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Towards Smart Green Blue Infrastructure

RECOVERY BRAKING IN ELECTRIFIED BOATS USING DUAL ACTIVE BRIDGE DC-DC CONVERTER WITH ULTRACAPACITOR

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1. **ABSTRACT**: Regenerative electric propulsion involves AC motors recharging batteries during sailing. This paper presents the application of a dual active bridge (DAB) DC-DC converter- based interface system for recovery braking in electrified boats (EBs), incorporating ultracapacitors. The study focuses on examining the charging and discharging scenarios of ultracapacitors in the system. The proposed method utilizes a simple proportional-integral (PI) controller to regulate the terminal inverter voltage direction by adjusting the phase shift angle of the DAB converter. The MATLAB/SIMULINK software package is employed to model and simulate the proposed interface system. The study explores energy recovery during braking operations in EB and proposes an effective control strategy for energy distribution from batteries and ultracapacitors for EB applications. This approach reduces electrical energy production. The DAB converter offers several advantages, including bidirectional power flow capability and high efficiency. By integrating ultracapacitors into the system, the recovery braking energy can be efficiently captured and stored for later use, enhancing the overall energy efficiency of EBs. The charging case involves transferring the excess energy from the braking process to the ultracapacitors, replenishing their energy storage. On the other hand, during the discharging case, the stored energy in the ultracapacitors is utilized to power the boat's electrical systems, reducing the reliance on the main power source. Permanent magnet synchronous motor (PMSM) is coupled to a DC/AC converter system that serves as a thruster system to simulate the energy requirements of an EB during propulsion operations. The main objectives of the proposed control approach are fast current tracking for the battery system, ultracapacitor-based DC bus voltage stability, and energy load distribution for an EB under a range of demand scenarios. The ultracapacitor which act as a secondary energy source for the EB shall be connected to a DC bus using a bidirectional DC-DC converter. Multiple cells are arranged in series and potentially also in parallel to make up an ultracapacitor pack.

2. INTRODUCTION

One of the marine and fluvial sectors' long-term objectives is to lessen the effect of ship emissions in order to best adhere to the International marine Organization's (IMO) greenhouse gas emission regulations. An interesting concept in this area is to develop the hybridization and electrification of propulsion chains [1].

The ability to run the thermal machines near to their rated power and ideal speed is one of the key benefits of these power systems. This enables them to operate more efficiently. Energy can also be

collected during braking if a reversible energy conversion system and an energy storage system are combined in an electric or hybrid system, as is commonly the case in terrestrial hybrid cars [2], [3].

In the naval sector, cutting energy consumption and minimizing the mass and volume of energy chain components while increasing platform speed are critical objectives. Therefore, propulsion mode— rather than energy generation—is optimized for propellers and other propulsion chains. The "Opal" hybrid-electric boat has been used to assess the feasibility of braking energy recovery. It has shown out that this boat uses a lot less energy than the diesel propulsion system that was previously in place. However, if the ship's operating modes involve brief cycles with significant speed variations, recovering energy during braking operations may be an intriguing approach [4].

Electrified boats (EBs) are currently garnering significant attention as a sustainable alternative to conventional boats powered by internal combustion engines. The rise in global awareness of environmental degradation, coupled with the surging cost of fossil fuels, has stimulated research into electrically powered transportation, specifically in marine applications. The conventional source of energy in battery-operated electric boats is the battery, which presents challenges such as restricted recharging cycles and limited power performance. The battery's limits can be overcome by combining it with another energy source, such as a flywheel, ultracapacitor, other electrochemical batteries, etc. One possible option for the main power source is a fuel cell, which has a huge storage capacity. However, there are several important downsides to this technology, such as its delayed dynamic reaction to load variations and its inability to recover energy from the load. The secondary energy storage system, such as an ultracapacitor, can supply the extra power needed for acceleration and absorb excess energy used during braking [5], [6].

One key method of optimizing the use efficiency of the battery in EBs is through recovery braking. This technique allows the mechanical energy of the motor to be converted into electrical energy when the boat is decelerating. The energy that would have otherwise been wasted is saved and used to recharge the battery. Based on this, ultracapacitors, due to their high dynamic response under load variations, can serve as an additional source in electric boat applications [7], [8].

