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A Cost-Effective Fast Cell Balancing Technique for Lithium-Ion Batteries Using a Single DC–DC Converter with Direct Energy Transfer

Challa Krishnarao[1,*], B. Manmadha Kumar[1], Sarat Kumar Sahoo[2], Killamsettypranitha[3], Yernagula Deekshitha[3], Bagatti Chiranjeevi[3], Lakkoju Harika[3]

Abstract

A novel quick lithium-ion battery balancing method with a single DC-DC converter for facilitating the direct energy transfer process in low and high voltage cells is introduced in this research work. Cost effectiveness in the design of the switch network is achieved by the use of relays in switching the cells. A control circuit including an MCU and a battery management IC is used for the sensing of cell voltages and hence the overall battery protection. The validity of the performance efficiency of this technology is justified by the creation of a prototype circuit setup by the employment of twelve lithium-ion batteries that consume an incredible balance time of 48 minutes during the charging process with a maximum efficiency of 89.85%. The efficiency of the proposed balancing circuit based on balance time and implementation cost is justified over the existing technology. Hardware details regarding Battery Management Systems in static and EV applications are considered in the article. This article helps in the determination and measurement of crucial parameters while designing a Battery Management System based on its implementation scenarios with a snapshot description regarding the existing trends in state-of-the-art technology. Implementation details regarding the battery packs based on the commercial models for EVs are discussed in this article. Implementation details regarding the measurement of critical parameters like temperature, voltage, and current and balance control strategies are considered in this article.

Keywords: Battery management system (BMS), cell balancing, DC-DC converter, MCU, efficiency

***Author for Correspondence**
Challa Krishnarao
E-mail: vhans2011@gmail.com

[1]Associate Professor, Department of Electrical and Electronics Engineering, Aditya Institute of Technology and Management, Tekkali, Srikakulam, Andhra Pradesh, India
[2]Professor, Department of Electrical Engineering, Parala Maharaja Engineering College, Berhampur, Odisha, India
[3]Student, Department of Electrical and Electronics Engineering, Aditya Institute of Technology and Management, Tekkali, Srikakulam, Andhra Pradesh, India

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INTRODUCTION

Lithium-ion batteries are increasingly being adopted in the automobile industry. The combination of batteries achieved through the interconnection of a number of batteries in a series and parallel combination needs to be stacked to achieve their deployment in power-consuming and high-voltage applications, such as the electric motor of an electric vehicle (EV) motor, Hybrid EV motor, and energy storage system (ESS) [1]. As a matter of fact, a cell configuration of a Li-ion battery in the Tesla Roadster electric motor of the EV car consists of no less than 6831 Li-ion batteries arranged in a stack consisting of 69 batteries in a series combination, each of which is consisted of 99 Li-ion batteries. The differences in properties may emerge on account of minute differences in the processing as well as usage requirements of Li-ion batteries in a particular string of batteries. These differences are reflected in the differences in the cell voltage of the batteries, which increase in each charge and discharge cycle of the batteries. Thus, as batteries are interconnected in a series combination in a cell string, the overall capacity of a battery string will ultimately be limited in view of the fact that the level of performance of a series of batteries would be determined on account of a cell holding a lower capacity in performance.

The cells in a string of batteries would be subjected to over-discharge and under charge conditions on account of being in use in a string combination within a particular application scenario. This would ultimately result in the failure of batteries in a particular cell string, as batteries in a cell fail as a result of being subjected to discharge and charge cycles a definite number of times [2]. Consequently, as batteries in a series combination are charged on a constant basis until the voltage of a particular string of batteries is brought to a nominal level under an ongoing charge process, the healthy or strong cell may be subjected to possible conditions of overcharging. In this case, because of the increase in the cell voltage of the healthy/best cell above its allowed safe charge voltage level, the failure of batteries in a cell may be accelerated because of possible conditions of overcharging of batteries. Consequently, cell balancing is also required in battery strings or modules [3]. Cell balancing techniques can be categorized as passive or active, based on their nature. Based on current paths, active techniques can be further divided into cell-to-pack, cell-to-cell, cell-to-pack-to-cell, and cell-to-cell-to-pack balancing techniques. In many active balancing techniques, a major drawback is their high cost and complexity owing to the large number of MOSFETs, gate drivers, and transformers, which also affects the balancing time. There are cell-to-cell balancing techniques with more favorable trade-offs between cost and performance. Despite the improvement in energy efficiency brought by soft-switching, problems associated with LC resonant cell-to-cell balancing are the increased number of switches and drivers, and hence balancing speed [4]. To address the problems associated with previous studies, this study proposes a cell-to-cell balancing system that adopts the use of a DC-DC converter to charge low-voltage cells through overcharging from high-voltage cells. A cell-to-cell balancing circuit using a relay can address the problems associated with balancing the battery pack. The BMS requirements, system design, results, and conclusions are discussed in the following sections.

BATTERY MANAGEMENT SYSTEM

The integration and requirements of a battery management system are shown in Figure 1, which refers to a set of characteristics, functions, and specifications necessary for the good management, control, and maintenance of batteries. Specifications are important in various applications, such as consumer electronics, electric vehicles, and renewable energy systems [5]. The longest life, safety, and optimized performance of batteries are achieved through efficient battery-management systems. The above-mentioned requirements are necessary for a battery management system.

State of Charge (SOC) and State of Health (SOH) Monitoring

The remaining battery capacity can be accurately measured using a BMS. The methods used to achieve this include voltage, current integration, and coulomb counting methods. A BMS must monitor capacity degradation based on a comparison of a battery's performance over time with a previously measured performance. This will help estimate the remaining battery life left in service.

Voltage and Current Monitoring

To prevent overcharging or over-discharging, the BMS always tracks the cell and pack voltages. The system ensures that neither a pack nor a cell operates above a safe voltage threshold. To prevent situations involving overcurrent, which can damage a battery and other components, one simply needs to monitor inputs and outputs of a current to a battery.

Temperature

The cell or entire pack temperature can be measured using the BMS. The BMS will have to provide ways to lower the cell temperature or prevent fast discharges and charges in case of a possibility of reaching dangerous temperatures.

