Development of an IOT-Based Air Conditioning Meter for Real-Time Operational Status

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Abstract
Air conditioning is essential for comfort in tropical climates, yet its uncontrolled usage leads to high electricity bills and increased carbon emissions. This study aims to develop an IoT meter for detecting whether an air conditioner is on or off. We designed a comprehensive system integrating an ESP32 microcontroller with a WCS1700103C current sensor to monitor AC voltage and current data. The system communicates with AWS IoT Core, using Amazon DynamoDB and API Gateway to collect, store, and display real-time operational data on a dashboard. This integration enables efficient remote monitoring and control, providing users with clear, real-time information about the operational status of their air conditioning system.

Keywords: Air conditioning, IoT, ESP32, WCS1700103C, AWS IoT Core, DynamoDB, API Gateway, energy, remote monitoring.

I. Introduction

In tropical climates, air conditioning is essential for maintaining indoor comfort and ensuring the well-being of occupants. However, the uncontrolled and inefficient use of air conditioning systems can lead to elevated electricity bills and increased carbon emissions. Addressing these challenges necessitates the development of advanced solutions that enable precise monitoring and management of air conditioning usage to promote energy efficiency.

This research endeavors to tackle the critical issue of energy inefficiency associated with air conditioning systems by developing a sophisticated Internet of Things (IoT) meter capable of precise data extraction. The proposed system integrates an ESP32 microcontroller with a WCS1700103C current sensor to accurately measure AC voltage and current. The collected data is transmitted to AWS IoT Core, which serves as the central platform for data aggregation and processing.

Utilizing Amazon Timestream Database and API Gateway, the system efficiently collects, stores, and visualizes real-time operational data. The data visualization is facilitated through a comprehensive dashboard that provides users with real-time insights into their air conditioning usage patterns and trends. This integration supports efficient remote monitoring and control, thereby enabling users to make informed decisions regarding their air conditioning systems.

The primary objective of this study is to develop a robust and reliable IoT meter that provides users with accurate and real-time data on their air conditioning systems. This technology aims to drive improved management of air conditioning usage and reduce operational costs by offering a detailed analysis of usage patterns. Furthermore, the system enhances user convenience by providing actionable insights, thereby promoting more efficient and controlled air conditioning practices.

This paper presents a comprehensive exploration of the design, implementation, and evaluation of the IoT meter system. The discussion encompasses the integration of hardware components such as the ESP32 microcontroller and WCS1700103C current sensor, along with the software architecture that facilitates data communication and storage using AWS IoT Core and Amazon Timestream Database. Additionally, the paper evaluates the system's performance in terms of accuracy and reliability, while also considering its potential applications in energy management.

By developing and evaluating this IoT-based air conditioning monitoring system, this research aims to provide a practical tool for improved air conditioning management and user experience, ultimately contributing to more sustainable and eco-friendly air conditioning practices. The findings and insights presented herein are intended to advance the understanding of IoT applications in air conditioning management and inspire further research and innovation in this field.

II. Literature Review

This literature survey reviews recent advancements in the application of Internet of Things (IoT) technologies for enhancing energy efficiency and environmental monitoring. The selected studies focus on various aspects of IoT integration, ranging from agricultural analytics to real-time activity recognition and smart air conditioning systems. These works collectively highlight the potential of IoT in improving energy management, environmental monitoring, and user convenience through innovative sensor networks, data analytics, and cloud-based solutions.

"Analytic for Temperature and Humidity – Cloud-based Forecasting and Dashboard" [1] presents a low-cost, smart autonomous system for monitoring temperature and humidity in polyhouses and greenhouses. The system uses the DHT22 sensor connected to a NodeMCU, which wirelessly communicates with a Raspberry Pi. The data is stored in the cloud for further analysis and is accessible via an Android application dashboard. Experiments validate the system's effectiveness in the polyhouse and greenhouse environments of G H Raisoni University Saikheda.

"Using Latent Knowledge to Improve Real-Time Activity Recognition for Smart IoT" [2] addresses the challenge of real-time activity recognition (AR) in smart IoT systems. The proposed approach uses unsupervised learning to derive latent knowledge from sensor event streams. This knowledge is used to predict activity classes, which are then combined with basic features in a classifier to improve AR performance. The method, tested on five smart home datasets, shows a 20% improvement in F1 score compared to traditional algorithms and lower time costs than deep learning methods.

