

Development of a LabVIEW-based battery management system for lithium-ion batteries

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ARTICLE INFO

Article history:

Received 2 June 2026

Revised 15 August 2026

Accepted 15 September 2026

Online first 30 September 2026

Published 30 September 2026

Keywords:

Battery Management System (BMS)

LabVIEW

NI myRIO

State of Charge (SOC)

State of Health (SOH)

Lithium-Ion Battery

DOI:

10.24191/esteem.v22iSeptember.10230

ABSTRACT

The increasing demand for safe, reliable, and efficient energy storage in electric vehicles, renewable energy systems, and portable electronics has amplified the importance of advanced battery management systems (BMS). However, many conventional BMS solutions, especially in entry-level or budget-sensitive designs, still rely on basic microcontroller units that lack flexibility in interfacing, advanced computation capabilities, and integration with high-level visualization or data-logging tools. Lithium-ion batteries, while providing high energy density and long cycle life, are highly sensitive to conditions such as overvoltage, overcurrent, and excessive temperature. Thus, without proper control, these factors can significantly affect battery lifespan. Therefore, an intelligent and cost-effective BMS was developed using the LabVIEW and NI myRIO platforms. This system monitors voltage, current, and temperature in real-time using the INA3221 and TMP102 sensors. Furthermore, the proposed system estimates the battery condition through a voltage-based method for State of Charge (SOC) and a capacity retention model for State of Health (SOH). A relay-based protection circuit is added to automatically disconnect the load or charging path when an abnormal condition is detected. Communication between NI myRIO and a host computer is established via TCP/IP, enabling real-time data logging, visualization, and control through a LabVIEW-based Graphical User Interface (GUI). The results show that

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the proposed system was successfully tested under controlled charge and discharge conditions, providing responsive protection, stable SOC and SOH monitoring, and proper hardware-software integration. This research presents a scalable and accessible BMS solution that is suitable for academic research and embedded energy applications.

1. INTRODUCTION

Lithium-ion batteries have been recognized as widely used energy storage devices, finding use in different sectors ranging from consumer electronics to EVs, aircraft, and renewable energy storage facilities in recent years. The widespread use of lithium-ion batteries compared with alternatives such as NiCd and lead-acid batteries is mainly attributed to their high energy density, lightweight nature, low self-discharge, and long cycle life [1]. Due to these features, battery-operated appliances can become more efficient and compact, meeting the ever-increasing demands for portable and eco-friendly sources of energy. However, the characteristics of electrochemical reactions performed by lithium-ion batteries impose certain safety risks and issues related to the reliability of the devices. Operating outside the recommended voltage, current, or temperature limits can lead to irreversible degradation and a reduced battery lifespan. In some cases, the violation of parameters within safe limits may provoke critical incidents, such as venting, swelling, fire, and even explosion caused by thermal runaway [2]. Therefore, any reliable battery system must provide effective protection, monitoring and response capabilities.

The Battery Management System (BMS) acts as the central monitoring and control component of a battery system in order to solve any potential issues regarding safety and proper operation. The functions performed by BMS include data acquisition in real time, monitoring of both electrical and thermal variables, estimation of SOC/SOH, fault detection and triggering protective action by means of relays and electronic switches [3]. A well-designed BMS maintains safe and effective operation by preventing overcharging, over-discharging, high currents, short circuits, and overheating of batteries. Some sophisticated BMS designs also allow for enhancing the performance of the battery system using cell voltage balancing, energy optimization and predictive maintenance [4].

The current research involves the design and development of a Battery Management System (BMS) using LabVIEW software and the NI myRIO hardware as the processing unit. The NI myRIO combines two ARM processor cores with a reconfigurable FPGA in a compact platform, providing the processing power needed for high-speed parallel operations and deterministic real-time control. Because the NI myRIO is compatible with LabVIEW, its graphical programming environment supports rapid development, modular implementation and easier debugging through visual programming. Unlike the traditional approaches where BMS development is carried out using text-based programming languages such as C/C++ or Python, the proposed solution allows BMS development in a graphical programming environment. Additionally, analog and digital I/O, I²C/SPI communication, and processing capabilities make the NI myRIO an ideal choice for real-time embedded control applications such as intelligent BMS [5].

