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Design and Implementation of a Real-Time Health Monitoring System for Lithium-Ion Batteries

Journal of Electrical Systems

Abstract: - This paper presents the design and implementation of a real-time health monitoring system specifically focused on the safety and performance of Li-ion batteries. The system accurately monitors key parameters such as the State of Charge (SOC) and temperature, which are critical for ensuring safety during charging and discharging operations. The monitoring system utilizes a resource-efficient IoT microcontroller, the STM32, making it suitable for applications with constrained processing and power capabilities. The current integrating method, also known as Coulomb counting, is employed to track the SOC. This method effectively measures the descent or growth of SOC based on the energy transfer to or from the battery. Furthermore, the paper details the methodology for processing sensor data, including voltage, current, and temperature readings, by leveraging the MATLAB-SIMULINK toolbox for accurate analysis and visualization. The experimental results, discussed in detail in the results section, demonstrate promising outcomes, confirming the effectiveness and reliability of the proposed system. This real-time monitoring approach enhances battery safety and also contributes to the development of more efficient battery management systems for future applications.

Keywords: Lithium-ion battery, Electric Vehicle, Battery Management System, State-of-Charge

1. Introduction

Lithium-ion (Li-ion) batteries have become the preferred choice for various applications due to their high energy density, long cycle life, and ability to maximize power output while extending battery lifespan. Compared to traditional battery technologies such as Nickel Metal Hydride (NiMH), Li-ion batteries offer superior performance in terms of both energy capacity and longevity, making them highly popular, especially in electric vehicles (EVs) and portable electronics increasingly rely on Li-ion batteries, proper management and accurate estimation of key battery states, such as the State of Charge (SOC) and temperature are essential to improving performance and ensuring safety **[1].** Accurate SOC estimation is critical to maximizing the utility of Li-ion batteries and preventing hazardous conditions that can arise during charging or discharging. The Battery Management system (BMS) plays a vital role in monitoring battery health, safety, and reliability. Key parameters such as SOC and temperature are essential for the BMS to ensure efficient and safe operation. The SOC reflects the remaining capacity of the battery, representing its ability to store and deliver energy in comparison to its fully charged capacity. Studies show that even in idle conditions, a battery's capacity decays over time due to internal aging processes, which can significantly affect performance and safety. Once a Li-ion battery charge fade below 20% in its nominal capacity, it is often considered unreliable, underscoring the importance of accurate SOC estimation to prevent critical failures and inform timely battery replacements **[2].** Several methods have been proposed in the literature for SOC estimation **[3].** One common and cost-effective technique is the Open Circuit Voltage (OCV)-based method, which establishes a relationship between the SOC and the battery's output voltage in an open-circuit state. Despite its simplicity, this method has notations. For instance, obtaining an accurate OCV measurement while the battery is in operation is challenging, and Li-ion batteries require long relaxation periods to accurately determine OCV after disconnection. Additionally, the OCV method is highly sensitive to aging process, further reducing its reliability for long-term applications. An alternative method for SOC estimation is Coulomb counting, which calculates SOC based on the net energy transferred to and from the battery over time [**4].**

This research presents an experimental implementation of a highly efficient battery health and safety monitoring system using the advanced STM32 microcontroller. Specifically, the STM32F411RE, a 32-bit microcontroller featuring a 100 MHz ARM Cortex-M4 core, 512 KB of Flash memory, 128 KB of SRAM, along with various digital and analog peripherals, ADC, communication interfaces, timers, and low-power modes. STM32

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microcontrollers are known for their strong performance in edge computing, offering a balance of processing power and low energy consumption for real-time, low-latency data processing. Their integration in edge devices facilitates on-device computation, analysis, and data preprocessing, enhancing system performance in applications such as IoT, industrial automation, and sensor networks. MATLAB-SIMULINK toolbox was employed for data processing and visualization

2. Materials and methods

The following sections provide a detailed explanation of the materials and methods used in this experimental research. Section 2.1 outlines the block diagram of the experimental setup, while Section 2.2 covers the method used for SOC (State of Charge) calculation. Section 2.3 explains the data processing flowchart and procedure.

