

CAPACITOR-BASED ACTIVE CELL BALANCING AND BALANCER DESIGN FOR BATTERY MANAGEMENT SYSTEMS

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ABSTRACT

This paper presents the development of a capacitor-based active cell balancing system and an accompanying control module tailored for lithium-ion battery packs used in electric vehicles. The system integrates multiple balancing topologies, including switched capacitors (SC), double-tiered switched capacitors (DTSC), and modular switched capacitors (MSC), offering flexibility for experimental evaluation. A control module equipped with an LCD interface, real-time clock (RTC), and data storage capabilities facilitates efficient monitoring and operation. Simulation results in previous work demonstrate the system's effectiveness in achieving balanced cell voltages and maintaining operational flexibility, paving the way for enhanced battery management in electric vehicle applications. By incorporating this experimental setup for the battery pack and balancer, we want to confirm the simulation results in future work.

Keywords: battery cell balancing, switched capacitors, active balancing topologies, electric vehicle batteries, Li-ion

1. INTRODUCTION

As electric vehicles (EVs) continue to gain widespread adoption, efficient lithium-ion battery (LIB) management has become increasingly critical. One of the key challenges in managing LIB packs is ensuring uniformity in the state of charge (SOC) across all cells. SOC imbalances can lead to reduced performance, decreased battery lifespan, and potential safety risks such as overcharging or overdischarging. This challenge is particularly relevant in large-scale battery systems, where variations in cell characteristics can accumulate over time [1], [2].

Cell balancing, also called cell equalization, is an essential battery management function to mitigate these imbalances. Cell balancing techniques can be broadly categorized into two types: passive and active. Both approaches offer specific benefits and drawbacks depending on the application requirements [3].

Passive balancing, which relies on dissipative elements such as resistors to equalize SOC by dissipating excess energy as heat, is simple and cost-effective but suffers from energy losses and slow balancing speeds. In contrast, active balancing transfers charge between cells using energy-storage components such as capacitors, inductors, or transformers, offering improved energy efficiency and faster balancing performance. However, active balancing methods also introduce added complexity in circuit design and control strategies [4], [5].

Among active balancing techniques, capacitor-based methods have gained particular attention due to their efficiency, flexibility, and scalability. Switched-capacitor balancing, double-tiered switched-capacitor balancing, and modular switched-capacitor circuits have demonstrated significant potential in improving the speed and effectiveness of charge redistribution [6], [7]. Our previous research focused on simulating different capacitor-based active balancing topologies using MATLAB and Simulink [8], [9]. These simulations revealed that while conventional switched-capacitor circuits provide adequate performance, more advanced configurations, such as double-tiered switched-capacitor circuits, achieve superior balancing

efficiency and speed under dynamic loading conditions. However, simulation-based validation alone is insufficient to confirm the real-world feasibility of these balancing techniques.

In this study, we build upon our previous findings by not only comparing different capacitor-based balancing topologies in simulations but also by developing a prototype balancer for experimental validation. This study focuses on the development of three key modules that constitute the complete active balancing system: the battery module, the control module, and the balancer module. Each of these components is addressed in detail within the scope of this article, highlighting their respective roles in ensuring effective cell balancing. The insights gained from this research contribute to the advancement of active balancing technologies, addressing key challenges in battery management for EVs and other energy storage applications.

2. CELL BALANCING

In lithium-ion battery packs, balancing is crucial to ensure uniformity in the SOC among cells connected in series. When cells are connected in series, the total voltage of the battery pack is the sum of the voltages of the individual cells. For optimal performance and longevity, all cells must operate within the same SOC range. An imbalance in SOC can lead to one cell reaching its voltage limits before others, potentially causing reduced battery efficiency, diminished lifespan, and safety risks [2]. Effective cell balancing addresses these issues by equalizing the SOC across all cells, thus maintaining the health and performance of the battery pack.

2.1. Passive Cell Balancing

Passive balancing is a method where excess energy from cells with higher SOC is dissipated as heat through resistors. This approach is straightforward and cost-effective, making it a common choice in many battery systems. However, it has significant downsides, including energy inefficiency, as excess energy is wasted rather than

redistributed. The process can also be slow, which may lead to not optimal performance if cells have substantial SOC imbalances. Passive balancing is typically used in scenarios where simplicity and low cost are prioritized over efficiency and speed [3].

2.2. Active Cell Balancing

On the other hand, active balancing involves transferring charge from cells with higher SOC to those with lower SOC. This method enhances energy efficiency by redistributing the excess energy rather than wasting it as heat. Active balancing systems are more complex and require advanced circuitry and control algorithms. Components such as capacitors, inductors, or transformers are often employed to facilitate energy transfer between cells [4].

One prominent technique within active balancing is capacitor-based balancing. In this method, capacitors are used to store and transfer energy between cells.

To improve the efficiency and speed of balancing, advanced structures like double-tiered switched-capacitor balancing have been developed. This approach employs two layers of capacitors, allowing for more direct and efficient energy transfer between cells. While this method enhances balancing performance, it also incurs higher costs due to the additional capacitors and increased battery size [7], [10], [11].

An additional capacitor can be added to a double-tiered switched-capacitor structure balancing to increase the speed of the balancing process. This capacitor connects the two outermost cells. Another method consists of adding capacitors between pairs or triplets, which can be used to increase the speed of the balancing process [7]. We call this method modular switched-capacitors (MSC).