The BMS framework will continuously monitor essential battery parameters such as voltage, current, and temperature, while estimating SOC and SOH using mathematical models. State of Charge (SOC) will be calculated using a voltage-based method that is suitable for systems without complex Coulomb counting. On the other hand, State of Health (SOH) will be calculated using a capacity retention approach based on discharge characteristics. A simulated load in the form of a DC motor connected via a Type-C USB interface is used to discharge the battery under controlled conditions. If the battery voltage drops below the user-defined minimum value (for instance, 3.0 V), NI myRIO sends a signal to trigger the relay, disconnect the load, and enable the charging process. To reduce thermal stress and improve safety during the simulation, the motor is stopped while the battery is charging. Once the battery reaches a full-charge state, the system automatically stops the charging process and re-enables the motor. These transitions occur

automatically in response to real-time inputs and predefined logic thresholds, without requiring manual intervention.

A key feature of this system is the use of TCP/IP communication for interaction between the NI myRIO device and the host PC. Theoretically, this TCP/IP ensures low-latency, reliable and bi-directional communication over the network, allowing the LabVIEW interface to stream data live, execute commands and visualize operating status. Parameters such as voltage, current, temperature, SOC and SOH are graphically displayed on a developed user-friendly Graphical User Interface (GUI). All results are stored simultaneously in an Excel-readable CSV file, which is time-stamped and organized, and supports post-processing data analysis, model validation, and data reporting. In other words, through this modular approach, users can modify threshold limits, adapt battery profiles and expand the system to accommodate additional channels or sensors. As a result, the project goes beyond a standalone application and provides a flexible research and development platform for experimentation, validation and educational use [6].

The aim of this project is to develop a smart, real-time BMS using the NI platform (LabVIEW and NI myRIO) that can monitor, estimate, protect and visualize the performance of lithium-ion batteries within a single framework. The developed system is scalable, safe and configurable by the user. It reacts dynamically to changes in battery status and at the same time provides information about system performance.

2. METHODOLOGY

In this section, the design and development of the LabVIEW Battery Management System (BMS) are presented, where the core control unit of the BMS is the NI myRIO. The BMS includes real-time measurement, SOC and SOH estimation, data logging and fault detection features to ensure accurate monitoring and safe operation of lithium-ion batteries. The general structure consists of sensors, protection circuitry, estimation algorithms, and the LabVIEW interface.

2.1 System Architecture

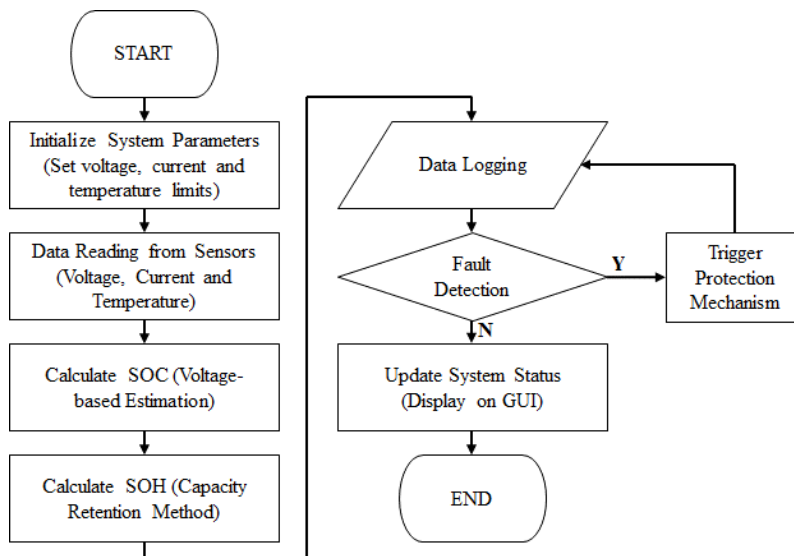


Fig. 1. Flow chart of the BMS System Architecture

2.2 Central Processing Unit (NI myRIO)

Additionally, a fault detection algorithm is embedded in the NI myRIO. In case any value exceeds specified thresholds (overvoltage, undervoltage, or overtemperature), the protection algorithm is triggered immediately [10]. Protection is provided by sending a digital signal from the NI myRIO to activate the 5V relay module, disconnecting the battery from the circuit to prevent further damage. Besides, the NI myRIO

manages all the analog and digital communication through MPIO channels. Therefore, it makes it possible to communicate with external sensors and actuators easily. The processed data are continuously sent to the LabVIEW interface for visualization, user feedback, and logging to external storage for further analysis [11].

