Current Control of Battery Pack Modules in Parallel Connection According to SoC

Mario Vrazic[1,*], Antonio Persic[1], Peter Virtic[2], Tomislav Ivanis[1]
[1]*Department of Electric Machines, Drives and Automation, Faculty of Electric Engineering and Computing, University of Zagreb,*
Unska 3, HR-10000 Zagreb, Croatia
[2]*Institute for Energy Technology, Faculty of Energy Technology, University of Maribor,*
Hocevarjev trg 1, 8270 Krsko, Slovenia
[*]*mario.vrazic@fer.hr; a.persic@novatec.tech; peter.virtic@um.si; tomislav.ivanis@fer.hr*

***Abstract*—Electric vehicles, especially cars, have been in the spotlight for some time now. In the focus of environmentalists, engineers, users, media, etc. With the growth and advancement of the market for such vehicles, other electric vehicles are also focussing on. One of such vehicles is boats, particularly smaller boats up to 8–10 meters in length. Of course, the biggest problem here is charging. The general idea is to use battery modules that can be easily carried and enable hot swapping. This paper investigates scenarios and simulations of the control system for hot swapping of the battery module. Simulations of connection of two and three battery modules to parallel operation and current control are presented in this paper, as well as applied control rules.**

***Index Terms*—Battery pack; Battery modules; Parallel connection; Bidirectional multiple input single output synchronous DC/DC converter; BMISO DC/DC converter; Hot-plugin; Smart SoC control; Advanced SoC control.**

I. INTRODUCTION

In the current transportation landscape, electrification has become ubiquitous, driven by the imperative to reduce greenhouse gas emissions. Established and emerging companies are pivoting toward electric vehicle technologies, manifesting themselves in electric cars, motorcycles, scooters, and boats. These vehicles primarily rely on rechargeable battery packs for electrical power. The battery packs operate until depletion, necessitating recharging, with charging infrastructure challenges looming large.

The hot swapping of batteries in electric cars is not a new idea. Stations for battery hot swapping existed even at the end of the nineteenth century. For example, in 1896, auto enthusiasts started to consider the exchange of depleted batteries with fresh ones to extend the range of electric cars. Also, in 1912, General Electric launched a service that enables electric car owners to swap batteries for a monthly fee and a variable per mile charge. Other similar services emerged in other large cities. Some stations offered semi-mechanised swaps that take as little as three minutes. When the battery is separated from the vehicle, the service helps to reduce the initial cost by a third or more.

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Today, there are many different electric vehicles, from cars, scooters, motorcycles to busses, trucks, and small planes.

Even electric ships and ferries were built and operate every day. Boats, especially up to 10 m long, are of great interest since they are available for a lot of people. There are many functions that such vehicles can perform, i.e., as fishing boats (especially for fresh water). The charging of vehicle batteries lasts for a long time and thus repels potential users. If one wants to use his/her boat frequently and for long time, battery swapping is a suitable system. Dividing the battery pack into modules that can be easily carried (with a module weight of up to 20 kg) presents a practical way to replace discharged modules quickly. Also, some fully charged modules can be stored onboard the boat so that some discharged modules can be replaced on the water during the operation of the boat.

Of course, a battery pack should be designed to consist of several parallels (modules) that can be separately disconnected and connected, and swapping should be hot, thus enabling swapping only bad and empty modules.

II. PROPOSED PRESUMPTIONS, PROBLEMATICS, AND SOLUTION

From the consumer's perspective, to achieve optimal convenience and safety, the battery pack must exhibit the following characteristics:

– *Scalability* - The vehicle's power system should demonstrate scalability, allowing operation on a single battery module or multiple interconnected battery modules to achieve adaptability to different power demands and energy storage requirements.

– *Charging Flexibility* - The battery modules must possess the capability for extraction and reintegration of individual, dual, and triple modules for recharging purposes, ensuring flexibility in the maintenance and management of the energy storage system.

