BATTERY MANAGEMENT SYSTEM IN AUTONOMOUS SURFACE VEHICLES FOR WATER QUALITY MONITORING

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***Abstract*— This project demonstrates the design and development of a Battery Management System (BMS) made for a 6 cell LiPo battery pack used in an Autonomous Surface Vehicle (ASV). The BMS architecture involves real-time voltage and current monitoring. State of Charge (SoC) is assessed using the traditional Coulomb Counting approach, The design also includes passive cell balancing to reduce cell drift and over-charging. An MSP430 microcontroller is used for data acquisition, control logic and communication. A third-order Thevenin (3RC) equivalent circuit is employed for battery modeling to represent the batteries' dynamic responses. The BMS algorithms are executed and illustrated using Simulink. Also, a hardware PCB design was adapted in EasyEDA using the Texas Instruments BQ76930 monitor IC as the main component, which implements measurement, balancing and protection features without the need for battery modelling. The simulation results showed accurate SoC tracking with errors between 2-3% for EKF estimation and 0-1% for UKF, successful balancing of a 6-cell pack, and consistent CCCV charging performance. Compared to traditional baseline BMS implementations, the proposed design demonstrated higher estimation accuracy and shorter balancing time, making it a more efficient alternative for ASVs.**

This research work's goal is to provide a compact, low-power and scalable BMS solution suitable for ASV applications where efficiency and operational safety are of utmost importance.

Keywords*— Autonomous Surface Vehicles, Battery Management System, Coulomb Counting, Extended Kalman Filter, Unscented Kalman Filter, LiPo batteries, Passive Cell Balancing, Thevenin Equivalent Circuit

I. INTRODUCTION

Autonomous Surface Vehicles are becoming increasingly popular for adaptation in fields such as water quality monitoring and environmental research mainly because of their ability to operate in remote and hard to reach areas. In order to increase duration of the missions done by an ASV, an efficient and reliable power system is required to ensure safe operation and maximize battery life. Since batteries are the only source of energy, their performance, safety and battery life must be managed properly to prevent risks such as overcharging and battery degradation. [1], [2].

A Battery Management System (BMS) is essential for proper usage of the battery, monitoring key parameters, estimating the State of Charge (SoC) and performing cell balancing.

Despite extensive research on BMS, most exciting new studies focus on EVs or energy storage systems, with limited emphasis on ASVs. In this work, a dedicated BMS architecture for ASV is proposed which includes battery modelling, advanced state of charge estimation techniques(EKF, UKF) and passive cell balancing for 6-cell LiPo battery pack configuration.

II. RELATED WORK

A. Battery Management System (BMS)

The task of a BMS is essentially to make sure the use of the energy inside the battery is safe and optimized. Also, providing accurate battery state data for the vehicular energy management system. It should also be able to intervene when the battery system is not operating in normal conditions. This can be accomplished by keeping an eye on and managing the battery's charging and draining processes [4].

1) **Battery Modelling**

Building an accurate and functional battery model is the fundamental to BMS design. There are different types of battery models which mainly depend on the complexity of the application. We mainly focus on Equivalent Circuit Model (ECM) for this research.

Equivalent Circuit Model or ECMs are used to incorporate the battery SoC by utilizing its relationship with the battery Open Circuit Voltage (OCV). The battery's OCV is estimated using the model and then the OCV-SoC curve is used to calculate the required SoC [6].

One of the most common ECMs is the Thevenin-Based Model. It predicts battery response to transient load events at a particular state of charge (SOC), by using OCV-SOC relationship and curve. From the review found in [7] and [3], the dynamic behavior of batteries is well captured by the Thevenin model.

2) **State of Charge**

The SoC is a crucial factor in battery operation, representing the level of charge relative to the battery capacity, SoC indicates the remaining amount of energy in a battery. The determination of battery SoC is a fundamental aspect of BMS. Accurate and reliable SoC estimation is crucial for vehicle energy management and the optimal design of control systems [3], [6].

a) SoC Estimation Methods:

The SoC estimation is an important function of the BMS and is the basis for the implementation of the control strategies. One of the methods that are frequently employed for estimating a battery's SoC are The Ampere Hour (Ah method) / Coulomb Counting (CC) which is calculation of the current SoC based on known SoC at a previous moment, and the charge and discharge capacity of the battery recorded during a certain period [6].