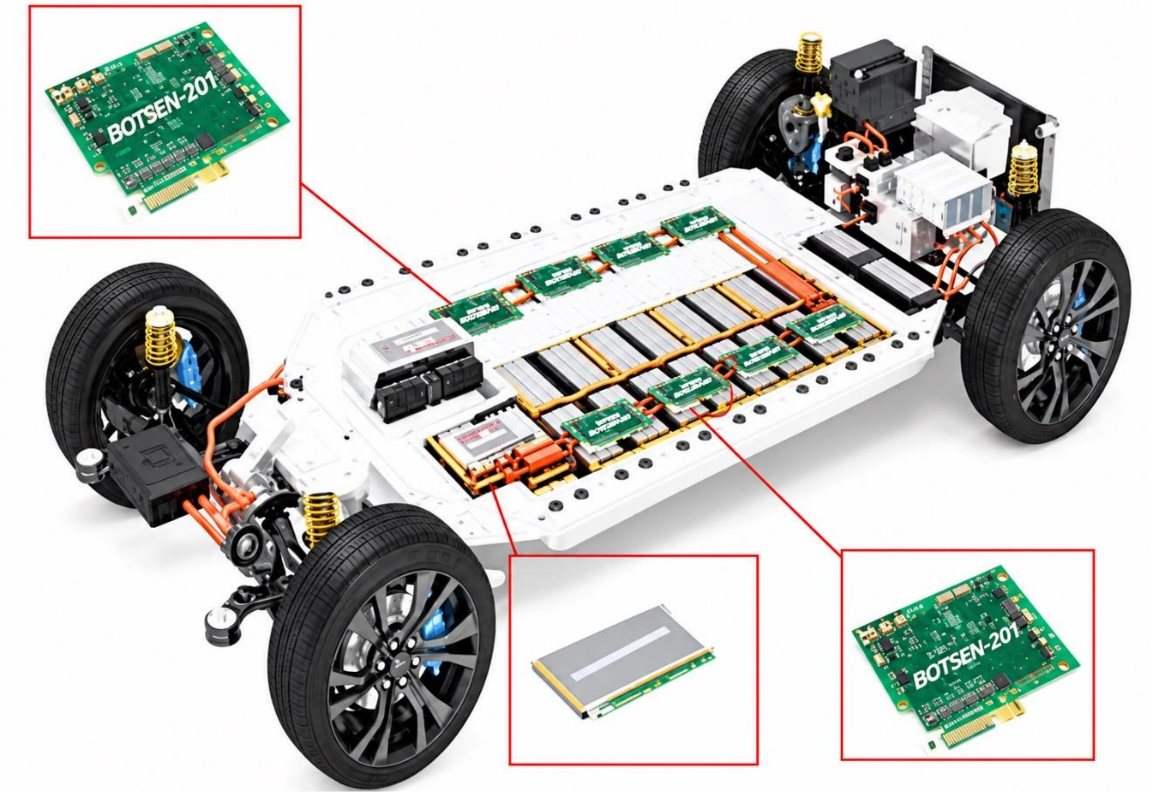

Figure 1. Battery management system (BMS) integrations.

Cell Balancing

To achieve charge balance across all cells, it is important for the BMS to monitor cell voltages and undertake cell balancing accordingly. The ideal BMS will possess a circuit capability to immediately disconnect a battery if an overcurrent or overvoltage is detected to prevent damage to both the battery and devices connected to it.

PROPOSED CIRCUIT FOR CELL BALANCING

Figure 2 proposed cell-to-cell balance circuit In the proposed system, the DC-DC converter enables the flow of charge from cell to cell using a relay system. The relays R3 to Rn-1 connect the selected cells to the primary terminal and the relays R5 to Rn-4 connect the selected cells to the secondary terminal. Thus, the flow of charge from the high-voltage cells to the low-voltage cells is possible. The system is controlled using a microcontroller that uses the voltage information from the sensing IC [6].

A DC-DC converter was preferred because of its simplicity, high efficiency, and controllability. A turn ratio of 1:1.2 and duty ratio of 0.5 were employed. The current was measured on the primary side using a sensing resistor. The secondary-side current was estimated using the transformer characteristics, considering the internal impedance of the cell.

Principle of Operation of Cell-Balancing Circuit

Figure 3 presents a flowchart of the cell balancing algorithm. First, the controller measures all the voltages of cells that are within the allowed range of operation (Sin) and the cell that has the maximum voltage (Vaux). The cell with Vaux is connected to the converter input by switching relay Remix on the input side. To connect the cell with Sin to the converter output, the relay Resuming is switched on the output side. The balancing of the two cells started immediately.

The controller continually tests all voltages and balancing current subsequent to the balance of these chosen cells. The average voltage of all cells was recalculated.