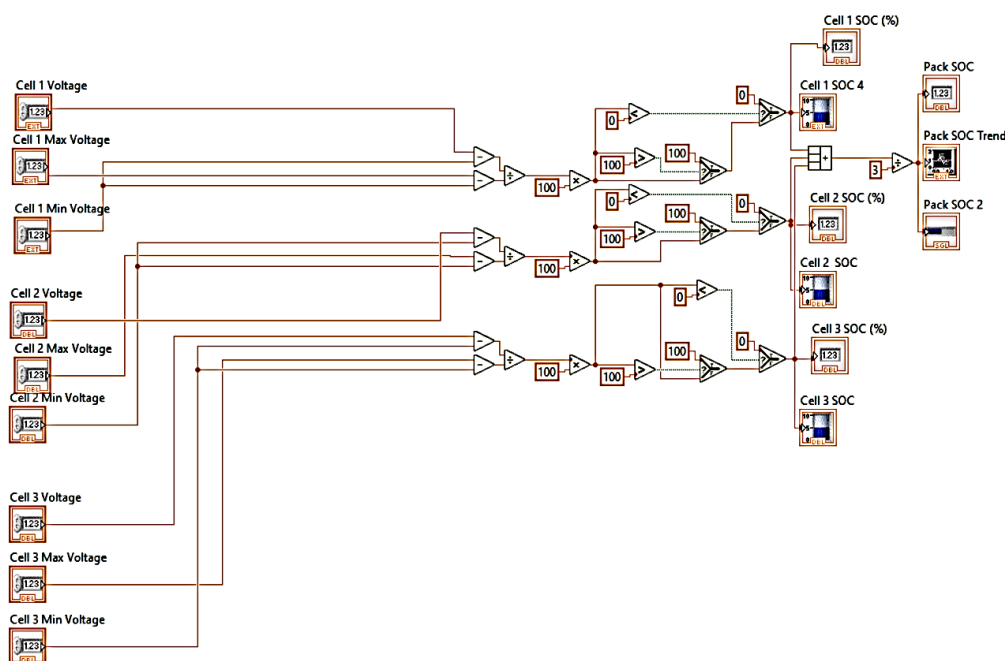


Fig. 3. The Block Diagram of Main.VI under LabVIEW

2.3 Sensor Integration and Data Acquisition

In Fig. 2, it can be seen that two primary sensors have been used to gather data related to the battery system. The first sensor that is being used here is the INA3221, which is a multichannel monitoring sensor and is capable of providing accurate readings of voltage and current for up to three battery cells. The INA3221 communicates with the NI myRIO via the I²C protocol, providing real-time acquisition and internal analog-to-digital conversion (ADC) for high-resolution monitoring. The second sensor the TMP102 digital sensor [12], provides precise sensor for temperature readings. Continuous data acquired from both are transmitted to the LabVIEW environment via NI myRIO [13].

2.4 Charging and Protection System

For a secure battery charge, a TP4056 charger board is used. The above board controls the CC/CV charging system while having overcharge protection for increased safety and battery life [14]. In addition to the above, a relay protection circuit is designed for fault detection. The relay circuit will be controlled using digital outputs from NI myRIO. Any fault, in terms of overvoltage, overcurrent and overheating, causes disconnection of the battery to prevent any form of damage. The process of fault detection is accomplished in LabVIEW using conditional structures to evaluate live sensor readings and take appropriate action where necessary [15].

2.5 State of Charge (SOC) Estimation Algorithm

SOC estimation is performed using a voltage-based method, selected for its simplicity and computationally efficiency [16]. The SOC estimation process involves matching the open-circuit voltage

(OCV) of the battery with the predefined maximum and minimum reference values. The SOC can be calculated as:

$$SOC = \frac{V_{measured} - V_{min}}{V_{max} - V_{min}} \times 100 \quad (1)$$

Where $V_{measured}$ is the measured cell voltage, while V_{min} and V_{max} represent the voltages at 0% and 100% State of Charge (SOC) respectively. This estimation method is implemented in LabVIEW through a dedicated SubVI, allowing real-time SOC visualization and logging within the interface.

2.6 State of Health (SOH)

The SOH is determined using the Capacity Retention Method which compares the current usable capacity of the battery with its nominal capacity to provide a measure of battery degradation [17]. The formula for calculating SOH is expressed as follows:

$$SOH = \frac{C_{measured}}{C_{nominal}} \times 100 \quad (2)$$

$C_{measured}$ is obtained by integrating current over time during a discharge cycle [18]. This algorithm is developed as a separate LabVIEW SubVI that enables continuous monitoring of the battery's health and long-term performance.

2.7 Data Logging and Visualization

All the recorded parameters, including voltage, current, temperature, State of Charge (SOC) and State of Health (SOH), are logged into an organized CSV file which is compatible with the Excel sheet format. The LabVIEW display will show live values of all the parameters with the additional information provided in form of progress bars of the State of Charge (SOC) and State of Health (SOH). Fault warnings are clearly displayed on the interface whenever an abnormal condition is detected. Moreover, the logs with timestamps are automatically stored for future evaluation of their performance.

