the relationship between stator current and electrical power consumption is presented to clarify how current demand translates into power usage.

Figure 7. Relationship between Stator Current and Electrical Power Consumption

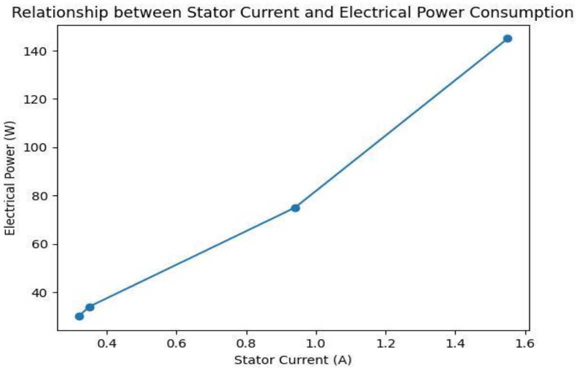


Figure 7 shows a direct relationship between stator current and electrical power consumption, where increases in current are accompanied by corresponding increases in power consumption.

DISCUSSIONS

The experimental results clearly demonstrate that capacitor capacitance significantly influences the electrical and mechanical characteristics of a single-phase induction motor operating under no-load conditions. The absence of a capacitor prevented motor rotation, highlighting the essential role of capacitive phase shifting in enabling motor operation.

Among the tested capacitance values, a capacitance of *4 μF* produced the most favorable operating condition. At this value, the motor achieved a high power factor while maintaining relatively low stator current and electrical power consumption. This indicates that the capacitive reactance at 4 *μF* effectively compensates for the inductive nature of the stator windings, resulting in a more balanced phase relationship between voltage and current.

As capacitance increased beyond *4 μF*, the operating condition shifted toward a leading power factor, indicating overcompensation. Although the magnitude of the power factor remained relatively high, the accompanying increase in stator current and electrical power consumption suggests reduced electrical efficiency. This behavior is attributed to excessive capacitive reactive current, which circulates within the motor windings without contributing to useful mechanical output.

The observed reduction in rotational speed with increasing capacitance further supports this explanation. Excessive capacitive compensation alters the electromagnetic field distribution in the motor, leading to changes in torque production and steady-state speed, even under no-load conditions. Similar trends have been reported in previous experimental studies, which emphasize that inappropriate capacitor sizing can negatively affect motor performance despite apparent improvements in power factor magnitude.

From a theoretical standpoint, capacitors in single-phase induction motors are intended to generate a phase-shifted auxiliary current that approximates a rotating magnetic field. When the capacitance value is appropriately selected, this mechanism improves power factor and reduces unnecessary current flow. However, excessive capacitance introduces surplus reactive power, increasing copper losses and degrading overall efficiency.

The results of this study are consistent with prior findings reported in the literature, which indicate that optimal capacitor selection is highly dependent on motor parameters and operating conditions. The identification of *4 μF* as the optimal capacitance under no-load conditions reinforces the importance of experimental validation when determining capacitor values for practical applications.

CONCLUSION

This study demonstrates that capacitor capacitance variation has a significant influence on the power factor and operating characteristics of a single-phase induction motor under no-load conditions. The installation of a capacitor enables motor operation by introducing the required phase displacement and directly affects power factor, stator current, electrical power consumption, starting voltage, and rotational speed.

Among the tested capacitance values, a capacitance of 4 μF provides the most favorable performance, yielding the highest power factor while maintaining relatively low current draw and electrical power consumption. Increasing the capacitance beyond this value tends to shift the operating condition toward excessive *leading* compensation, which is accompanied by higher current and power consumption as well as a reduction in rotational speed.

These findings highlight the practical importance of selecting an appropriate capacitor value to achieve effective power factor improvement without incurring unnecessary energy losses. From an application perspective, proper capacitor sizing is essential to ensure efficient and stable operation of single-phase induction motors.

The present study is limited to a single motor type operating under no-load conditions. Future research is recommended to investigate the effects of capacitor capacitance under varying load conditions and across different motor ratings to enhance the generalizability of the results.

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Journal of Electrical Engineering and Informatics (JEEI)

Vol. 1, No. 1, February (2026), pp. 21-32 | p-ISSN: xxxx-xxxx, e-ISSN: xxxx-xxxx
doi: https://doi.org/xxx.xxx

Design and Implementation of an Arduino-Based Food Delivery Robot with Bluetooth Control

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Article History: *Received: January, 19th 2026; Accepted: February, 12th 2026; Published: February, 27th 2026*

ABSTRACT

The development of service robots has gained increasing attention as a solution to improve efficiency and consistency in food delivery services, particularly in environments with limited space and dynamic conditions. This study aims to design and implement an Arduino-based food delivery robot with Bluetooth control operated via a smartphone. The research employs a prototype-based development method, encompassing system requirement analysis, mechanical and electronic design, prototype construction, and functional testing. The robot is equipped with an Arduino Uno R3 microcontroller, DC gearbox motors, a Bluetooth HC-06 module for wireless communication, and an audio system to support basic human–robot interaction. System testing focuses on evaluating the robot's ability to respond to movement commands and audio activation instructions transmitted through a smartphone application. The results demonstrate that the developed prototype is capable of executing directional movement commands and activating the audio system consistently within the defined operational range. These findings indicate that low-cost embedded platforms can be effectively utilized to develop functional food delivery robot prototypes suitable for controlled environments such as parties or small-scale service settings. This study contributes to the validation of a simple and replicable service robot design that may serve as a foundation for further development toward more autonomous and intelligent robotic service systems.

Keywords: arduino; *bluetooth control; food delivery robot; service robot; smartphone control.*

INTRODUCTION

Recent advances in robotics and embedded systems have significantly accelerated the adoption of automation within the service sector, particularly in applications that require efficiency, consistency, and operational reliability. Service robots have emerged as an effective technological solution to support or substitute human labor in non-industrial environments, including food and beverage services, where repetitive and time-sensitive tasks are prevalent (Wirtz et al., 2018; Ivanov & Webster, 2019). The deployment of such robots has been shown to reduce operational errors, optimize labor utilization, and enhance service performance.

In conventional food-serving practices, especially during large-scale events such as parties or receptions, food delivery activities are predominantly carried out by human attendants. However, human performance is inherently affected by factors such as fatigue, health conditions, and workload intensity, which may reduce service efficiency and consistency. Prior studies have indicated that service robots are capable of mitigating these limitations by providing stable and repeatable performance, while still supporting acceptable levels of human–robot interaction when appropriately designed (Belanche et al., 2020; Kim et al., 2021).

Food delivery robots represent a specific category of mobile service robots designed to transport items within confined or semi-structured environments. These systems typically consist of integrated mechanical structures, electronic components, and control mechanisms to ensure reliable mobility and task execution (Siegwart et al., 2017). Several previous studies have explored microcontroller-based food delivery or service robots for restaurant applications. However, many existing implementations rely on fixed-path navigation or line-following mechanisms, which limit flexibility in dynamic environments (Eriyani et al., 2018; Ridarmin et al., 2019). As a result, their applicability to event-based settings such as parties, where spatial layouts frequently change, remains constrained.

The Arduino Uno R3 microcontroller is widely used as a control platform in prototype development due to its low cost, ease of programming, and extensive hardware–software ecosystem. Arduino-based systems have been demonstrated to be effective for early-stage robotic development, particularly in integrating actuators, communication modules, and control logic in a modular manner (Banzi & Shiloh, 2022; Monk, 2021). In addition, Bluetooth-based wireless communication enables direct and intuitive robot control via smartphones, allowing real-time operation without requiring complex network infrastructure. This approach is considered suitable for short-range service robot applications in controlled environments (Lu et al., 2022).

Based on these considerations, this study aims to design and implement an Arduino-based food delivery robot equipped with Bluetooth control through a smartphone interface. The research focuses on system design, prototype implementation, and functional performance evaluation to validate the feasibility of the proposed approach. The expected contribution of this study is the development of a simple, cost-effective, and replicable service robot prototype that can serve as a foundational model for further research and development toward more autonomous food delivery systems in limited and dynamic service environments.

THEORETICAL BACKGROUND

Service Robots

Service robots are defined as robotic systems designed to perform useful tasks for humans or equipment in non-industrial environments, particularly within service-oriented sectors such as hospitality, healthcare, and food services (Wirtz et al., 2018). Unlike industrial robots that operate in highly structured settings, service robots are required to function in semi-structured or dynamic environments and often interact directly with human users. Consequently, reliability, safety, and usability are critical design considerations in service robot development.

