Towards Sustainable Energy Storage: A Low-Cost IoT Solution for Real-time Monitoring of Lead-Acid Battery Health

Hacia el almacenamiento de energía sostenible: una solución de IoT de bajo costo para el monitoreo en tiempo real del estado de las baterías de plomo-ácido

Rumo ao armazenamento de energia sustentável: uma solução IoT de baixo custo para monitoramento em tempo real da saúde da bateria de chumbo-ácido

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Summary. - This research article introduces a microcontroller-based prototype system called the Battery Health Monitoring System (BHMS), designed to evaluate the health and condition of lead-acid batteries. The focus of the study is on utilizing the Internet of Things (IoT) for real-time battery monitoring. The system incorporates various sensors to track and record critical parameters such as current, voltage, power drain, state of charge (SOC), temperature, and overall battery health. These sensors are configured to trigger an alert when any monitored parameters fall below predefined values. The study aims to validate the effectiveness of the proposed low-cost system in real-time monitoring of lead-acid batteries.

Keywords: Lead-acid battery, Temperature, IoT, ESP8266.

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Resumen. - *Este artículo de investigación presenta un sistema prototipo basado en microcontrolador llamado Sistema de monitoreo del estado de la batería (BHMS), diseñado para evaluar la salud y el estado de las baterías de plomo-ácido. El objetivo del estudio es utilizar el Internet de las cosas (IoT) para monitorear la batería en tiempo real. El sistema incorpora varios sensores para rastrear y registrar parámetros críticos como corriente, voltaje, consumo de energía, estado de carga (SOC), temperatura y estado general de la batería. Estos sensores están configurados para activar una alerta cuando algún parámetro monitoreado cae por debajo de los valores predefinidos. El estudio tiene como objetivo validar la eficacia del sistema de bajo coste propuesto en el seguimiento en tiempo real de baterías de plomo-ácido.*

Palabras clave: *Batería de plomo-ácido, Temperatura, IoT, ESP8266.*

Resumo. - *Este artigo de pesquisa apresenta um protótipo de sistema baseado em microcontrolador denominado Battery Health Monitoring System (BHMS), projetado para avaliar a saúde e a condição de baterias de chumbo-ácido. O foco do estudo está na utilização da Internet das Coisas (IoT) para monitoramento da bateria em tempo real. O sistema incorpora vários sensores para rastrear e registrar parâmetros críticos, como corrente, tensão, consumo de energia, estado de carga (SOC), temperatura e integridade geral da bateria. Esses sensores são configurados para disparar um alerta quando algum parâmetro monitorado cair abaixo dos valores predefinidos. O estudo visa validar a eficácia do sistema de baixo custo proposto no monitoramento em tempo real de baterias de chumbo-ácido.*

Palavras-chave: *Bateria de chumbo-ácido, Temperatura, IoT, ESP8266.*

1. Introduction. - Batteries are critical in various applications, including automotive, renewable energy, and telecommunication systems [1]. The failure of batteries can lead to significant consequences, including power outages, equipment damage, and economic losses. Therefore, it is essential to monitor the health of batteries in real time to ensure their optimal performance and prevent failure. Figure I show the market demand for lead acid batteries in the general market.

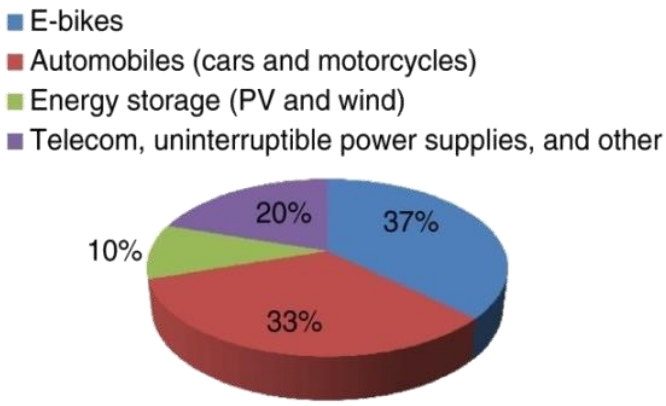

Figure I. Market Distribution of Lead Acid Battery[2]