2.8 TCP/IP Communication Protocol

The connection between the NI myRIO hardware and the LabVIEW host computer is established using the TCP/IP protocol. TCP/IP enables reliable, two-way real-time transmission of parameter values and control commands between the devices. TCP/IP protocol was chosen due to its reliability, standard implementation and ability to be used both in LabVIEW application and NI myRIO hardware. In this setup, the NI myRIO acts as a TCP server, while LabVIEW application running on the PC acts as a client. The server streams voltage, current and controls flags, while client reads inputs and processes data for visual representation, decision-making and logging [19]. Such structure provides an opportunity to show real-time feedback on user interface and to act in case of detected faults or changes in state of the system. For example, when the voltage reaches the discharge threshold, an appropriate signal is sent via the TCP socket to implement relay-switching logic. Using the TCP/IP protocol increases system modularity by separating computation and visualization layers [20]. This approach allows easier expansion of the system, for example, in case of implementing remote monitoring, cloud-based analytics for analysis or expanding the number of battery channels. Real-time properties of the protocol provide low latency in control implementation and contribute to responsiveness and reliability of the Battery Management System.

2.9 Hardware-Software Integration

This system operates on a closed-loop structure whereby sensing, estimation and control are performed as a single process. Data from the sensors regarding the state of the battery is fed into the NI myRIO where the processing of data takes place followed by the estimation of SOC and SOH. In case of a fault being detected, the protection mechanism is immediately executed through the relay. Simultaneously, the LabVIEW interface provides real-time data and continuously logs system operations, supporting both operational safety and analytical traceability [21].

3. RESULTS AND DISCUSSION

Finally, the prototype for the Battery Management System was designed and tested after integration of all its hardware and software elements. Fig. 4 shows the BMS prototype. During preliminary design and simulation phases, manually generated voltage and current values were used to test the fundamental control algorithms and the state-of-charge/state-of-health (SOC/SOH) estimation algorithms. For system performance tests, real-time values have been taken from the hardware circuit where the DC motor was used as a simulator of the battery load, relay modules and the NI myRIO controller, connected to a host computer via TCP/IP connection. The test was carried out to determine the system's real-time monitoring ability, fault detection reaction, automatic switching from discharge to charge mode and vice versa and data logging abilities.

Prior to actual system operation, several safety limits were defined: minimum voltage (3.0 V), maximum voltage corresponding to a fully charged battery (for lithium-ion cell it is about 4.2 V), maximum allowable current, and safe operating temperature limits. All these parameters have been set up in the LabVIEW application. After connecting the power supply to the system, the motor is turned on in order to create load on the battery by drawing current through Type-C connector. Real-time voltage and current values have been sent from the hardware circuit to the LabVIEW application using TCP/IP connection, thus providing reliable communication between the NI myRIO and the host PC.

The interface shown in Fig. 5 demonstrates the main user interface designed for the Battery Management System (BMS). The interface shows the status of the system during the normal operation and during faults. It helps in organizing the view of the battery status as well as its real-time monitoring. In case of fault, for instance, if there is voltage or temperature higher than the set safety threshold, the interface is modified to show the occurred fault. Error messages are displayed, and visual indicators are updated. The relay logic will work to isolate the battery from either load or charger depending on the particular situation. Thus, the immediate action provides prompt feedback to protect the battery from further damage. Therefore, this transition represents the real-time monitoring and fault handling used in the proposed BMS.

During the discharging, the battery voltage decreased progressively as expected. State-of-charge (SOC) was calculated using the open-circuit voltage approximation algorithm. At the same time, the state-of-health (SOH) was assessed via the capacity-retention approach based on the comparison of discharge characteristics to the nominal battery capacity. The estimated SOC and SOH were shown via progress bars and numerical values on the graphical user interface. During the test, the voltage, current, SOC, SOH and temperature were logged into a CSV file with their time stamps. The data collected formed the basis of further analysis to validate the performance of the Battery Management System (BMS).

Fig. 6 illustrates the voltage monitoring interface that has been designed in LabVIEW for monitoring the voltage level of the battery while it is being charged or discharged. This interface displays the measured voltage values continuously by obtaining the values using the INA3221 sensor through the NI myRIO device. During the whole operation, the measured voltage is continuously checked to make sure if the battery runs in the specified voltage range. In case the battery voltage becomes less than the minimum voltage limit, then the relay responsible for the load connection is activated to protect the battery from over-discharge. On the other hand, if the voltage becomes equal to the maximum charging voltage limit, then

the relay responsible for charging gets de-activated to protect the battery from overcharging. The importance of this voltage interface is seen in the fact that it allows us to observe the functioning of our system visually at any given point in time. It also provides visual confirmation that the battery is operating within safe voltage limits, improving both usability and real-time safety assurance.