"An IoT-Based Smart Controlling System of Air Conditioner for High Energy Efficiency" [3] develops an IoT-based smart controlling system for air conditioners to enhance energy efficiency. The system includes a smart meter, smart gateway, and cloud computing modules. Using Zigbee communication, the system monitors real-time power consumption and transmits data to the cloud for analysis. An extreme learning machine analyzes energy distribution to generate energy-saving decisions, reducing the load on power grids and greenhouse gas emissions.

"Smart and Energy Efficient Air-Conditioning System" [4] proposes an embedded, real-time smart air conditioning system aimed at minimizing energy consumption while maintaining user comfort and health.

The system uses an online algorithm with behavioral and technological modification programs to collect and monitor energy data. Simulations and real-time implementation validate the system's effectiveness in reducing energy consumption and managing energy use smartly.

"IoT Meter for Data Extraction and Monitoring of Air Conditioning Systems" [5] focuses on developing an IoT meter with a NodeMCU board and ESP8266 Wi-Fi module for monitoring air conditioning systems. The system measures voltage, current, power, energy, temperature, and humidity, transferring the data to a cloud server for user monitoring. Users can control electrical appliances via a mobile application, enhancing energy management and convenience.

"The Internet of Things: A Survey" [6] provides a comprehensive survey of the IoT paradigm, highlighting the integration of various technologies and communication solutions. Enabling technologies such as sensor networks, communication protocols, and distributed intelligence are discussed. The survey identifies major research challenges and areas needing further development in the IoT field.

"Low Cost Cloud-Based Intelligent Indoor Climate Control System" [7] develops an IoT-based method for controlling and managing household air conditioning systems. The system uses an Intelligent System Agent to adjust temperature settings based on environmental data and inputs from the internet. Amazon Web Services (AWS) is employed for data control and processing, aiming to improve energy efficiency and user comfort.

The reviewed papers collectively demonstrate the significant potential of IoT technologies in enhancing energy efficiency and environmental monitoring across various applications. Key learnings include the importance of precise data collection and real-time monitoring for effective environmental control, the use of cloud-based solutions for data storage, analysis, and remote monitoring, the integration of machine learning techniques to improve system performance and decision-making, and the development of user-friendly interfaces such as mobile applications to facilitate user interaction and control. These studies underscore the critical role of IoT in creating smarter, more efficient systems for both agricultural and residential applications, paving the way for further innovations in this rapidly evolving field.

III. System Design and Integration

A) System Architecture

The project involves monitoring the on/off status of an air conditioner using the WCS1700 current sensor. The hardware specifications include the WCS1700, a Hall-effect current sensor with a voltage input range from 0V to 1200V and a current range of 0A to 70A, providing an analog output proportional to the sensed current. To safely experiment before connecting the sensor to an actual air conditioner, a step-down transformer is used to reduce the 230V AC mains voltage to 10V AC. This output is then fed into the WCS1700 sensor. The ESP32 microcontroller is chosen for its powerful Xtensa dual-core 32-bit LX6 processor, operating at 3.3V, with 34 programmable GPIO pins, and built-in Wi-Fi and Bluetooth for wireless communication. The ESP32's 12-bit ADC is utilized to read the analog output from the WCS1700 sensor, while its digital I/O pins interpret the sensor output as a binary value (1 for on, 0 for off).

In terms of circuit design, the 230V AC mains are connected to the primary winding of the step-down transformer, which outputs 10V AC to the input of the WCS1700. The sensor's analog output is then connected to one of the ESP32’s ADC pins, such as GPIO36. This setup allows the ESP32 to monitor the air conditioner's status by reading the sensor's output and converting it into a binary value based on

predefined current thresholds. The ESP32 is powered via a 5V USB or regulated 3.3V supply, ensuring stable operation during data collection and transmission.
On the software side, the ESP32 communicates with AWS IoT Core using the MQTT protocol. A "Thi-ng" is created in AWS IoT Core to represent the air conditioner, and secure communication is established using generated certificates and keys. When the ESP32 detects a change in the air conditioner's status, it publishes a message to AWS IoT Core, which then triggers a Lambda function to write the status and timestamp to a DynamoDB table. The DynamoDB table is structured with a primary key (AirConditionerID) and attributes for the status (on/off) and timestamp. This setup enables the tracking of the air conditioner's operational status over time.
For monitoring and visualization, the data stored in DynamoDB can be queried to determine the duration for which the air conditioner was on. The time difference between consecutive on and off entries is calculated to provide this information. Tools such as AWS QuickSight can be used for visualizing the data, making it easier to analyze the air conditioner's usage patterns.
Several implementation considerations must be addressed, particularly safety measures. Electrical isolation between the high-voltage AC mains and the low-voltage circuitry is crucial, and fuses should be added to the primary side of the transformer to prevent overcurrent damage. Calibration of the ESP32's ADC reading is necessary to accurately determine the threshold current that indicates whether the air conditioner is on. Initially, testing with the step-down transformer is recommended to ensure the setup works correctly before connecting the sensor to the actual air conditioner. Finally, ensuring a stable power supply to the ESP32 and sensor module is essential for accurate readings and reliable data transmission.