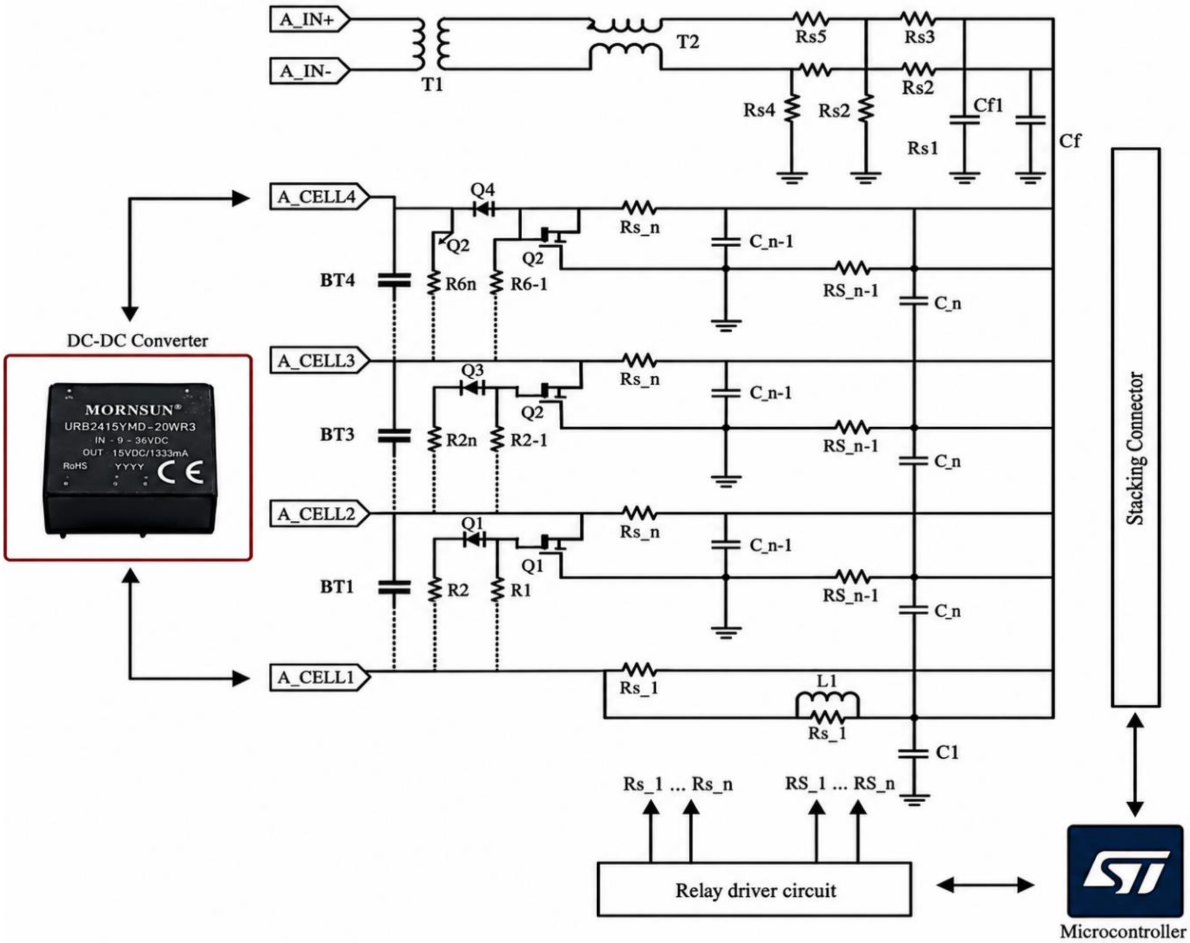

Figure 2. Cell-balancing circuit.

The two relays, RR max and Rs min, are turned off when a cell in balance attains the average voltage. The next two cells with the highest and lowest voltages are identified for another balance cycle by the controller [7].

A specific cell pair is connected to the converter with the notation cell BTn for the cell with the highest voltage and cell BT1 for the cell with the lowest voltage. Relay Rrm links cell BT n to the converter input, and relay Rs1 links cell BT1 to the converter output. The remaining relays were not used. The DC-DC converter immediately begins cell balancing.

BATTERY MANAGEMENT SYSTEM TESTING STRUCTURE.

The testing environment for a battery management system can be achieved using a virtual battery and a high-precision current source simulator to simulate analog signals in a real battery pack [8]. A closed-loop testing system for a battery management system can be established using a real-time simulation system. Figure 4 illustrates the hardware and software elements of the testing platform.

It contains a master board, slave board, battery pack, high-speed voltage equipment, current source device, and real-time target machine. The software provides high precision for the battery pack and estimation of the SOX reference value. The upper computer management software facilitates machine-researcher interaction, data monitoring management, visualization of each platform module, supervision of test circumstances, configuration of the initial state of the battery pack model, and control of the test start-stop functions.