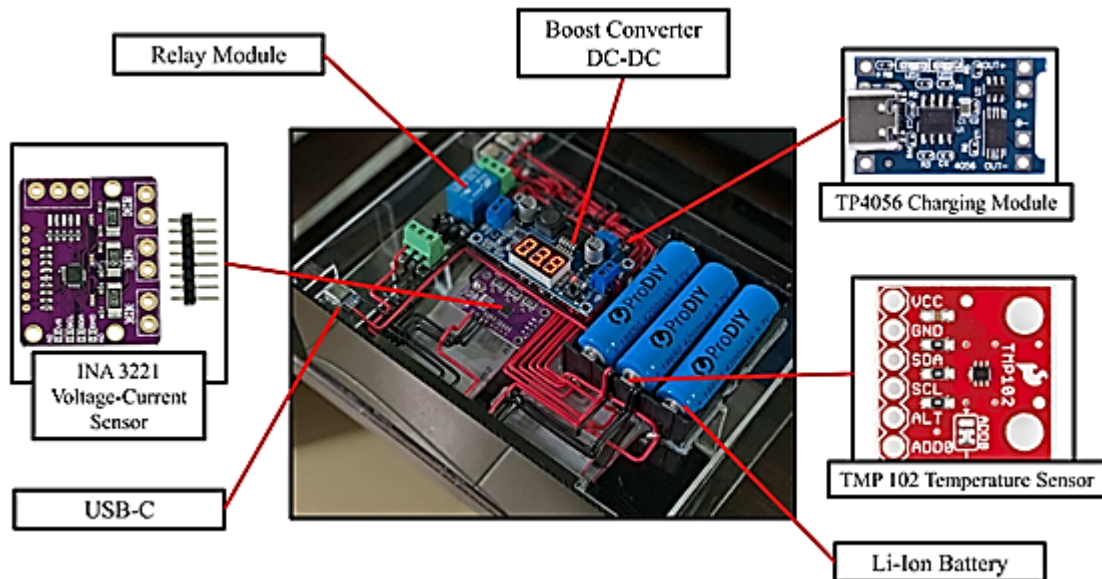


Fig. 4. Hardware Development

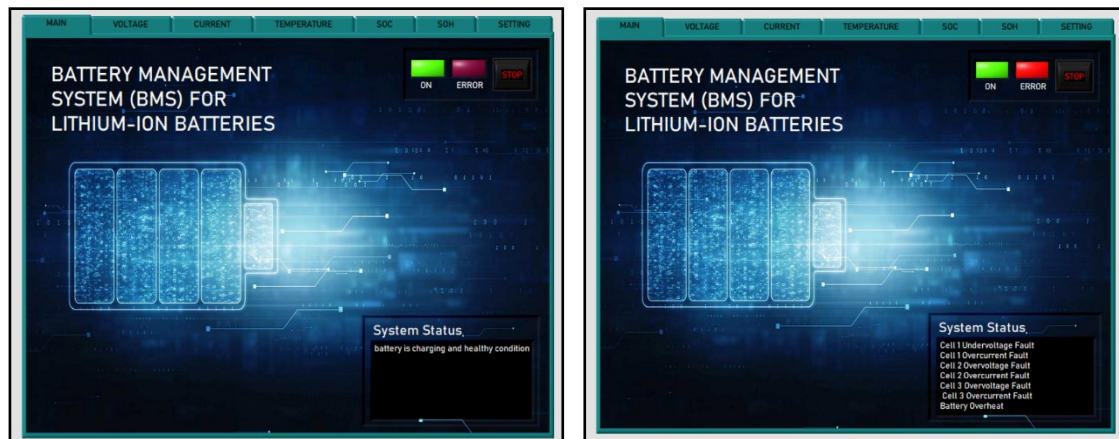


Fig. 5. Graphical User Interface (GUI) for the BMS system (left) without errors and (right) with errors

The voltage readings of the constructed BMS have been compared with the industrial voltmeter in Table 1 below. It can be observed that the operation of the constructed BMS is in accordance with the expected performance. The system voltage decreased up to the lower threshold value of 3.0 V. As a result, the protection mechanism included in the NI myRIO detected the fault, which caused disconnection of the motor through deactivation of the discharge relay to avoid additional decrease of the system voltage due to load conditions. After the fault has been detected, the system automatically switched to charging mode and the second relay connected to the charging module was activated. The transition from discharge to charge modes was done without any actions from the user, showing the autonomous nature of the constructed

system. During charging, the motor remained disconnected to minimize the risk of simultaneous charging and discharging, which could lead to overheating or battery stress.