In many hybrid applications, energy storage systems like batteries and ultracapacitors are used [9], [10]. It has recently been discovered that ultracapacitors outperform batteries in electric vehicles because they have far greater power densities than batteries and much higher energy densities than standard electrolytic capacitors [11], [12]. The graph in Figure 1 shows the areas where different energy storage systems can be used [13].

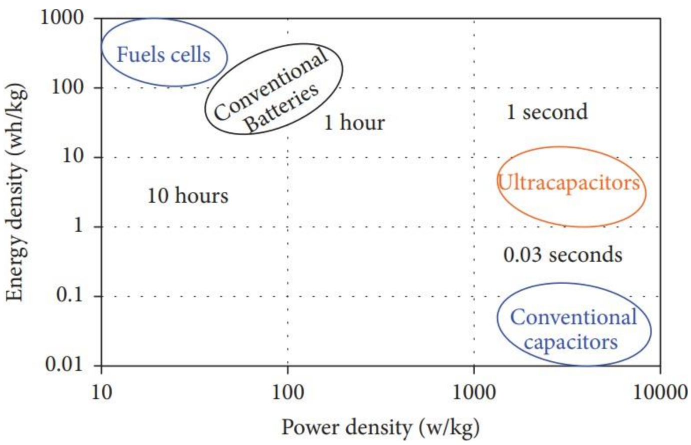

Figure 1: Ragone diagram of energy storage sources [13]

The dual active bridge DC-DC converter is a power electronics device that allows bidirectional power flow by controlling the voltage and the current across the primary and secondary sides. This converter is ideal for use in energy recovery systems as it enables efficient conversion of the recovered energy to a usable form. It offers advantages such as high conversion efficiency, fast response time, and voltage regulation capabilities, making it a suitable choice for EBs [8].

The ultracapacitor, also known as a supercapacitor, is a high-capacity energy storage device that can rapidly store and release energy. It is different from traditional batteries as it stores energy electrostatically rather than chemically [14]. Ultracapacitors have a much higher power density and longer lifespan compared to batteries, making them ideal for high-power applications such as recovery braking. Their ability to deliver and absorb high power levels with minimal losses allows for efficient energy recovery and regenerative braking [7], [15].

Efficient control strategies play a crucial role in optimizing the performance of recovery braking systems in EBs. Literature in this domain covers various control techniques, with a focus on proportional-integral (PI) controllers [16]. Existing research explores the application of PI controllers in regulating terminal inverter voltage direction and adjusting the phase shift angle of DAB converters. Comparative analyses of different control strategies contribute to identifying the most effective approach for energy recovery during braking operations [17], [18].

In this work, a novel recovery braking system for the Permanent Magnet Synchronous Motor drivetrain in EBs was presented. The proposed interface system uses a bidirectional DC-DC converter to link an ultracapacitor to a DC bus. A PI controller is used to assess the charging and discharging states of the ultracapacitor system in order to regulate the terminal inverter voltage direction through the phase shift angle of the Dual Active Bridge converter. Using the MATLAB/Simulink software tool, the suggested system is modelled and virtually tested. The outcomes are contrasted against two control strategies.

3. PROPOSED SYSTEM OVERVIEW

Usually, the architecture of electric hybrid boats consists of two or more energy sources and the energy converters that go with them, as shown in Figure 2. Figure 2 depicts the recovery (regenerative) braking system abbreviated in a block diagram. As seen in Figure 2, the battery and ultracapacitor are linked in parallel in this configuration. The main components of an EB's propulsion system are the motor, controller, power source, charger, gearbox, and thrusters. When the driver uses the brakes while the boat is travelling down a straight road and encounters an obstacle, some of the kinetic energy is stored as electrolytic charge in the batteries and the remaining charge is stored in the ultracapacitor. A DC-DC controller is designed to control this. When the controller determines that the battery is fully charged, it supplies the charge to the capacitor. The changes installed a braking circuit that could transfer power to the EB's traction system.