In lead-acid batteries, State of Charge (SOC), describes how charged the battery is right now about its maximum capacity [3]. Usually, it is stated as a percentage, where 100% denotes a fully charged battery and 0% denotes a fully discharged battery. For the battery to operate at its best and last as long as possible, it is imperative to monitor its state of charge (SOC). A typical formula for calculating a 12V lead-acid battery's SOC can be written as;

$$\text{SoC}= \frac{Remaining\ Capacity}{full\ charge\ capacity\ (Temperature,\ \ Present\ charge\ or\ discharge\ rate)} \qquad \text{Eq (1)}$$

The opposite of the SOC, the State of Discharge (SOD) in lead-acid batteries indicates how much of the battery's capacity has been utilized.

$$\text{SOD}=100\%-\text{SOC} \qquad \text{Eq (2)}$$

With the advent of the Internet of Things (IoT) [4-5], battery health monitoring systems can now be designed and implemented at low costs with increased efficiency.

This research paper focuses on designing and implementing a low-cost battery health monitoring system using IoT for real-time monitoring of lead-acid batteries. Since lead acid batteries have high reliability and low maintenance requirements, they are widely used in various applications. The major issue with lead-acid batteries is the problem of sulfation [6], water loss, and corrosión. Careful monitoring of these batteries is required to prevent failure and enhance lifespan. In this article, we proposed the battery health monitoring system consists of IoT based system that collects data from various sensors attached to the lead-acid batteries. The sensors are responsible for calculating the parameters like temperature, voltage, current, and electrolyte level, to provide the status of the battery's health. Collected data is then transmitted to the IoT platform for real-time monitoring and analysis.
In the proposed system, we have used all the components that are easily available in the market to reduce cost. Even the IoT platform (ThinkSpeak) is used as open-source software. The real-time monitoring features of the system allow users to recognize possible battery problems and take preventative measures before damage is done.

2. Literature Review.- Lead acid batteries are one of the essential power sources that are extensively used in various industries, these industries include automotive, telecommunications, power generation, distribution, etc [7]. Hence it is important to have an effective battery system. The problem with lead acid batteries is rated to their cost (expensive), and their continuous usage may cause performance degradation. There is also a recycling process issue with the lead acid batteries which cause damage to the environment [8]. As a result, it is important to keep vigilant in the management and handling of lead acid batteries to minimize adverse effects and increase their lifespan.

There has been a lot of research work done in the field of monitoring the health of lead-acid batteries. Extensive work is presently related to the battery management systems (BMS) required for lead acid batteries. Authors in [9] demonstrate how to calculate the state of charge (SoC) and introduce the concept of the battery management system (BMS) that is used for systems like uninterruptible power supplies (UPS), hybrid electric vehicles (HEVs), and electric cars (EVs). No concept of real-time monitoring was present in this research work. The work on the accuracy of battery monitoring circuits for portable communication devices is proposed in [10]. However, this system's accuracy is subject to debate because when all the parameters are considered, it produces an error margin of up to 10%. Working on parameters like temperature, voltage, current, and SoC was done in [11] with the analysis of battery discharging parameters. This research provided the key importance of monitoring all batteries in a battery bank to keep the ideal operating levels and circumstances. Discussion and development tendencies of electric vehicle (EV) batteries were done in [12], in these articles author emphasizes the importance of the BMS in both electric and hybrid vehicles. This study describes how BMS features including cell balancing, charge management, and state monitoring are combined to guarantee dependable and safe battery operation. However, again in this work, real real-time monitoring feature was not included. In [13], the authors address the present issues with BMS and emphasize the significance of assessing a battery's condition, including its longevity, health, and charge. Through an examination of the most recent methods for battery condition evaluation, it also addresses upcoming issues and possible fixes for BMS.

Today's electric vehicles prefer lithium-ion (Li-ion) batteries for energy storage due to their high energy density, strong output, extended lifespan, low self-discharge rate, and lack of memory effect [14]. However, a well-designed BMS is crucial to ensuring safety, dependability, performance optimization, and cost-effectiveness while lowering manufacturing complexity and weight [15]. Table 1 represents the guide for the common battery used worldwide.