The **Open Circuit Voltage (OCV)** method is one of the fundamental methods of estimating SoC. It mainly relies on the relationship between the battery's SoC and the terminal voltage of the battery when the battery is at rest.

Model Based Estimations (EKF, UKF)

In Model Based approaches, a battery model needs to be designed to fit the requirements of the application.

One of the more advanced and commonly adopted estimations techniques is the Extended Kalman Filter (EKF). It offers flexibility through its ability to be compatible with different battery models and allows the usage of non-linear systems, making it highly suitable for real-time SoC under dynamic conditions. EKF handles the system non-linearities by approximating the mathematical model around the current state estimate using a first-order Taylor expansion. This approach allows EKF to apply KF principles to non-linear systems enabling the recursive estimation of the inhabited state [5].

The Unscented Kalman Filter (UKF) is an advanced estimation method that improves on the EKF. Instead of using Taylor's expansion to try and linearize the battery's nonlinearity, it employs a sampling method known as the sigma points to capture real statistical moments of the battery's non-linear behavior. Compared to the EKF, it can offer a more precise SOC estimation.

3) Cell Balancing

Cell balancing is typically making all the cells in the battery charge and discharge at same time instead of each cell having a different SOC.

Passive Cell Balancing is one of the commonly used techniques when it comes to cell balancing, as described in [8] it works by dissipating the extra energy from the cells through a resistor. The clear disadvantage of this method is that it is inefficient due to wasting energy to maintain the balance.

4) Battery Charging Techniques

The Constant Current Constant Voltage (CC-CV) charging method is said to be standard for Lithium-Ion batteries charging for providing a balance between faster charging, safety and ease of implementation. [9]

III. PCB And System Design

This section presents a system overview of the proposed Battery Management System design, which includes a description of the planned components and aspects of the system design. Each section will briefly explain the choice made for the design according to the specifications needed for the application. Afterwards, a PCB design will be shown and explained, showing how the system can be implemented into a real-life hardware solution suitable for the ASV, the design was carried out using EasyEDA software.

A. System Overview

The Battery Management System (BMS) consists of voltage and current sensing, State of Charge estimation, control, and safety blocks. The voltage and current measurements will be carried out using an integrated Texas Instruments BQ76930 battery monitor IC. An MSP430 microcontroller will be used to manage passive cell balancing and prevent over/under-voltage and overcurrent risks. A dedicated external charger will be used to charge the battery.

B. PCB Design

A PCB was designed to interpret the system into a real-life hardware system suitable for the ASV, the design was carried out using EasyEDA software. The PCB design includes the use of a real-life application Texas Instruments BQ76930 Battery Monitor [10], according to its datasheets, it supports 3-10 cell Li-ion/LiPo batteries, it provides voltage monitoring, temperature and current sensing and passive cell balancing.

The BQ769x0 was chosen specifically because it features flexibility in implementation and highly integrated feature set and low power consumption.

The design is based on a 6-cell design consideration from the datasheet which integrates all the required components for the design of a high-performing BMS and it could be viewed in [11].

It communicates with the microcontroller, the Texas Instruments MSP430 via I²C, by connecting the dedicated pins (SDA, SCL). The role of the microcontroller is handling the SoC estimation and controlling the FETs based on the value of the voltage preventing overvoltage and undervoltage risks.

As noted in the bq769x0 data sheet, the bq769x0 family is flexible in the number of cells. For every cell count, the datasheets explain how the pins are supposed to be connected, and which ones are supposed to be shorted, as the BQ76930 has ten VC pins.

These pins (VCx) are connected to sense and monitor the voltage levels of the battery pack. The current is measured by a shunt resistance between the SRP and SRN pins, the value of the resistance is scaled according to the required current thresholds, which in our case aligns to the requirements, so the value of the shunt resistance is kept the same as the design configuration.

The bq769x0 family has integrated cell balancing FETs, which make it simple to implement cell balancing. Low-pass filters are still required for the input of the cell pins to prevent noise and spikes.