2.1 Block diagram

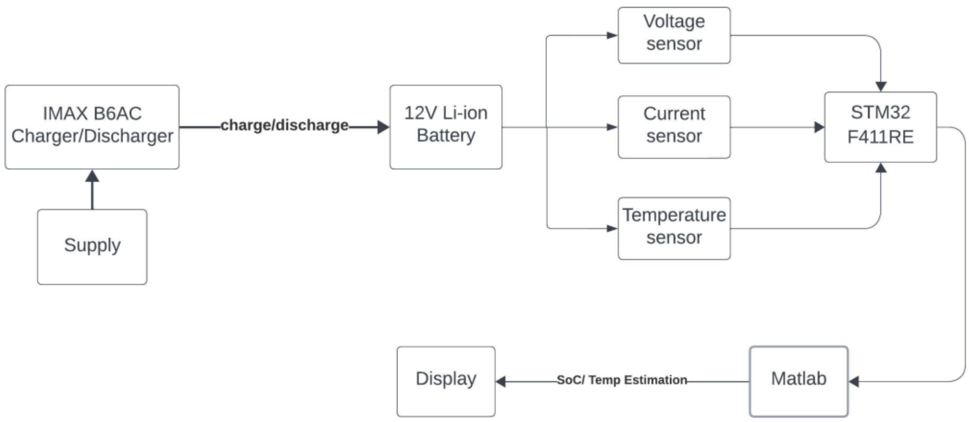

Figure -1. System Block diagram

The above block diagram [Figure-1] depicts the experimental setup we have created for this research work. We have used a Lithium-ion battery with a voltage rating of 12 volts and a capacity of 20 Ah. The DOD (depth of discharge) is up to 100%, so it can discharge more power than other batteries. For getting an output of 12V, nine lithium-ion cells each of 3.7V with 2.2Ah capacity are arranged in 3S-SP configuration by means of spot welding. For charging and discharging the battery pack we have used iMAX B6AC, a versatile battery charger and balancer for various rechargeable battery types. The iMAX-B6AC can charge and discharge NiMH, NiCd, Pb, LiPo, Li-ion, and Li-Fe batteries with individual cell balancing for up to 6 lithium cells. It features a built-in adapter that can be powered from 100–240 VAC, or it can alternatively be powered via an 11–18 VDC input. The adapter has versatile charging capabilities and advanced features like input power monitoring, cyclic charging, and discharging. The sensors used are the Current sensor, voltage sensor and temperature sensor.

As a current sensor, we have used ACS712ELC-05BA sensor designed to measure and monitor electrical current up to 30 amperes. The device consists of a precise, low-offset, linear Hall circuit with a copper conduction path located near the surface of the die. Applied current flowing through this copper conduction path generates a magnetic field which the Hall IC converts into a proportional voltage. Here a voltage divider is used as a voltage sensor by creating a circuit with two resistors in series to divide the input voltage down to a level that can be safely measured by a microcontroller. Thermistor, NTC type was used for temperature sensing. NTC (Negative Temperature Coefficient) thermistors are temperature-sensitive resistors that decrease the resistance as the temperature increases. When placed in a circuit, they change their resistance based on the surrounding temperature, providing a signal that can be interpreted to determine the temperature. The microcontroller we used was STM32 MCU Nucleo board F411RE. The STM32F411RE is a 32-bit microcontroller with a 100 MHz ARM Cortex-M4 core, 512 KB Flash memory, 128 KB SRAM, various digital and analog peripherals, ADC, communication interfaces, timers, low-power modes, and support for development tools. It is an Arduinocompatible STMicroelectronics board. It offers a powerful and flexible platform for prototyping and developing various applications using STM32F411REmicrocontrollers.