The transfer of data between controllers and sensors has led to the development of wireless Battery Management Systems (WBMSs). These systems alleviate wiring issues and allow for more flexible placement of battery modules. Utilizing 5G or 4G networks [16-18] along with an IoT gateway, WBMSs employ IoT protocols (such as those in energy management systems or converters) to directly connect with cloud support servers for tasks like fault diagnostics and battery state monitoring.

	PROS	CONS	COMMON APPLICATION
LEAD ACID	Rechargable, Extremely Common, High Power Density, Durable, Wide Temperature Range	Low Energy Density, Very Heavy, Large in Size	High Current Demand Applications, Car Batteries, Large Scale Battery Banks
ALKALINE	Extremely Common, Cheap, Decent Power Density, Low cost	Susceptible to Natural Rupture, Generally Non-Rechargable, Short Lifetime	Non-Rechargable Consumer Electronics, Flashlights, Toys, Household Items
NICKEL-METAL HYDRIDE	High Current Ability, Less Susceptible to Memory Issues, Lower Cost	Short Storage Life, Susceptible to Overcharge	Power Tools, RC Airplanes and Drones, Portable Systems
LITHIUM ION	Very High Energy Density, Limited Memory Effect, Long Life, Low Maintenance, Rechargable	High cost, Vunerable to Stress (and Exploding!), Require Lots of Protection	Space Constrained Products, Weight Constrained Products, Cell Phones, IoT Devices, Electronic Watches

Table I. Pros and cons of common battery

In this paper, an IoT-based prototype model for real-time lead acid battery monitoring is provided. The objective is accomplished by taking into account variables like temperature, voltage, current, power, and SOC, which are the indicators of the battery's state of health. It is important to note that the proposed prototype is designed to accommodate various capacities of 12V lead acid batteries, allowing versatility in its application.

3. Proposed system model.- The proposed system monitors the voltage, current, power utilized, state of charge (SoC), health, and temperature of a lead-acid battery. The gathered data is sent to the IoT platform Thingspeak using the ESP8266 [19] module, which is programmed with Arduino software. Arduino [20] is used to store and handle the data generated by sensors. A voltage division circuit is used with an ACS712 sensor [21] to measure the voltage; it divides the 12V from the lead-acid battery into 8.7V and 3.3V, with the 3.3V input going to the ESP8266 module.

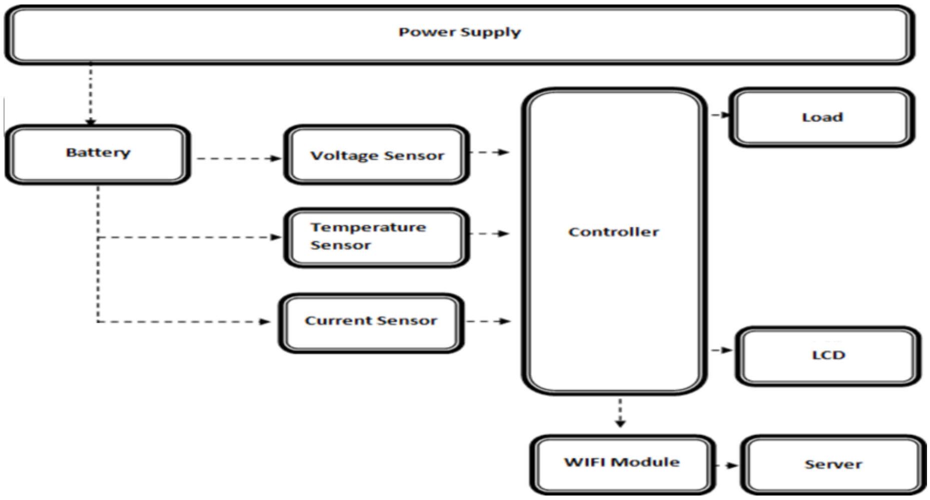

Figure II. System Block Diagram

The battery's voltage can be converted to a percentage to calculate the State of Charge (SoC). Since it is difficult to measure the battery's interior temperature, the external temperature is instead monitored. A DHT 11 sensor [22] is used for this. Thingspeak is used to monitor all of these characteristics, and updates are made in real-time every 15 seconds. This proposed system can be put in remote locations, reducing the need for periodic power management system maintenance. To achieve the claimed functionality, the component used in the proposed system model can be seen in Figure III.