Fig. 7 shows the current interface in real-time that has been designed using LabVIEW, showing the real-time current being utilized in the battery system. The current is continuously measured using the INA3221 current sensor and is then transferred to the graphical interface via NI myRIO. The interface will provide information on changes in current when either charging or discharging is taking place. During discharge, current increases due to the load applied by the attached motor. Conversely, during charging, current draws from the TP4056 charging module. The current interface is very useful in identifying any abnormal currents, such as overcurrent, which may trigger the fault protection system. The real-time view provided by the interface improves monitoring and increases safety by making sure that the current is operating within the defined limits.



Fig. 6. The display of battery's voltage during both charging and discharging processes (in real time)

Table 1. Tabulated data of voltage reading between BMS vs Voltmeter

Test condition	BMS system (V)	Voltmeter (V)	Difference (V)
Low voltage (3.0V)	3.01	3.0	+0.01
Mid voltage (3.6V)	3.59	3.58	+0.01
High voltage (4.2V)	4.21	4.20	+0.01

Table 2. Tabulated data of current reading between BMS vs Ammeter

Test condition	BMS system (A)	Ammeter (A)	Difference (A)
Low current (0.5A)	0.51	0.50	+0.01
Mid current (1.0A)	1.02	1.00	+0.02
High current (2.0A)	2.02	2.00	+0.02

The difference between the measured value of the current using the designed BMS and that of an industrial current ammeter is depicted in Table 2. Similarly, the charging procedure was observed in real-time fashion. As soon as the BMS detected the maximum value of the voltage level, which implies that the batteries were fully charged, the relay responsible for charging turned off while that of the motor turned on. This cycle demonstrated the system's effectiveness in managing critical battery operations with minimal human involvement while improving safety through real-time sensor feedback and intelligent control logic.



Fig. 7. The Current Interface displays the real-time current flow through the battery system



Fig. 8. Temperature Interface

Fig. 8 illustrates the temperature interface, allowing the user to monitor the temperature state of the battery in real time by making use of the information provided by the TMP102 digital temperature sensor. The temperature information is continuously refreshed on the LabVIEW interface, where it is collected through the NI myRIO interface. This interface is necessary for thermal management especially during charging and discharging processes where heat production of the battery may pose a challenge. The system

has predetermined maximum temperatures; whenever the maximum temperature is exceeded, a fault condition is triggered, and the relay disconnects the battery to prevent overheating or thermal damage.

The differences between the temperatures acquired from the BMS and those measured using an infrared thermometer are shown in Table 3. This temperature sensor is helpful in increasing the safety of the system by allowing visual display of battery temperature in real time and taking prompt measures in case of any unusual values. It helps in logging the data for future analysis of the temperature of the battery.

Table 3. Temperature reading between BMS system vs infrared Thermometer

Test condition	BMS system (°C)	Infrared thermometer (°C)	Difference (°C)
Low Temperature (25°C)	25.2	25.0	+0.2
Mid Temperature (40°C)	40.5	40.4	+0.2
High Temperature (60°C)	60.8	60.7	+0.1



Fig. 9. (above) SOC and (bottom) SOH Interface

The system performed well throughout the testing process, with the SOC and SOH algorithms staying constant while the SOC showed changes according to the expected behavior while the battery charged and discharged. For the SOH calculation, a simplified method based on the calculation of the capacities was used, as opposed to the Coulomb counting algorithm. However, the results of the estimation of the SOH still proved to be quite helpful in terms of determining the relative state of the battery in a case of a prototype aimed at experimental use. The fault detection feature proved to be consistent in its reaction to reaching the pre-set safety threshold, which would result in the necessary actions being taken. The relay switching, carried out by means of the digital outputs from the NI myRIO, was fast and offered good isolation to the load in case of fault detection.

Fig. 9 presents the interface of SOC and SOH designed in LabVIEW for showing the real-time calculation of SOC and SOH of the battery. Specifically, SOC is calculated using a voltage-based method that compares measured battery voltage corresponding residual capacity. As for the calculation of SOH, it is carried out according to the capacity retention technique by estimating the value of the current battery capacity in relation to the initial battery rated capacity. Both values are calculated in the process of system work and shown by means of progress bars and numerical indicators, which makes it possible to present the battery state and residual energy in an easily perceivable way. Besides, the continuous monitoring of the battery condition via the interface can help to detect changes caused by the degradation of the battery. The integration of the SOC and SOH estimation algorithms into the real-time monitoring interface provides information that can support decisions related to battery operation and maintenance.