2.2. Method for calculating SOC

SOC is the ratio of the available charge capacity (also called capacity) of the battery (Qcurrent) to the capacity of a fully charged battery (QFC) expressed in percentage **[5]**

$$SOC = \frac{Q_{current}}{Q_{FC}} \qquad \text{Equation – (1)}$$

SOC is an indication of the available charge in the battery at each moment. If the initial SOC is known, SOC at any instant can be estimated from the current drawn from the battery as follows

$$SOC_t = SOC_{t0} - \frac{\int_{t0}^{t} \eta \, I_{L} d_t}{Q_{FC}} \qquad \text{Equation – (2)}$$

where I_L is the load current and η is the coulombic efficiency which is defined as the ratio of the charge delivered during discharge and the charge stored during previous recharge.If there are no significant unwanted parasitic reactions in a Li-ion cell and the electrodes show no significant mechanical degradation, then the coulombic efficiency can be assumed as unity.

In electric vehicles (EVs), the state of charge (SOC) of lithium-ion batteries is crucial for determining how much driving range is available. By maintaining the SOC within optimal levels, the battery's lifespan can be extended which ensures consistent performance over time. Under ideal conditions, a 100% SOC indicates a fully charged battery whereas a 0% SOC indicates a fully discharged battery as shown in **Figure-2.**

The most common method for calculating SOC is Open Circuit Voltage (OCV)Method. The OCV curve represents the relationship between battery voltage and SOC for a specific battery chemistry and temperature. Using the OCV method, the battery voltage is measured when it is at rest (no charge or discharge current flowing). However, during charging/discharging, voltage translation cannot be used to estimate SOC, since beyond a particular range of voltage, relation between SOC and voltage is non-linear as shown in **Figure-2**.

On the other hand, Coulomb counting directly measures the charge/discharge current flowing into/out of the battery, providing real-time information about the amount of charge stored or consumed. Hence accurate values of SOC is obtained. Hence, we have employed the Coulomb counting method for estimating SOC in this research work

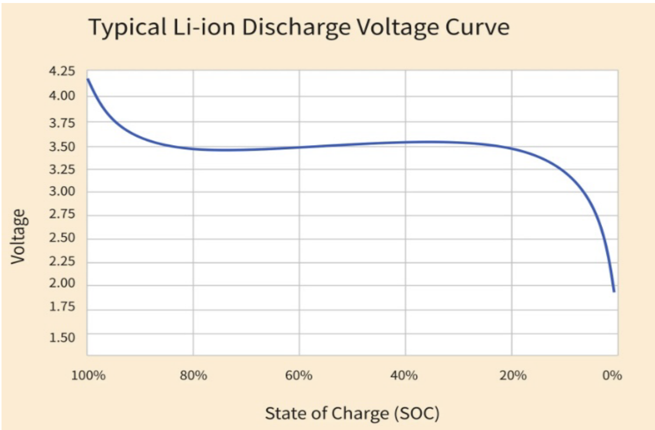

Figure 2: Voltage vs SOC

2.3 Experimental Setup and Implementation Procedure

Figure -3 illustrates the experimental setup, and the detailed specifications of the components and tools used for implementation, along with the procedures followed, are described in the subsections below.