In conclusion, balancing is essential for maintaining the performance and longevity of lithium-ion battery packs. While passive balancing remains a cost-effective solution, active balancing techniques, particularly those utilizing capacitors, offer superior efficiency and performance. The choice between these methods depends on the specific requirements of the battery system, including cost, complexity, and energy efficiency.

3. SIMULATIONS

In previous articles, we focused our research on switched-capacitors, where the simulations and results are more detailed [8], [9]. Multiple simulations have been conducted in MATLAB Simulink to achieve progress in this research area.

The initial focus was on the switched-capacitor circuit, followed by a double-tiered switched-capacitor circuit, and then a more advanced model incorporating an additional capacitor between the first and last cell. These simulations were carried out in MATLAB Simulink using 12 lithium-ion cells. The simulations were conducted using the same initial parameters across all cases, with different SOC values for individual cells but consistent within each simulation. The balancing process was then activated using

various topologies. The parameters we compared included the final SOC after 2000 seconds of simulation and the specific time at which the SOC difference between the highest and lowest SOC reached exactly one percentage point.

In the first simulation, we implemented the switched-capacitor circuit, achieving a one percentage point SOC imbalance in 1312 seconds. The second simulation, using the double-tiered switched-capacitor circuit, improved this time to 1186 seconds, demonstrating faster balancing due to the additional capacitor layers. However, in the third simulation, where we introduced another capacitor between the first and last cell, the balancing process slowed slightly, taking 1195 seconds.

Comparing these results, the double-tiered switched-capacitor circuit proved most effective, achieving the smallest SOC difference after 2000 seconds (0.65 percentage points), followed by the version without the additional capacitor (0.68 percentage points), and lastly, the basic switched-capacitor circuit (0.72 percentage points). These findings highlight the potential of capacitor-based balancing circuits to enhance performance, though modifications like adding extra capacitors do not always yield improvements.

Further research involved refining the battery model to better meet real-world conditions by incorporating real cell impedance measurements. The simulations were extended to include dynamic loading, involving charging, discharging, and idle phases. Cells with varying SOC values were used to test balancing performance under realistic conditions. The double-tiered switched-capacitor circuit was selected for these simulations, which showed that greater initial SOC imbalances led to faster balancing due to larger voltage differences between cells. However, current spikes during switching to constant voltage charging suggest a need for further research to optimize these circuits for real-world applications. More is mentioned in [8].

4. HARDWARE REQUIREMENTS AND SOLUTION ANALYSIS

To validate our simulation results, we will design and build the hardware for the balancer. To ensure modularity, flexibility, and ease of modification, we have divided the hardware into three distinct PCB modules: the battery module, the control module, and the balancer module. The modules will be interconnected with cables and wires. The control module is crucial for enabling real-time monitoring, creating controlled disbalances in individual cells to ensure repeatable initial test conditions, and collecting data during charging and discharging processes. Additionally, it will manage the independent balancer module. A key advantage of this design is that a single control module can operate various balancing circuit configurations in the future.

We designed the modules using Fusion software, where we created both the circuit schematics and PCB layouts. This modular concept does not only simplify future adjustments but also enhances the system's versatility and adaptability to different setups.

Table 1 Used devices and parameters

Devices, parameters	Parameters	
Battery module	Custom made	
Battery cell LithiumWerks (LFP)	APR18650M1B	
Battery cell nominal voltage	3.3	V
Battery cell capacity	1.2	Ah
Impedance (1 kHz AC)	12.6	mΩ
Control module	Custom made	
Microcontroller (Microchip)	AVR128DB64	
Voltage sensing board (Texas Instruments)	TLE9012DQU	
Balancer module	Custom made	
Transistor N-MOSFET (Shindengen)	P140LF4QL	
Gate driver (Texas Instruments)	UCC21330BDR	
Capacitor capacitance	4700 / 10000	μF
Switching frequency	1	kHz
Deadband	500	ns