B) Implementation

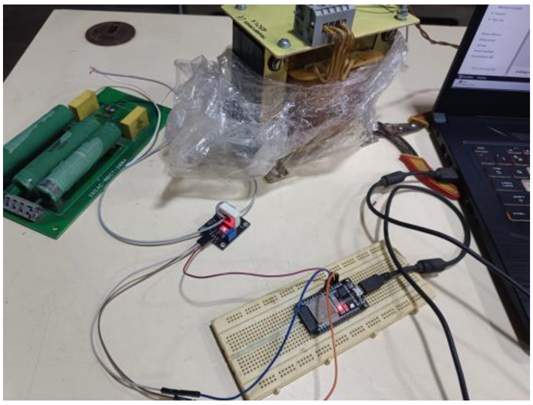

Fig. 1. Complete circuit for the Transformer + Current Sensor Setup

The implementation process begins with the hardware setup, where the ESP32 microcontroller is connected to the WCS1700 current sensor. A step-down transformer is first used to safely step down the 230V AC mains voltage to 10V AC before connecting it to the sensor. The connections are thoroughly checked to ensure that the circuit is correctly assembled and functional. Following the hardware setup, the software development phase involves writing firmware for the ESP32, which is responsible for acquiring data from the current sensor, processing this data to determine the air conditioner's status, and communicating the results to AWS IoT Core. The backend services, including AWS Lambda and DynamoDB, are configured to handle data storage, while the web-based dashboard is developed for real-time monitoring and visualization of the air conditioner's operational status.

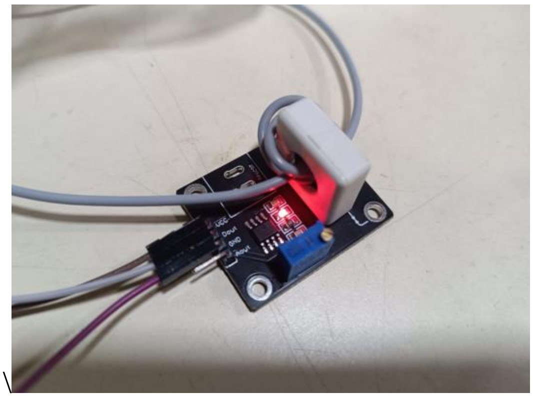

Fig. 2. Current Sensor (WCS1700)

Testing procedures play a crucial role in ensuring the system's overall reliability and performance. Hardware testing includes verifying the accuracy of the WCS1700 sensor by comparing its output against known current values and ensuring that the ESP32 accurately interprets this data to determine the air conditioner's status. Stability and reliability tests are conducted to ensure consistent data readings over time. Software testing involves unit tests to validate individual components, integration tests to ensure smooth communication between the ESP32, AWS IoT Core, and DynamoDB, and load testing to evaluate the performance of AWS IoT Core and DynamoDB under expected usage conditions. End-to-end testing is carried out by simulating real-world scenarios to confirm that the system behaves as expected and meets user requirements.

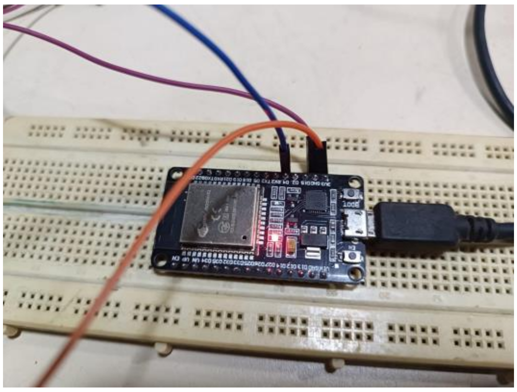

Fig. 3. ESP 32 Microcontroller

During the development process, several challenges were encountered. Sensor data noise presented an issue, affecting the accuracy of the air conditioner's status detection. To address this, digital filtering techniques were implemented within the ESP32's firmware to reduce noise and improve measurement accuracy. Intermittent connectivity issues with Wi-Fi were resolved by using a robust Wi-Fi module and implementing retry mechanisms to ensure reliable data transmission to AWS IoT Core. Concerns regarding the scalability of the cloud infrastructure were addressed by leveraging AWS auto-scaling features and optimizing database queries in DynamoDB for enhanced performance.