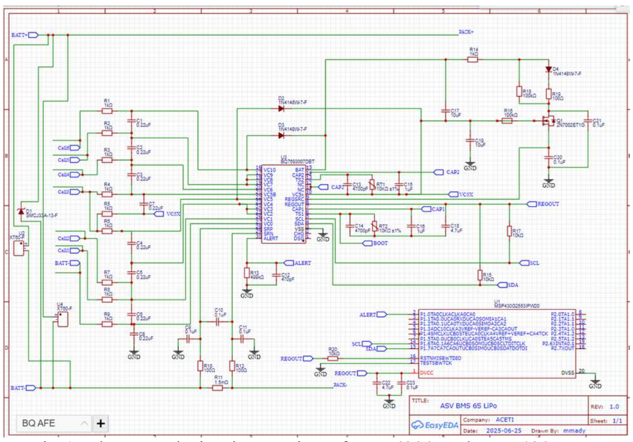

Fig 1. The PCB design integration of BQ76930 and MSP430.

The design was adapted to the EasyEDA software, with the confirmation of values for the components being suitable for the ASV application and the battery specification. Fig. 1 shows the design that integrates between the MSP430 and the BQ76930 with all the appropriate pins being connected for proper BMS operations.

After the initial schematic design of the components was completed in EasyEDA software, the next step was to translate this schematic into a practical printed circuit board (PCB). This was achieved by switching from schematic capture mode to PCB layout mode within EasyEDA. In this stage, component footprints were assigned, electrical connections from the schematic were automatically imported, and the physical arrangement of the components on the board was optimized. Careful attention was paid to trace widths, ground planes, and thermal considerations to ensure the board could safely handle the expected current levels and provide reliable operation within the ASV's environment.

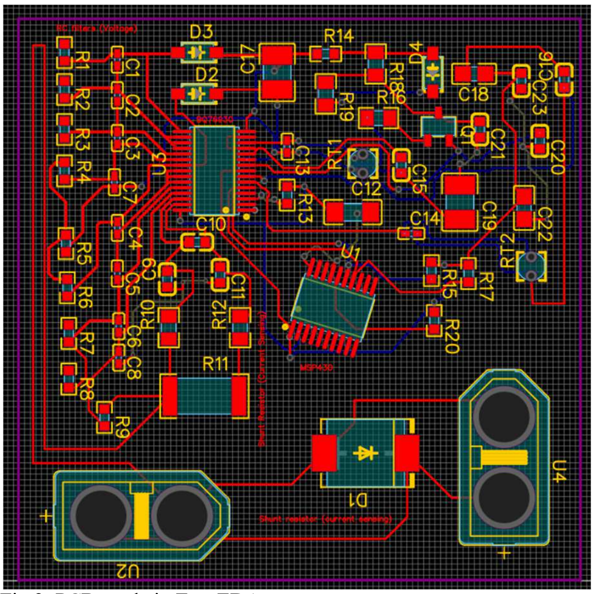

Fig 2. PCB mode in EasyEDA

This design of the BMS PCB has been adopted within EasyEDA, and the final layout is ready to be fabricated. However, due to the tight project timeline, it was not possible to have it fabricated on time before the submission deadline. Therefore, the validation and testing phase of the hardware PCB remains as future work to be done. To complement this setback, the following section of the system algorithm simulation has been carried out in the project.

IV. System Algorithm Simulation

This section shows the implementation of the proposed Battery Management System (BMS) by means of simulation. The simulations were implemented to describe the functionality of the algorithms for Battery Modelling, SoC Estimation, CCCV Charging and Passive Cell Balancing.

A. Battery Modelling in Simulink

The simulation of the battery model was primarily based on the Battery Equivalent Circuit block provided in Simulink; The block provides the flexibility to select between 0- and 3-time constants, i.e. (Rint, 1RC, 2RC, 3RC), depending on the level of accuracy wanted in the application. The model also allows for the incorporation of the temperature of the cell which gives a more realistic simulation of the battery behavior under varying thermal conditions.

A Hybrid Pulse Power Characterization (HPPC) test was done to obtain the battery data, the test in theory is very similar to the discharge test to obtain the OCV-SoC relationship curve, earlier discussed in the related works section.