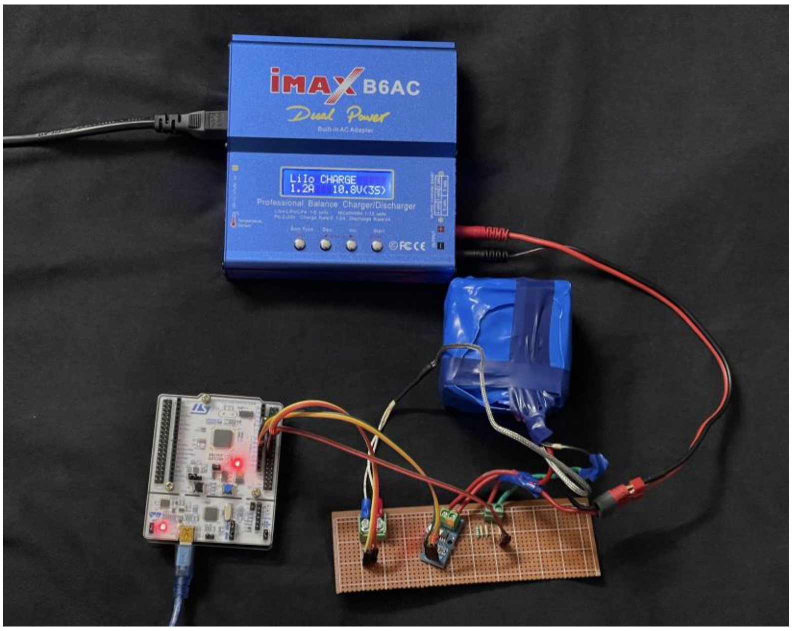

Figure 3: Experimental setup

- **Charging/Discharging of Li-ion Battery**

Plug the lithium-ion battery into the iMAX-B6 charger, ensuring correct polarity. Initiate the charging process. The charger will follow the charging phases (CC, CV) automatically. The charger should automatically stop charging when the battery reaches the set voltage or when a certain amount of time has elapsed. For discharging Connect a suitable load or iMAX-B6 charger/ discharger to the battery output. Initiate the discharging process. Monitor the charger display for real-time information. The charger should automatically stop discharging when the battery reaches the set voltage or when a certain amount of time has elapsed.

- **Current, Voltage and Temperature Sensors**

To measure current, voltage, and temperature, an ACS712 30A current sensor module is connected in series with the battery to sense the current. This sensor requires calibration, which is done by passing a 1A current through it, resulting in a reading of 0.038. For voltage measurement, the voltage across the battery terminals is monitored. A voltage divider circuit, consisting of two resistors in series, is used to reduce the input voltage to a safe level for the microcontroller to measure. An NTC-type thermistor is employed as the temperature sensor, positioned near the battery to monitor its temperature.

- **STM32 Microcontroller**

The STM32 Nucleo F411RE(Figure-4) is built around the STM32F411RE MCU, which belongs to the ARM Cortex-M4 family. It operates at a clock frequency of up to 100 MHz.It typically has 512 KB of Flash memory and 128 KB of RAM, providing sufficient resources for a wide range of embedded applications. The Nucleo board includes an ST-Link debugger/programmer, allowing for easy programming and debugging of the STM32.To log the data connect the output of the current, voltage and temperature sensors to the corresponding analog input pins on the STM32. The analog values are converted into digital values using STM. The values are then transferred to MATLAB environment, which are obtained in the range of 0-1. These values are then multiplied by the gain to obtain the actual values of current/voltage.

- **STM-MATLAB interface**

Installed the STM32 support package from the Add-Ons Explorer within MATLAB. Connection of STM32F411RE Nucleo board to computer is done using a USB cable. Create a new Simulink model. From the Simulink Library Browser, the necessary blocks are dragged and dropped onto the model to configure the communication with the STM32F411RE board. The parameters of STM32 blocks are configured according to the requirements. The blocks are connected to define the flow of data and control between the STM32 board and other components of the system. After the model is ready, initiation is done to generate the code for the STM32F411RE board. Then, the code is deployed to the board using the appropriate options in Simulink. After deploying the code, the Simulink model is run. MATLAB then communicates with the STM32F411RE board and executes the specified tasks. The behavior of the battery is analyzed by visualizing the data collected from STM which includes current, voltage, temperature and SOC variations in real time. Using the Simulink model as described in the below section