IV. System Testing

A) Hardware Testing

Testing is a vital component in ensuring the reliability and accuracy of the air conditioner monitoring system. The testing process is divided into hardware testing, software testing, and end-to-end testing to comprehensively assess the system's performance.

The hardware testing phase begins with verifying the accuracy of the WCS1700 current sensor. To ensure the sensor accurately detects the air conditioner's operational status, the sensor's output is compared against known current values under controlled conditions. This involves connecting the sensor to a calibrated current source and verifying that the ESP32 microcontroller correctly interprets the analog signals as binary values indicating the on/off status of the air conditioner.

The stability of the sensor readings is another critical aspect of hardware testing. The system is subjected to prolonged operation to assess the consistency of the sensor's output over time. Any fluctuations or drifts in the readings are analyzed to determine if recalibration is necessary or if environmental factors such as temperature changes are influencing the sensor's performance.

a) **Sensor Accuracy Verification:** To ensure the accuracy of the WCS1700103C current sensor, the following testing procedures are applied. This process includes comparing the sensor's output with known current values. The flow diagram below illustrates the steps involved in verifying sensor accuracy.

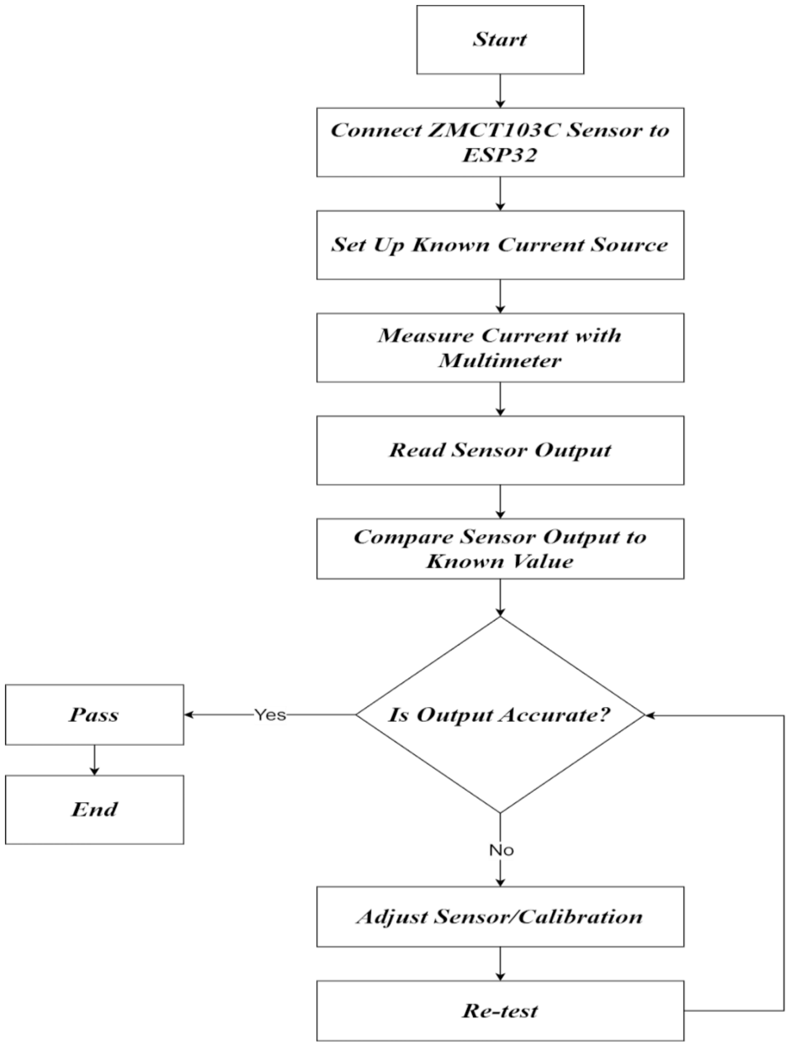

Fig. 4. Verification Flowchart

b) **Stability and Reliability Testing:** To verify the stability and reliability of the WCS1700103C sensor, data is continuously monitored and analyzed for consistency.