An open-source MathWorks library example was adapted in this application, they used a Lithium-Polymer (LiPo) battery with similar specifications to the battery used for the ASV in this project, however not identical. The test was performed at a series of different temperatures and the equivalent circuit parameters were obtained and used for the simulations.

The data obtained from the MathWorks library example which contains the *Em* (terminal voltage), *R0* (Internal resistance) and values for 3 *RC* pairs for 3 different temperatures in Kelvin [278.15 293.15 313.15] taken at 0.1 SoC intervals.

B. SoC Estimation Methods

In this project, several methods of estimating the battery's state of charge (SoC) were used. The Battery Equivalent Circuit block in Simulink can internally estimate the SoC by integrating the supplied current over time, which is based on the Coulomb Counting (CC) method, and is taken to be the 'Real SoC' in this scenario.

The MathWorks example used adapted the Extended Kalman Filter to estimate the battery's state of charge and compare it with the Real SoC. To improve the accuracy of the estimation even more, the Unscented Kalman Filter (UKF) was tried and compared to the other methods.

The model for the SoC estimation is shown in Fig.4, which was modified to add CCCV charging block instead of a random pulse current input. The estimated SoC using the EKF algorithm is being compared to the 'Real SoC' which is based on the CC method as discussed earlier.

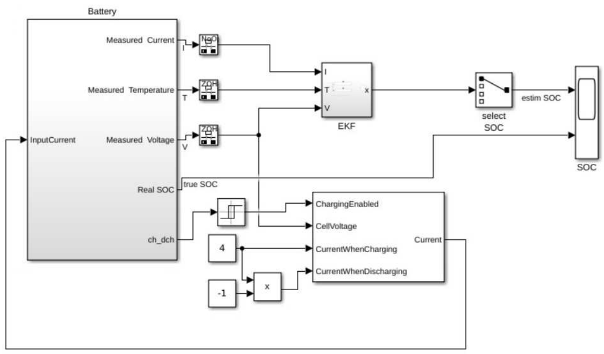

Fig. 3 The Simulink model for the battery SoC estimation

A Relay block was also added to the system, in addition to the presence of the state transition block, they together control the current at which is being introduced to the battery. The charging process is triggered only when the lower SoC threshold of 0.3 is reached and on the other hand the discharging starts when the limit of 0.9 is reached.

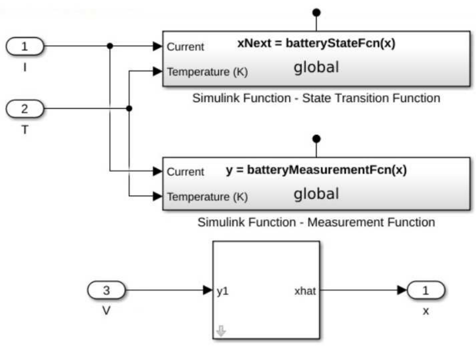

Fig. 4 SoC estimation technique (EKF) in detail

The SoC estimation process in this model, shown in Fig.3, is described in the block called 'EKF', when expanded as seen in Fig.4, you can see it consists of three blocks, 2 functions and one built-in Simulink 'Extended Kalman Filter'

The model was later modified for higher accuracy, and the Extended Kalman Filter block was replaced with the Unscented Kalman Filter block as shown in Fig. 5.

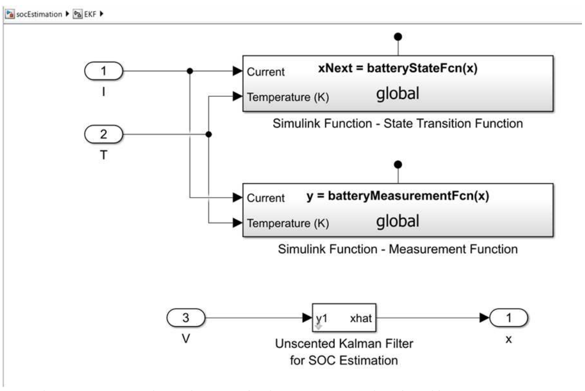

Fig. 5 SoC estimation technique (UKF) in detail

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The Battery Equivalent Circuit block is equipped with a thermal model for clear temperature modelling, using a convective heat transfer block, an ideal temperature source with the input being the ambient temperature at 25 degrees Celsius and a temperature sensor for monitoring.