– *Advanced SoC Control* - The battery pack demands a sophisticated SoC control system that enables the coordinated manipulation of energy reservoirs. This includes targeted energy discharge from a designated module, simultaneous energy discharge from all modules, sequential module-by-module charging, simultaneous charging of all modules, coordinated energy transfer from the remaining modules to a single selected module, aggregation of energy from the collective into one or two designated modules, energy equalisation across all modules via redistribution from one.

– *Smart SoC Control* - Intelligent selection of the aforementioned SoC control modes.

To realise the previously mentioned attributes, the battery pack must comprise numerous identical modules designed for parallel connection. This involves configuring the voltage of each module to align with the voltage specifications of the powertrain, ensuring that the capacity of a single module is adequate for the nominal operation of the powertrain, with additional modules serving to extend the duration of the powertrain operation.

The proposed electrical system solution, depicted in Fig. 1, involves three battery packs connected in parallel. These packs can be discharged from the powertrain and charged via optional regenerative braking, if available. The core component that unifies all the features and components mentioned above into a unified entity is the bidirectional multiple input single output synchronous DC/DC converter, further known as the BMISO DC/DC converter.

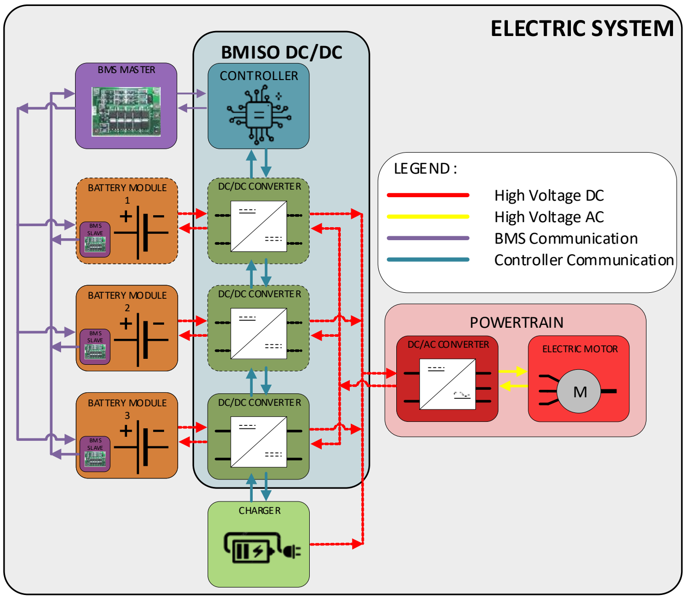

Fig. 1. Proposed electric system.

III. Proposed Solution

The BMISO DC/DC converter in Fig. 1 consists of four major components: three half-bridge buck-boost DC/DC converters and a controller. The controller manages the energy flow by assigning duty cycles to each converter.

A. Half-Bridge Buck-Boost DC/DC Converter

The half-bridge buck-boost DC/DC converter is shown in Fig. 2.

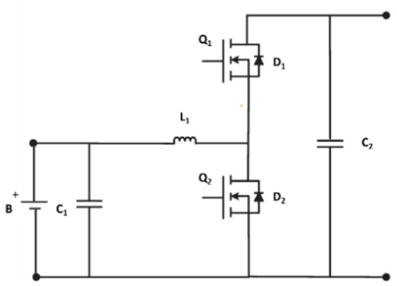

Fig. 2. Half-bridge buck-boost DC/DC converter.

Capacitor C_2 serves as a filter for the DC link voltage output, and B designates a single battery module. In the scenario where energy flows from the battery to the DC link, the converter operates as a boost converter, effectively elevating the output voltage above the input voltage. The duty cycle of metal oxide semiconductor field-effect transistor (MOSFET) Q_2 is crucial in regulating power transmission to the DC link. In contrast, during braking or the charging phase, the energy is changed from the DC link to the battery module, causing the converter to act as a buck converter. This configuration results in the output voltage being lower than the input voltage, equivalent to the battery voltage. The extent of power transferred to the battery is dictated by the duty cycle of MOSFET Q_1 [1].