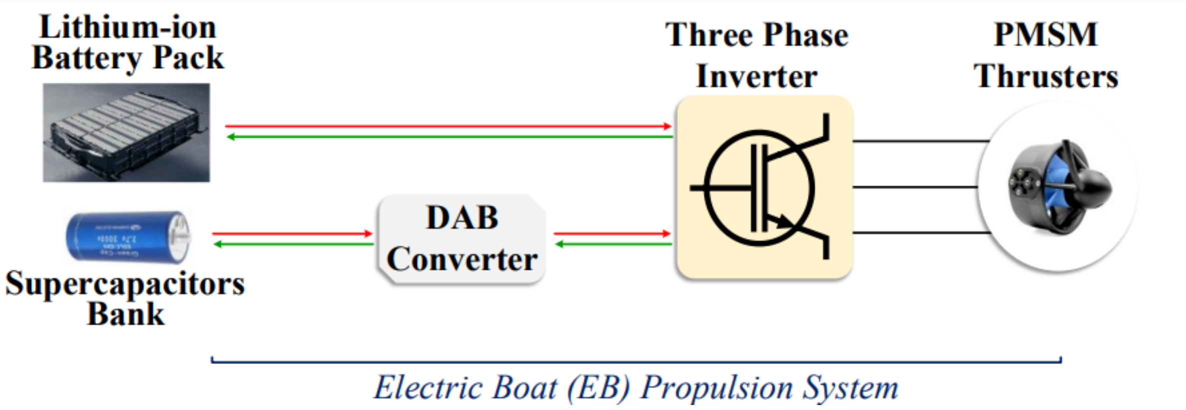

Figure 2: Proposed System

Whether the energy from a charger or regenerative braking flows to the battery pack or is stored in the ultracapacitor is determined by an internal controller. This provides continuous battery usage. The DC current from the battery is converted into AC current for the motor using an inverter. The ultracapacitor, which is currently holding the charge, can supply power when the AC motor needs it. The battery may begin to discharge once more if the ultracapacitor is depleted or running low on power. The DC-DC converters that connect the DC link and the ultracapacitor might have a wide variety of topologies. Depending on whether or not they use galvanic insulation, DC-DC converters can be classified as either non-isolated or isolated. The proposed converter was a DAB which is a DC-DC converter offering galvanic isolation and bidirectional power flow. The galvanic isolation is ensured by a high-frequency intermediary transformer.

One essential part of the system that enables developing technologies to be controlled is the ultracapacitor. The essential elements of the ultracapacitor system are the battery pack, the smoothing aluminum inductor Ls, the ultracapacitor, and the DC-DC converter base on the insulated gate bipolar transistor [IGBT]. During acceleration, the ultracapacitor's capacitor voltage was permitted to fall to one-third of its nominal value. During deceleration, the energy that the capacitor released during acceleration is recovered and charged back into the ultracapacitor. Ultracapacitors are used primarily because they have a 20 times higher energy storage capacity than electrolytic capacitors. Ultracapacitor specifications are listed in Table 1. Ultracapacitors also increase the transient performance of EBs while extending battery life. The distance is increased and additional supply is given to EBs by the ultracapacitor.

Table 1. Ultracapacitor specifications

Parameter	Value
Rated capacitance	80 F
Equivalent DC series resistance	8..93 mΩ
Rated voltage	400 V

4. ROLE OF DAB IN THE PROPOSED TOPOLOGY

The converter topology is displayed in Figure 3. Two complete bridges, a high-frequency transformer, an energy transfer inductor, and DC-link capacitors make up the selected DC-DC converter. In the model, "energy transfer inductance" refers to the leakage inductance of the transformer as well as any necessary external energy transfer inductance. The two legs of each full-bridge are driven by square-wave pulses that complement each other. Power flow in the DAB can be regulated by using phase shift modulation to phase-shift the pulses of one bridge in relation to the other. The control routes power between the two DC buses so that the leading bridge can deliver power to the lagging bridge.