Voltage and current noise were added to account for measurement uncertainties and improve the realism of the simulation.

C. *Passive Cell Balancing and CCCV Charging in Simulation*

The Simulink model used in this project [13], initially had a two-cell configuration which showed the two cells having different initial SoCs.

The cell with higher voltage and higher SoC is discharged through bleeding resistors of a certain value until the balancing process is completed. To extend the functionality and to make this model relatable to our application, the two-cell configuration was successfully turned into a 6-cell pack which resembles the pack required for the ASV. This allows the BMS to selectively discharge the cells with higher voltages until they matched the lower voltage cells. However, the increase in the number of cells highlighted a major drawback of passive cell balancing, which is the increase in the time needed to achieve balancing as we increase the cell count.

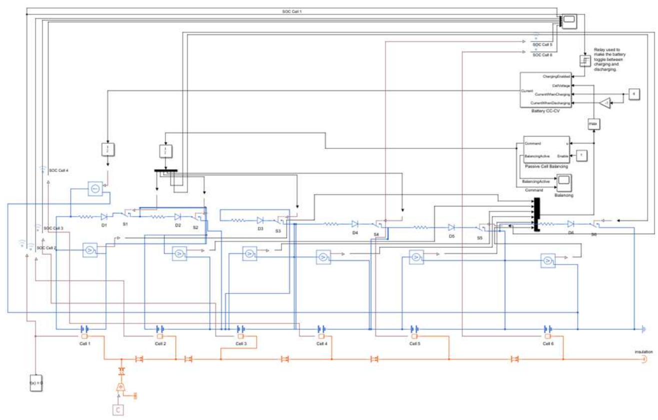

Fig. 6 Cell Balancing Model for 6S configuration

A CCCV Simulink block, shown in Fig. 6, alongside the Passive Cell Balancing block used to activate the balancing technique. In this setup, bleed resistors are connected through the voltage sensor in each parallel branch of the cells, with a voltage source driving the battery block.

To reduce the long SoC balancing time, the values of the bleed resistors were adjusted. By lowering the resistor values, from 10 to 5 ohms, the balancing current increases which allows the cells with higher SoC to discharge faster, shortening the overall balancing duration. The new resistor values were chosen to achieve a practical compromise between faster balancing and minimal impact on the overall system voltage and energy efficiency.

V. RESULTS AND DISCUSSION

A. *Battery Model Validation*

The Equivalent Circuit block successfully represented the battery dynamics. The simulated voltage response under pulsed loads closely matched expected behavior from literature, validating the choice of the 3RC model for system-level studies. While the dataset was not from the exact 6-cell pack used, its similarity in chemistry and characteristics allowed for meaningful results.