The advantage of this topology lies in its utilisation of only two controlled switches with complementary pulse durations. This design simplifies drive circuits and control systems. Furthermore, the limited number of switches and the absence of a transformer contribute to an efficiency that exceeds 90 % [2]. The main drawback of the half-bridge converter is its discontinuous output current during boost mode, which influences the size of the output capacitor [2]. Additional drawbacks include voltage restrictions during boost mode and a lack of galvanic isolation for the energy storage element [3].

B. Bidirectional Multiple Input Single Output Synchronous DC/DC Converter

The block schematic of the BMISO DC/DC converter, as depicted in Fig. 1, differs slightly from the actual implementation. The actual configuration is presented in Fig. 3.

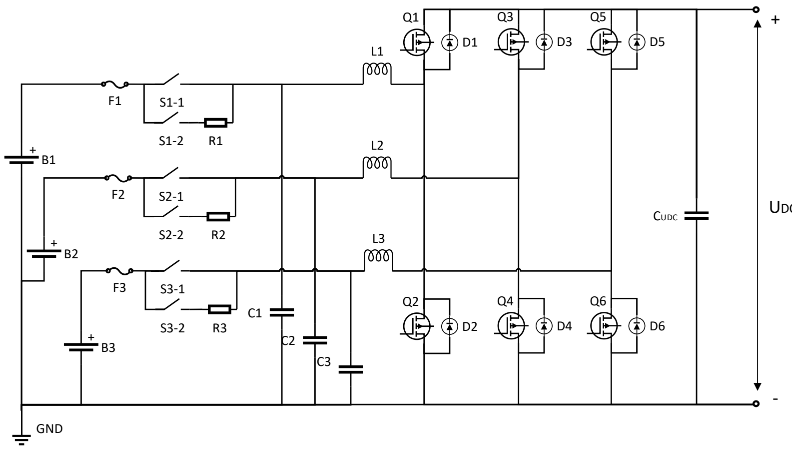

Fig. 3. Bidirectional multiple input single output synchronous DC/DC converter.

The converter has the ability to flow in both directions, making it ideal for use in parallel connection of the battery pack. The schematic representation of the converter in Fig. 3 has three inputs and one output. In this configuration, each individual battery pack is connected to the inputs, combining them in parallel at the output. The nature of the converter itself implies that it will successfully boost the voltage of the DC link when the battery packs are depleted, i.e., when their voltage drops. Additionally, since the connection is bidirectional, it enables the flow of energy back to the battery packs, such as during regenerative braking, allowing battery charging [4].

The battery modules must have an internal precharge circuit to limit the current of the module to protect the converter and the battery module when racking-in and racking-out the modules [5]. Instead of precharge, an additional power supply can be used to maintain voltage when no batteries are connected. Precise control of the MOSFET duty cycles is essential for enhancing speed and efficiency. The upcoming chapter will provide a detailed explanation of this centralised control approach [6].

IV. Simulation Environment

The simulation environment is established using PLECS software, and Fig. 4 depicts the averaged model of the electrical system within this PLECS environment. The model comprises the following components:

1. Averaged model of the battery modules (3 pcs.);
2. Averaged model of the half-bridge buck-boost DC/DC converter;
3. Averaged model of the current proportional-integral (PI) controller (3 pcs.);
4. Averaged model of the voltage PI controller;
5. SoC Comparison and Current Management Script.

A. Averaged Model of the Battery Modules

A single battery module comprises 28 cells connected in series and 6 cells in parallel. Each cell has a nominal capacity of 3.45 Ah, a nominal voltage of 3.6 V, and an energy capacity of 12.42 Wh. Consequently, the battery module exhibits a nominal voltage of 100.8 V, a capacity of 20.7 Ah, and an energy capacity of 2086.56 Wh (equivalent to 2.086 kWh). The estimated mass of this module is approximately 13 kg. All necessary resistances and loads are taken into calculation [7].

B. Averaged Model of the Half-Bridge Buck-Boost DC/DC Converter

The averaged model of the half-bridge buck-boost DC/DC converter (labelled “BAT+DC/DC_X”) is depicted in Fig. 5. It comprises an averaged Lithium-ion battery pack model connected to an averaged half-bridge converter model. Within this model, a capacitor and a resistor serve as voltage filters, while an inductor filters out the current.