Previous studies have highlighted that the implementation of service robots can improve operational efficiency, reduce human workload, and enhance service consistency, especially for repetitive and routine tasks (Ivanov & Webster, 2019). In the food service domain, service robots are increasingly adopted to support food delivery, order handling, and customer interaction, contributing to improved service performance when appropriately integrated into the service process (Belanche et al., 2020).

Food Delivery Robots

Food delivery robots represent a subclass of mobile service robots designed to transport food items within confined or controlled environments. These robots typically integrate mechanical structures, electronic subsystems, and control mechanisms to ensure stable movement and task execution (Siegwart et al., 2017). In indoor applications, food delivery robots are commonly employed in restaurants, hotels, and event venues where predefined operational boundaries exist.

Several prior studies have reported successful development of food delivery or restaurant service robots using microcontroller-based platforms. However, many implementations rely on fixed navigation paths or line-following techniques, which limit adaptability in environments with frequently changing layouts (Eriyani et al., 2018; Ridarmin et al., 2019). As a result, manually controlled or semi-autonomous systems remain relevant alternatives, particularly for event-based settings such as parties, where flexibility and direct operator control are required.

Arduino Uno R3 as a Robotic Control Platform

Arduino Uno R3 is a widely used microcontroller development board based on the ATmega328P architecture and is commonly employed in embedded system and robotics research. Its popularity stems from its low cost, simplicity, open-source ecosystem, and extensive community support (Banzi & Shiloh, 2022). Arduino Uno R3 supports programming in C/C++ through the Arduino Integrated Development Environment (IDE), enabling rapid development and testing of control algorithms.

In robotic applications, Arduino-based platforms are frequently utilized during the prototyping stage to validate system concepts and functional integration. Previous studies have demonstrated that Arduino microcontrollers are capable of controlling actuators, processing sensor inputs, and managing communication modules effectively, making them suitable for the development of low-cost robotic prototypes (Monk, 2021).

Bluetooth-Based Control Systems

Bluetooth is a short-range wireless communication technology widely adopted in embedded systems and robotics due to its ease of implementation and low power consumption. Modules such as the HC-06 enable serial communication between microcontrollers and external devices, including smartphones, in real time. Bluetooth-based control systems are particularly suitable for applications that require direct user interaction within limited operational distances (Lu et al., 2022).

In service robot applications, Bluetooth communication allows intuitive and responsive control through smartphone interfaces without requiring complex network infrastructure. Previous research indicates that Bluetooth-based control provides sufficient reliability and responsiveness for indoor robotic applications, especially during the prototyping and validation stages (Kim et al., 2021).

Smartphone-Controlled Robotic Systems

Smartphone-controlled robotic systems utilize mobile devices as human–machine interfaces for sending control commands to robotic platforms. This approach leverages the widespread availability of smartphones and their built-in capabilities, such as touch interfaces and wireless connectivity. In such systems, smartphones function as command transmitters, while the robot executes received instructions through its embedded control unit (Siciliano & Khatib, 2016).

The use of smartphones for robot control has been shown to improve usability and reduce system complexity, particularly in service robot applications that require manual supervision. This control strategy is suitable for environments where autonomous navigation is not yet required, allowing operators to maintain direct control over robot movement and interaction functions.

RESEARCH METHODS

Research Design

This study adopts a prototype-based research design aimed at developing, implementing, and functionally validating a food delivery robot system. The prototype approach is appropriate for engineering-oriented studies that emphasize system construction and direct performance verification prior to large-scale deployment. The methodology focuses on translating system requirements into a functional prototype and evaluating its operational performance under controlled conditions.

The research workflow consists of four main stages: (1) system requirement analysis, (2) system design, (3) prototype construction and integration, and (4) functional testing and evaluation.

System Requirements Analysis

System requirements were identified to ensure that the developed prototype fulfills the intended function as a food delivery robot with smartphone-based control. The requirements analysis covers both hardware and software components necessary for system operation.

Table 1. Hardware Requirements for the Food Delivery Robot Prototype

No.	Component Name	Quantity
1	Arduino Uno R3	1
2	Jumper Wires	20
3	DC Gearbox Motor	2
4	Bluetooth HC-06 Module	1
5	L298N Motor Driver	2
6	18650 Battery	5
7	18650 Battery Holder	2
8	PAM8403 Audio Amplifier	1
9	DFPlayer Mini	1
10	DC Step-Down Converter	1
11	5V Relay Module	1
12	On/Off Switch	2
13	Speaker Driver	1

The hardware requirements include a microcontroller unit, DC gearbox motors as actuators, a motor driver module, a Bluetooth communication module, a power supply system, and an audio output unit. These components collectively support robot mobility, wireless control, and basic human–robot interaction.

Table 2. Software Requirements for Programming and Control of the Robot Prototype

No.	Software Name	Function
1	Arduino IDE	Used for programming and uploading the control code to the Arduino Uno microcontroller.
2	Bluetooth RC Controller	Used to control the robot's movement through a smartphone-based application.

The software requirements consist of the Arduino Integrated Development Environment (IDE) for programming the microcontroller and a smartphone-based Bluetooth control application used to transmit control commands to the robot. The selected software tools enable real-time command transmission and rapid system testing.

System Design

The system design stage involves mechanical design, electronic circuit design, and control logic design. The mechanical structure of the robot is designed to support food and beverage loads while maintaining balance and stable movement on flat surfaces. The arrangement of components follows the mechanical design illustrated in the prototype design figures provided in the manuscript.

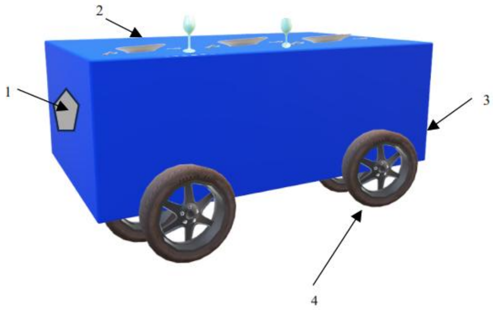

Figure 1. Mechanical Design of the Food Delivery Robot Prototype

The electronic system integrates the Arduino Uno R3 microcontroller as the main control unit, DC motors for locomotion, a motor driver for actuator control, a Bluetooth HC-06 module for wireless communication, and an audio module for sound output. The electronic circuit configuration follows the schematic diagrams presented in the manuscript and serves as a reference for system assembly.

Table 3. Description of Components in the Mechanical Design of the Robot Prototype

Label Number	Description
1	IBIK Logo
2	Plates and Glasses
3	Arduino and Electronic Components Storage Box
4	DC Gearbox Motor and Wheels

Control logic is implemented through a program written in C/C++ using the Arduino IDE. The control algorithm is designed to interpret incoming Bluetooth commands and translate them into corresponding motor actions and audio outputs.

Prototype Construction and Integration

Prototype construction is carried out by assembling the mechanical structure and installing all electronic components according to the predefined design. The integration process includes wiring the electronic components, configuring the power supply, and embedding the programmed microcontroller into the system.

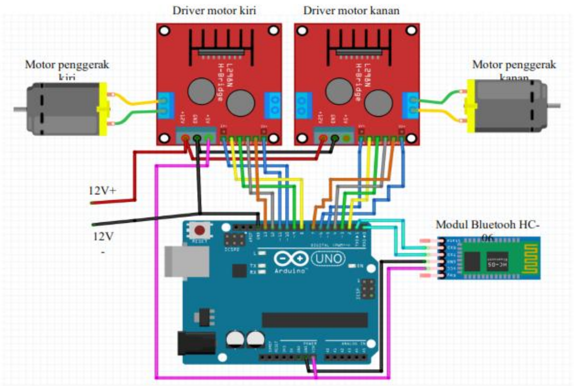

Figure 2. Electronic Circuit Schematic of the Arduino-Based Robot System

Programming is performed incrementally, starting with basic motor control tests, followed by Bluetooth communication validation, and finally integrating the audio system. This stepwise integration approach ensures that each subsystem functions correctly before full system operation.

Functional Testing Procedure

Functional testing is conducted to evaluate the operational performance of the prototype robot. Testing focuses on verifying the system's ability to respond accurately to control commands transmitted via a smartphone application.

The testing procedure includes issuing directional commands (forward, backward, left, and right) and observing the corresponding robot movements. In addition, audio system functionality is tested by activating sound output commands with predefined interaction scenarios. All test results are recorded in the functional testing tables presented in the manuscript.

Data Analysis Technique

Data analysis in this study is performed using a descriptive qualitative approach. The analysis evaluates whether the observed system responses correspond to the predefined functional requirements. The testing outcomes are used to determine the reliability and consistency of the prototype in executing movement and audio commands, thereby validating the feasibility of the proposed system design.