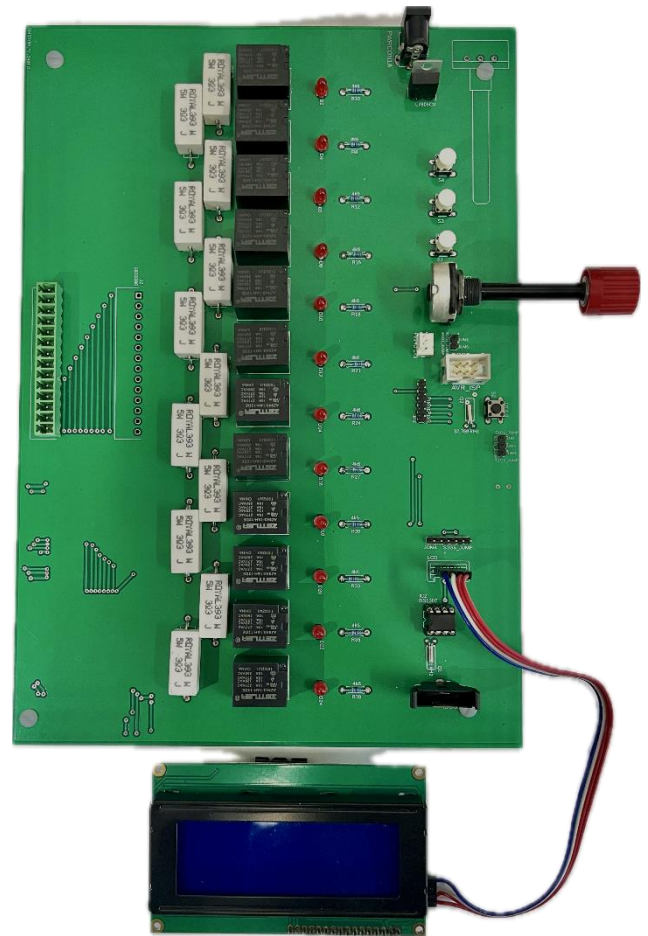
4.1. Battery module

The battery module is composed of cell holders arranged in series, with each cell terminal connected to a dedicated connector. These connectors serve for both voltage sensing and balancing. To protect the circuitry, the signals are routed through SMD fuses. This module is illustrated in Fig. 1. Additionally, for further protection, we included a fuse holder for the entire battery module with a fuse rating of 6 A. The SMD fuses used for battery voltage sensing are rated at 3 A. Furthermore, we incorporated an ACS712-05 current sensor into the circuit. This sensor provides an analog output and is capable of measuring currents in the range of -5 A to 5 A. It requires a 5 V power supply, and thus, a connector for both power and signal is included on the PCB, allowing the data to be processed by a microcontroller. This setup also enables quick battery cell replacement. LFP-based battery cell APR18650M1B from Lithium Werks is used for our purposes.

**Fig. 1** Battery module

The PCB for the battery module has dimensions of 138x284 mm. The components were strategically positioned to minimize trace lengths. The PCB was designed as a single-sided board, and where necessary, vias

were used to bridge connections through the top layer. In areas of the board where there were no traces, a copper pour was left. This copper pour is not connected to any signal and was mainly left to expedite the manufacturing process of the PCB.

**Fig. 2** Control module with LCD display

4.2. Control module

The control module is composed of two main sections. The first section is the control unit, which houses the microcontroller, signal processing components, data storage, an RTC (real-time clock) circuit, a programming connector, and connectors for interfacing with external devices and the human-machine interface (HMI).

The second section is designed to achieve the desired initial state of individual cells. This section consists of a set of discharge resistors, which are connected to the individual battery cells via switching relays. The principle of operation is as follows: based on user settings, specific cells are connected by a signal from the microcontroller to a discharge resistor for a predetermined period. This process continues until the desired voltage level for each cell is reached. This design allows precise control over the cell voltages, ensuring that the battery is appropriately balanced or unbalanced and ready for further testing or operation.

The PCB dimensions are 180x260 mm and it is constructed from FR-4 material, known for its durability and stability, making it ideal for this application.

4.2.1. Control unit

The entire PCB is powered by a 12 V power supply. This 12 V supply is primarily used for switching the relay coils. Since the microcontroller operates at 5 V, we achieve the required voltage using an L7805 voltage regulator to step down from 12 V to 5 V.

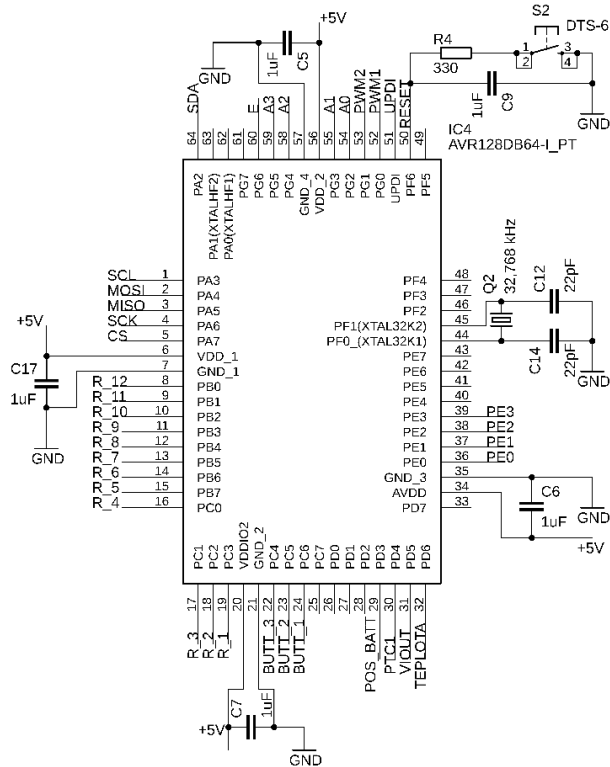


Fig. 3 Microcontroller connection schematic

For this project, we selected the AVR128DB64 microcontroller from Microchip, housed in a 64-pin SMD package. It features 128 kB of flash memory, a maximum frequency of 24 MHz, and supports I2C (Inter-Integrated Circuit) and SPI (Serial Peripheral Interface) communications. Additionally, it includes 22 12-bit differential analog-to-digital converters (ADC). This microcontroller was chosen for its extensive control signal capabilities, which align with the modular design approach, allowing for future expansion to accommodate additional signals or devices as needed. The basic schematic of the microcontroller is shown in Fig. 3.