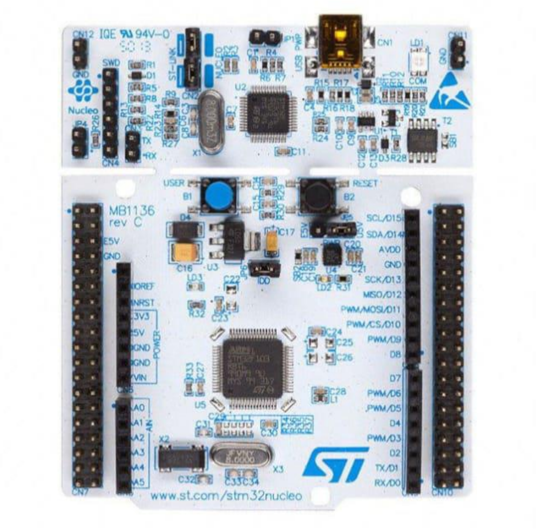

Figure 4: STM32 F411RE MCU Nucleo board

- **Data Processing Flow Chart and Procedure**

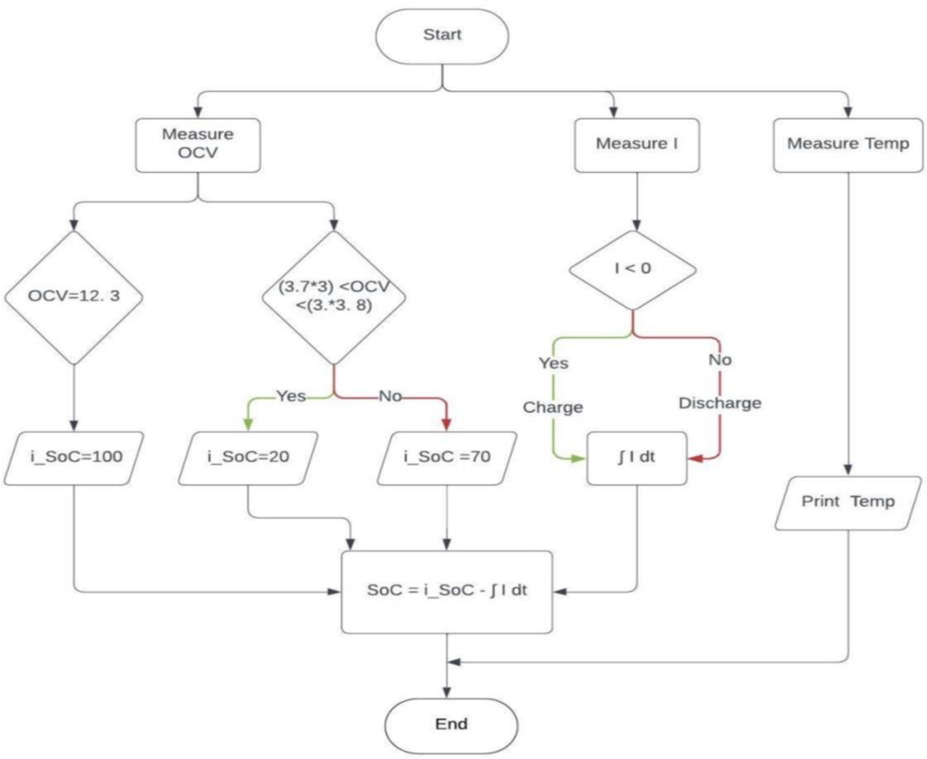

Figure 5: Flowchart for the data processing

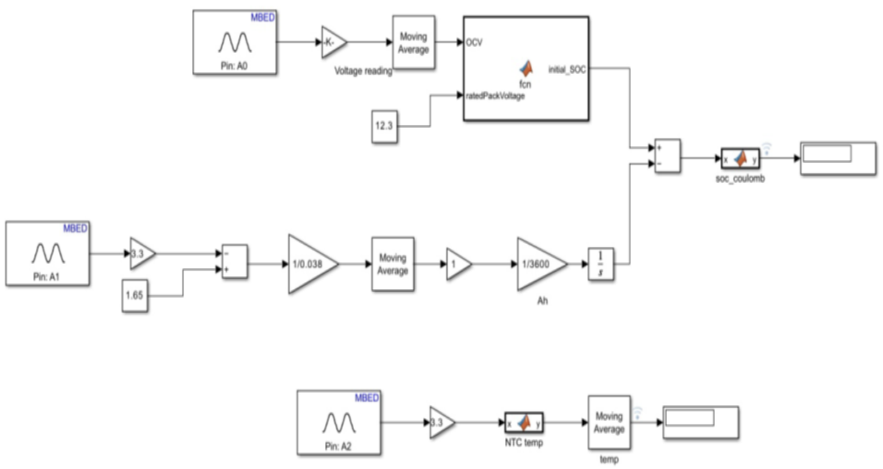

Figure 6: Simulink Model

- **Experiment Procedure**
- The analog pins A0, A1 and A2 reads voltage, current and temperature respectively.
- The A0 analog input block converts the voltage in the range of 0 to 1. It is to be multiplied by 13 to get the actual voltage value.
- Since there are oscillations in the voltage wave, it is given to the moving average block which reduces the oscillations in the output.
- This output voltage is then compared with the rated voltage (12.3 V) to get the initial SOC value.
- In the MATLAB function block, it is coded for three values of initial SOC. If the output voltage equals 12.3 V, the initial SOC is taken as 100%. If it lies within the range of (3.7*3) to (3.8*3), the initial SOC is taken as 20%, else, it is taken as 70%.
- Similarly, the analog input block A1 reads the input current as voltage in the range of 0 to 1. It is then multiplied by 3.3 to get the actual output voltage. But the current sensor senses both positive and negative currents. So it is to be subtracted by 1.6 to get the actual values of positive and negative currents.
- The current is negative during charging and positive during discharging.
- The current sensor has been calibrated such that it has to be multiplied by (1/0.038) to obtain the actual value of current.
- This value of current is integrated over time to obtain the current in Ah.
- The output current in Ah is subtracted from initial SOC to obtain the actual SOC value.
- The A2 analog input block senses the temperature of the battery which is calibrated to minimize the errors in the actual value of temperature.

3. Results and Discussion

This section presents the results obtained along with their plots for analysis. The SOC values and temperature were calculated using the previously mentioned procedures and are analyzed in this section**.**