Table 4. Comparison of SOC between BMS system vs Actual SOC

Test condition	BMS System estimated SOC (%)	Actual SOC (%)	Difference (%)
Fully Charged (100%)	100.2	100	+0.2
Mid-Discharge (50%)	50.5	50	+0.5
Low Charge (10%)	9.8	10	-0.2

Differences between SOC values determined by the developed BMS and the actual SOC values are shown in Table 4. The actual SOC values were established based on the total capacity extracted from the battery when it was being discharged. These differences were within the acceptable range of the required BMS application, which indicates the possibility of monitoring the battery charge state with sufficient accuracy. Comparison between SOH values determined by the developed BMS and the reference SOH values measured in terms of the actual battery capacity is shown in Table 5. These results prove that the developed BMS is able to estimate the condition of the battery, including the possibility to provide information about its health status. It is necessary to mention that reliable SOH estimation is a crucial part of battery management as the estimated health status of the battery can be applied to make decisions about battery replacement and charging/discharging parameters.

Table 5. Comparison of SOH between BMS system vs Actual SOH

Test condition	BMS System SOH (%)	Reference SOH (%)	Difference (%)
New Battery (100%)	100.2	100	+0.2
Moderate Degradation (80%)	80.4	80	+0.4
Severe Degradation (50%)	49.8	50	-0.2

Moreover, the introduction of TCP/IP communication contributed to the flexibility of the system architecture. It allowed to separate hardware processing from the user interface elements, thus makes future developments such as remote control, the Internet of Things (IoT), or cloud-based monitoring applications. The ability to record data proved to be useful for the verification of testing results and troubleshooting anomalies, since log files provided a detailed overview of each phase of the battery working cycle.

Fig. 10 shows the BMS configuration interface implemented using LabVIEW software and which is used for defining the main operating parameters before the start of the system operation. Parameters such as the capacity of the battery, current limit and voltage threshold of individual cells can be defined using the provided fields. Using the configurable parameters makes it possible to tailor the system to different battery and application conditions. A separate logging data field has been incorporated, where users can define the file path, the IP address of the NI myRIO system and the data logging interval. On successful configuration, the system will be able to log real-time data on SOC, SOH, Voltage, Current and temperature. The availability of user-defined thresholds for operation and logging helps in providing greater flexibility to the system setup and supports continuous performance analysis of BMS system.

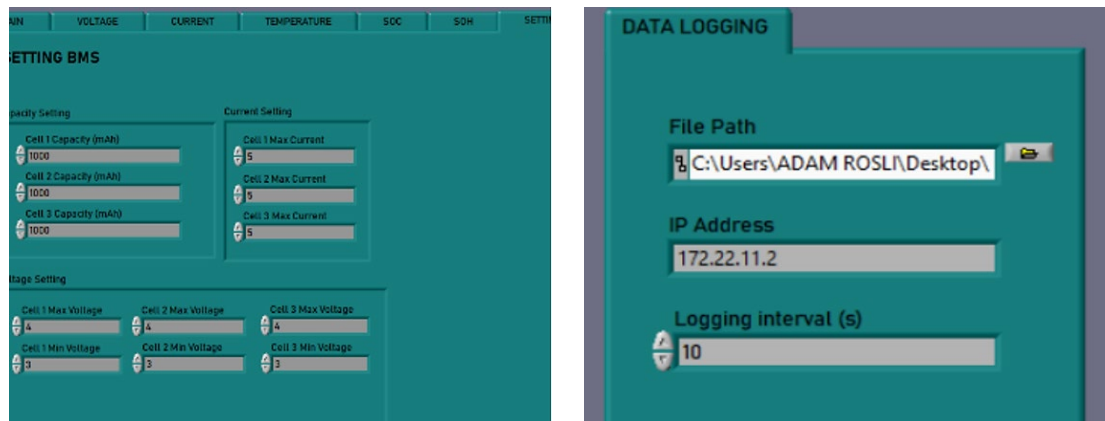


Fig. 10. TCP/IP Setting interface

Table 6. BMS Protection System

Test condition	BMS system (V)	Expected action	Action taken
Overvoltage (>4.2V)	4.3	Disconnect Load/Charger	Load Disconnected
Undervoltage (<3.0V)	2.8	Disconnect Load/Charger	Charger Disconnected
Normal Voltage (3.6V)	3.6	No Action	No Action
Test condition	BMS system (A)	Expected action	Action taken
Overcurrent (>2.5A)	2.7	Disconnect Load	Load Disconnected
Normal Current (1.0A)	1.0	No Action	No Action
Test condition	BMS system (°C)	Expected action	Action taken
Overtemperature (65 °C)	65	Disconnect Load/Charger	Load Disconnected
Normal Temperature (40 °C)	40	No Action	No Action
Overtemperature (63 °C)	63	Disconnect Load/Charger	Charger Disconnected