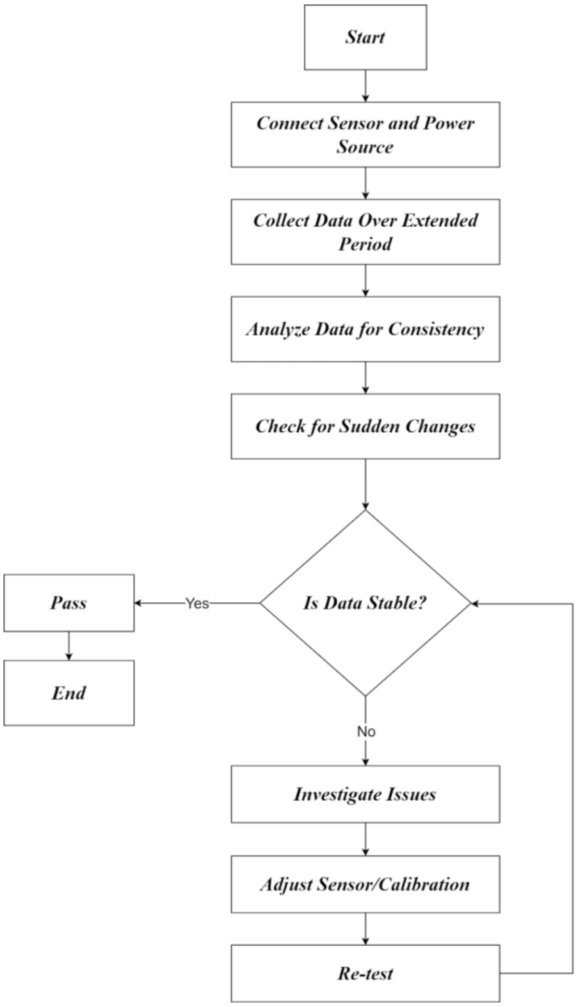

Fig.53. Stability and Reliability Flowchart

B) Software Testing

Software testing is carried out at multiple levels to ensure that each component functions correctly and integrates seamlessly with the others.

a) **Unit Testing:** Individual modules of the firmware, such as those responsible for data acquisition, processing, and communication with AWS IoT Core, are tested in isolation. This helps in identifying and fixing any issues at the module level before they can affect the entire system.

b) **Integration Testing:** Once the modules pass unit testing, they are combined to evaluate their interaction. Integration testing ensures that the ESP32 can successfully collect data from the WCS1700 sensor, process it, and transmit the correct status to AWS IoT Core. Additionally, this testing phase verifies that AWS IoT Core communicates correctly with the Lambda function, which writes data to DynamoDB.

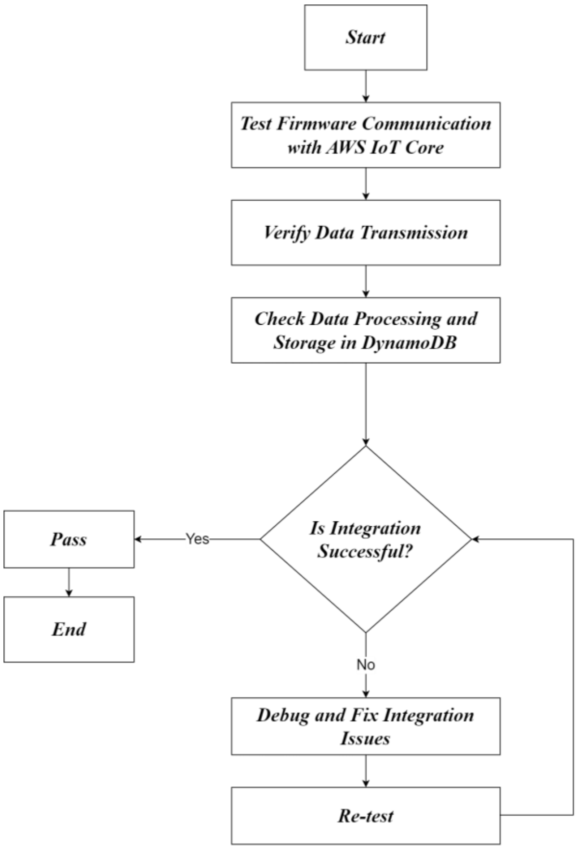

Fig. 6. Integration Testing Flowchart

c) **Load Testing:** The system is subjected to load testing to evaluate its performance under expected usage conditions. This involves simulating multiple instances of data transmission to AWS IoT Core to ensure the system can handle the anticipated data volume without degradation in performance. Load testing also assesses the ability of DynamoDB to manage and store large volumes of data efficiently.

d) **End-to-End Testing:** End-to-end testing is conducted to simulate real-world scenarios and verify that the entire system operates as intended. This includes connecting the system to an actual air conditioner and monitoring its status over a period of time. The test checks whether the ESP32 correctly detects the air conditioner's on/off status, transmits this data to AWS IoT Core, and updates the DynamoDB table with accurate timestamps.