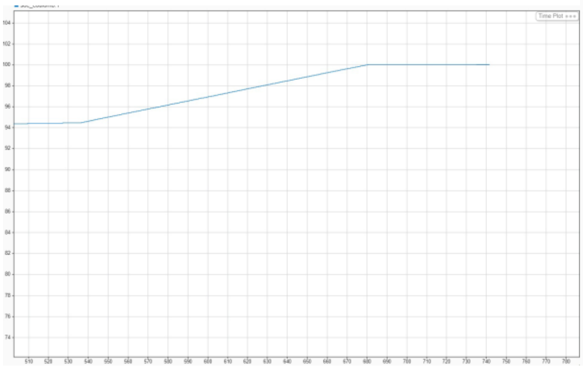

Figure7: SOC - Normal Charging

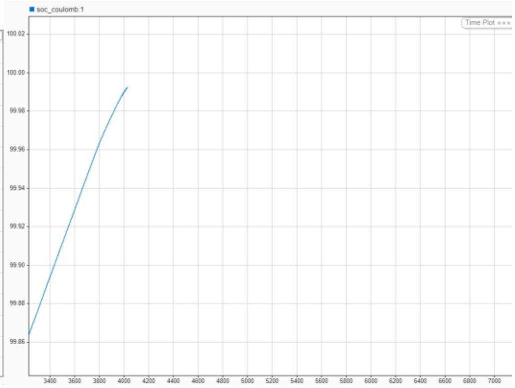

Figure 8: SOC - Fast Charging

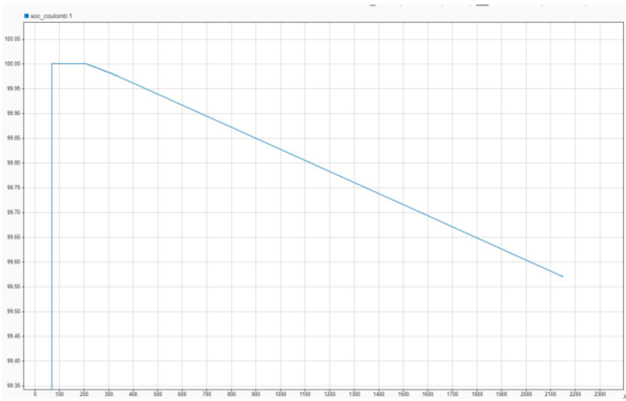

Figure 9: SOC – Discharging

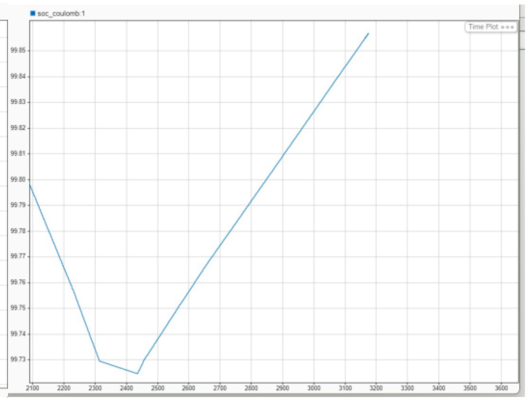

Figure 10: SOC - Discharge + Normal Charging

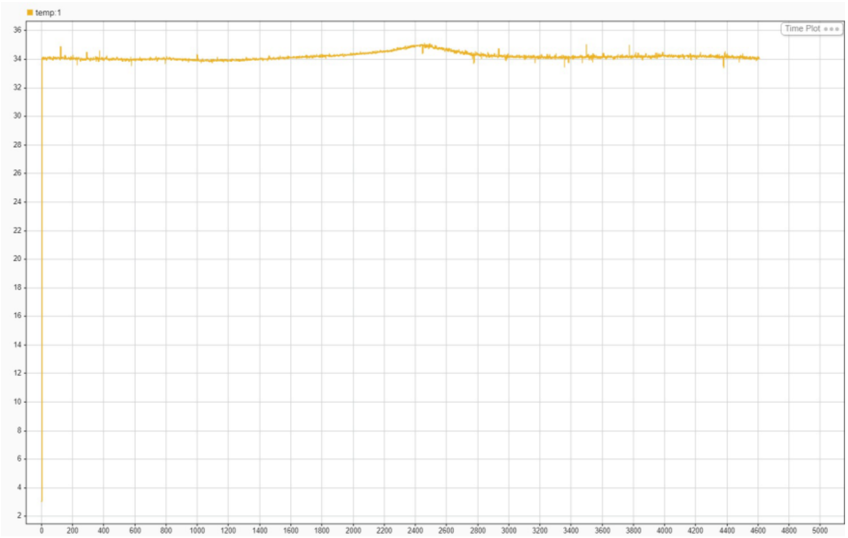

Figure 11: Temperature variations during Charging/Discharging Conditions

Table 1. Normal Charging

No.	Time(s)	SOC(%)	Temperature(°C)
1	2450	99.7284	34.1
2	2660	99.7676	34.2
3	2900	99.809	34.4
4	3197	99.8634	34.9

Table 2. Fast Charging

No.	Time(s)	SOC(%)	Temperature(°C)
1	2450	99.7218	33.9
2	2660	99.774	34.029
3	2900	99.8337	34.094
4	3197	99.9067	34.104

Table 3. Discharging

No.	Time(s)	SOC(%)	Temperature(°C)
1	1410	99.998	34.010
2	1650	99.927	34.142
3	1900	99.853	34.246
4	2306	99.7316	34.725

The SOC analysis was conducted under two conditions: normal charging and fast charging, using an iMAX-B6 charger. The variations in SOC and temperature over time were recorded and tabulated. From the tables, it is evident that the battery's temperature remained relatively stable at around 34°C, with only a slight increase observed during extended charging and discharging periods. Both external and internal factors may contribute to a temperature rise, though the limited duration of the experiment (around 24 hours) likely minimized these effects. As expected, SOC increased during charging and decreased during discharging. The SOC and temperature values for both normal and fast charging modes have been plotted, as shown in Figures (5-11).

4. Conclusion

Considering the safety challenges associated with Li-ion batteries in electric vehicles, a real-time health monitoring system has been developed, marking a significant improvement in energy storage management. This system is designed to incorporate advanced microcontroller STM32 and data analytics to ensure effective, intelligent battery health monitoring. The system utilizes modern sensors and communication protocols to continuously collect real-time data from Li-ion batteries. This enables seamless data exchange between devices, facilitating quick decision-making and preventive actions. By integrating advanced algorithms and data visualization tools, the system offers industry professionals real-time insights, allowing them to predict potential issues, enhance performance, and extend battery life. The system's design ensures scalability and flexibility, adapting to evolving technologies, while its integration with industrial IoT allows for remote monitoring and management, supporting a more agile and responsive approach to battery health maintenance.

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