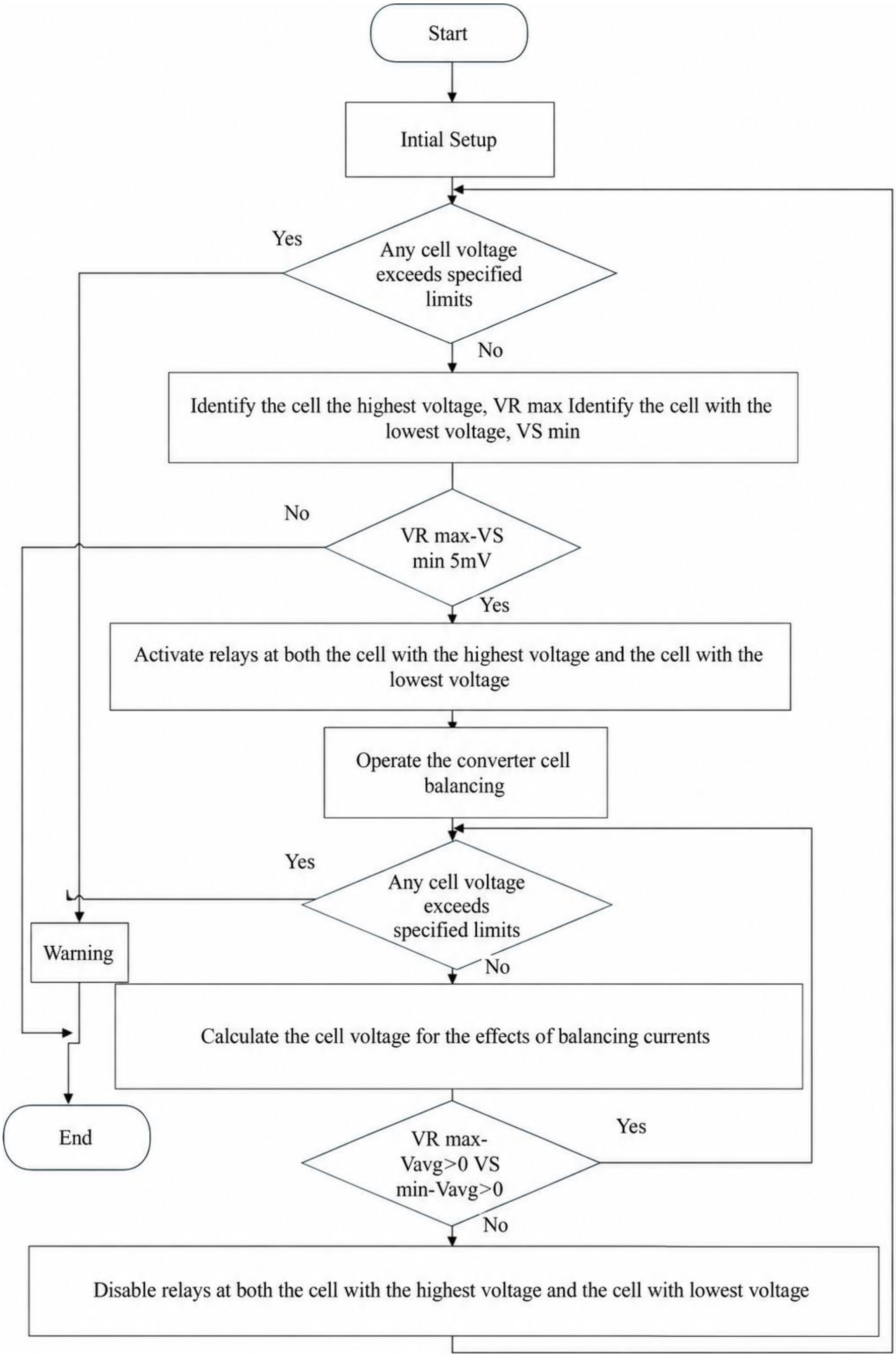

Figure 3. Algorithm method of cell balancing

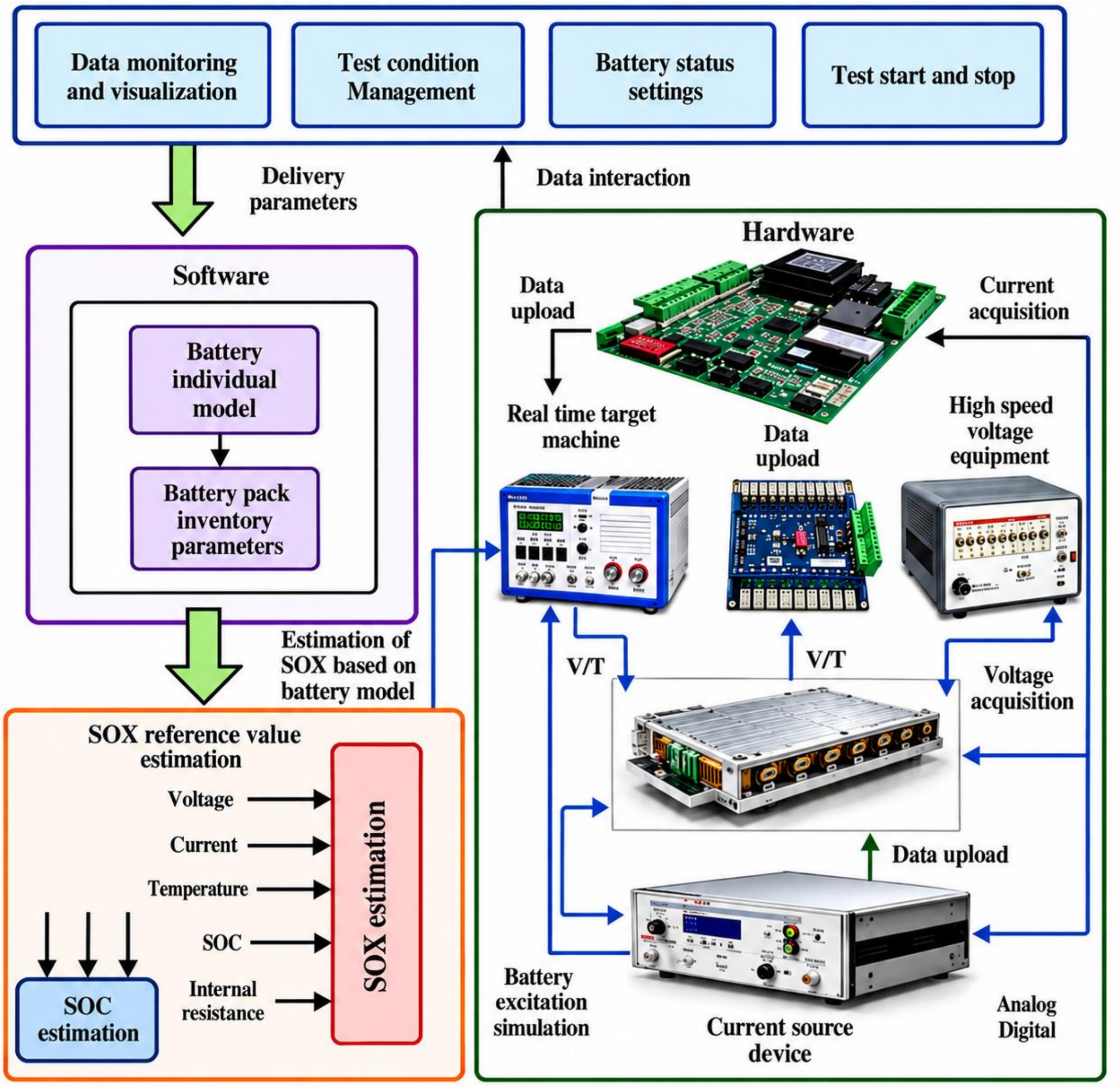

Figure 4. Framework of the testing platform (hardware and software)

Hardware Section

The hardware component description includes a master board, slave board, battery pack, current source, high-speed voltage measurement unit, and target machine working in real time. The battery pack produces analog signals, such as voltage and temperature measurements, which are usually measured using a thermistor and translated voltage measurements into temperatures. The current source produces a unidirectional signal indicating the battery currents, which are then converted into bidirectional signals using a full-bridge conditioning circuit.

Each component was controlled by a real-time target machine, which also functioned as the software control unit. High-precision data acquisition components receive voltage and current signals and relay them to a host computer. In this design, the voltage measurement was integrated with the virtual battery, and the current measurement was integrated with the current source using the measured reference data to test the performance of the BMS.

Software Section

The software contains seven modules: launch control, battery model, virtual battery control, current source control, BMS data interaction, signal update, and port configuration. Among them, the most important is the battery model, mainly used for analog signal output control, such as the temperature of every battery cell, voltage, and total current. The main function of the virtual battery control is to convert data from the model calculation into data that the hardware part understands while using a preselected communication specification. During unidirectional current source signal tuning, the current source control guarantees the continuity of the current path.

This is the architecture of the BMS software, vSTM32CubeMonitor, based on a modular design paradigm, where several functional units perform their duties as separate modules in communication interfaces, cell monitoring, thermal management, and condition estimates. It has also taken care that all these modules are bridged through well-defined communication routes by which coordination and sharing of data can be smoothly affected [9].