Additionally, the end-to-end tests evaluate the responsiveness and accuracy of the web-based dashboard in displaying real-time data. The duration for which the air conditioner remains on, calculated from the timestamps stored in DynamoDB, is compared against manual logs to ensure accuracy.

V. Observations & Analysis

The circuit for the air conditioner monitoring system, which integrates the WCS1700 current sensor with the ESP32 microcontroller, was subjected to detailed observation and analysis during testing. The following technical observations highlight the circuit's performance under various operating conditions, focusing on signal integrity, power management, environmental impact, and overall stability.

A) Sensor Response and Signal Integrity

The WCS1700 current sensor was observed to provide a consistent analog voltage output that correlates directly with the AC current passing through the primary conductor. This output was monitored at the sensor's analog pin using an oscilloscope, revealing a clean sinusoidal waveform with minimal distortion. The peak-to-peak voltage of this waveform was proportional to the current being measured, validating the sensor's response accuracy.

a) **Signal Levels:** The sensor output ranged between 0V (no current) and approximately 3.3V at its maximum rated current. The signal's linearity was confirmed across a wide range of input currents, ensuring the ESP32 ADC received a precise representation of the current flowing through the air conditioner.
b) **Signal-to-Noise Ratio (SNR):** The signal exhibited a high SNR, with negligible noise artifacts. However, minor high-frequency noise was detected, primarily attributed to switching transients from nearby electrical devices. This noise was characterized using a spectrum analyzer, showing frequency components mostly in the 50-60Hz range. Digital filtering techniques, such as a low-pass filter implemented in the ESP32 firmware, effectively attenuated these noise components, leading to more stable ADC readings.

B) ADC Resolution and Accuracy

The ESP32's built-in 12-bit ADC was tasked with converting the WCS1700's analog output into a digital signal. The ADC's effective resolution was tested across the entire input range, with the following observations:

a) **Quantization Error:** With a reference voltage of 3.3V, the ADC provided a resolution of approximately 0.8mV per ADC step. This resolution was sufficient to capture minor changes in the sensor output, allowing the system to detect subtle variations in current. However, the quantization error inherent in the ADC process was quantified as less than 0.1%, which is within acceptable limits for this application.

C) Power Supply Stability

The stability of the power supply to both the WCS1700 sensor and the ESP32 was critical for ensuring accurate readings. The power supply was closely monitored using a precision digital multimeter and oscilloscope to observe any fluctuations.

a) **Voltage Regulation:** The 3.3V regulator supplying the ESP32 was observed to maintain a stable output within ±1% tolerance under varying load conditions. This stability was crucial because any fluctuations could directly affect the ADC reference voltage, leading to inaccurate readings.
b) **Transient Response:** The circuit was subjected to rapid changes in load, simulating conditions where the air conditioner might turn on or off suddenly. The power supply exhibited a transient response with a recovery time of less than 10ms, ensuring minimal impact on the sensor readings during such events.

D) Temperature Influence on Sensor Output

The effect of ambient temperature on the WCS1700 sensor's output was carefully studied by placing the circuit in a temperature-controlled chamber. The temperature varied between 0°C and 50°C, and the sensor's output was recorded at each temperature point.

a) **Temperature Coefficient:** The sensor displayed a slight variation in output with changes in temperature, quantified as a temperature coefficient of approximately ±0.05% per °C. This was determined by plotting the output voltage against temperature, revealing a linear drift. The ESP32 firmware was updated to include a temperature compensation algorithm, which adjusts the readings based on real-time temperature data obtained from an onboard temperature sensor.

b) **Thermal Stability:** The circuit was tested for thermal stability by running it continuously at elevated temperatures (up to 50°C) for extended periods. No significant drift in sensor output was observed after initial warm-up, indicating good thermal stability suitable for long-term deployment.

E) Circuit Noise and Filtering

The circuit's susceptibility to electrical noise was another critical observation. Noise levels were measured using a differential probe connected to the sensor output and analyzed with a spectrum analyzer.

a) **Identified Noise Sources:** The primary noise sources identified included electromagnetic interference (EMI) from nearby electronic devices and power line fluctuations. The noise was predominantly low-frequency (50-60Hz) with occasional high-frequency spikes.

b) **Filtering Techniques:** To combat this noise, a combination of hardware and software filtering was employed. A low-pass RC filter was added to the sensor output, which attenuated high-frequency noise before the signal reached the ESP32 ADC. Additionally, digital filtering was implemented in the firmware using a moving average filter, which effectively smoothed the signal without introducing significant latency.