RESULTS AND DISCUSSION

Research Result

This section presents the implementation and testing results of the Arduino-based food delivery robot with Bluetooth control via a smartphone. The results are organized in accordance with the research objectives and methodology, focusing on system implementation, electronic integration, and functional performance outcomes.

Prototype Implementation Results

The implementation results demonstrate that the developed food delivery robot prototype successfully integrates the mechanical structure and electronic components as specified in the system design. The assembled prototype represents the physical realization of the mechanical design and electronic configuration described in the Methodology section.

Figure 3. Assembled Food Delivery Robot Prototype after System Integration

The prototype is capable of supporting food and beverage items placed on the upper platform while maintaining structural stability during movement on flat surfaces. These results indicate that the mechanical design and component placement adequately fulfill the basic functional requirements of a food delivery robot intended for controlled environments.

Electronic System Implementation Results

The electronic system implementation shows that all electronic components are properly interconnected and operate as an integrated control system. The Arduino Uno R3 functions as the central control unit, receiving command signals from the Bluetooth module and executing corresponding control actions.

Figure 4. Implementation of the Electronic System after Assembly

The motor driver modules successfully regulate the rotation and direction of the DC gearbox motors, enabling controlled robot movement. In addition, the integrated audio system operates as intended, allowing sound output to be activated through commands transmitted from the smartphone. These outcomes confirm that the electronic configuration supports both mobility control and basic human–robot interaction functions.

Functional Testing Results

Functional testing was conducted to evaluate the robot's response to control commands transmitted via the smartphone-based Bluetooth application. The overall functional testing results are summarized in Table 4, which presents the relationship between control commands, motor responses, and audio system activation.

Table 4. Functional Testing Results of Robot Control and Audio System

No.	Control Button	Motor Movement	Speaker Output
1	Forward	Moves forward	–
2	Backward	Moves backward	–
3	Right	Turns right	–
4	Left	Turns left	–
5	Speaker icon (1× click)	–	Continuous sound output
6	Speaker icon (2× clicks)	–	Single sound output

The test results indicate that the robot responds appropriately to directional movement commands, including forward, backward, left, and right motions. Each command issued through the control application produces a corresponding and consistent physical response from the robot. Furthermore, the audio system functions according to the predefined interaction scenarios, activating continuous or single sound output based on the control input provided.

The functional testing results demonstrate that the Bluetooth-based control system performs reliably within the specified operational range. The robot consistently receives and executes control commands during the testing process, indicating stable system performance under the tested conditions.

Discussions

The results of this study demonstrate that the developed Arduino-based food delivery robot with Bluetooth control is capable of performing its intended service functions reliably within a controlled environment. The prototype consistently responded to directional movement commands and audio activation instructions transmitted via a smartphone interface, indicating that the system architecture and control logic were implemented effectively. These findings confirm that the functional objectives of the research were achieved without requiring complex navigation or sensing mechanisms.

From a theoretical perspective, the observed system performance aligns with the fundamental principles of service robot design, particularly for mobile service robots operating in semi-structured environments. Service robots are expected to prioritize reliability, usability, and task repeatability rather than full autonomy at early development stages (Wirtz et al., 2018). The use of a microcontroller-based control system enables stable coordination between mechanical actuation and electronic control, supporting the notion that low-cost embedded platforms can adequately fulfill basic service robot requirements (Ivanov & Webster, 2019).

When compared with previous studies on food delivery and restaurant service robots, the results of this research are consistent with findings reported by Eriyani et al. (2018) and Ridarmin et al. (2019), who demonstrated that microcontroller-driven robots can effectively support food delivery tasks in indoor environments. However, unlike many earlier implementations that rely on fixed-path navigation or line-following techniques, the robot developed in this study employs direct smartphone-based Bluetooth control. This approach offers greater operational flexibility in environments where spatial layouts are not fixed, such as parties or temporary event settings. Similar control strategies have been recognized as suitable alternatives for early-stage service robot applications where adaptability is prioritized over autonomy (Lu et al., 2022).

In terms of practical implications, the findings suggest that the proposed prototype can serve as a functional support system for food distribution in small-scale service scenarios. The integration of an audio output mechanism provides a simple yet effective form of human–robot interaction, enhancing user awareness during food delivery tasks. Additionally, the use of widely available components such as Arduino Uno R3 and Bluetooth modules contributes to the system's affordability and replicability, making it accessible for educational purposes, small businesses, or further experimental development.

From a broader theoretical standpoint, this study contributes to the growing body of literature on low-cost service robot development by demonstrating that meaningful service functionality can be achieved through simplified control architectures. The results reinforce prior research suggesting that manual or semi-manual control strategies remain relevant, particularly in contexts where full autonomy may be impractical or unnecessary (Belanche et al., 2020; Kim et al., 2021). As such, the prototype presented in this study may be viewed as an intermediate step toward more advanced service robot systems.

Despite these contributions, several limitations should be acknowledged. The robot's operational range is constrained by Bluetooth communication, limiting its use to short-distance applications. Furthermore, the system does not incorporate autonomous navigation, obstacle detection, or adaptive decision-making capabilities. These limitations indicate that the developed prototype is best characterized as a proof-of-concept rather than a fully autonomous service robot. Future research is therefore recommended to integrate longer-range communication technologies, environmental sensors, and autonomous navigation algorithms to enhance system scalability and intelligence.

CONCLUSION

This study has successfully designed and implemented an Arduino-based food delivery robot controlled via Bluetooth using a smartphone interface. The developed prototype demonstrates reliable execution of basic service functions, including directional movement control and audio activation, in accordance with the defined system requirements. These results confirm the feasibility of employing a low-cost embedded platform to develop a functional service robot prototype for controlled environments.

The main contribution of this research lies in validating a simple and replicable design approach for food delivery robots that does not rely on complex navigation or autonomous decision-making. By utilizing widely available hardware components and a straightforward control architecture, the proposed system offers a practical foundation for early-stage service robot development and experimental applications in small-scale service settings, such as parties or temporary events.

From a practical perspective, the findings indicate that the proposed prototype can support food distribution tasks by assisting human operators and improving service efficiency. However, the system remains limited by short-range Bluetooth communication and the absence of autonomous navigation and environmental sensing capabilities. Future work is therefore recommended to incorporate longer-range communication technologies, obstacle detection sensors, and autonomous navigation algorithms to enhance the system's adaptability and operational scope.

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Journal of Electrical Engineering and Informatics (JEEI)

Vol. 1, No. 1, February (2026), pp. 33-45 | p-ISSN: xxxx-xxxx, e-ISSN: xxxx-xxxx
doi: https://doi.org/xxx.xxx

An IoT-Enabled Monitoring System for Real-Time Water Quality Management in Catfish Aquaculture

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Article History: *Received: February, 5th 2026; Accepted: February, 27th 2026; Published: February, 28th 2026*

ABSTRACT

Water quality management is a critical factor in determining the productivity and sustainability of catfish (*Clarias sp.*) aquaculture. Conventional monitoring practices are generally manual, periodic, and inefficient, limiting farmers' ability to respond promptly to environmental changes. This study presents the design and implementation of an Internet of Things (IoT)–based water quality monitoring system for catfish ponds using an ESP8266 microcontroller, a type-K thermocouple temperature sensor, and an SEN0161 pH sensor. The proposed system enables real-time monitoring of water temperature and pH, wireless data transmission to an online database, and continuous visualization through a web-based interface. System performance was evaluated in three pond environments indoor, semi-outdoor, and outdoor during a six-hour observation period, yielding a total of 1,012 measurement data points. The results indicate that the recorded water temperature and pH values generally fall within the recommended ranges for catfish aquaculture, demonstrating stable monitoring performance across different environmental conditions. Linear regression analysis further confirms the consistency of temperature and pH trends during the monitoring period. The findings show that the developed system is capable of providing reliable real-time water quality information and can support data-driven pond management while reducing dependence on manual measurements. Despite its effectiveness, the system's performance is influenced by internet connectivity and is currently limited to temperature and pH parameters. Future work may focus on extending monitoring duration, improving communication reliability, and integrating additional water quality indicators to enhance system comprehensiveness.

Keywords: *internet of things; water quality monitoring; catfish aquaculture; esp8266; smart aquaculture systems*

INTRODUCTION

Catfish (*Clarias sp.*) aquaculture represents one of the most strategic freshwater farming sectors contributing to food security and economic development in Indonesia. The increasing demand for catfish, particularly in urban areas, necessitates more efficient and sustainable aquaculture management practices. However, the success of catfish farming is highly dependent on aquatic environmental quality, especially water temperature and acidity (pH), which directly influence fish metabolism, growth performance, and survival rates (Boyd, 2020; Badiola et al., 2018).