1. *Modularity and interfacing:* This makes each module of the BMS-for example, the thermal management module or the cell monitoring module for voltage and current measurements–independent, while interacting with other modules through standardized interfaces. In addition to increasing the flexibility of the system design, this modularity facilitates the incorporation of updates and new features.
2. *Communication protocols:* Reliable data transmission between modules is ensured using robust protocols, such as CAN. These protocols define a message format, error handling procedures, and time restrictions that guarantee the integrity of the data throughout the system.
3. *Centralized control and monitoring:* The entire BMS is controlled by a centralized control unit, also called the master module. It gets the information from each module, does the processing with algorithms for defect identification and status estimate, and sends the command back to the modules for remedial measures. This centralized approach will ensure that the system functions reliably under different circumstances and maximizes performance.
4. *Fault tolerance and redundancy:* The architecture must include redundancy and fault-tolerant features to make it dependable and safe for a system such that the BMS can keep functioning in case of module failure or failures in communication.

MODULARIZATION

The application of higher power and/or more energy consumption requires the integration of many cells within the battery pack. Special ICs have been developed for such systems, offering current monitoring and balancing capabilities simultaneously, the latter being superfluous in single-cell systems. More often than not, advanced functionalities are grouped within a single module known as the ECU or BMS-Master [10]. Complex power prediction algorithms and algorithms concerned with state-of-charge estimation are computationally intensive. The system structure represents a typical setup, as shown in Figure 5.

The Battery Management System slaves are the modules where the front-end monitoring ICs are placed, dealing with the basic tasks involving signal processing and filtering. This is already a provided capability by several vendors, such as Maxim Integrated and Linear Technology, and is already able to support active or passive cell balance [11]. Redundancy for voltage sensing can also be provided for increased safety using secondary ICs for protection or a fully redundant BMS implementation. The concern over early fault detection is introduced by commercial electric vehicles, particularly when a high-voltage Information Technology system is involved, where the body electrical separation is considered, especially because electrical safety concerns come into play if one single failure is not hazardous, but another failure can lead to critical conditions, requiring strictly detailed safety measures, where immediate power turn-off during operation brings up another risk [12].

Functions and Features for Advanced Battery Monitoring and Balancing

The ECU or Bushmaster plays a critical role in ensuring the safe functioning, long lifespan, and maximum possible performance of the battery pack. This device always tracks the voltages of individual cells for imbalance detection, subsequent degradation prevention, and any potential safety issues [13].

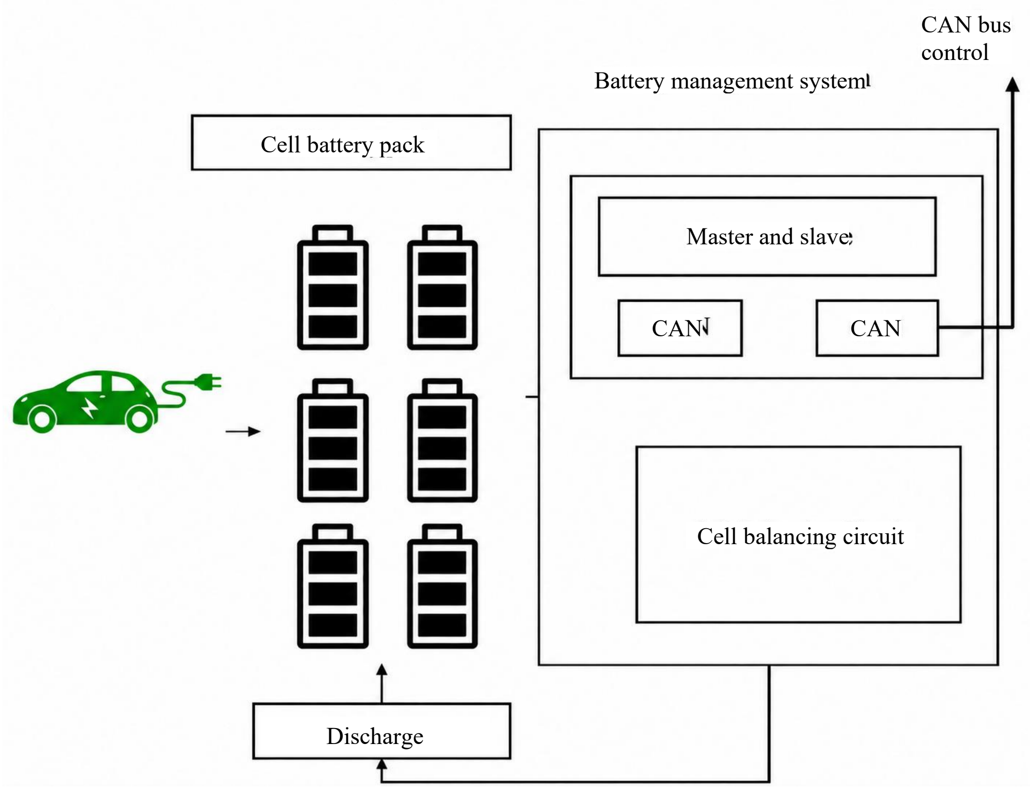

Figure 5. Structure of BMS for EV applications.

On the other hand, through complex algorithms processing the obtained information, the estimation of the State of Charge (SOC) is performed to provide correct information about the available capacity and the estimation of the State of Health (SOH) for the evaluation of the battery's aging and subsequent planning for any required maintenance actions. Furthermore, the device tracks the temperatures of the cells and the overall battery pack and through implemented thermal management strategies always maintains the batteries within the required safe operating limits. Current measurements enable the correct regulation of the charging and discharging rates and at the same time prevent the occurrence of overcurrent flows. Cell balancing, performed by active or passive balance operations, aims to achieve balanced performance and a long lifespan of batteries. In addition, the BMS Master/ECU is responsible for the detection of any faults and malfunctions related to overvoltage, undervoltage, overheating, and overcurrent, and follows the implementation of protective actions for their prevention and subsequent prevention of any adverse effects on the batteries and the overall system's efficiency and reliability [14].

EXPERIMENTAL SETUP

A prototype of the electronic control and monitoring circuit was developed for demonstration and analysis of its functionality. The circuit is made up of many interconnected modules such as the stepdown transformer, rectifier, and filter for changing AC to DC, and also uses voltage regulators for stability. The circuit diagrams on the PCBs use resistors, capacitors, diodes, transistors, and ICs for their functioning. A cooling fan is also used to cool the device to avoid heating, while an LCD of the 16×2 type shows the voltages and status of the device [15].