The microcontroller requires four power circuits, a reset circuit, and an external crystal to achieve a frequency of 32.768 kHz. It is connected to 12 digital signals for switching the discharge resistor relays, 3 user interface buttons, control signals for MUX switches, a programming connector, PWM outputs, and SPI/I2C communication interfaces. The analog-to-digital inputs and outputs are used for monitoring the individual cell voltages, controlling the potentiometer, and measuring the battery temperature.

I2C communication is used to control both the display and the RTC circuit. I2C (also known as TWI, or Two-Wire Interface) is a bidirectional synchronous serial bus, commonly used in embedded systems for short-distance communication between integrated circuits.

For our design, we utilized a 20x4 character LCD display as our HMI interface, which offers enough space to

show key information such as cell voltages, temperature, time, date, and current in the user interface. Typically, connecting this type of display to a microcontroller requires 16 wires. To minimize I/O port usage, we chose a version with the PCF8574 module, which serves as an 8-bit I/O expander for the I2C bus. This modification reduces the connections to just four wires. Two for power (5 V and GND), and two for the I2C communication lines (SDA and SCL). With an I2C address set to 0x27, this chip allows control of both data transmission and display backlight. This setup simplifies the circuit design and optimizes the use of microcontroller ports. It is shown in Fig. 4.



Fig. 4 PCF3874 module for LCD display

The control module board is equipped with 4 buttons and a potentiometer to facilitate user-friendly operation of the balancing program through an LCD display. One button serves as a reset function, another as a confirmation key, while the remaining two buttons are intended for navigation or other tasks to be defined during programming.

The RTC module tracks seconds, minutes, hours, the day of the month, the month, the day of the week, and the year. The module also features a 3V coin-cell battery slot to maintain timekeeping in the event of a main power (5 V) failure. For this project, we selected the DS1307 RTC, known for its low power consumption and 56-byte SRAM memory. The module operates with an external 32.768 kHz oscillator for clock precision. Data and address transmission are handled via a 2-wire bidirectional I2C bus using SDA and SCL connections. The DS1307 includes a built-in power failure detection circuit that automatically switches to battery power during outages.

Data storage is managed through SPI communication between the microcontroller and a microSD card. For the microSD card, we selected a module that includes both a power level adjustment for the card and a logic level shifter to convert from 5 V to 3.3 V for communication. This module is designed with a connector on the PCB. Data such as current measurements, cell voltages, and timestamps are stored on the microSD card, providing a comprehensive record of the battery performance over time.

When addressing the voltage sensing of individual battery cells, we encountered a challenge: although the microcontroller has enough differential ADC inputs, it was not possible to connect all the cells directly. Our battery consists of 12 cells connected in series, meaning the last cell would have a voltage exceeding 38 V, which could damage the microcontroller. To solve this, we implemented a system where only one cell is connected to the processor at a time. This is achieved using two analog-to-digital

multiplexers HEF4067BT.653. One multiplexer connects the positive terminal of the cell to the ADC input of the microcontroller, while the other connects the negative terminal to the ground. This setup ensures that the sensed voltage remains below 4.2 V, which is the maximum voltage for a single cell. The multiplexers are controlled by four digital signals that select the desired output. Both multiplexers are designed to be controlled by the same signals, ensuring synchronized operation.

During initial testing, this circuit configuration proved to be non-functional due to the multiplexer's internal structure. In a series-connected battery pack, voltage differences between cells created unintended current paths through the multiplexer's internal diodes. This makes ADC voltage measurements impossible. Consequently, an alternative solution was adopted for cell voltage sensing. The TLE9012DQU development board from Texas Instruments (Fig. 9 above battery cells) was selected and used for accurate cell voltage monitoring. This change required a minor modification to the transistor gate drivers: the bootstrap capacitor could no longer be used and two independent isolated DC/DC converters were required for gate operation. Without this adjustment, the bootstrap path would connect the DC/DC converters in series, creating a high-voltage source that could damage other devices. This connection is further described in section 4.3.

4.2.2. Discharge unit

The discharge circuit, as previously mentioned, is designed to bring the battery cells to their initial state for subsequent experimental measurements. The core component of this circuit is the discharge resistor AX5W-3R3, with a resistance value of $3.3\ \Omega$ and a power rating of 5 W. We selected this resistor to ensure that the discharge current does not exceed 1C (1.1 A). This resistor is connected to the cell through a relay switch AZ943-1AH-12DE, whose coil is controlled by a 12 V signal. Since the control signal from the microcontroller operates at 5 V, we use a BC817-40W-R1 transistor to switch the 12 V required for the relay coil. When the contacts are closed, the resistor is connected to the cell, and an LED indicator lights up to signal that the discharge is active. The detailed discharge circuit for the first cell is shown in Fig. 5, and this design is replicated for all twelve cells.