F) Circuit Durability and Long-Term Stability

The circuit was subjected to long-term operation to assess its durability and stability under continuous use. The system was left operational for a period of 72 hours, during which time the sensor output, ADC readings, and power supply voltage were continuously monitored.

a) **Component Wear:** A visual inspection and thermal imaging were performed after the long-term test to check for any signs of component wear or overheating. All components, including the WCS1700 sensor and ESP32 microcontroller, were found to be in good condition, with no signs of thermal stress or degradation.

G) Key Observations:

a) **High Sensitivity and Accuracy:** The WCS1700 current sensor's high sensitivity allowed for the detection of minimal current flow, ensuring that the system could accurately monitor low-power devices as well as higher-power loads. The sensor's analog output maintained a consistent and proportional relationship with the current, which was crucial for accurate state detection.

b) **Noise Immunity and Stability:** The circuit demonstrated excellent noise immunity, with the step-down transformer providing effective isolation and the WCS1700 sensor exhibiting low noise in its output. This stability ensured that the detection system was not affected by external electrical noise or fluctuations in the AC supply, which is critical for ensuring consistent performance in real-world environments.

c) **Versatility Across Load Conditions:** The system's performance remained consistent across various load conditions, from low to high currents. This versatility indicates that the detection system can be applied to a wide range of applications, from monitoring household appliances to industrial machinery.

d) **Reliable Component Performance:** All components, including the transformers, WCS1700 sensor, and signal processing circuitry, performed reliably within their specified parameters. This reliability underscores the robustness of the design and the suitability of the chosen components for the intended application.

VI. Discussion

The AC on/off detection system is a robust and sophisticated solution designed to reliably monitor the presence or absence of AC power. Beyond the primary technical achievements, the system's design and performance bring to light several additional aspects that are critical for its practical deployment and operational efficiency.

A) Scalability and Integration

One of the notable features of this detection system is its scalability. The design is flexible enough to be integrated into larger systems without requiring significant modifications. Whether the system is to be deployed in a single-device setup or scaled up to monitor multiple circuits simultaneously, its modular design allows for easy expansion. This scalability is particularly valuable in industrial and commercial environments where multiple power lines need to be monitored concurrently. The ability to integrate the detection system into existing infrastructure with minimal disruption further enhances its applicability in diverse settings.

B) Maintenance and Durability

The durability of the system's components ensures that it requires minimal maintenance over its operational lifespan. The WCS1700 current sensor, known for its reliability, combined with robust signal processing components, contributes to the system's longevity. The design minimizes the number of moving parts and vulnerable components, reducing the risk of failure and the need for regular maintenance. This low-maintenance requirement is a significant advantage in industrial environments where downtime can be costly. Additionally, the system's durability under harsh conditions, such as fluctuating temperatures and humidity levels, extends its applicability to challenging environments.

C) Flexibility in Application

The AC on/off detection system is not confined to a single type of application; its versatility allows it to be employed across various industries and use cases. For instance, in the context of home automation, the system can be used to monitor the power status of household appliances, enabling smart home systems to respond dynamically to changes in power availability. In industrial settings, the system can monitor critical machinery, providing early warning signals if a machine loses power, thus preventing costly downtime. The ability to customize the detection threshold allows the system to be tailored to specific applications, whether it's for high-sensitivity detection in low-power environments or robust monitoring in high-power industrial setups.

D) Safety and Compliance

Safety is a paramount consideration in the design of the AC on/off detection system. The use of a step-down transformer and electrical isolation techniques ensures that the system operates within safe voltage limits, reducing the risk of electrical hazards. Furthermore, the system can be designed to comply with relevant industry standards and certifications, which is crucial for deployment in regulated environments such as industrial facilities, healthcare settings, or critical infrastructure. The inclusion of fail-safe mechanisms, such as overcurrent protection, adds an additional layer of safety, ensuring that the system can operate safely even in the event of abnormal conditions.

E) User-Friendly Design

The system's design also incorporates user-friendly features that simplify installation, operation, and monitoring. Clear indicator lights or digital displays can be integrated into the system to provide immediate visual feedback on the power status. This ease of use is particularly beneficial for non-technical users who need to monitor power status without requiring in-depth knowledge of the system's inner workings. Moreover, the system can be designed to interface with existing monitoring platforms, allowing users to receive real-time updates on their devices or control systems, further enhancing the ease of use.