The electrical system model incorporates three subsystems labelled “BAT+DC/DC_X”, where X denotes the converter number, all connected to the same output. An load of resistive and capacitive character is present on the output for filtering purposes. These models are controlled through an antiwindup current PI controller. The duty cycle reference from the PI controller is fed to the battery models, and the current feedback is returned to the PI controller. This particular PI controller is selected for its slower and more stable control, achieved through a high integration component and a low proportional component. The antiwindup feature is incorporated to prevent overshoots and oscillations [8].

C. Control Logic

The main control circuit utilises the same PI controller employed with the battery models. It maintains a constant set point and receives an output voltage reference. This controller operates as a voltage controller, resulting in a cascade configuration with the current controller controlled by the voltage controller [9].

Before supplying the current controller with a set point, a script module is implemented to arrange the State of Charges (SoC) of the battery modules from lesser to higher SoC state. This arrangement ensures that the appropriate current set points are provided to the correct current controllers [10]. The battery modules with the lesser level of od SoC receive more current, conversely the battery modules with a higher SoC receive less current.

This script is a C programme that performs the following.

1. It defines and initialises input variables for SoC values of three battery modules (SOC1, SOC2, SOC3) and a reference current.
2. It calculates the current set point on the basis of the input values. The calculation depends on the sign of the reference current [11].
3. If the reference current is greater than zero (i.e., the battery is discharging), it calculates the current set point

based on the proportion of SOC1 relative to the total SoC of all three modules.

4. If the reference current is less than zero (i.e., the battery is charging), it calculates the current set point by sorting the SoC values and applying charging current values to determine the appropriate set point current. The charging current is determined by the relative SoC values, and the script assigns different currents to the battery modules according to their SoC levels.

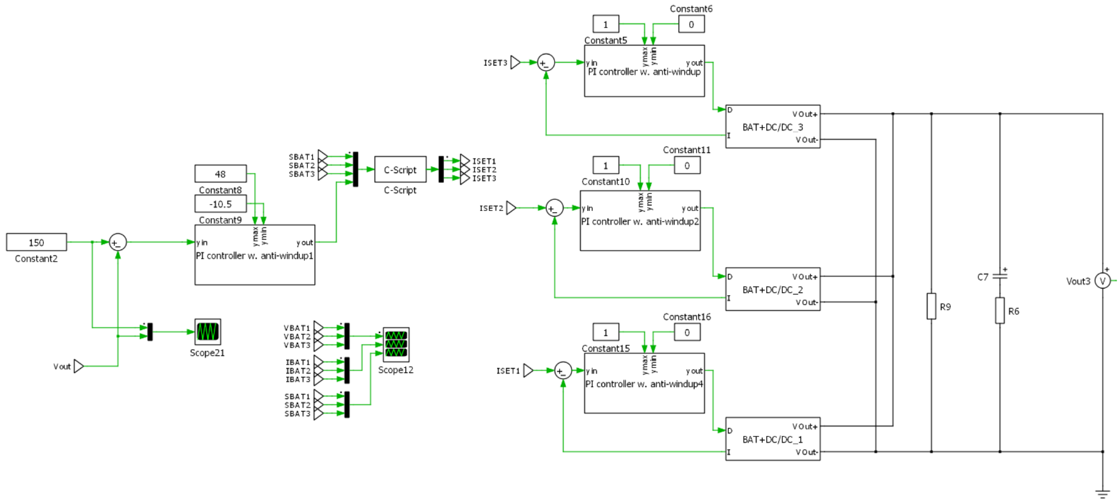

Fig. 4. Averaged model of the bidirectional multiple input single output synchronous DC/DC converter in the PLECS environment.