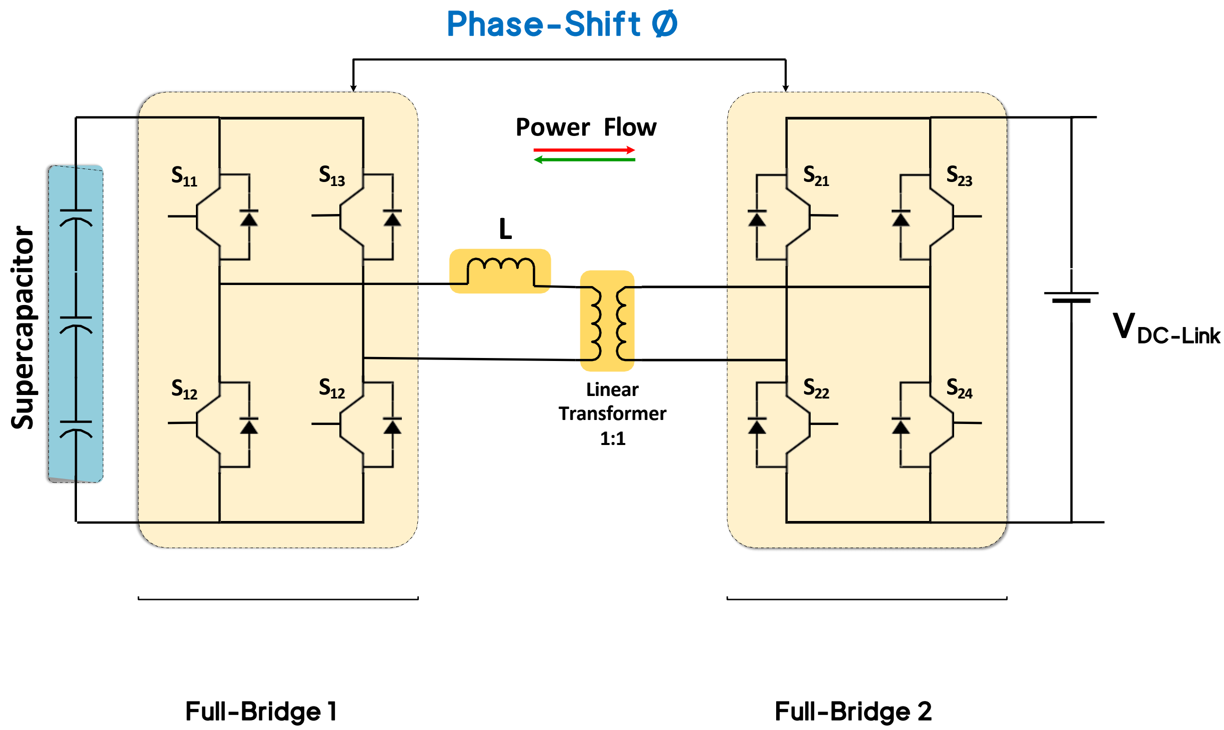

Figure 3: Topology of DC-DC converter

The voltage differential created across the energy transfer inductance by the square waves applied to the bridges directs the stored energy in the inductance. With the help of Table 2's DAB parameters. Two modes exist. (a) Charging mode: In this scenario, the three-phase inverter's DAB (second bridge to first bridge) converter is used by the load to supply energy to the capacitor. (b) Discharging mode: In this scenario, the three-phase inverter comes first, then the DAB (first bridge to second bridge) to transport energy from the ultracapacitor to the load. The DAB converter's switches all transfer power in both directions utilizing a 50% duty ratio and a phase shift (φ) between the primary and secondary side voltages [19]. The switch pairs in the two bridges both have the same switching period, but because of how they are controlled, a different phase shift between each bridge is introduced depending on the modulation determined from feedback measurements. Based on a fixed-point value, an output voltage error signal is generated, and this signal is sent via a digital PI controller to produce the phase shift ratio for the PWM modulator. Power is transferred from the primary to the secondary side if the phase of the primary side is faster than that of the secondary side. Power is transferred from the secondary to the primary side if the secondary side's phase is faster. The inductor receives the voltage difference brought on by the phase shift, which it uses to distribute power based on the phase shift and store energy [20], [21].

Table 2. Parameters of DAB

Quantity	Value
Turns ratio N1/N2	2/1
Coupling inductance of the DAB	0.0102 mH
Switching frequency of the DAB	5 KHz

5. THE PROPOSED CONTROL STRATEGIES FOR THE DAB

The DAB converter is made up of two H-bridges and a high-frequency transformer, as shown in Figure 4. The two H-bridges operate under control to generate high-frequency square-wave voltages with a set 50% duty cycle and the same frequency. The high-frequency transformer regulates the phase shift between the two square wave voltages in order to manage the flow of electricity. The direction of power flow can be controlled by the DAB converter based on which bridge generates the leading square wave. When the square wave voltage produced at Full-Bridge 1 exceeds that generated at Full-Bridge 2, power moves from the source connected to Full-Bridge 1 to Full-Bridge 2 and vice versa. Eq. (1) describes the link between the DAB converter's DC-side terminal voltages and output power. [22]:

$$P = \frac{V_1 V_2}{a\omega L}\varphi\left(1 - \frac{|\varphi|}{\pi}\right) \tag{1}$$

where V_1 and V_2 are the DC-side voltages of the two bridges, φ is the phase shift angle between the AC voltages produced from the two H-bridge converters, α is the turns ratio of the transformer, L is the total series inductance, and $\omega = 2\pi f$ is the angular frequency where f is the operating frequency of the converters.

