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A Low-Cost MQTT-Based IoT Framework for Real-Time Monitoring of Battery Energy Storage Systems

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***Abstract*—Electricity consumption continues to increase in line with population growth and the rising demand for energy. However, this trend is inversely proportional to the availability of electrical energy resources, particularly those supporting clean energy. One of the renewable energy sources is solar power generation, which utilizes solar radiation. In practice, solar power systems cannot operate optimally under cloudy conditions or during nighttime. Therefore, a Battery Energy Storage System (BESS) plays a crucial role in providing a reliable and continuous energy supply over a certain period. In addition, BESS requires proper monitoring to assess its operational condition. This study presents the development of an IoT-based real-time monitoring system for BESS using the MQTT communication protocol. An ESP32 module is employed as the internet gateway (publisher), while a cloud-based compute engine functions as the subscriber. The proposed system enables real-time monitoring of key parameters, including voltage, current, power, temperature, as well as battery charging and discharging states, which are stored and visualized in a cloud database. The results demonstrate that the developed prototype is capable of publishing and subscribing energy storage data effectively, with a sensor accuracy error of approximately 1%. The overall system achieves an average response time of 1.41 seconds, indicating reliable real-time performance.**

***Keywords*— Battery Energy Storage System; Internet of Things; MQTT; Cloud Computing; Real-Time Monitoring.**

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I. INTRODUCTION

Electricity utilization continues to increase in line with population growth and the rising demand for energy. However, this condition is inversely proportional to the availability of energy resources worldwide, particularly clean energy sources [1]. Population growth also drives economic development and advancements in information technology, including increased internet usage, which contributes to an annual rise in electricity consumption of approximately 6% [2]. Therefore, efforts to reduce dependence on fossil energy, which has negative environmental impacts, are necessary. One such effort is the development of renewable energy sources, such as Solar Power Plants (PLTS).

In practice, PLTS has several limitations, including the relatively low efficiency of photovoltaic modules, which is around 16%, resulting in high installation costs per kW [3]. In addition, solar energy cannot be utilized optimally during cloudy conditions or at night [4]. Consequently, an energy storage system is required to provide a reliable and continuous power supply over a certain period, namely the Battery Energy Storage System (BESS) [3].

Based on existing literature, battery monitoring, particularly during charging and discharging processes, is essential to obtain an accurate state of charge, thereby preventing premature battery degradation [5]. Previous studies have shown that IoT-based battery monitoring systems generally consist of communication channels between devices, data acquisition algorithms, cloud systems, and a Human Machine Interface (HMI) accessible via desktop or mobile devices [6]. Furthermore, cloud-based monitoring systems enable real-time and accurate observation of battery conditions, as well as battery health analysis using high-performance computing [7].

In this study, a performance monitoring system for a Battery Energy Storage System (BESS) is developed using an IoT-based approach with the MQTT communication protocol. The system utilizes Google Cloud Platform (GCP) as the server infrastructure, with a compute engine for data processing and CloudSQL as the database, integrated with phpMyAdmin for data visualization and export by users.

The developed system is integrated with an off-grid solar power system, where battery performance parameters are measured using sensors and transmitted by a microcontroller acting as a publisher to a cloud server functioning as a subscriber via the Internet (IoT). The solar module converts solar energy into electrical energy during sunlight exposure. This electrical energy is then transferred to the battery and stored as chemical energy. During the charging process, electrical energy is stored in the battery cells, while during discharging, the stored chemical energy is converted back into electrical energy [8]. An inverter is used to convert DC (Direct Current) voltage into AC (Alternating Current) so that it can be utilized by electrical loads [10], while a charge controller regulates the charging process and automatically stops the current flow when the battery is fully charged [9].

The BESS monitoring prototype is developed using INA219, PZEM004T, and DS18B20 sensors, integrated with an ESP32 microcontroller as the internet gateway equipped with a built-in WiFi module [11][12][13].

This paper is organized as follows. Section 1 presents the introduction, Section 2 describes the design and modelling of the BESS monitoring system using the MQTT broker, Section 3 discusses the functional testing and performance evaluation, and Section 4 concludes the study. This study contributes by developing a low-cost IoT-based monitoring system integrated with cloud computing that provides real-time performance analysis with low latency and high accuracy.