Poor water quality management can induce physiological stress, reduce feeding activity, and increase disease susceptibility, ultimately leading to decreased productivity. Previous studies have reported that optimal growth conditions for catfish occur at water temperatures ranging from 25 to 30 °C and pH values between 6.5 and 8.0, while deviations from these ranges may significantly impair production performance (El-Sayed, 2019; Effendi et al., 2016). These findings are consistent with the Indonesian National Standard SNI 6484.3:2014, which specifies recommended water quality parameters for catfish seed production, as well as international guidelines issued by the Food and Agriculture Organization (FAO) for sustainable aquaculture management (FAO, 2017).

In practice, water quality monitoring in catfish ponds is still predominantly conducted using manual and periodic measurements. Such conventional approaches are inherently limited, as they do not provide continuous or real-time information, thereby delaying the detection of unfavorable environmental changes. Consequently, farmers often experience difficulties in implementing timely corrective actions, particularly in intensive aquaculture systems where water quality fluctuations may occur rapidly (Ahmed et al., 2021).

The advancement of Internet of Things (IoT) technology offers a promising solution to these challenges. IoT enables the integration of sensors, microcontrollers, and communication networks to perform real-time environmental monitoring and transmit data over the internet with minimal human intervention (Gubbi et al., 2019). The application of IoT-based systems in aquaculture has been shown to enhance operational efficiency, reduce labor requirements, and support data-driven decision-making processes (Li et al., 2020; Tzounis et al., 2017).

Several previous studies have developed IoT-based water quality monitoring systems using various platforms and sensors, including Wi-Fi-enabled microcontrollers such as the ESP8266. These systems generally focus on acquiring temperature and pH data and visualizing the measurements through online platforms (Zhou et al., 2018; Rahman et al., 2020). Nevertheless, challenges remain with respect to sensor accuracy, calibration reliability, data transmission stability, and the integration of monitoring functions with automated control mechanisms under different pond environmental conditions (Islam et al., 2021; Kumar & Rani, 2022).

Addressing these research gaps, there is a need for a well-calibrated, real-time water quality monitoring system that can be reliably implemented across various pond configurations, including indoor, semi-outdoor, and outdoor systems. Therefore, this study aims to design and implement an IoT-based water quality monitoring system for catfish ponds using an ESP8266 microcontroller, a type-K thermocouple temperature sensor, and an SEN0161 pH sensor. The proposed system is expected to continuously monitor temperature and pH parameters, store measurement data in an online database, and present real-time information via a web server, thereby supporting effective, accurate, and standards-compliant water quality management in catfish aquaculture.

RESEARCH METHODS

This study adopts a design and implementation research approach to develop an Internet of Things (IoT)–based water quality monitoring system for catfish ponds. This approach is widely applied in sensor- and network-based engineering research to ensure system replicability and measurable performance evaluation (Tzounis et al., 2017).

Research Object and Parameters

The research object comprises catfish (*Clarias sp.*) aquaculture ponds under three environmental conditions: indoor, semi-outdoor, and outdoor ponds. The monitored water quality parameters include:

1. Water temperature (°C), measured using a type-K thermocouple sensor.
2. Water acidity (pH), measured using an SEN0161 pH sensor.

These parameters were selected based on aquaculture literature identifying temperature and pH as primary indicators affecting the growth and health of freshwater fish (Boyd, 2020).

Monitoring System Design

The monitoring system was designed using an ESP8266 microcontroller as the main control unit and Wi-Fi communication module. The temperature and pH sensors were integrated with the ESP8266 to perform periodic data acquisition. The measured data were subsequently transmitted via an internet connection to an online database before being visualized on a web server.

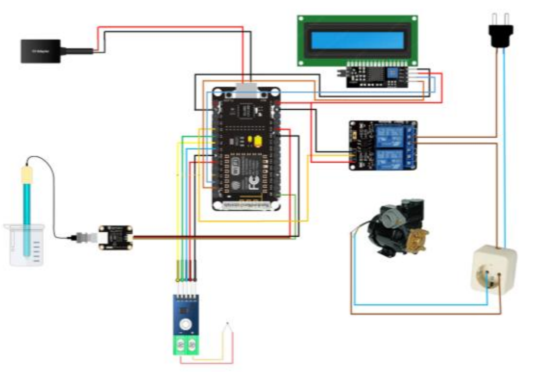

Figure 1. Schematic

The overall system architecture and interconnections among hardware components are illustrated in Figure 1 (Schematic). This architecture aligns with IoT-based aquaculture monitoring frameworks that integrate sensors, microcontrollers, and cloud platforms for real-time data management (Li et al., 2020).

Sensor Calibration Procedure

Prior to system operation, a sensor calibration process was conducted to ensure measurement accuracy. The temperature sensor was calibrated by comparing thermocouple readings with a glass thermometer, while the pH sensor was calibrated using a digital pH meter as the reference instrument. The calibration procedure is shown in Figure 2.

Figure 2. The calibration procedure

$$RMSE = \frac{\sqrt{\sum_{i=1}^{N}(T_{i,p}-T_{i,s})^2}}{1}\ldots\ldots(1)$$

$$RSME = \sqrt{\frac{(39-39,50)^2}{1}}\ldots\ldots(2)$$

$$RSME = 0,25\ldots\ldots(3)$$

$$RSME = \sqrt{\frac{(8,42-8,33)^2}{1}}\ldots\ldots(4)$$

$$RSME = 0,008\ldots\ldots(5)$$

Measurement error was evaluated using the Root Mean Square Error (RMSE) method, as expressed in Equations (1)–(5). RMSE is commonly applied in sensor-based monitoring studies to assess the deviation between sensor measurements and reference values, where lower RMSE values indicate higher measurement accuracy (Islam et al., 2021).

System Operational Procedure

Following calibration, the system was operated to perform real-time water quality monitoring. The temperature and pH sensors continuously acquired data, which were then transmitted by the ESP8266 to the ThingSpeak database platform. The stored data were subsequently displayed on a web server in the form of numerical values and graphical visualizations.

In addition to monitoring, the system incorporates a basic control mechanism based on a predefined threshold. When the detected water temperature exceeds 40 °C, the ESP8266 activates a relay to turn on a water pump, thereby reducing the temperature until it falls below the threshold. The complete system workflow is presented in Figure 3 (System Flowchart). This approach is consistent with IoT monitoring systems that integrate sensing and basic control functions (Kumar & Rani, 2022).