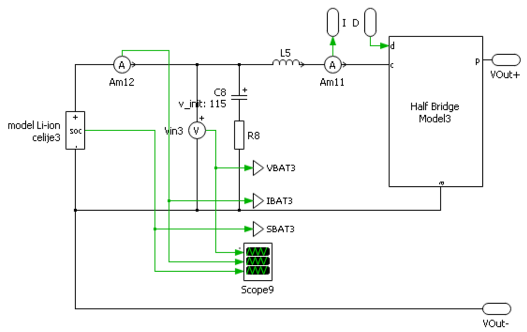

Fig. 5. Averaged battery module.

The script essentially adjusts the reference current for charging or discharging based on the SoC values of the battery modules to manage the set point of current appropriately [12]. The following section presents the simulation results of this model.

V. Tests and Simulation Results

Several tests were performed to test the current control algorithm.

The first test was with a load of 10 A and regenerative breaking with 5 A (Fig. 6). Ramps of 5 A/s are made from 0 to 10 A and back to 0 A, and from 0 A to -5 A and back to 0 A.

Battery modules have a start voltage of 114,6 V, 111,9 V, and 108,7 V, respectively, for modules with SoC 90 % (blue), 50 % (red), and 10 % (green), so the first module is the best, second 50 % charged, and the last is almost empty, 10 % charged. When the test started, the voltages immediately decreased linearly to the SoC of each module. So, the voltage of the first module dropped from 0,6 V to 114 V. The voltage of the second module dropped from 5,9 V to 108 V. The biggest voltage drop was for the third (the emptiest module) and was 16,7 V. So, the voltage was 92 V.

The largest SoC change (drop) during load shows the module with largest SoC (blue) and the largest change (rise) during regenerative breaking shows the module with the smallest SoC (green). This can be seen in the SoC change diagram.

This confirms the initial idea that this system actively balances energy in modules during normal operation and ensures that the SoC of the module cannot drop below the secure level.

The SoC relative change [%] diagram shows even better, according to (1), where this contribution to the “green” module during regenerative breaking is showing much more change

$$SoC\ relative\ change\,[\%] = \frac{\left(SoC_{mom.} - SoC_{start}\right)}{SoC_{start}} \times 100, \quad (1)$$

where $SoC_{mom.}$ is the momentary SoC and SoC_{start} is the SoC on the start of the test.

The second test was with a continuous load of 30 A for a long period of time. The SoC delta diagram represents the difference between module 2 and module 1 (green line) and the difference between module 2 and module 3 (red line), and shows the approach SoCs of the module with the higher SoC and the module with the lowest SoC to the SoC of the module with the middle SoC. Two diagrams show the beginning of test (Fig. 7) where two deltas are approaching each other, and the end of the test (Fig. 8) where all three modules are very near SoC of 50 % (module with SoC of 0,49 % is the one that started with SoC 0,1 %, module with SoC of 0,5 % is the one that started with SoC 0,5 %, and module with SoC of 0,51 % is the one that started with SoC 0,9 %). This also shows active balancing even during heavy load and not only during regenerative breaking, as the first test showed.

The third test shows the responses on step load +30 A and step regenerative breaking of -5 A (Fig. 9). Again, the relative change of SoC [%] is calculated according to (1) and shows that each module is loaded according to its SoC (so all lines are on top of each other), but charging (during regenerative breaking) occurs in such a way that the module with the lowest SoC receives most of the energy and its change of SoC is the greatest.