The health of a motor is imperative for the functionality of a vehicle, as this component delivers the power required for the vehicle to move. The functionality of related systems, such as lubrication, cooling, fuel and air intake, and electrical systems, requires utmost attention. A faulty motor can be determined by checking for signs such as noise production, presence of smoke, leakage of motor oil, excessive heating, or decreased efficiency. A relay and transistor array were incorporated into the PCB to allow for the simple connection of two cells to the DC-DC converter. Figure 6 shows the experimental setup used for testing.

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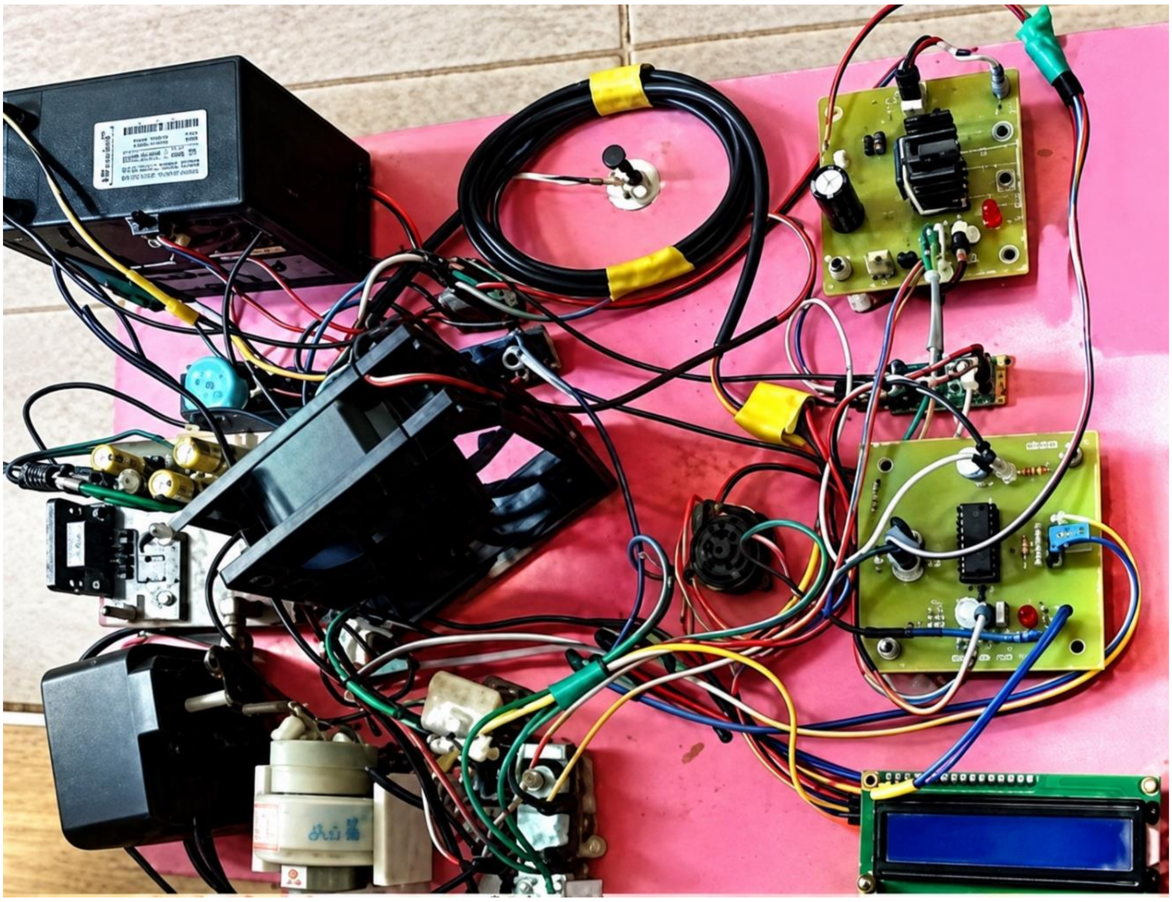

Figure 6. Vehicle health monitoring system

Table 1. Components list of the proposed BMS circuit.

Component	Parameter/Function	Likely Part Number
Microcontroller	Data acquisition and control	ATmega16/ ATmega32/ PIC16F877A
Step-down transformer	AC to low voltage supply	230V to 12V, 1-2A
Bridge rectifier	AC to DC conversion	KBPC5010/ W10
Voltage regulator	5V logic supply	LM7805
Filter capacitors	Ripple reduction	470μF/ 1000μF electrolytic
Crystal oscillator	MCU clock	8 MHz / 16 MHz
Relay	Load isolation/protection	SRD-05VDC-SL-C
Relay driver transistor	Relay switching	BC547/ 2N2222
Fly back diode	Relay protection	1N4007
LCD display	Parameter display	16×2 LCD (HD44780)
Potentiometer	LCD contrast	10 kΩ
Cooling fan	Thermal management	12 V DC fan
Voltage divider resistors	Battery voltage sensing	10 kΩ-100 kΩ

Table 1 lists the components of the proposed BMS circuit. Battery enclosure components include: the contactors for inverter DC charge, fuses, a service socket, an LEM current transducer, an insulation monitor, and a cooling fan, in addition to cell modules. The pack, located below the left-hand car seat, is split into two parts when viewed after the service plug is removed. The pack is further divided into two halves by a main fuse [16]. Small plastic tubes transport chilled air from the car's air conditioning system, which is subsequently released through a fan. The Battery Management Unit, or "BMS Master," is a unit found outside the battery enclosure and is responsible for interacting with the vehicle’s other systems. The BMU is situated below the rear bench seat and is directly connected to both the insulation monitor, contactors, and current transducer. Additionally, an internal CAN bus enables the connection and communication with the microcontroller in each cell module from the BMU. The main CAN bus in a vehicle can also incorporate some messages from the CAN bus in the batteries, although with a lower resolution [17]. The DC-DC converter in the designed battery management system plays a vital role in voltage regulation and charge distribution, with pulse-width modulation applied to convert different voltages of the batteries to a constant output level suitable for the connected load or battery charging circuit [18]. It is applicable in the area of the distribution of charges into series-connected battery cells, considering aspects of voltage regulation with extensive operation ranges, typically 4.5-36 V capable of delivering 12 V of output level and including several protection mechanisms: thermal shutdown, undervoltage lockout, and overcurrent protection. The system has a conventional PCB arrangement designed for two battery cell configurations of four and eight cells, integrated with temperature sensors, while the master BMS is located below the rear seat, with capabilities for communication with vehicle control units and connected through contactors, current sensors, insulation monitors, and CAN bus [19]. Critical components are included in the battery case, namely, fuses, cooling fans, and service plugs. Figure 7 shows the battery pack module of the BMS for electric vehicles.