In Table 6, the BMS (Battery Management System) reaction on faulty conditions associated with the battery is indicated. In particular, the BMS detects over-voltage and undervoltage conditions and takes necessary protective measures in order to protect the battery from damages. In the course of experiment, battery voltage was changed intentionally to be more than the set threshold or lower than the other one. If the voltage becomes higher than 4.2V or lower than 3.0V, the protective relay disconnects the battery from the load or charger. Moreover, the system is aimed to minimize possible over-current situations that might cause potential damage to the battery. According to Table 6, when the current exceeds the protection threshold of 2.5 A, the BMS automatically activates the relay to disconnect the battery from the load. Also, the BMS has a temperature protection system that prevents from overheating of the battery.

From the above findings, it can be seen that the proposed BMS based on LabVIEW successfully achieves its key goals. The system successfully incorporates live monitoring, real time estimations, automatic relay control and data logging into a unified and scalable platform. There is an ability to improve this system in the future through incorporation of multiple cell balancing, machine learning for state of health (SOH) prediction and advanced charging algorithms among others. As such, the BMS is not only successful in providing basic safety of the batteries, but it is also a great tool for education and experiments.

4. CONCLUSION

This research developed and implemented an intelligent Battery Management System (BMS) based on the NI myRIO and LabVIEW platform. The developed system is capable of monitoring battery voltage, current and temperature as well as providing fault protection, State of Charge (SOC) and State of Health (SOH) estimation as well as data logging facilities. In the testing phase, the system was able to monitor the parameters of the battery and perform the necessary protection procedures by relay switching when certain threshold values are exceeded. The SOC estimation process was conducted using the voltage-based method, whereas the SOH estimation process was performed using a capacity retention approach. The LabVIEW-based interface offers a user-friendly way of viewing the measured and estimated parameters of the battery whereas TCP/IP communication offers the facility of transferring data in real-time from NI myRIO to the host computer. In conclusion, the Battery Management System (BMS) that was designed can serve as a practical and cost-effective platform for the protection and management of lithium-ion batteries which can be applied in different cases including educational laboratories, research prototypes and basic energy storage systems.

While the Battery Management System (BMS) that was developed performed well within the controlled environment of this experiment, there is scope for further development in a number of aspects. Conducting further tests using the complete operating range of the battery will provide additional data for analyzing the BMS under varying operating parameters. The SOC estimation process can be refined by combining the existing method based on voltage estimation with Coulomb counting to increase accuracy, especially in situations where the loads are dynamic. SOH estimation, on the other hand, can be further developed through methods like the use of impedance techniques or machine learning approaches to acquire deeper knowledge about battery degradation and aging processes. Another way of advancing the BMS would be to develop a wireless capability for monitoring and incorporating cloud-based functionality, along with extending the system to support multiple battery cells. This will enhance the scope of possible uses of the platform and include more challenging uses of the system like electric cars and energy storage using renewable energy while providing a sound basis for future research into battery management.

5. ACKNOWLEDGEMENTS/FUNDING

The authors would like to acknowledge the support of Universiti Teknologi Mara (UiTM), Cawangan Pulau Pinang for providing the facilities and financial support on this research.

6. CONFLICT OF INTEREST STATEMENT

The authors agree that this research was conducted in the absence of any self-benefits, commercial, or financial conflicts and declare the absence of conflicting interests with the funders.

7. AUTHORS' CONTRIBUTIONS

Nor Azlan Othman: Supervision, conceptualization, methodology, formal analysis, investigation, writing – original draft and writing – review and editing. **Mohammad Adam Rosli:** Conceptualization, methodology, formal analysis, validation, investigation and writing – original draft. **Nor Salwa Damanhuri:** Conceptualization, formal analysis and validation. **Belinda Chong Chiew Meng:** Validation and writing – review and editing. **Rozan Boudville:** Formal analysis and validation. **Mohd Hussaini Abbas:** Writing – review and editing. **Sarah Addyani Shamsuddin:** Writing – review and editing. **Takumi Tamamoto:** Formal analysis and validation.

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