The power flow direction will be as shown in Figure 4 during the ultracapacitor discharging operation when the EB accelerates. This is the fundamental topology of the DAB converter. In contrast, as the EB slows down (brakes), the power flow reverses, as seen in Figure 5, and the ultracapacitor charges. Figures 4 and 5 show the proposed controller block diagram for the two modes a)charging and b)discharging. PI controller was used to regulate the DC-link current during charging and discharging operations. The reference value of the current is positive for discharging and negative for charging. Therefore, the controller will first create pulses for the first H-bridge (Full-Bridge 1) in the discharging mode where the reference current is positive in order to lead the pulses of the second H-bridge (Full- Bridge 2) and cause the current to flow through the inverter to PMSM. When in charging mode, where the reference current is negative, the controller will first pulse the second H-bridge of the DAB converter in order to charge the ultracapacitor while switching the power flow direction at braking (deceleration) from the PMSM to the three-phase rectifier. The remaining things are the same for both operations.

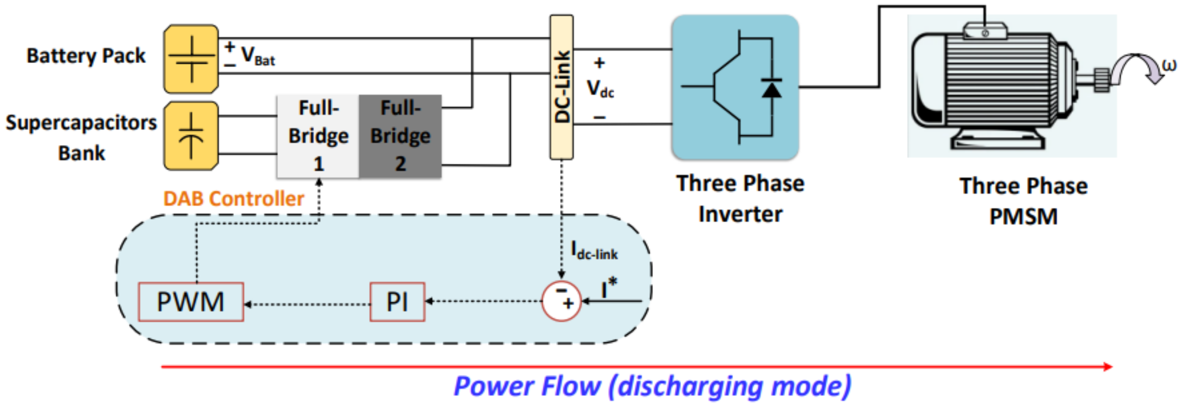

Figure 4: Topology of DC-DC converter (discharging mode)

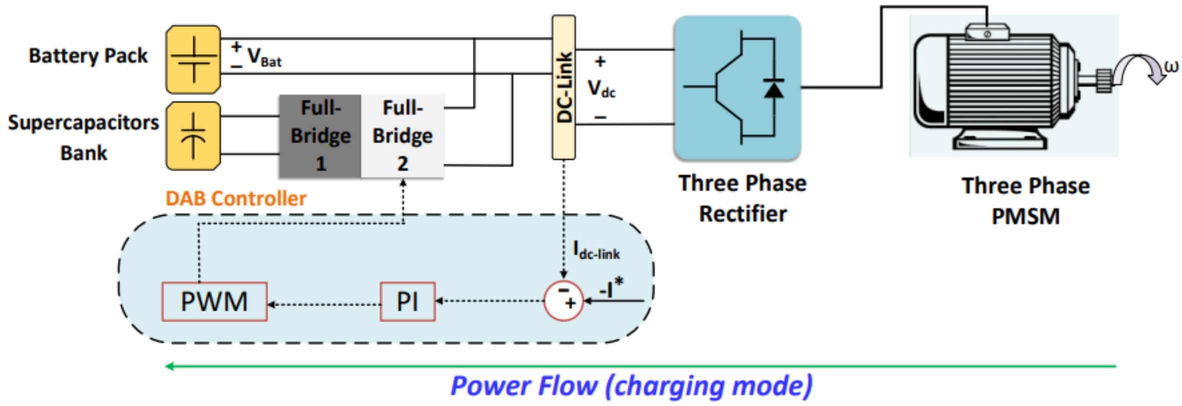

Figure 5: Topology of DC-DC converter (charging mode)