II. METHODOLOGY AND SYSTEM DESIGN

A. System Block Diagram

The proposed IoT-based Battery Energy Storage System (BESS) monitoring system utilizes the MQTT communication protocol. The system receives input energy from an off-grid solar power system, generating DC voltage, current, and power, which are measured using sensors. The acquired data are processed by an ESP32 microcontroller acting as a publisher and transmitted to a cloud platform, where they are stored in a CloudSQL database. The overall system consists of both hardware and software components. The system architecture is illustrated in Figure 1.

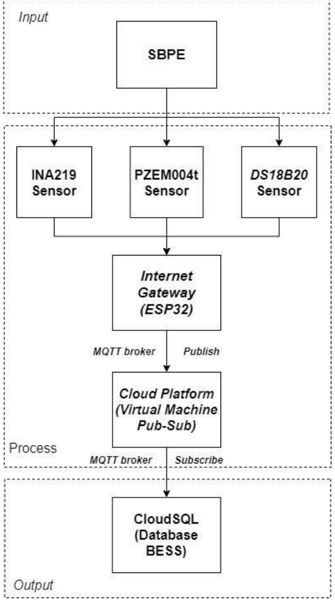

Figure 1. Block diagram system.

In Figure 1, SBPE refers to the Solar Battery Power Ecosystem, which consists of the photovoltaic module, charge controller, battery energy storage system, inverter, and monitoring components integrated into the proposed framework.

B. Hardware Design

The BESS is powered by a solar panel system, where the generated electrical energy is regulated by a solar charge controller to manage battery charging. An inverter is used to convert DC voltage into AC voltage for load applications.

Electrical parameters, including voltage, current, and power, are measured using the INA219 sensor for DC and the PZEM004T sensor for AC. In addition, the DS18B20 sensor is used to measure battery temperature. All sensors operate at 5 V supplied through an LM2596 voltage regulator module. The hardware design is shown in Figure 2.

The INA219 sensor is a high-side current and voltage monitoring module capable of measuring DC voltage up to 26 V and current through a shunt resistor with high accuracy. In this study, INA219 is used to monitor battery charging parameters, including DC voltage, current, and power.

The PZEM004T sensor is designed for AC electrical parameter measurement and can monitor voltage, current, power, energy consumption, frequency, and power factor. In the proposed system, the sensor is installed on the inverter output side to evaluate battery discharging performance through AC load measurements.

The DS18B20 is a digital temperature sensor with a measurement range of −55°C to 125°C and a typical accuracy of ±0.5°C. The sensor is attached to the battery surface to monitor thermal conditions during charging and discharging operations.