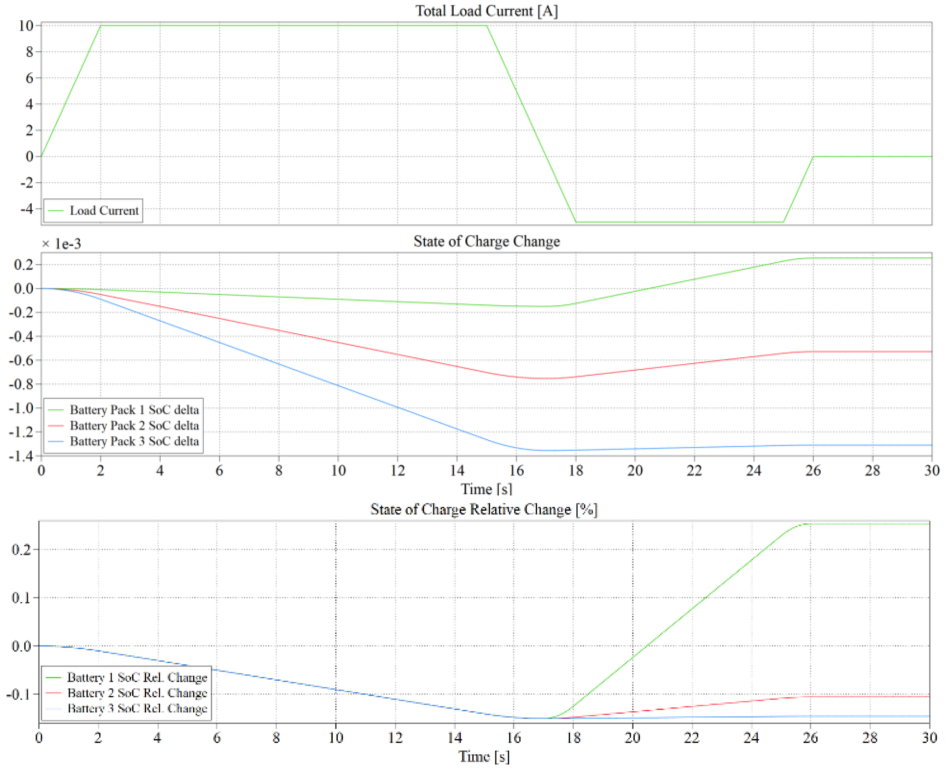

Fig. 6. Test with 10 A load and 5 A regenerative breaking.

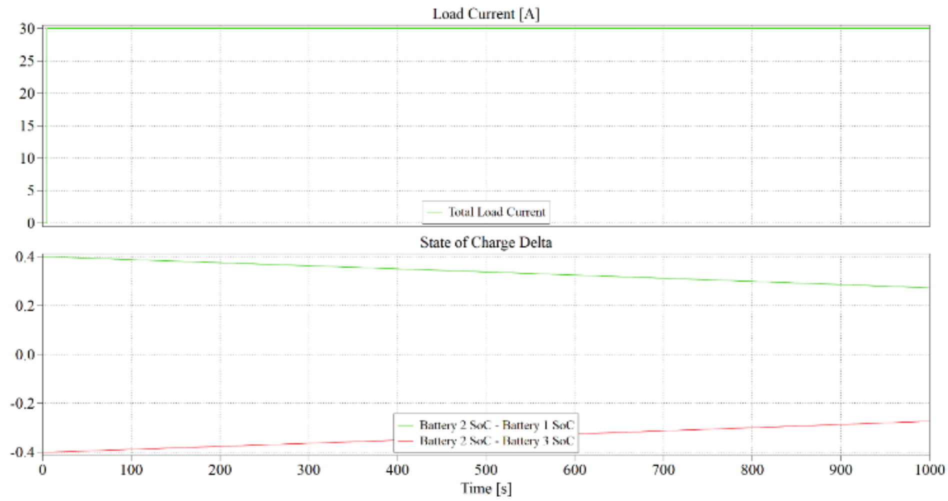

Fig. 7. Test with continuous load of 30 A at the beginning of the test.