6. SIMULATION RESULTS

For the bidirectional DAB-based ultracapacitor interface system intended for PMSM recovery braking in EB applications, various operating conditions are used to assess the dynamic performance of the suggested control approach. The motor's ratings are shown in Table 3. In this paper, the results seek for the ultracapacitor charging and discharging modes. Charging mode will take place during applying braking on the PMSM where the boat starts to decelerate. While in discharging mode, when the boat starts to accelerate, the ultracapacitor will work as an additional power source for the EB.

Table 3. Motor Specifications

Description	Value
Torque	0.8 Nm
Input Voltage	300 V
Rated Speed	3000 rpm

The MATLAB/SIMULINK software package is used to model and simulate the proposed control approach shown in Figure 5. The first and second tables display the system parameters. First, the behavior of the ultracapacitor is examined when the EB PMSM is working in the acceleration (discharging) mode. Secondly, the behavior of the ultracapacitor is examined while the PMSM of the EB operates under braking (charging) conditions. Finally, a hybrid condition combines both conditions.

6.1Discharging Mode

In this case, the ultracapacitors are discharging while the speed of the motor is increasing, which means that it is an additional power source with the battery pack unit. Figure 6 shows the driving behavior of the driver, motor speed, and SOC waveforms of the ultracapacitors. It can be observed that while the speed of the boat increases, the ultracapacitor starts to discharge at the same time. Based on the referenced signal, the PI controller will generate the pulse signals for the DAB converter. The first H-bridge pulses will lead the second H-bridge pulses as shown in figure 7. In this case, the ultracapacitor works as a power source for the EB. Hence, the power flows from the ultracapacitor to the DAB then to the inverter, and finally to the motor.

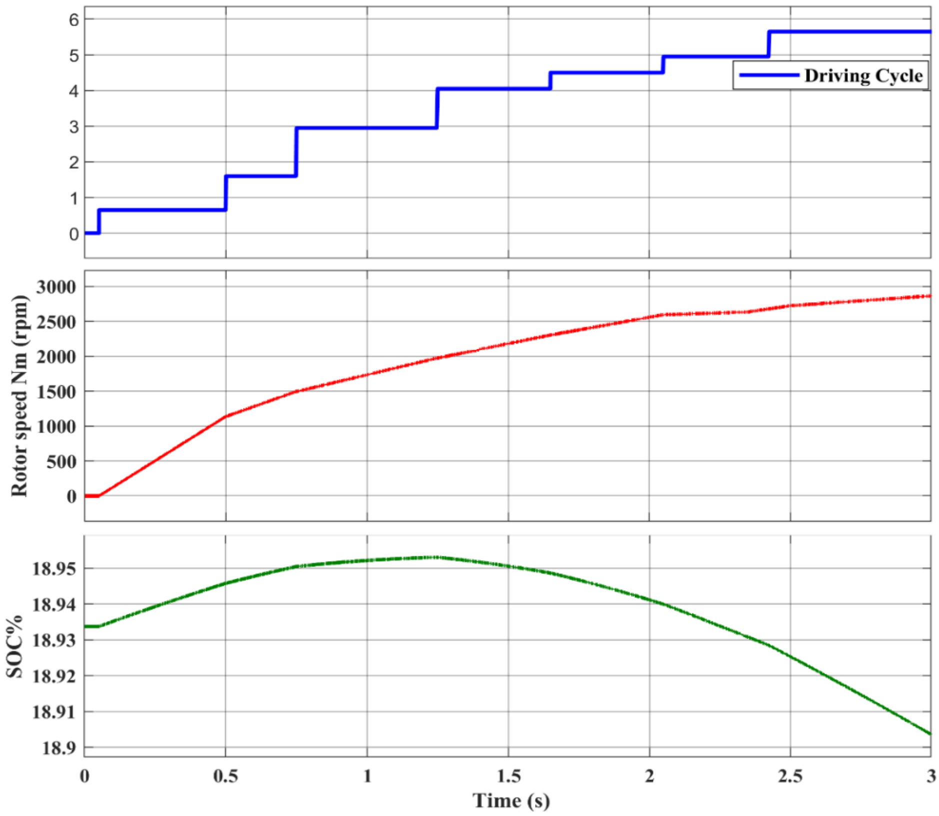

Figure 6: Driving behavior, motor speed, and SOC waveforms of the ultracapacitors (discharging mode)