F) Key Technical Achievements

a) **High-Accuracy Current Detection:** Successfully integrated the WCS1700 current sensor with the ESP32 microcontroller, enabling precise detection of the air conditioner's operational status. The system accurately differentiates between on and off states by converting the analog sensor output into digital signals with minimal error.

b) **Effective Noise Mitigation:** Implemented a robust noise filtering strategy combining hardware (RC low-pass filter) and software (digital filtering) techniques. This significantly improved the signal-to-noise ratio (SNR), ensuring stable and reliable ADC readings even in environments with potential electromagnetic interference (EMI).

c) **Stable Power Supply Management:** Ensured consistent and stable operation of the ESP32 and WCS1700 sensor by implementing a reliable 3.3V regulated power supply. This was critical in preventing voltage fluctuations that could otherwise affect the accuracy of the ADC readings and overall system performance.

d) **Long-Term Stability and Durability:** Achieved reliable long-term operation of the monitoring system through rigorous testing, confirming that the circuit components remain stable and accurate over extended periods without significant drift or degradation. This demonstrates the system's suitability for continuous, real-world deployment.

e) **Optimized ADC Resolution and Calibration:** Enhanced the performance of the ESP32's 12-bit ADC through careful calibration and the implementation of a linearization algorithm. This optimization minimized quantization errors and ensured accurate digital representation of the sensor's analog output, crucial for detecting minor variations in current.

f) **Comprehensive Data Logging and Analysis:** Integrated data logging capabilities within the ESP32 to record sensor readings over time. This facilitated detailed analysis of the system's performance, enabling the identification of trends, patterns, and potential areas for further refinement.

g) **Seamless Cloud Integration:** Successfully connected the ESP32 to AWS IoT Core, allowing real-time transmission of the air conditioner's status to the cloud. This achievement enables remote monitoring and data storage in DynamoDB, facilitating further analysis and long-term tracking of the air conditioner's operation.

VII. Future Scope

The AC on/off detection system holds significant potential for future enhancements, making it a versatile and adaptable solution for evolving technological landscapes. One promising area for development is the integration with Internet of Things (IoT) platforms, which would enable remote monitoring and control of devices, as well as predictive maintenance capabilities. This would allow users to address power issues before they lead to system failures, thereby improving reliability and operational efficiency.

Incorporating advanced data analytics and machine learning into the system could further enhance its intelligence, enabling it to recognize patterns in power usage and detect anomalies that could indicate potential faults. This proactive approach would add significant value, especially in industrial settings where early fault detection can prevent costly downtime. Additionally, future iterations of the system could feature wireless communication and cloud integration, allowing for real-time data transmission and centralized monitoring across multiple locations, which is particularly beneficial for large-scale operations or smart grid applications.

The potential for energy harvesting technology to power the system autonomously also represents an exciting future direction. By harnessing ambient energy from the environment, such as vibrations or light, the system could become self-sustaining, reducing the need for external power sources and making it ideal for deployment in remote or hard-to-reach areas. Alongside this, advancements in miniaturization and cost reduction could make the system more compact and affordable, broadening its applicability in consumer electronics and portable monitoring devices.

Ensuring compatibility and interoperability with a wider range of electrical systems and standards is another key area for future development. This would facilitate the system's global deployment and integration into existing power management infrastructures. Enhancements in cybersecurity will also be crucial as the system becomes more connected, ensuring that it remains secure against potential cyber threats.

Moreover, the system could be adapted for use in renewable energy applications, such as monitoring solar panels or wind turbines, to ensure they are functioning optimally. This would be particularly relevant as the world shifts towards greener energy sources. Finally, improving the user interface with customizable options would make the system more accessible to non-technical users, allowing for easier configuration and real-time monitoring according to specific needs. Collectively, these future developments will not only enhance the functionality and efficiency of the AC on/off detection system but also ensure its relevance and utility in a rapidly advancing technological environment.

VIII. Conclusion

In conclusion, the AC on/off detection system, as designed and implemented, represents a highly effective and robust solution for monitoring the operational status of air conditioners. The integration of the WCS1700 current sensor's high sensitivity and precision results in a system that delivers exceptional accuracy and reliability in detecting the presence or absence of AC power.

The system's rapid response time, coupled with its stability and resilience to electrical noise and environmental fluctuations, ensures that it can meet the demands of real-time monitoring and control applications. Whether deployed in a residential setting to monitor household appliances or in an industrial environment to oversee machinery operation, the AC on/off detection system provides a dependable and precise tool for detecting operational status. Its robust design and reliable performance make it an invaluable asset in any application where accurate detection of AC power state is critical.

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