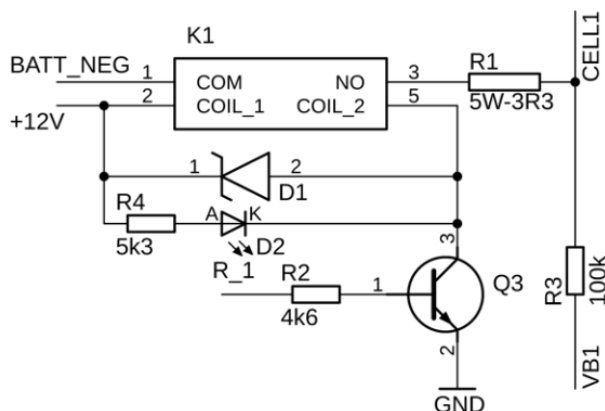


Fig. 5 Discharge circuit

4.3. Balancer module

The balancer module is basically composed of switches and capacitors, designed for flexibility and adaptability in research applications. Multiple capacitor-based active cell balancing topologies are integrated into the board, with various configurations connected through jumpers (Fig. 7). These jumpers allow for reconfiguration, enabling the use of different balancing topologies or adjusting the number of capacitors involved in the balancing process. N-channel MOSFETs (P140LF4QL) serve as the switches, with two of them assigned per cell to manage the balancing process. Each cell is connected to the balancer circuit through a multi-pin connector, ensuring secure and efficient integration with other modules. PCB dimensions are 172x360 mm and it is also constructed from FR-4 material. Balancer module board is depicted in Fig. 6.

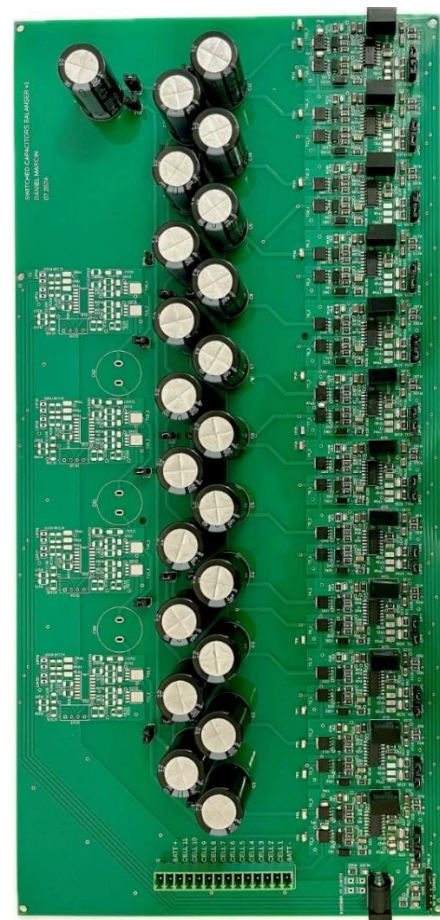


Fig. 6 Balancer module

To ensure precise measurements during balancing research, the battery cells do not supply power to auxiliary circuits. Instead, two dedicated power supplies are used. A 12 V supply to control the MOSFET gates, and a 5 V supply for the driver circuits that manage each MOSFET pair. These power supplies are shared with the control unit. PWM signals from the microcontroller in the control unit controls the balancing operations, utilizing two complementary PWM signals (PWM_A, PWM_B). For monitoring, LED indicators display the status of the 12 V, 5 V, and PWM inputs. However, the TLE9012DQU development board is designed to draw power directly from the monitored cells, so it could not be wired differently.