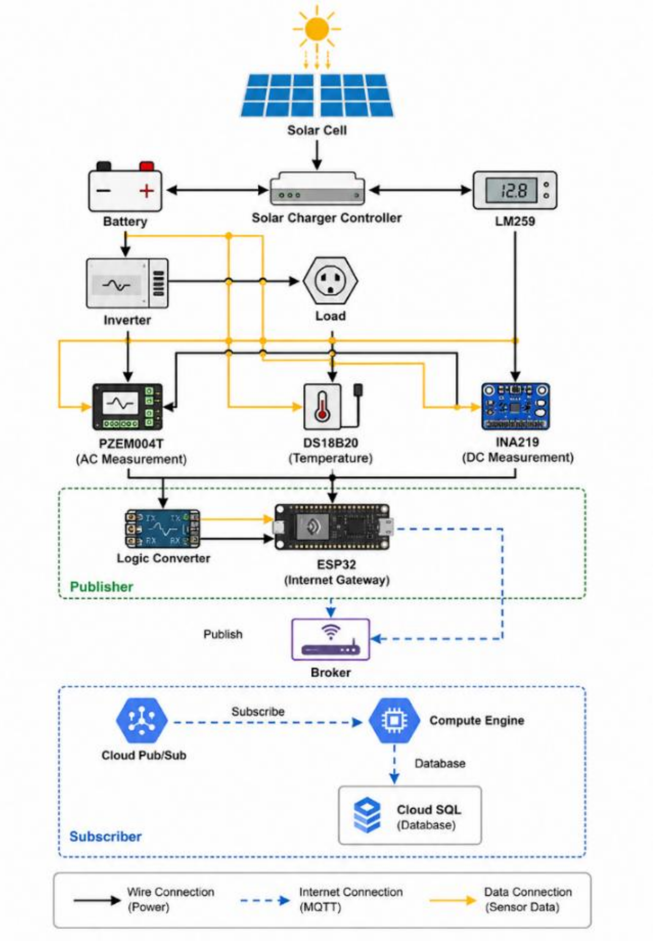

Figure 2. Hardware design.

C. Software Design

The ESP32 microcontroller functions as an internet gateway and is programmed using Arduino IDE in C language. It connects the sensors (INA219, PZEM004T, and DS18B20) to the cloud platform using the MQTT publish–subscribe mechanism. The collected data are stored in a CloudSQL database.

The system allows users to access monitoring data via a cloud platform. Users can activate the system through Secure Shell (SSH) on a virtual machine and access the database via phpMyAdmin. The monitored parameters include battery input voltage (Vin), current (Iin), power (Pin), output voltage (Vout), current (Iout), power (Pout), and temperature.

Data transmission is carried out through a publisher–subscriber mechanism, where sensor data are published by the ESP32 and subscribed by the cloud-based compute engine using MQTT. The software design is presented in Figure 3.

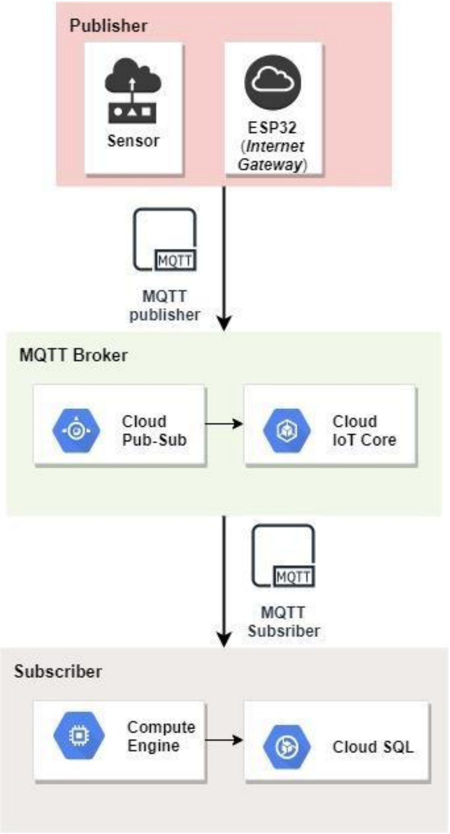

Figure 3. Software design.

III. RESULT AND DISCUSSION

A. Implementation

The implementation of the system consists of three main parts: the solar panel switch system, the BESS monitoring system, and the load as a testing parameter. The overall hardware implementation is shown in Figure 4.

The solar panel system supplies energy to the battery through a charge controller, while the inverter converts DC power into AC for the load. The sensing modules, ESP32 microcontroller, voltage regulator, and communication interfaces were integrated into a single monitoring platform. Sensor data acquired from the charging and discharging processes were processed by the ESP32 and transmitted to the cloud server using the MQTT publish–subscribe mechanism. The cloud platform then stored and visualized the data for real-time monitoring purposes.

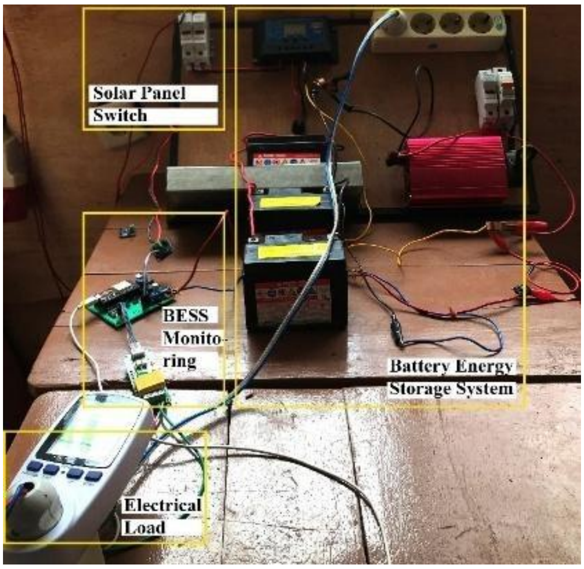

Figure 4. Proposed system.