The cooling of the battery is enhanced by air intake from the cool ducts with discharge of hot air, thereby maximizing space used in the battery.

RESULT ANALYSIS

For the DC-DC converter, a 50% duty cycle was employed to ensure easy charge transfer from the high-voltage cell to the lower-voltage cell. The switching clock of the DC-DC converter was set at 270 kHz, and the waveforms captured at the input and output voltage of 3.8 V and 3.65 V are shown in Figure 8. The MOSFET Switching ensured effective charge transfer, causing the variations in the efficiency level to range from 86.3% to 89.7%.

High efficiency was achieved owing to the proposed design, resulting in easy charge transfer between the two cells. The operation of the cell-to-cell balance charging and discharging technique is shown in Figures 9 and 10 [20].

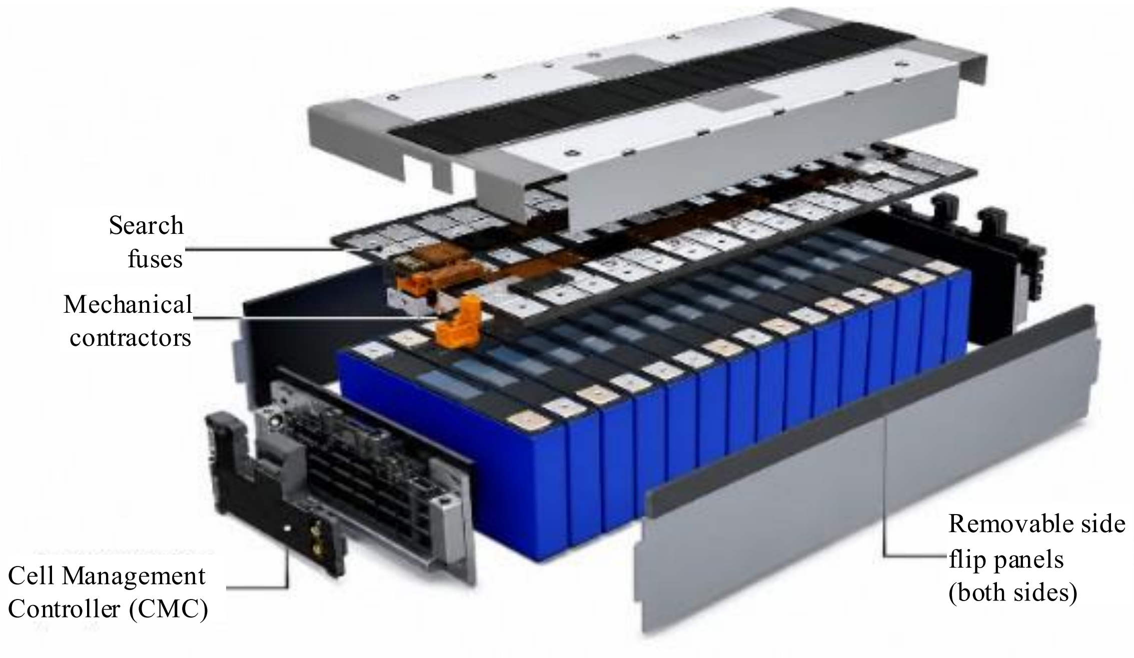

Figure 7. Battery pack module of BMS for electric vehicles.