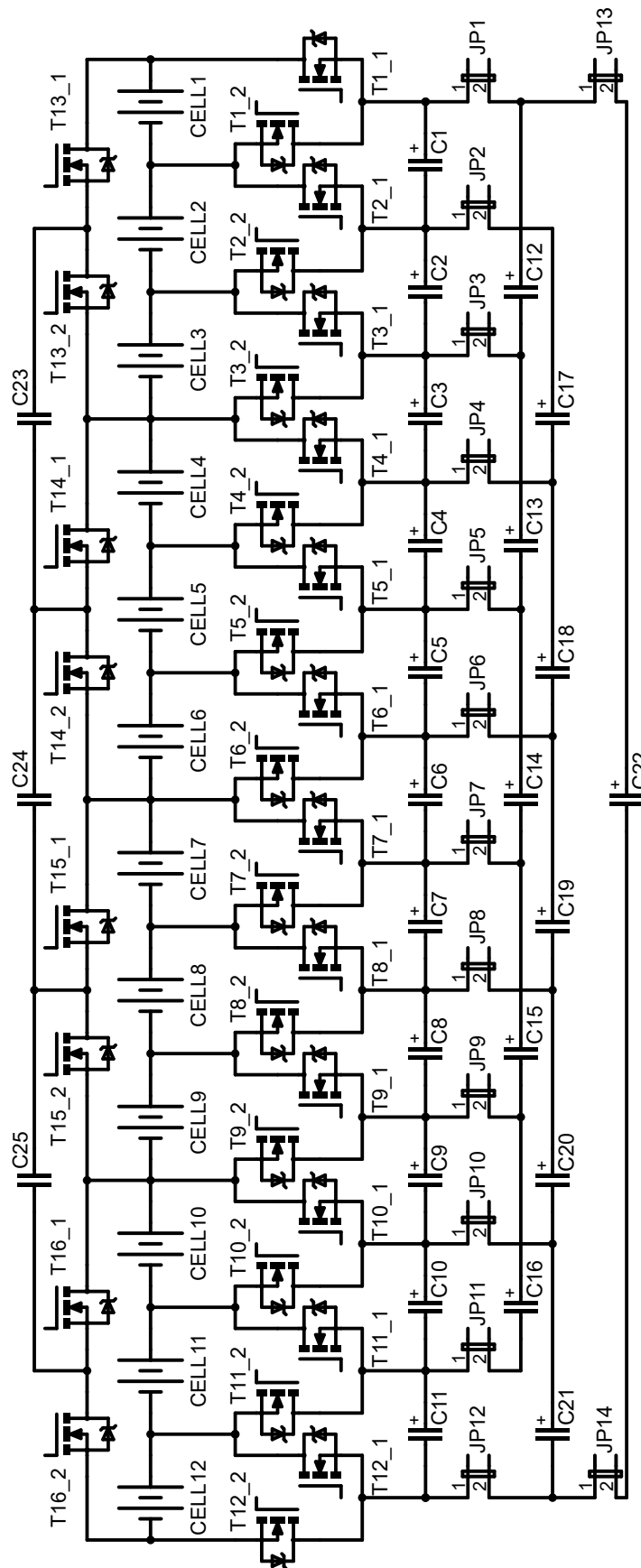


Fig. 7 Simplified electrical connection of balancer module

Each pair of MOSFETs is driven by an isolated dual-channel gate driver (UCC21330BDR) with programmable dead time. This driver operates on the 5 V supply for input logic, which also serves as a reference for the PWM signals. RC filters are placed at the inputs for both the PWM signals and the power supply, based on the manufacturer's specifications. A 56 k Ω resistor R_{DT} is used to set the dead time to approximately 500 ns. The high-side transistor and the low-side transistor are powered by a pair of 12 V-to-12 V isolated DC/DC converters, one for each output channel. The turn-on resistance is managed with a 15 Ω R_{ON} resistor, while turn-off is facilitated by a Schottky diode and a 3.3 Ω R_{OFF} resistor. This electrical schematic is shown in Fig. 8 and is repeated 12 times for operating 12 battery cells. In the actual setup, the schematic from Fig. 8 was modified by removing the bootstrap capacitor and using two separate DC/DC converters for the VDDA (VDD for high-side channel) and VDDB (VDD for low-side channel) supplies. This adjustment was necessary to accommodate the integration of the TLE9012DQU development board.

As detailed earlier, multiple capacitor-based active cell balancing topologies are integrated into the electrical

schematic in Fig. 7 through jumpers. Four distinct balancing topologies are implemented:

- Switched-capacitors (SC).
- Double-tiered switched-capacitors (DTSC).
- Double-tiered switched-capacitors with an Additional capacitor (DTSCAC).
- Modular switched-capacitors (MSC).

The SC topology employs 11 capacitors ($C1 - C11$) and 24 transistors ($T1_1 - T12_2$). The DTSC topology builds on SC by adding 10 additional capacitors ($C12 - C21$). The DTSCAC configuration further extends DTSC by incorporating one more capacitor ($C22$). The MSC topology introduces a unique approach by connecting capacitors across triplets of cells. This configuration uses three additional capacitors ($C23 - C25$) and eight additional transistors ($T13_1 - T16_2$). However, the use of additional transistors is not required in this configuration.

These configurations provide a modular and flexible platform for evaluating different balancing strategies within the same hardware design.

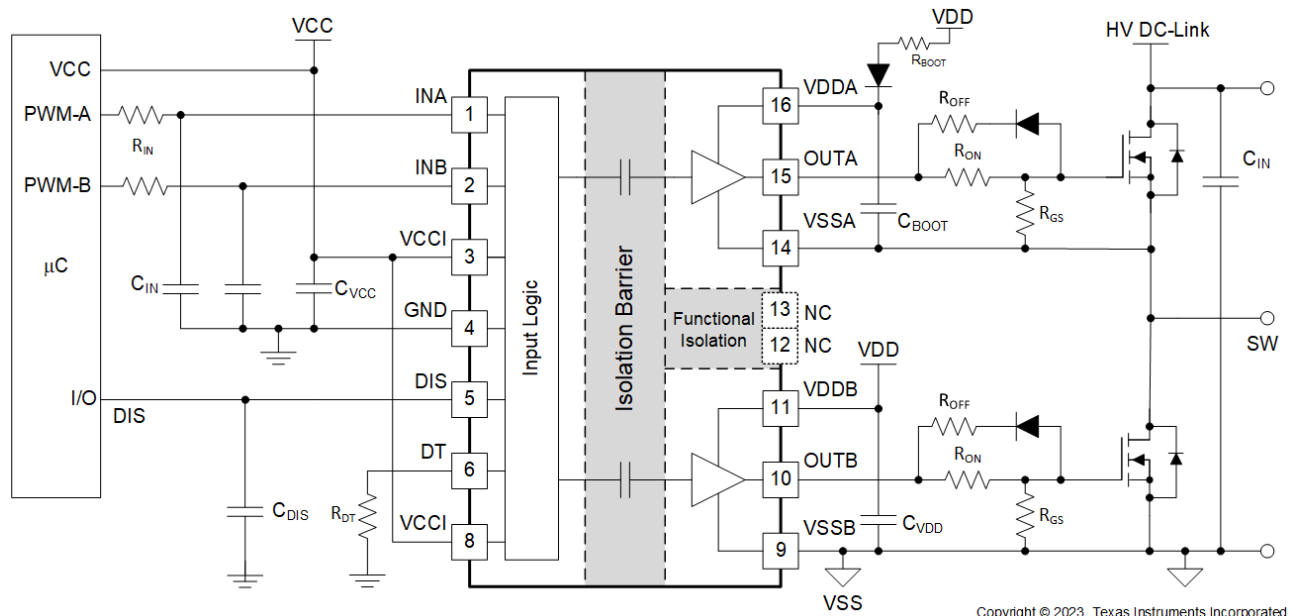


Fig. 8 Electrical connection of UCC21330BDR gate driver

To optimize the performance of each topology, capacitors with distinct capacities and voltage ratings will also be utilized. These variations are necessary due to the

differing connections within the topologies, as some capacitors connect in parallel to one, two, or three cells, depending on the specific balancing strategy employed.