The software implementation involves programming the ESP32 using Arduino IDE. The program includes libraries for generating JSON Web Tokens (JWT), configuring MQTT security on Google Cloud Platform (GCP), establishing MQTT communication, and publishing sensor data.

Data transmission is performed by sending sensor data from the ESP32 (publisher) to a cloud-based virtual machine via MQTT. The compute engine acts as a subscriber, receiving and processing the data before storing them in the CloudSQL database.

B. Testing

The system testing focuses on monitoring battery performance during charging and discharging processes, including voltage, current, power, and temperature measurements. Three types of tests were conducted: INA219 sensor for charging (DC measurement), PZEM004T sensor for discharging (AC measurement), andDS18B20 sensor for temperature monitoring. The software performance was evaluated based on system response time, including data transmission from the ESP32 (publisher), MQTT broker processing (subscriber), and data storage in the cloud database.

1) Charging Analysis: The charging process is shown in Figure 5. The results indicate fluctuations in voltage and current due to variations in solar irradiance. The maximum input voltage from the solar panel is approximately 18 V DC. The sensor demonstrates good linearity with an error value below 1%, indicating high measurement accuracy. Minor differences are mainly caused by the limitations and specifications of the measuring instruments.

2) Discharging Analysis: The discharging characteristics are presented in Figure 6. The measured voltage ranges from 180 V to 219 V with a relatively linear trend. The current ranges from 0.1 A to 0.3 A and is relatively small due to the characteristics of AC systems designed for transmission efficiency.

3) Temperature Analysis: The temperature monitoring results are shown in Figure 7 The average temperature during charging is 28.66°C, while during discharging it is 26.58°C, with an error below 1%. A slightly higher temperature during charging is observed due to higher current flow compared to the discharging process. This indicates stable battery operation under both conditions.

4) ESP32 Response Time: The response time between the sensor and ESP32 is shown in Figure 8, with an average value of 71.95 ms. The fluctuations are influenced by CPU usage on the cloud platform.

5) MQTT Broker Response Time:The MQTT broker response time is presented in Figure 9, with an average value of 239 ms. This delay represents the time required for data subscription and storage in the database.

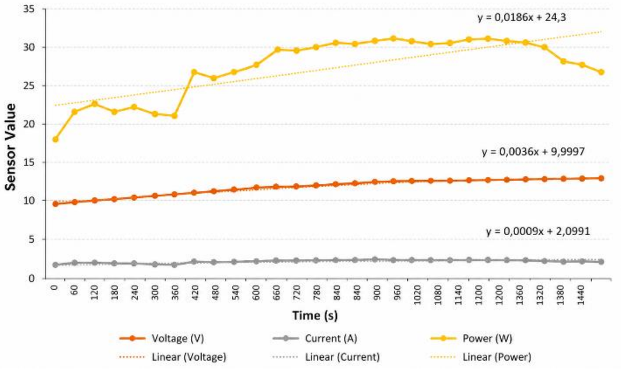

Figure 5. Charging process.

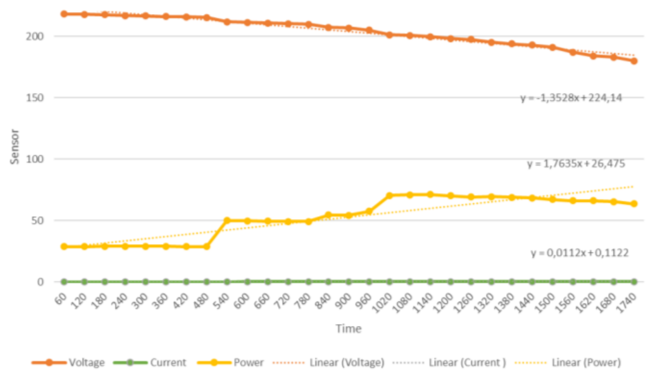

Figure 6. Discharging process.