Figure III. Components for the prototype model

The voltage method used in this proposed prototype uses voltage analysis rather than current measurements to indirectly derive the State of Charge (SoC). Thingspeak provides temperature, current, voltage, battery health, and state of charge (SoC) data of the battery in a graphical format, facilitating remote monitoring via an IoT platform. In this model, the load attached to the battery is a 12V DC fan.

4. Results.- After installing the Arduino software, the libraries for the DHT 11 sensor, ZMPT101B, ACS712, and ESP8266 were downloaded. The coding for the proposed system model was completed using the Arduino software, incorporating mathematical formulas to determine the SOC% from voltage data. Additionally, the calculation of power utilized was performed using the formula provided in equation (3).

$$\text{Power} = \text{Voltage} \times \text{Current} \qquad \text{Eq (3)}$$

The ESP8266 transmits all the sensor data to Thingspeak, an IoT platform, for monitoring. When there is a change in battery current and voltage due to the load of a 12V DC fan, these changes can be observed in the graphs.

Figure IV. Battery Charge Status.

Figure IV shows that battery charge status, readings were recorded at 10-minute intervals from 13:37 to 13:47. The state of charge (SOC) indicates that 75% of the battery's charge remains when no load is connected. At 13:40, a 12V DC fan was used as a load, causing the SOC graph to drop. Once the charge in the battery drops to 55%, the charging circuit activates and increases the SOC to 98%. When the battery reaches this charge level, the charging stops, resulting in a constant SOC graph as the DC fan is switched off at this time. After 1 minute, the fan switches on again, causing the SOC to drop from 98%. Figure V shows the change in voltage due to the resistive load. Notably, when the voltage level drops to 10V at 21:10, the battery starts charging and remains in charging mode until it reaches 11.6V. The variation in voltage drop is due to the DC fan speed, which consumes more current, as shown in Figure VI.

Our proposed system works perfectly and matches the theoretical results of power utilization in mW with the simulation results obtained from Figures V and VI, as seen in Figure VII.

Figure V. Change in battery voltage concerning the resistive load.

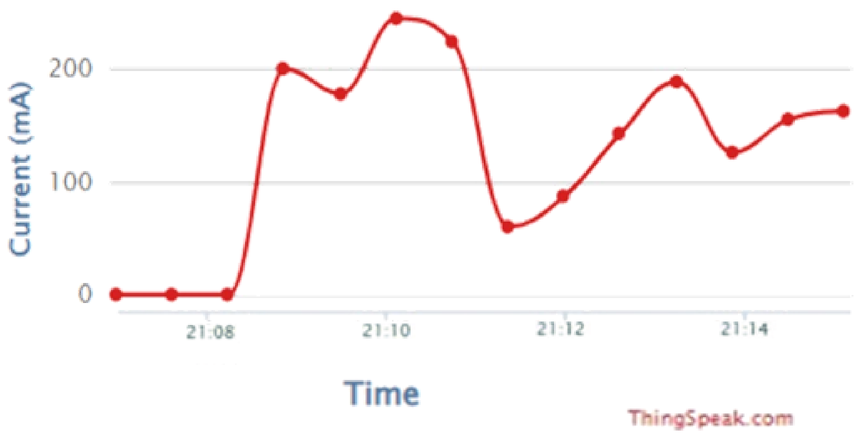

Figure VI. Change in battery Current concerning the resistive load.