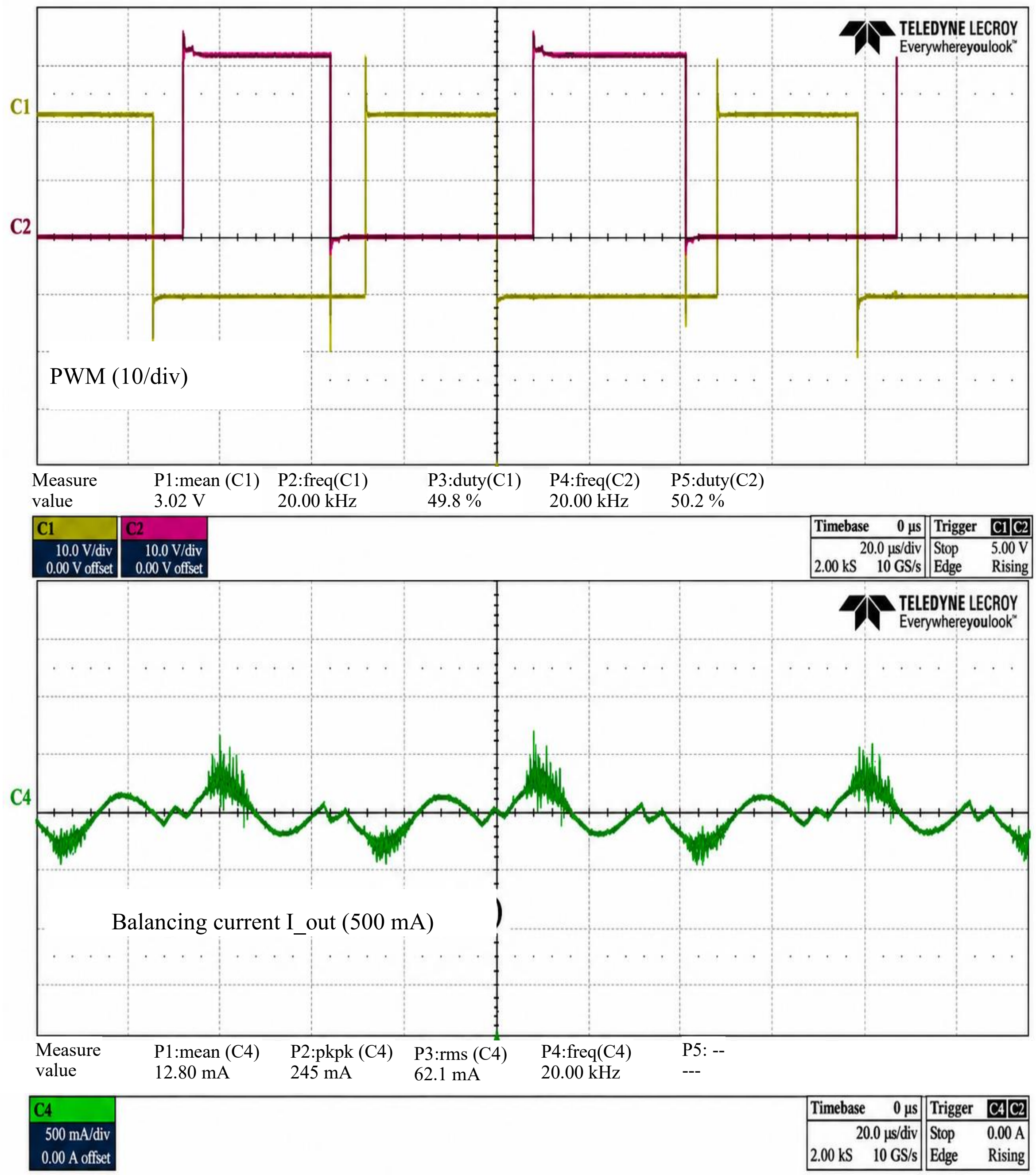

Figure 8. Waveform of DC–DC converter (PWM waveforms and cell balancing current).

The prototype was subjected to relaxation tests using 12 cells. First, the system assessed that cell number 7 had the maximum voltage of 3.78 V, while cell number 4 had the minimum voltage of 3.6 V. Later, cell number 7 stabilized to 3.705 V within a total of 19 min. Cells 6 and 8 were also assessed to have maximum and minimum voltage values, respectively. Finally, after a total of fifty-four minutes, the 12 cells stabilized to have an equal voltage of 3.705 V within a margin of 12 mV.

Figure 9 and 10 The design of the new charging circuit and control algorithm enhances the efficiency of charge transfer and maintains voltage balance in charging and discharge cycles. The design prevents the risks of charging and undercharging the battery since it has the capability to control the currents based on voltage measurement and predictions. Figures 9 and 10 show the cell voltages during charging/discharging as regulated by the proposed cell-balancing circuit.

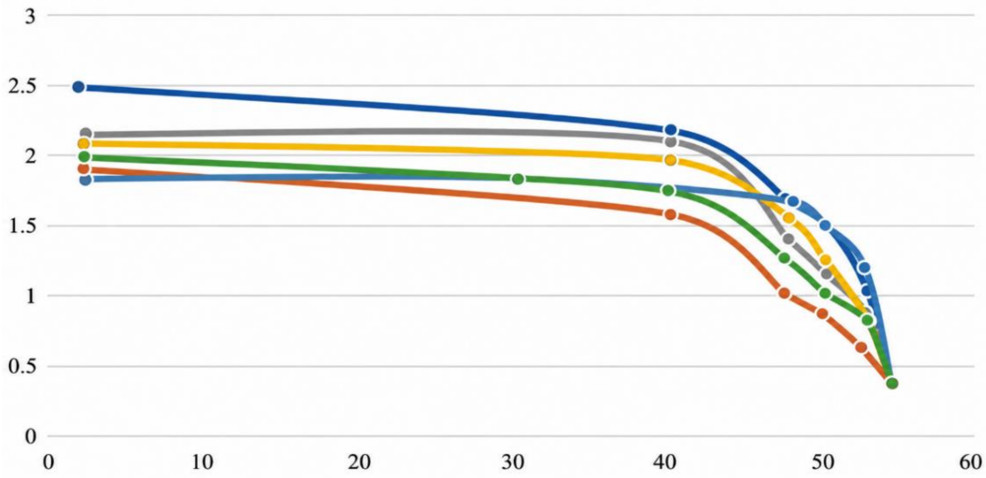

Figure 9. Cell voltages during charging as regulated by the proposed cell-balancing circuit.

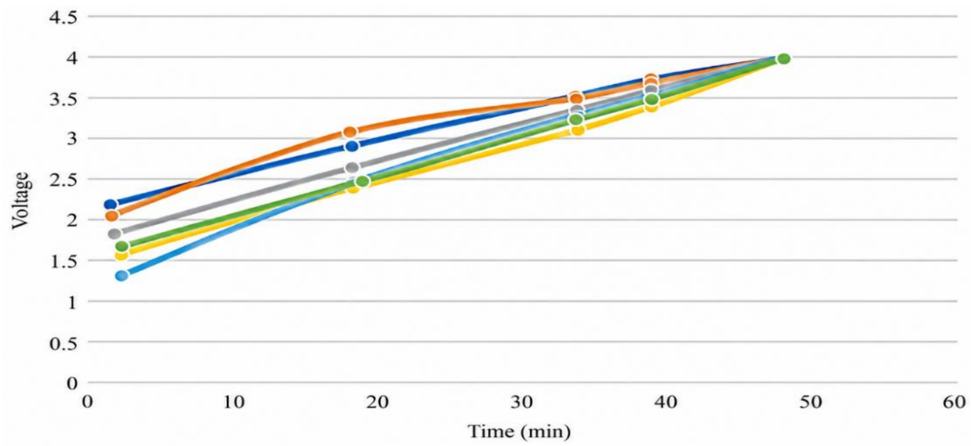

Figure 10. Cell voltages during discharging as regulated by the proposed cell-balancing circuit.

CONCLUSION AND FUTURE WORK

This paper presents an efficient and fast cell-to-cell active balancing circuit with low costs, where the DC–DC converter is exploited to directly balance the charge between cells in a series of cells. The test was performed on 12 lithium-ion cells, where their voltage was balanced within 48 min using a simple balancing strategy because it required less time than other balancing circuits. The new direct shift balancing strategy achieved an efficiency of 89.85%. In future studies, a better estimation of the state of charge should be achieved when considering aging, temperature effects, and dynamic behavior to improve the estimation performance. Developments in fault detection techniques, new advancements in cell balancing strategies, standardization of BMS interfaces, and sensors are important to improve performance and scalability for different applications, such as consumer electronics and x-by-wire applications in electric vehicles and other renewable energy applications in the future.

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