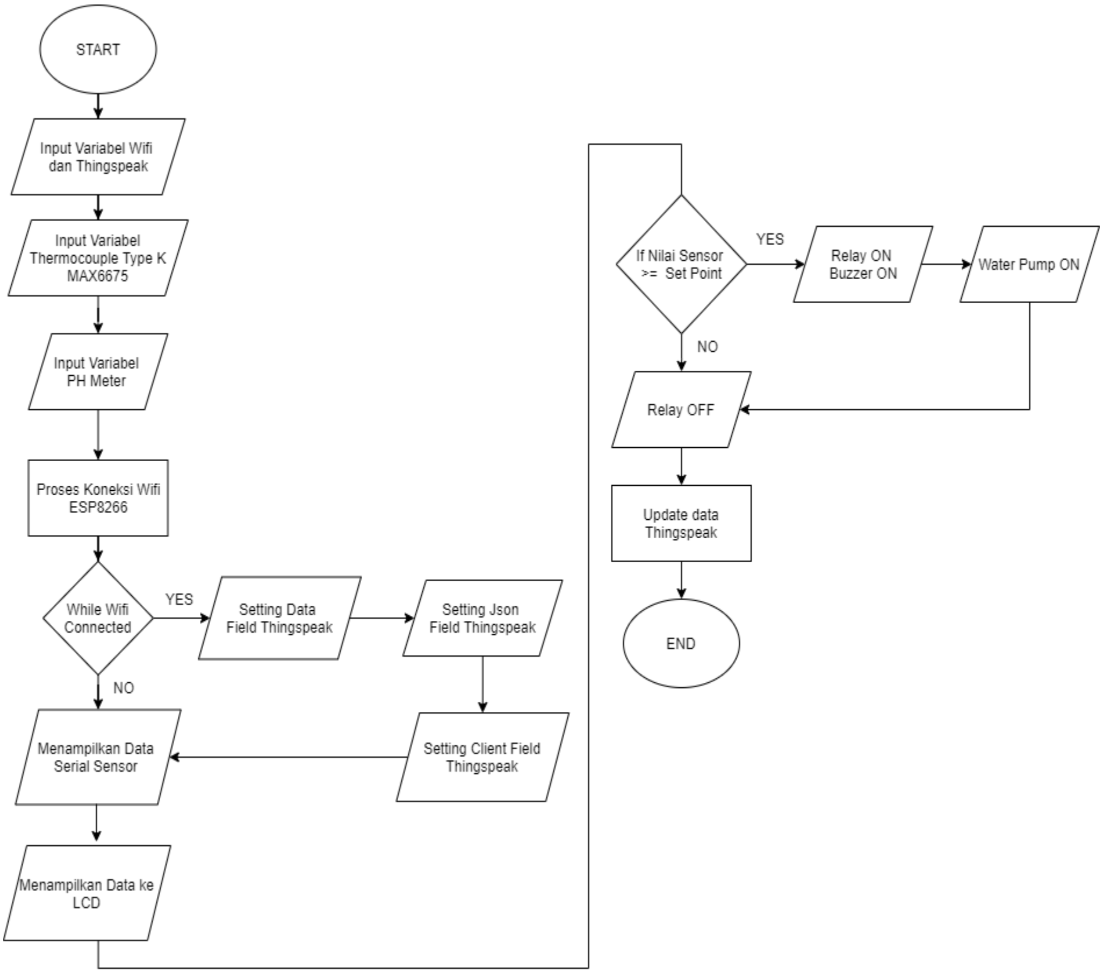

Figure 3. Flowchart System

Data Acquisition and Analysis

Data collection was conducted on 13 July 2021, from 11:00 to 16:00 WIB. A total of 1,012 measurement data points were obtained, comprising 378 data points from indoor ponds, 279 from semi-outdoor ponds, and 355 from outdoor ponds. Data analysis was performed using two main approaches:

1. Measurement error analysis, employing RMSE to evaluate sensor accuracy after calibration.
2. Trend analysis, using linear regression to examine temperature and pH variation trends during the observation period for each pond condition.

The analysis results are presented in the form of graphs and linear regression equations in the Results and Discussion section.

RESULTS AND DISCUSSION

Research Result

The performance evaluation of the water quality monitoring system was conducted in catfish aquaculture ponds under three environmental conditions, namely indoor, semi-outdoor, and outdoor ponds. Data acquisition was carried out on 13 July 2021, from 11:00 to 16:00 WIB. A total of 1,012 measurement data points were collected, comprising 378 data points from indoor ponds, 279 from semi-outdoor ponds, and 355 from outdoor ponds.

Results of Indoor Pond Monitoring

The results of temperature and pH monitoring in the indoor pond are presented in Figure 4 and Figure 5. The recorded water temperature ranged from 27 to 29 °C, while the pH values were within the range of 6 to 8. The graphs indicate relatively stable temperature and pH conditions throughout the observation period.

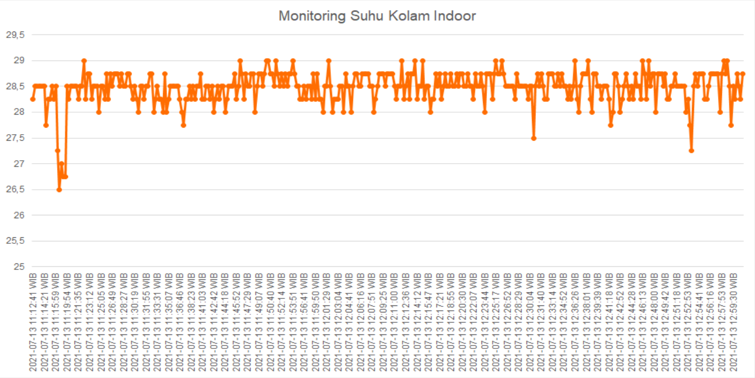

Figure 4. Monitoring Results of pH and Temperature in Indoor Pond

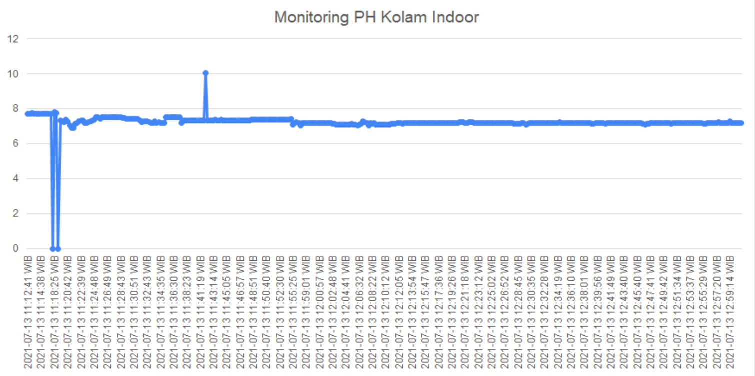

Figure 5. Monitoring Results of pH in the Indoor Pond

Several data points with zero values appear in the graphs. These values resulted from temporary internet connectivity disruptions during data acquisition, which caused certain sensor readings to fail to be transmitted to the database. In addition, a single pH reading reached a value of 10, which occurred when the pH sensor was momentarily lifted above the water surface during measurement.

The linear regression results for the indoor pond are shown in Figure 6. The regression equation reflects a stable trend in both temperature and pH over the monitoring period.

$$y = 0{,}4624\text{x} - 5{,}9493 \ldots\ldots (6)$$

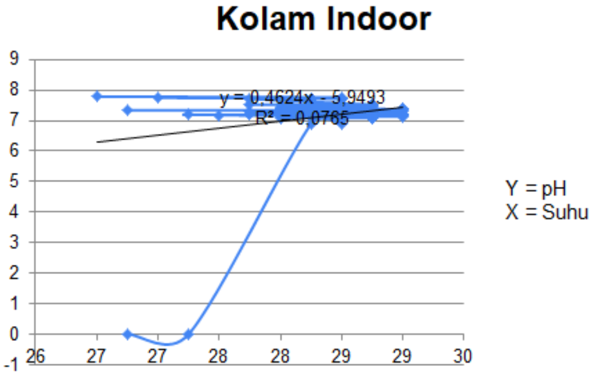

Figure 6. Linear Regression Results of the Indoor Pond

Results of Semi-Outdoor Pond Monitoring

The temperature and pH monitoring results for the semi-outdoor pond are illustrated in Figure 7 and Figure 8. The measured water temperature ranged from 27 to 29 °C, while pH values were observed within the range of 6 to 8. The graphical trends demonstrate that temperature and pH fluctuations in the semi-outdoor pond remained within acceptable limits for catfish cultivation.

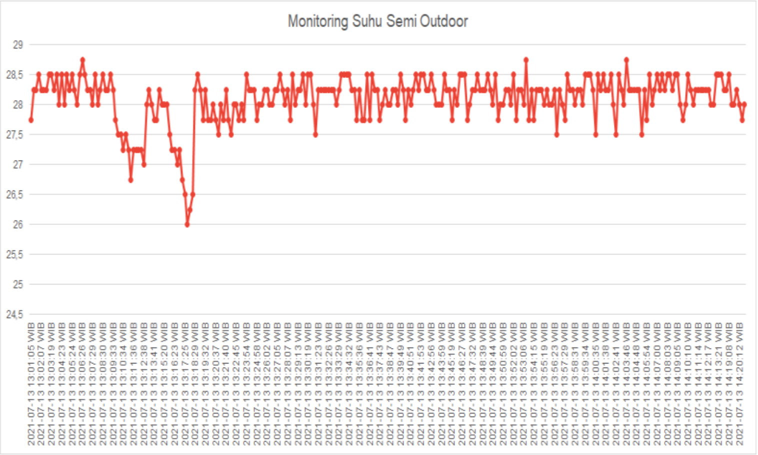

Figure 7. Monitoring Results of pH and Temperature in the Semi-Outdoor Pond

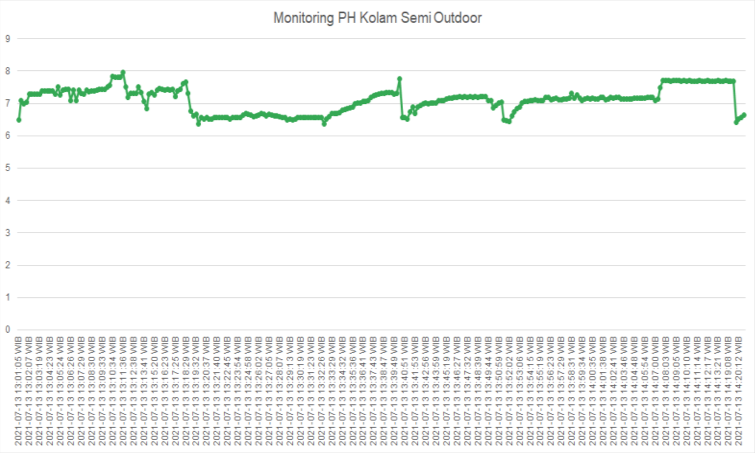

Figure 8. Monitoring Results of pH in the Semi-Outdoor Pond

The linear regression analysis for the semi-outdoor pond is presented in Figure 9. The regression results indicate that the variations in temperature and pH did not exhibit significant deviations during the observation period.