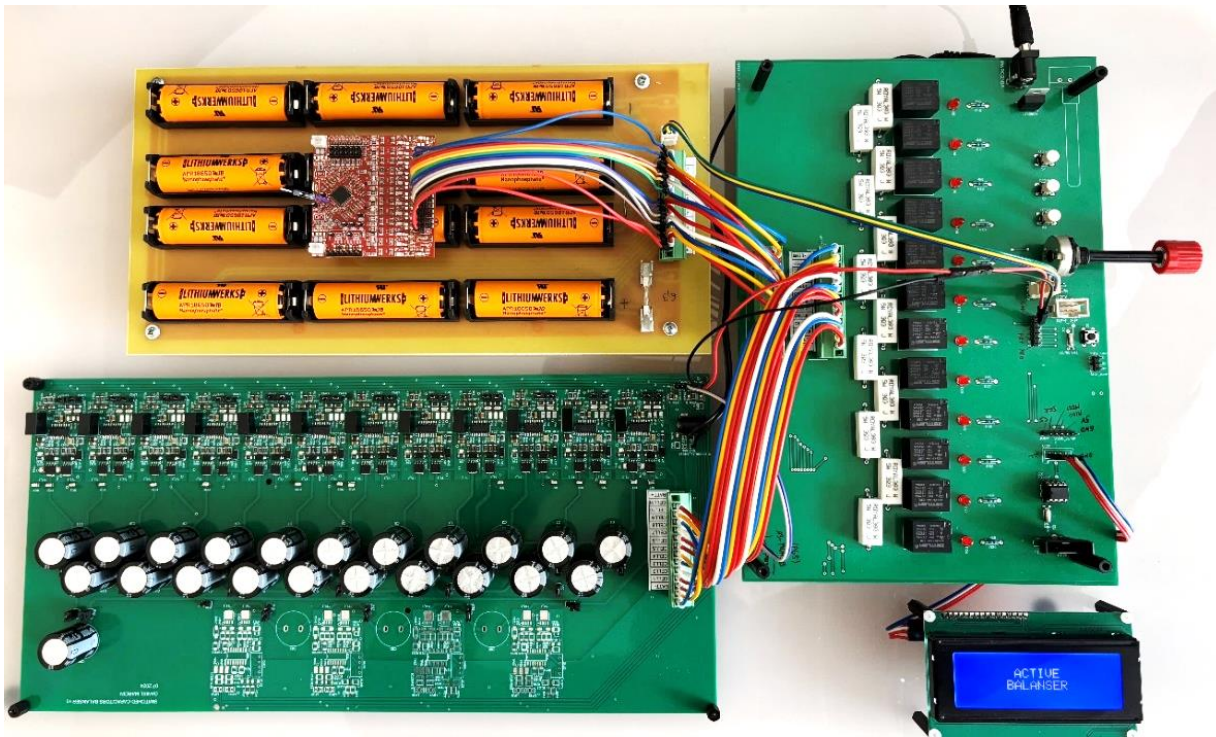


Fig. 9 Full balancer setup with wiring during software programming stage

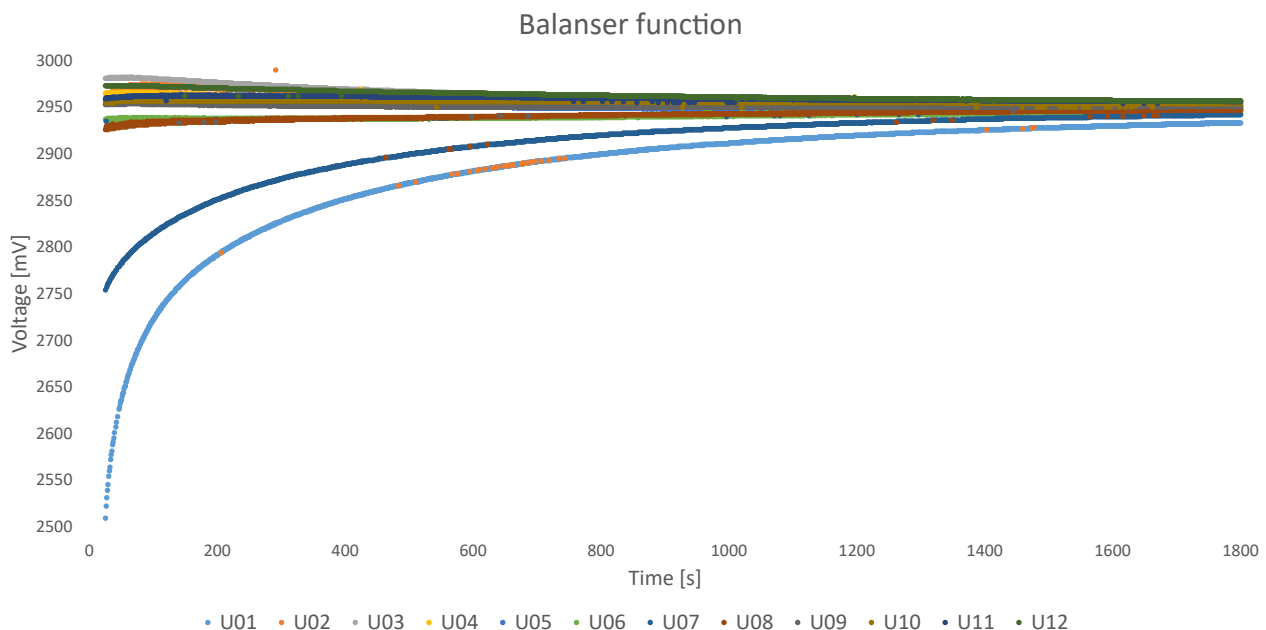


Fig. 10 Preliminary results from balancer – first measured data during balancing process on slightly unbalanced pack

5. RESULTS

The developed system (Fig. 9) was prepared for a 12-cell lithium-ion battery pack. Key results include:

- Voltage balancing using multiple capacitor-based topologies (SC, DTSC, and MSC configurations).
- Implementation of a discharge circuit for establishing precise initial balancing conditions.

- Comprehensive performance tracking enabled by data logging functionality via the microSD module, including timestamps and cell voltages for further analysis.
- A modular design that allows seamless switching between topologies, enhancing research flexibility.
- Construction of a real-world experimental model, providing a robust platform for future research.

- Preliminary evaluation (Fig. 10 Preliminary results from balancer – first measured data during balancing process on slightly unbalanced pack Fig. 10) demonstrates that the device functions as intended, with fully implemented software enabling accurate measurement of all cell voltages. The active balancing process has been successfully initiated and verified for correct operation. Detailed experimental results will be reported in a forthcoming publication.
- Functional software, discharge unit and balancer module according to results from Fig. 10.

These results demonstrate the practicality and effectiveness of the system for further experimental studies.

6. CONCLUSIONS

This work presents a practical and effective approach to active cell balancing for lithium-ion battery systems using capacitor-based topologies. The proposed system incorporates switched capacitors (SC), double-tiered switched capacitors (DTSC), double-tiered switched-capacitors with an additional capacitor (DTSCAC), and modular switched capacitors (MSC), offering a versatile platform for future experiments. The accompanying control module is the head