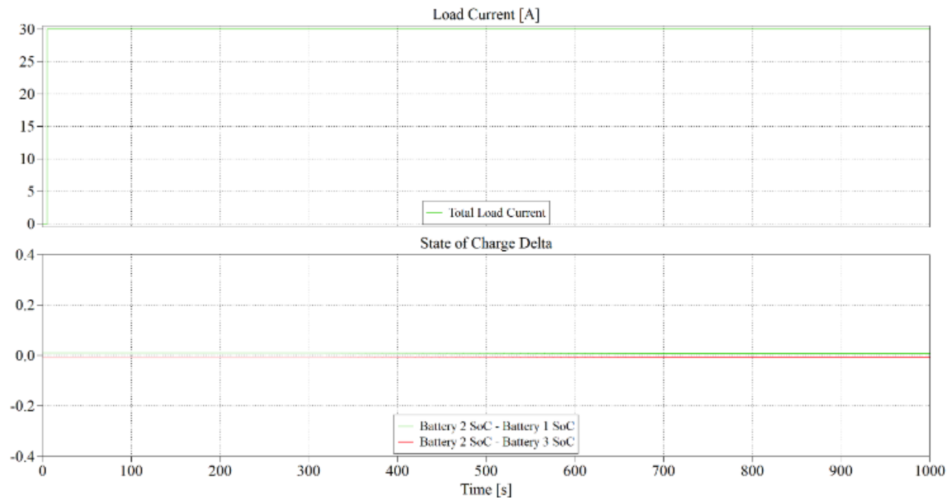

Fig. 8. Test with continuous 30 A load at the end of the test.

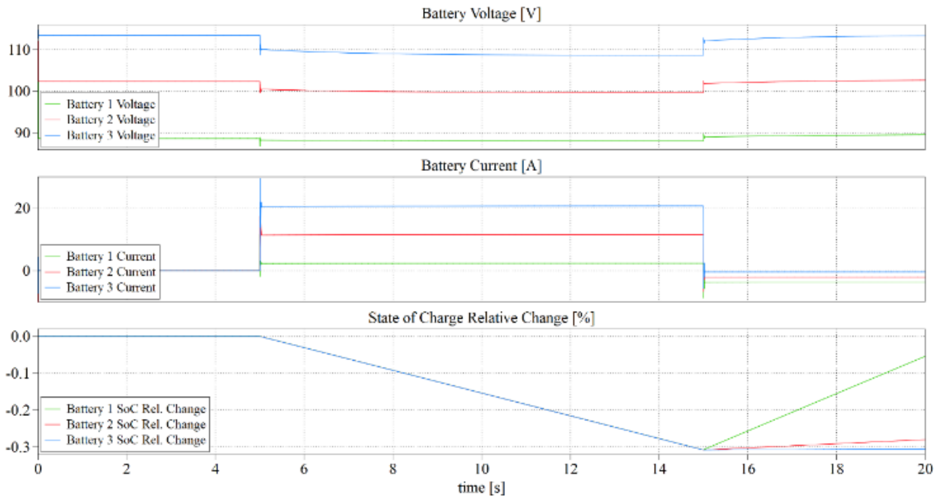

Fig. 9. Step responses (+30 A and -5 A).

This change is so great that it is observable even after 5 s. Also, the detail on the load step from +30 A to -5 A is shown in Fig. 10. The change (detail from 15,000 s to 15,004 s) shows, especially for the green module (which started with the lowest SoC of 0,1 %), the quality of current control where the current of the module with the lowest SoC switches from lowest current during load to highest current during regenerative breaking and receives on this way the largest portion of energy.

The detail of the response to step load is shown in Fig. 11. The transient finishes after 30 ms and shows proper functioning of current controllers.