$$y = -0{,}1035x + 10{,}009 \quad \text{......(7)}$$

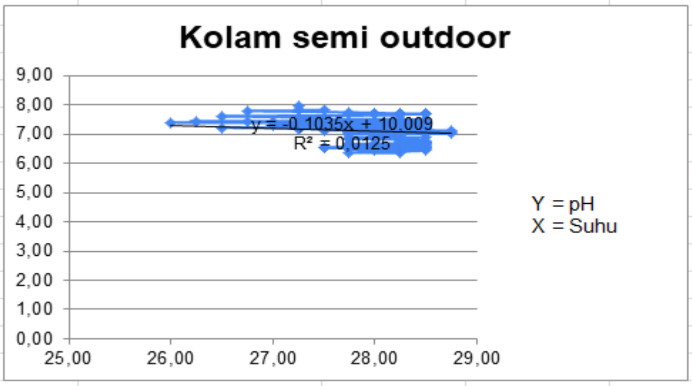

Figure 9. Linear Regression Results of the Semi-Outdoor Pond

Results of Outdoor Pond Monitoring

The monitoring results for the outdoor pond are shown in Figure 10 and Figure 11. The recorded water temperature ranged from 26 to 29 °C, while pH values were observed within the range of 5.5 to 8. Compared to the indoor and semi-outdoor ponds, the outdoor pond exhibited slightly greater variability, particularly in pH values.

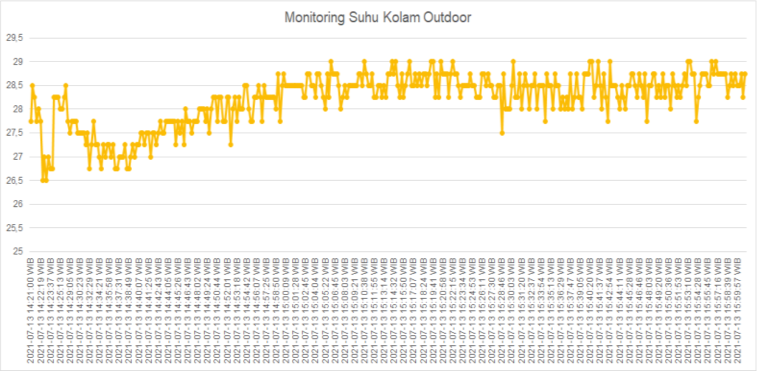

Figure 10. Monitoring Results of pH and Temperature in the Outdoor Pond

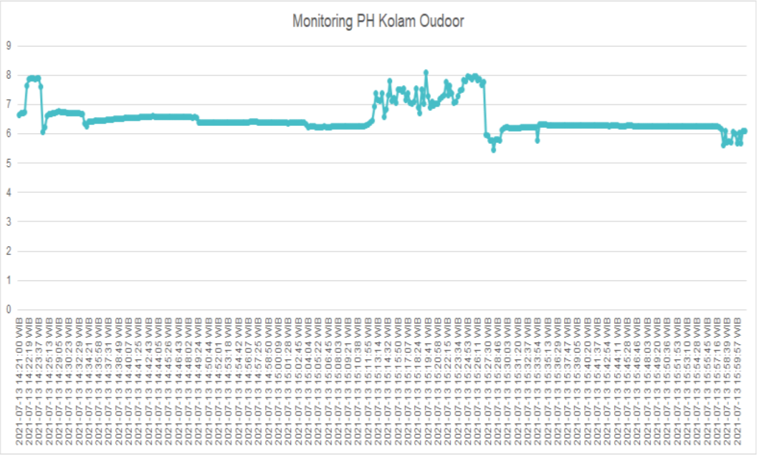

Figure 11. Monitoring Results of pH in the Outdoor Pond

The linear regression results for the outdoor pond are provided in Figure 12. The regression analysis shows that temperature and pH trends remained generally stable throughout the monitoring duration.

$$y = -0{,}0852\,x + 8{,}9332 \;\ldots\ldots\ldots\ldots\ldots\ldots \tag{8}$$

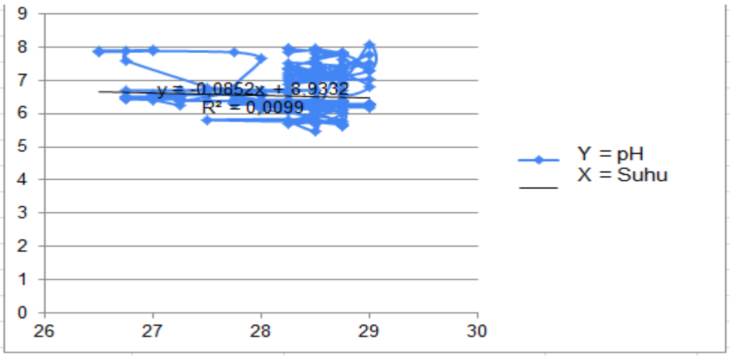

Figure 12. Linear Regression Results of the Outdoor Pond

Summary of Monitoring Results

Overall, the monitoring results demonstrate that the developed system was capable of continuously measuring water temperature and pH across all three pond conditions. The recorded temperature and pH values in the indoor, semi-outdoor, and outdoor ponds largely fell within the recommended ranges for catfish aquaculture. Although several data anomalies were observed due to technical factors during data acquisition, the system consistently captured and transmitted water quality parameters during the monitoring period.

Discussion

The results demonstrate that the proposed Internet of Things (IoT)–based water quality monitoring system is capable of continuously monitoring temperature and pH in catfish ponds under indoor, semi-outdoor, and outdoor conditions. Across all pond types, the measured temperature and pH values generally fell within the recommended ranges for catfish aquaculture, namely 25–30 °C for temperature and pH 6.5–8.0, as reported in aquaculture literature and water quality standards (Boyd, 2020; El-Sayed, 2019).

The relative stability observed in the monitoring graphs and linear regression trends indicates that the system can reliably capture real-time environmental conditions. From a physiological perspective, maintaining stable temperature and pH is essential for sustaining metabolic balance in fish, as excessive fluctuations may induce stress responses and reduce survival rates (Badiola et al., 2018). Therefore, the system's capability to record continuous trends in temperature and pH constitutes a critical feature for data-driven aquaculture management.

Differences in monitoring characteristics among indoor, semi-outdoor, and outdoor ponds further highlight the influence of environmental exposure on water quality. Outdoor ponds exhibited greater variability in pH compared with indoor and semi-outdoor ponds. Theoretically, this can be attributed to direct exposure to external factors such as solar radiation, rainfall, and air–water interactions, which affect the chemical dynamics of pond water (Ahmed et al., 2021). This observation is consistent with previous studies reporting higher water quality fluctuations in open ponds than in enclosed or semi-enclosed systems (Li et al., 2020).

Data anomalies, including zero values and occasional pH readings exceeding optimal limits, should not be interpreted as system failures but rather as consequences of technical conditions during data acquisition. Temporary internet connectivity disruptions resulted in incomplete data transmission to the database, while elevated pH readings occurred when the pH sensor was momentarily lifted above the water surface. Similar issues have been reported in prior IoT-based aquaculture monitoring studies, where network reliability and sensor positioning are recognized as critical factors influencing data accuracy (Islam et al., 2021).

In comparison with previous research, the system developed in this study demonstrates performance consistent with ESP8266-based IoT monitoring systems reported by Zhou et al. (2018) and Rahman et al. (2020), particularly in terms of real-time acquisition and online visualization of temperature and pH data. However, the present study extends existing work by evaluating system performance across three different pond environments, thereby providing a more comprehensive assessment of monitoring reliability under varying aquaculture conditions.

From a practical standpoint, the proposed monitoring system has the potential to assist catfish farmers in conducting continuous water quality supervision without relying on repetitive manual measurements. Real-time access to temperature and pH information enables timely corrective actions when deviations from optimal conditions occur, thereby improving pond management efficiency and reducing the risk of production losses. From a theoretical perspective, these findings further support the effectiveness of IoT integration in aquaculture as a foundation for precision farming and data-driven decision-making (Tzounis et al., 2017; Kumar & Rani, 2022).

Despite these contributions, several limitations should be acknowledged. First, the data collection period was relatively short and may not fully represent seasonal variations in water quality. Second, system performance remains dependent on internet connectivity, which can affect data completeness. Third, the monitored parameters were limited to temperature and pH; future studies could incorporate additional indicators such as dissolved oxygen and turbidity to enhance system comprehensiveness.