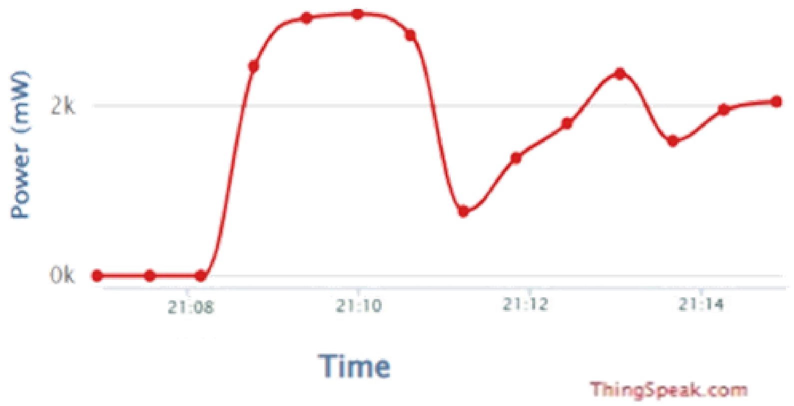

Figure VII. Power is drawn from the battery.

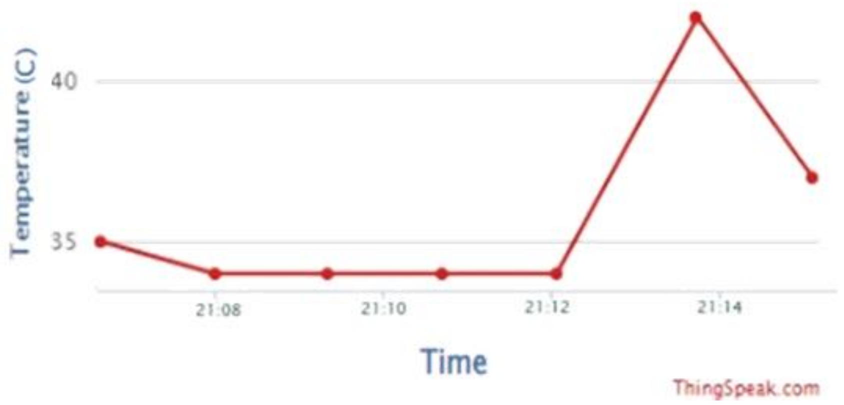

Figure VIII. Change in battery surface temperature due to change in current.

Figure VIII illustrates the variation in the surface temperature of the battery during charging and discharging. This temperature change results from fluctuations in the temperature of the acid inside the battery that stores the charges. Additionally, as the temperature rises, the battery's health deteriorates, as depicted in Figure IX. The battery's health is determined using the formula provided in equation (4).

$$\text{SoH} = \frac{full\ charge\ capacity\ (25C,\ \ Design\ Capacity\ charge\ or\ discarge\ rate)}{Design\ Capacity} \qquad \text{Eq (4)}$$

Figure IX. Change in battery health.

There were some limitations encountered while testing this proposed system. One of the main challenges was synchronizing data with the cloud. Additionally, obtaining a clear graph during variations in DC fan speed proved difficult. The room temperature also affected the monitoring of the battery's surface temperature during charging and discharging.

5. Conclusion.- Monitoring battery health is crucial for lead-acid batteries, and with the rise of wireless technology, IoT has become a widely utilized feature in this prototype model. This functionality allows users to monitor lead-acid battery parameters remotely and at any time. The proposed system model consists of basic components readily available in local markets, and sensor coding to interface with the microcontroller is easily accessible online. Results obtained from the model include State of Charge (SoC), voltage, current, power drained, surface temperature, and battery health.

It's important to note that the performance of the proposed system may vary among different brands of lead-acid batteries due to their unique discharge signatures. A notable aspect of the system is a 15-second delay before data is uploaded to the cloud. It should be acknowledged that the system's accuracy may be compromised when dealing with series and parallel combinations of batteries in power banks, as its optimization is geared toward single batteries. Additionally, incorporating control features could be considered for future enhancements to this proposed system.

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Nota contribución de los autores:

1. Concepción y diseño del estudio
2. Adquisición de datos
3. Análisis de datos
4. Discusión de los resultados
5. Redacción del manuscrito
6. Aprobación de la versión final del manuscrito

SUR ha contribuido en: 1, 2, 3, 4 y 5.
HM ha contribuido en: 5 y 6.
MAS ha contribuido en: 5 y 6.
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