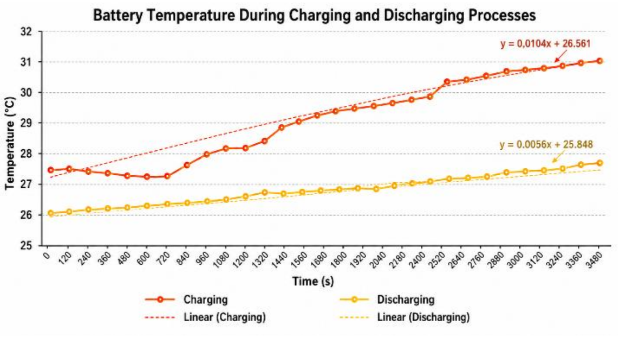

Figure 7. Temperature monitoring.

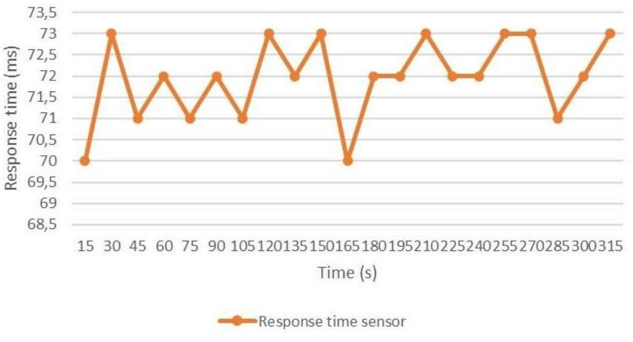

Figure 8. ESP response time.

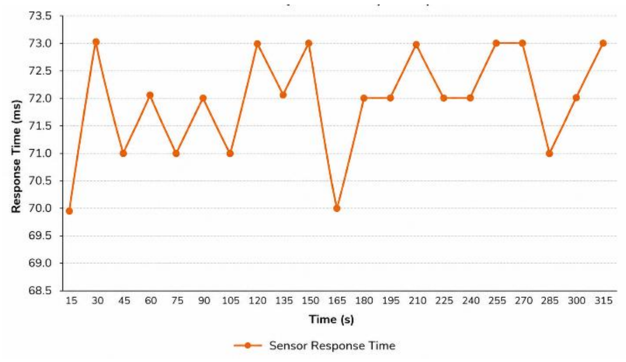

Figure 9. MQTT broker response time.

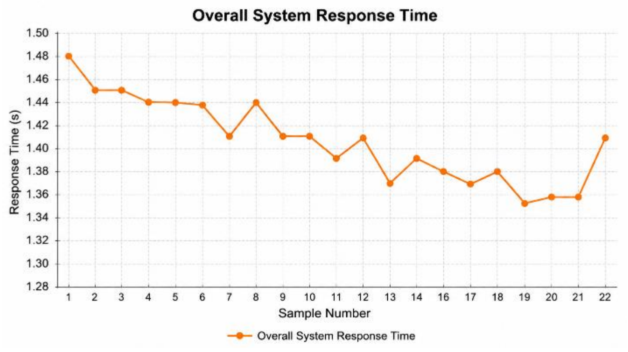

Figure 10. Overall system response time from data acquisition to cloud database storage.

6) Overall System Response Time: The overall system response time, from data acquisition to storage in the cloud database, is illustrated in Figure 10. The average delay between data publishing and storage is 1.41 seconds. The variation in response time is influenced by network conditions and CPU usage on the cloud server. Despite these variations, the system demonstrates reliable real-time performance for monitoring applications

IV. CONCLUSIONS

This study presents the development of an IoT-based monitoring system for Battery Energy Storage Systems (BESS) using the MQTT communication protocol. The proposed system integrates INA219, PZEM004T, and DS18B20 sensors with an ESP32 microcontroller to measure and monitor electrical parameters and battery temperature during charging and discharging processes.

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