CONCLUSION

This study successfully designed and implemented an Internet of Things (IoT)–based water quality monitoring system for catfish ponds using an ESP8266 microcontroller, a type-K thermocouple temperature sensor, and an SEN0161 pH sensor. The developed system is capable of performing real-time monitoring of water temperature and pH, storing measurement data in an online database, and continuously presenting the information through a web server.

Experimental evaluation conducted in indoor, semi-outdoor, and outdoor ponds indicates that the measured temperature and pH values generally fall within the recommended ranges for catfish aquaculture. These results confirm that the system provides adequate measurement performance and can reliably represent pond water quality across different cultivation environments.

The primary contribution of this study lies in the implementation of a calibrated IoT-based monitoring system evaluated under multiple pond conditions, offering a more comprehensive assessment of system performance than single-environment testing. From a practical perspective, the system has the potential to assist catfish farmers in conducting continuous water quality supervision, reducing reliance on manual measurements, and enabling faster, data-driven decision making.

Nevertheless, several limitations should be acknowledged. The data collection period was relatively short, and system performance remains dependent on internet connectivity. In addition, the monitored water quality parameters were limited to temperature and pH. Future research is therefore recommended to extend the monitoring duration, enhance communication reliability, and incorporate additional parameters—such as dissolved oxygen and turbidity—to improve the completeness and accuracy of the monitoring system.

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Journal of Electrical Engineering and Informatics (JEEI)
Vol. 1, No. 1, February (2026), pp. 46-54 | p-ISSN: xxxx-xxxx, e-ISSN: xxxx-xxxx
doi: https://doi.org/xxx.xxx

IoT-Based Monitoring of Evaporator Icing and Electrical Current in Precision Air Conditioning

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Article History: *Received: February, 5th 2026; Accepted: February, 26th 2026; Published: February, 28th 2026*

ABSTRACT

Precision Air Conditioning (PAC) systems play a critical role in maintaining thermal stability in telecommunication data centers that operate continuously. One common operational issue in PAC systems is evaporator icing, which can degrade heat transfer performance and compromise system reliability, while electrical current instability may indicate abnormal compressor operation. This study proposes an Internet of Things (IoT)-based monitoring system for real-time observation of evaporator temperature and electrical current as an early detection mechanism for potential faults in precision air conditioning systems. The system was developed using an ESP8266 microcontroller, a DS18B20 temperature sensor, and a PZEM-004T current sensor, with Telegram employed as a remote monitoring interface. Experimental testing was conducted on a precision air conditioning unit under normal operating conditions. The results demonstrate that the DS18B20 sensor provides accurate and consistent temperature measurements, with evaporator temperatures recorded within the normal operating range. Electrical current measurements obtained from the PZEM-004T sensor show close agreement with reference multimeter readings, indicating reliable current monitoring performance. The developed system successfully transmits temperature and current data in real time with stable communication performance. By integrating thermal and electrical parameters within a single IoT-based monitoring framework, the proposed system supports early fault detection and preventive maintenance in PAC systems. This approach enhances operational reliability and provides a practical, low-cost monitoring solution for telecommunication data center cooling applications.

Keywords: *internet of things; precision air conditioning; evaporator temperature monitoring; electrical current monitoring; preventive maintenance*

INTRODUCTION

Precision Air Conditioning (PAC) systems play a critical role in maintaining the thermal stability of telecommunication data centers that operate continuously on a 24-hour basis. Network equipment such as servers, routers, and switches generates substantial heat due to intensive data processing activities, thereby requiring cooling systems with high temperature and humidity stability to ensure reliable operation. Failure of the cooling system may lead to overheating, performance degradation, component damage, and even service downtime, which can significantly affect the continuity of telecommunication services (ASHRAE, 2021; Zhang et al., 2018).

One of the common issues encountered in precision air conditioning systems is the formation of ice on the evaporator surface. This phenomenon is generally caused by disturbances in the refrigeration system, such as improper refrigerant flow, capillary tube blockage, or operation below the recommended temperature range. Evaporator icing inhibits effective heat transfer, resulting in reduced cooling capacity and increased compressor workload, which may accelerate system degradation (Cai et al., 2019; Kim & Braun, 2020). In addition, instability in the electrical current supplying the PAC system directly affects compressor performance and other electrical components, potentially leading to premature system failure over prolonged operation (Saidur et al., 2017).

In practice, monitoring of precision air conditioning systems is still predominantly conducted using conventional approaches, including periodic inspections or built-in system alarms. These methods are limited in their ability to provide real-time information on temperature and electrical current conditions and are generally not accessible remotely. Delayed detection of anomalies may therefore result in more severe system failures before corrective maintenance actions can be implemented (Li et al., 2020).

The advancement of Internet of Things (IoT) technology has enabled the integration of sensors, microcontrollers, and internet connectivity to facilitate real-time and remote monitoring of system conditions. Numerous studies have demonstrated that IoT-based monitoring solutions in electrical and cooling systems can enhance operational efficiency and support data-driven maintenance strategies (Gupta & Johari, 2019; Al Faruque et al., 2016). However, most existing IoT-based air conditioning monitoring studies primarily focus on ambient room temperature measurements, without considering electrical current parameters or evaporator conditions that are directly associated with the risk of icing formation.

Addressing this research gap, this study proposes an IoT-based monitoring system for evaporator temperature and electrical current in precision air conditioning systems as an early detection mechanism for evaporator icing and electrical abnormalities. The proposed system utilizes an ESP8266 microcontroller, a DS18B20 temperature sensor, and a PZEM-004T current sensor, with Telegram employed as the monitoring interface. The developed system is designed to provide real-time, simple, and flexible visualization of temperature and current data, thereby supporting preventive maintenance activities and enhancing the reliability of cooling systems in telecommunication data center environments.

RESEARCH METHODS

This study employs an experimental and system design–implementation approach to develop an Internet of Things (IoT)-based monitoring system for evaporator temperature and electrical current in Precision Air Conditioning (PAC) units. This approach was selected to ensure that the proposed system operates under real conditions, produces measurable outputs, and can be replicated in similar operational environments.

The object of the study is a precision air conditioning system used in telecommunication network facilities. The monitored parameters include evaporator temperature, which serves as an indicator of potential icing formation, and electrical current, which reflects the operational condition of the PAC electrical and compressor systems.

Evaporator Temperature Monitoring in Precision Air Conditioning

Temperature monitoring focuses on the evaporator outlet of the PAC unit, as temperature stability is critical for maintaining reliable cooling performance in network equipment operating continuously. A DS18B20 temperature sensor was selected due to its high accuracy, stability, and wide measurement range (−55 °C to +125 °C), making it suitable for cooling system applications (Zhang et al., 2019).

The sensor is positioned between the evaporator and the expansion valve to obtain temperature readings that accurately represent actual refrigeration system conditions. In this study, operational temperature thresholds are defined based on PAC working characteristics: temperatures below 5 °C indicate a potential risk of evaporator icing, while temperatures exceeding 22 °C suggest reduced cooling effectiveness and a potential risk of equipment overheating.

Electrical Current Monitoring in Precision Air Conditioning

Electrical current monitoring is conducted to evaluate power supply stability and compressor operating conditions in the PAC system. A PZEM-004T current sensor is utilized to measure alternating current in real time, with a measurement capacity of up to 100 A. This sensor has been widely applied in IoT-based energy monitoring systems due to its reliability and measurement accuracy (Saidur et al., 2017).

The current sensor is installed in a plug-and-play configuration on the PAC power input line without modifying the internal electrical configuration of the system. The acquired current data are used to identify abnormal operating conditions, where current fluctuations may indicate excessive load, electrical disturbances, or degradation in compressor performance.

System Design and Implementation

The monitoring system is developed using an ESP8266 microcontroller as the central data processing and communication unit. The DS18B20 temperature sensor is connected to the ESP8266 via a one-wire configuration with a 4.7 kΩ pull-up resistor, while the PZEM-

004T current sensor is interfaced through serial communication. The circuit configurations for the temperature and current sensors are presented in Figure 1 and Figure 2, respectively.