B. *SoC Estimation Comparison*

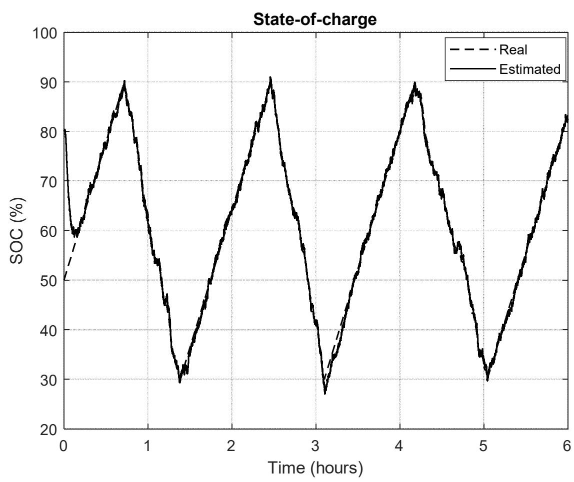

Fig.7 SoC estimation between EKF and Real

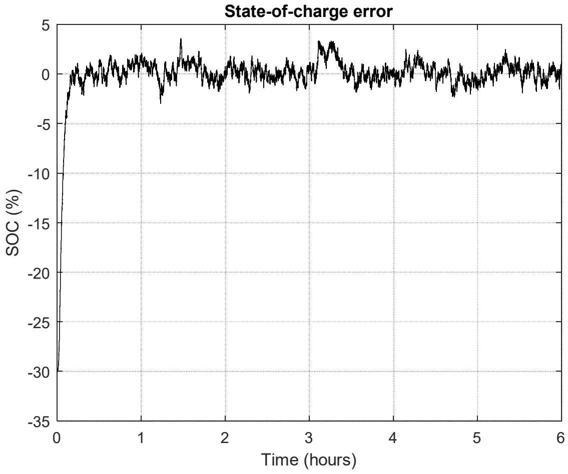

Fig. 8 SoC error between EKF and Real

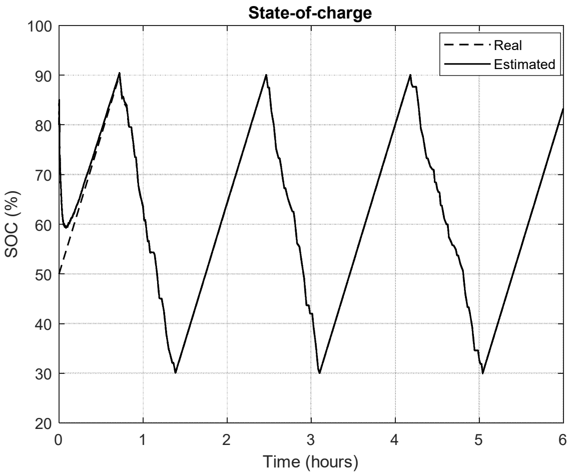

Fig. 9 State of Charge estimation, UKF vs Real

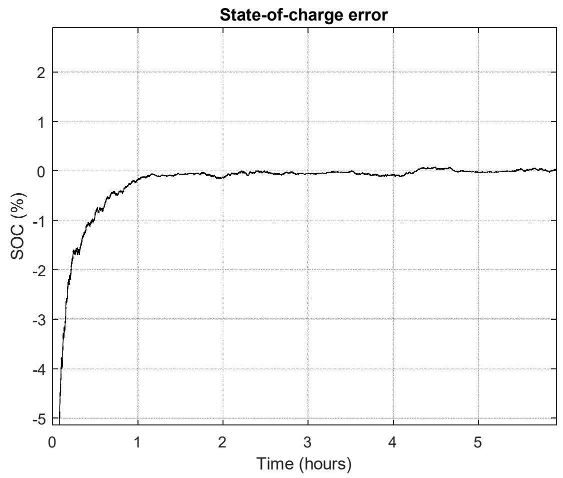

Fig.10 SoC error between UKF and Real

Figs. 7, 8, 9 and 10 show the difference in SoC estimation between the ‘Real SoC’ in this scenario, the Battery Equivalent Circuit internal calculated SoC, and the Extended Kalman Filter estimation. The results showed slight differences between the real and estimated values as illustrated. The SoC error, which is the difference between the estimated SoC and Real SoC is around the threshold of 2-3% while using the EKF estimation method, this is a relatively high error. The Unscented Kalman Filter showed much better results than the EKF estimation, as there are less errors in the estimation process, due to the almost identical values between the estimation and real value.

C. Passive Cell Balancing Results

For the 6-cell pack, cell balancing was achieved but required considerably longer, demonstrating the limitations of passive balancing for larger packs. The results confirm that while passive balancing is simple and effective, it is inefficient for high-capacity systems such as those used in ASVs.

Fig. 11 showing the results of the cell balancing before adjusting the bleeding resistance value is shown as follows, where the cell balancing technique starts working effectively after around 23000 seconds.