of this setup, and it also enhances the system's functionality by providing real-time monitoring, data storage, and user-friendly operation through an LCD interface. Previous simulation results validate the system's ability to maintain balanced cell voltages, contributing to the importance of continuing this research.

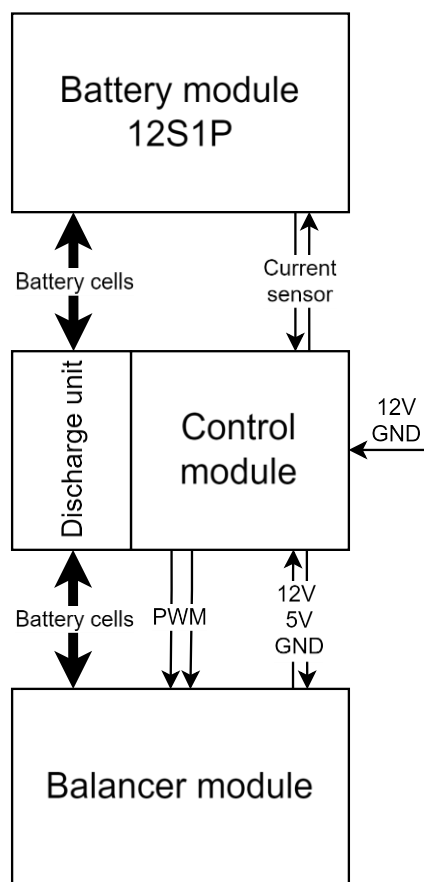


Fig. 11 Battery module, control module, balancer module interconnections

The primary aim of this work is to establish a real-world model capable of replicating the simulation outcomes and facilitating direct comparison with experimental results. This work focuses on the development of a fully integrated system, comprising a 12-cell battery pack, a control module, and a balancer module. The control module is interconnected with both the battery and balancer modules, incorporating the afore mentioned capacitor-based topologies to enable required cell balancing. This research serves as a foundational step for further refinement and real-world application of active balancing technologies in electric vehicles, where efficiency and reliability is critical. By bridging theoretical concepts and practical experimentation, this work contributes significantly to advanced energy storage technologies. The developed system, comprising a 12-cell battery pack, a control module and a balancer module, has been successfully tested, and all functions including cell voltage monitoring and active balancing operate as designed.

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BIOGRAPHIES

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Milan Lacko received an MSc. and a PhD. degrees in electrical engineering from the Technical University of Kosice, Kosice, Slovakia, in 2005 and 2010, respectively. He is currently an Associate Professor in the Department of Electrical Engineering and Mechatronics, Technical University of Kosice, where he is engaged in teaching and research. His field of interest includes microcontrollers in embedded systems, digital signal controllers, and design of power electronics converters.