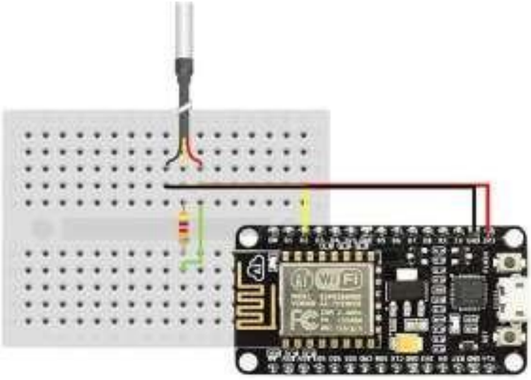

Figure 1. Dallas 18b20 Sensor Circuit

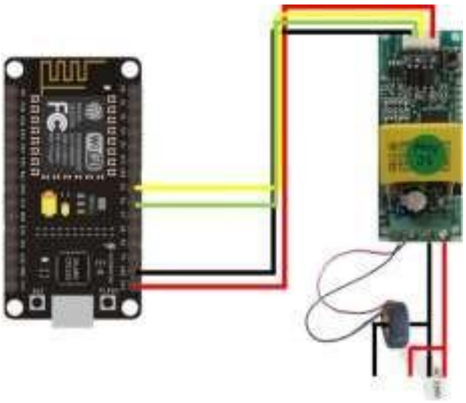

Figure 2. Pzem 004t Sensor Circuit

Measurement data from both sensors are processed by the ESP8266 and transmitted via a WiFi network to the Telegram platform, which serves as the monitoring interface. Telegram is selected due to its ease of access, simple data visualization, and cross-platform compatibility, enabling real-time and remote monitoring without requiring additional dedicated applications.

Sensor Calibration

Calibration of the DS18B20 temperature sensor is performed by comparing sensor readings with a reference thermometer using a water medium at several temperature points. This procedure ensures measurement accuracy and consistency. Temperature values displayed on the Arduino IDE serial monitor are compared with those transmitted to the Telegram interface to verify data integrity during transmission.

Calibration of the PZEM-004T current sensor is carried out by comparing sensor measurements with readings obtained from a digital multimeter under specific electrical load conditions. The measurement deviation is evaluated to ensure that sensor readings remain within acceptable tolerance limits for monitoring applications.

System Testing and Data Analysis

System testing is conducted directly on the precision air conditioning unit under normal operating conditions. The temperature sensor is placed at the evaporator area, while the current sensor is installed on the PAC power input line. Temperature and current data are collected continuously and displayed in real time via the Telegram interface.

Data analysis is performed using a descriptive–comparative approach, in which sensor measurements are compared with reference instrument readings. System performance evaluation includes sensor accuracy, data transmission stability, and the system's capability to provide real-time monitoring information as a basis for early detection of potential faults in precision air conditioning systems.

RESULTS AND DISCUSSION

Results of the IoT-Based Monitoring System

The experimental results indicate that the developed Internet of Things (IoT)-based monitoring system is capable of performing real-time monitoring of evaporator temperature and electrical current in Precision Air Conditioning (PAC) units via the Telegram application. The tests were conducted to evaluate sensor performance, data transmission reliability, and measurement agreement with reference instruments.

Calibration and Testing Results of the DS18B20 Temperature Sensor

Calibration of the DS18B20 temperature sensor was performed by comparing sensor readings with those obtained from a reference thermometer using a water medium. The calibration results show a high level of agreement between the sensor readings and the reference values, with measurement deviations remaining within acceptable tolerance limits.

Temperature values displayed on the Arduino IDE serial monitor and those transmitted to the Telegram interface were identical, indicating that data transmission from the ESP8266 microcontroller to the monitoring interface occurred without value discrepancies.

During operational testing on the PAC unit, the DS18B20 sensor was positioned at the evaporator area. The measured evaporator temperature was within a range of 12 °C, which falls within the normal operating range of the cooling system. Temperature data were displayed continuously and in real time via the Telegram application, enabling direct observation of evaporator temperature conditions during PAC operation.

Calibration and Testing Results of the PZEM-004T Current Sensor

Calibration of the PZEM-004T current sensor was conducted by comparing sensor measurements with those obtained from a digital multimeter under a specific electrical load. When tested using a laptop charger as the load, the PZEM-004T sensor recorded a current value of approximately 0.3 A, which is consistent with the multimeter readings.

Subsequent testing was performed on the PAC unit under normal operating conditions. The PZEM-004T sensor measured the operating current in the range of 4.1–4.2

A, while the multimeter indicated a current value of 4.17 A. The observed measurement difference remained within acceptable tolerance limits, demonstrating that the PZEM-004T sensor is capable of accurately measuring the electrical current of the PAC system.

The measured current data were successfully transmitted and displayed in real time through the Telegram interface without noticeable delays, enabling continuous monitoring of the PAC electrical condition.

Monitoring System Performance and Data Presentation

Based on the experimental results, the communication system involving the sensors, ESP8266 microcontroller, WiFi network, and Telegram platform operated in a stable manner. Temperature and electrical current data were received and displayed consistently throughout the testing period.

The integration of evaporator temperature and electrical current monitoring enables simultaneous observation of two critical operational parameters within a single monitoring system. Data presentation through the Telegram interface provides simple and accessible visualization, allowing monitoring results to be observed directly without the need for additional dedicated software.

Discussions

The experimental results demonstrate that the proposed Internet of Things (IoT)-based monitoring system is capable of reliably monitoring evaporator temperature and electrical current in Precision Air Conditioning (PAC) units in real time. The integration of DS18B20 temperature sensors and PZEM-004T current sensors with the ESP8266 microcontroller and the Telegram interface operated stably throughout the testing period, indicating that the system architecture is suitable for practical deployment in cooling applications.

The measured evaporator temperature remained within a range of approximately 12 °C during PAC operation, indicating normal cooling performance and the absence of conditions conducive to icing formation. From a thermodynamic perspective, excessively low evaporator temperatures promote moisture condensation and subsequent freezing on the evaporator surface, which impedes heat transfer and reduces system efficiency (Cai et al., 2019; Kim & Braun, 2020). Therefore, direct monitoring of evaporator temperature provides a critical early indicator for identifying abnormal operating conditions before icing adversely affects the cooling process.

Electrical current measurements showed average values between 4.1 and 4.2 A, which closely correspond to the multimeter reference measurement of 4.17 A. This agreement confirms that the PZEM-004T sensor accurately represents the operating current of the PAC system. From an electrical engineering standpoint, stable current consumption reflects normal compressor operation and healthy electrical conditions, whereas significant current fluctuations may indicate excessive loading, electrical faults, or component degradation (Saidur et al., 2017).

Compared with previous IoT-based air conditioning monitoring studies, which predominantly focus on ambient room temperature monitoring or general control strategies (Gupta & Johari, 2019; Al Faruque et al., 2016), this study offers an extended contribution by directly monitoring evaporator temperature and incorporating electrical current as an additional diagnostic parameter. This approach aligns with recent research emphasizing the importance of monitoring internal cooling system parameters to enhance system reliability and support preventive maintenance strategies (Li et al., 2020; Zhang et al., 2018).

From a practical perspective, the developed monitoring system can serve as an effective preventive maintenance tool for precision air conditioning systems, particularly in telecommunication data center environments that demand high operational reliability. Real-time visualization of temperature and current data via the Telegram platform enables remote monitoring and facilitates timely maintenance actions when early signs of abnormal operation are detected. From a theoretical standpoint, the findings indicate that integrating thermal and electrical parameters within a unified IoT-based monitoring framework enhances early fault detection capability in precision cooling systems.

Despite these contributions, several limitations should be acknowledged. The proposed system currently monitors only two parameters—evaporator temperature and electrical current—and does not include other potentially influential variables such as refrigerant pressure, humidity, or overall energy consumption. In addition, system testing was conducted on a limited scale and did not encompass long-term performance evaluation under varying operational loads. Future research is therefore recommended to incorporate additional monitoring parameters and to conduct extended testing periods to obtain a more comprehensive assessment of system performance and robustness.

CONCLUSION

Based on the system design, implementation, and experimental evaluation, it can be concluded that the proposed Internet of Things (IoT)-based monitoring system for Precision Air Conditioning (PAC) operates reliably in monitoring evaporator temperature and electrical current in real time. The integration of DS18B20 temperature sensors and PZEM-004T current sensors with the ESP8266 microcontroller and the Telegram interface enables accurate and remotely accessible visualization of PAC operating conditions.

The experimental results indicate that the measured evaporator temperature remains within the normal operating range and that the electrical current measurements are consistent with reference instruments, confirming the reliability of the developed system as a monitoring tool. By integrating thermal and electrical parameters, the proposed system contributes to early detection of potential faults, including evaporator icing and electrical instability, which may adversely affect PAC performance.

From a practical perspective, the developed monitoring system has the potential to support preventive maintenance in telecommunication data center environments that require high reliability and continuous operation. The main limitations of this study are the limited number of monitored parameters and the absence of long-term performance evaluation. Future research is therefore recommended to incorporate additional monitoring variables and to conduct extended operational testing to enhance the comprehensiveness and robustness of the system.

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