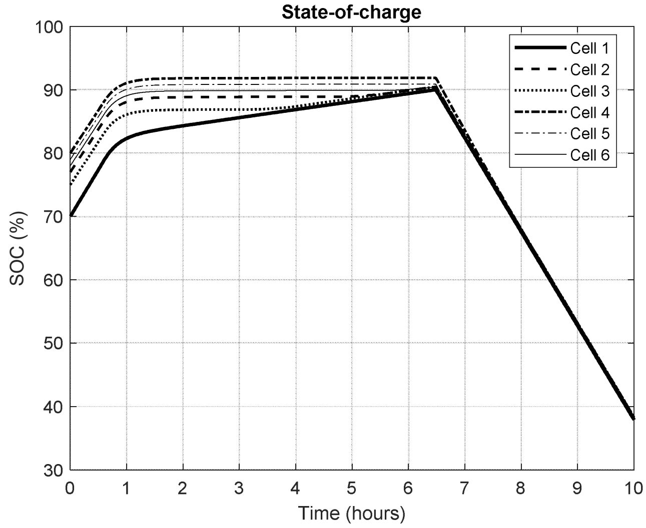

Fig. 11 SoC settling time for the 6-cell configuration after adjustment

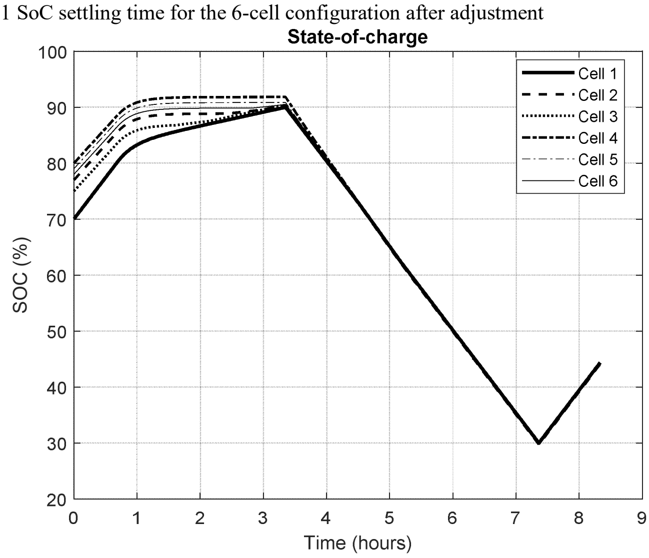

Fig. 12 SoC settling time for the 6-cell configuration after adjustment

As shown in Fig.12, after the adjustment of the resistance value decreased the balancing time significantly making the balancing technique effective after around 12000 seconds.

1) Discussion

The results obtained from simulation provide strong evidence of the effectiveness of the proposed BMS for ASV applications. The SoC estimation study compared the EKF improved accuracy and UKF against the ‘Real SoC’ and UKF demonstrated superior performance, achieving almost identical readings to the Real SoC while the EKF had less accurate results as the error was relatively much higher. This confirms the fact that UKF is much more reliable and suitable for the ASV dynamic missions where nonlinear effects and load variability are common.

The passive cell balancing experiments further reinforce the effectiveness of proposed algorithms. The process was deemed effective at the required task in hand, equalizing cell voltages. However, the balancing time increased with the increasing the number of cells, highlighting a well-known drawback of the passive balancing method. To reduce the balancing time, the bleed resistance value was reduced from 10 ohms to 5 ohms, this resulted in the reduction of the balancing time, demonstrating a trade-off between balancing time and energy efficiency as more energy is being depleted by the bleeding resistance. This confirms that while passive cell balancing is a simple and compact design, it might not be enough for higher-capacity ASVs and perhaps active cell balancing could provide better battery performance.

The PCB design using EasyEDA and the Texas Instruments BQ76930 battery monitor enabled a practical hardware implementation that is compact and energy-efficient. Integration with the MSP430 microcontroller via I²C communication provides flexibility for implementing control logic, safety features, and advanced algorithms.

Overall, the proposed design strikes a balance between simplicity, scalability, and accuracy, making it suitable for ASV applications where compactness and low power consumption are essential.

2) Future Work:

- Performing the actual HPPC tests on the 6-cell battery for a more accurate parameter extraction reflecting dynamic behavior of the battery closer to the real-life battery behavior.
- Fabrication and testing of the proposed BMS PCB design under real ASV operating conditions to confirm its robustness and effectiveness.
- Introduce thermal modelling of the battery, where temperature is monitored and controlled, given that the change in temperature affects the LiPo battery greatly when exposed to different environments, for example during different seasons or cities.
- The investigation of active cell balancing algorithms to overcome the limitations of passive methods, especially for larger packs and high-demand applications.
- Advanced state estimation: Implementation of hybrid methods combining Kalman filtering with data-driven or machine learning approaches to improve accuracy under complex mission profiles.

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