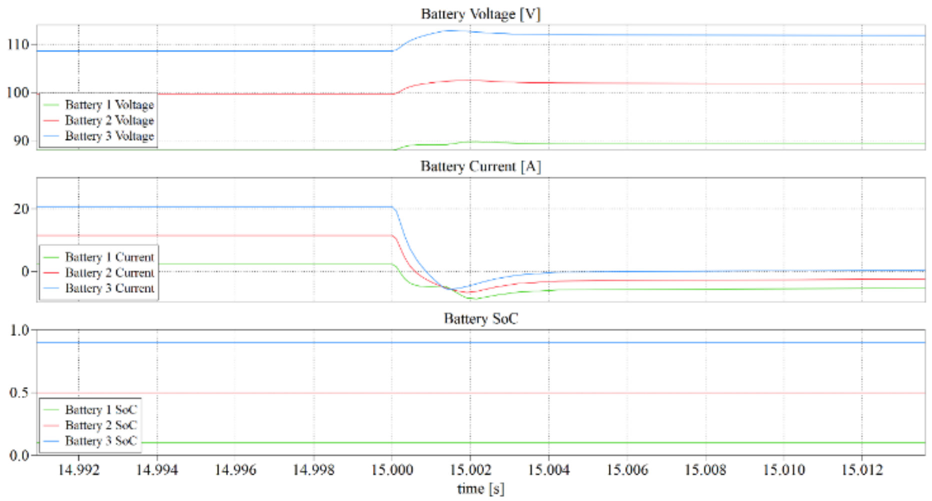

Fig. 10. Step responses - details on the change from +30 A to -5 A.

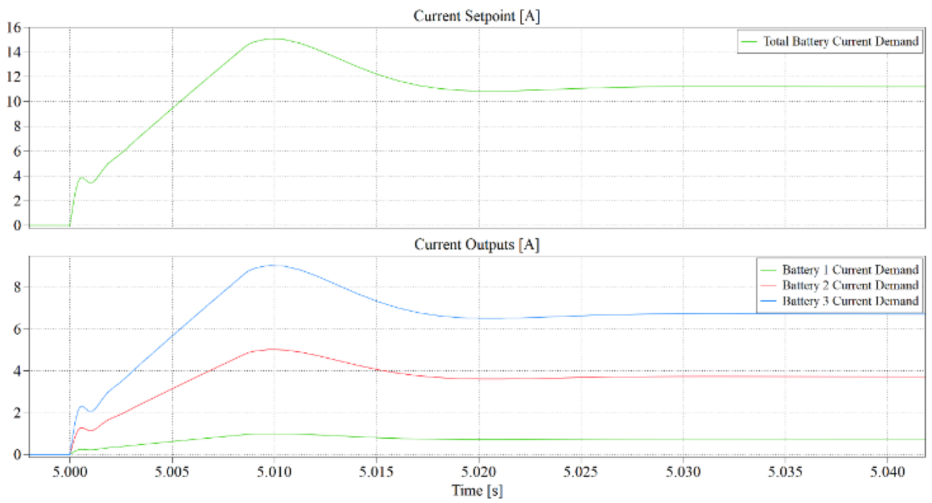

Fig. 11. Detail of the load step responses.

VI. CONCLUSIONS

In summary, this study addresses the engineering challenges associated with the management of parallel-connected battery modules in hot-swappable electric boat systems. As electric vehicles, including boats, gain prominence, efficient battery charging becomes a critical concern. This research explores control systems for hot-swappable battery modules, specifically focussing on scenarios involving two and three battery modules in parallel operation and the associated current control strategies.

User requirements include scalability, flexible charging, advanced state of charge (SoC) control, and intelligent SoC control. To meet these requirements, the proposed solution incorporates three battery packs connected in parallel, allowing power discharge to the powertrain of the boat and recharging via regenerative braking. Central to this solution is the bidirectional multiple input single output synchronous DC/DC converter (BMISO DC/DC converter), which integrates all these functions.

The BMISO DC/DC converter comprises three half-bridge buck-boost DC/DC converters and a controller to manage energy flow through duty cycle allocation. This research provides insights into the operational principles and characteristics of these components, highlighting the simplicity and high efficiency of the half-bridge converter, along with its limitations.

The study emphasises the importance of precise MOSFET duty cycle control for improved speed and efficiency. It lays the foundation for further research into these control mechanisms, offering advanced and scalable solutions for electric boats and similar applications requiring hot-swappable, parallel-connected battery modules.

This research provides valuable engineering insights into power management systems that can revolutionise the performance and charging capabilities of electric boats.

The initial work in this research was the creation of a model, the core of which is the current management system of individual modules, to enable the replacement of modules that are empty and connections with modules that are full or partially discharged. It is important that balancing, in this case, does not happen in the way energy is exchanged between modules, but rather that balancing is done through the load or through regenerative braking.

VII. FUTURE WORK

Further work on this research will be carried out in the direction of developing models of battery modules and creating a physical laboratory model of the entire battery pack.

CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.

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