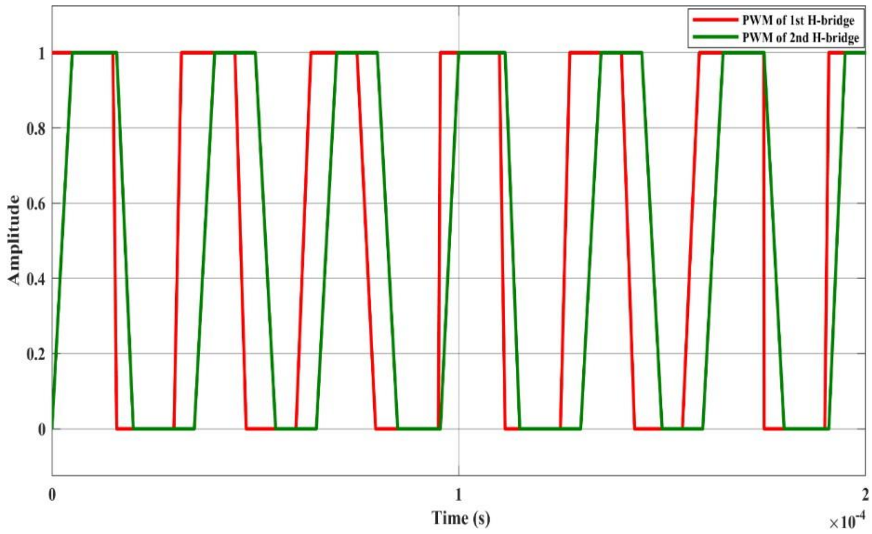

Figure 7: Gate pulses of the DAB (discharging mode)

6.2 Charging Mode

In this scenario, the motor is slowing down as the ultracapacitors are charging. At this point, the EB's motor was subjected to braking force. Figure 8 depicts the driver's behavior while driving, the motor speed, and the ultracapacitors' SOC waveforms. As the boat slows down, it can be seen that the ultracapacitor begins to charge at the same time. The PI controller will produce the pulse signals for the DAB converter based on the referenced signal. As depicted in Figure 9, the second H-bridge pulses will come first. Regenerative braking mode will be taken into account in this scenario. There will be a ultracapacitor charge. As a result, power passes from the motor to the rectifier, the DAB converter, and ultimately the ultracapacitor.

6.3 Hybrid Mode

In this mode, different scenarios are studied for both charging and discharging modes depending on the driver's behavior. It can be observed from Figure 10 that when the EB accelerates, the ultracapacitor starts to discharge at the same time. In case of deceleration of the boat, the ultracapacitor starts to charge. This demonstrates the significant dynamic response of the ultracapacitor pack's integration with the battery pack.

7. CONCLUSION

One of the key systems in the development of EBs is recovery (regenerative) braking. Regenerative braking has the power to conserve waste energy by up to 8 to 25 percent. Ultra-capacitors and DC-DC converters, two modern power electronic components, have improved the regenerative braking system. According to the findings, many EBs currently use regenerative braking. The surge in petrol prices has sparked research and advancement in energy saving. In this study, a DAB converter-based interface system for ultracapacitor charging and discharging for regenerative braking of PMSM is suggested. Ultracapacitor's charging and discharging strategies are moreover offered for the suggested DAB interface system. The DAB converter's phase shift angle is controlled by the PI controller. The technique is modeled and simulated under the MATLAB/SIMULINK environment. The simulation results show that the ultracapacitor has a fast response and accurate performance in the charging mode and the discharging one. In discharging mode, the ultracapacitor's SOC starts to degrade with acceleration while the PMSM slows, and the SOC begins to increase once more.

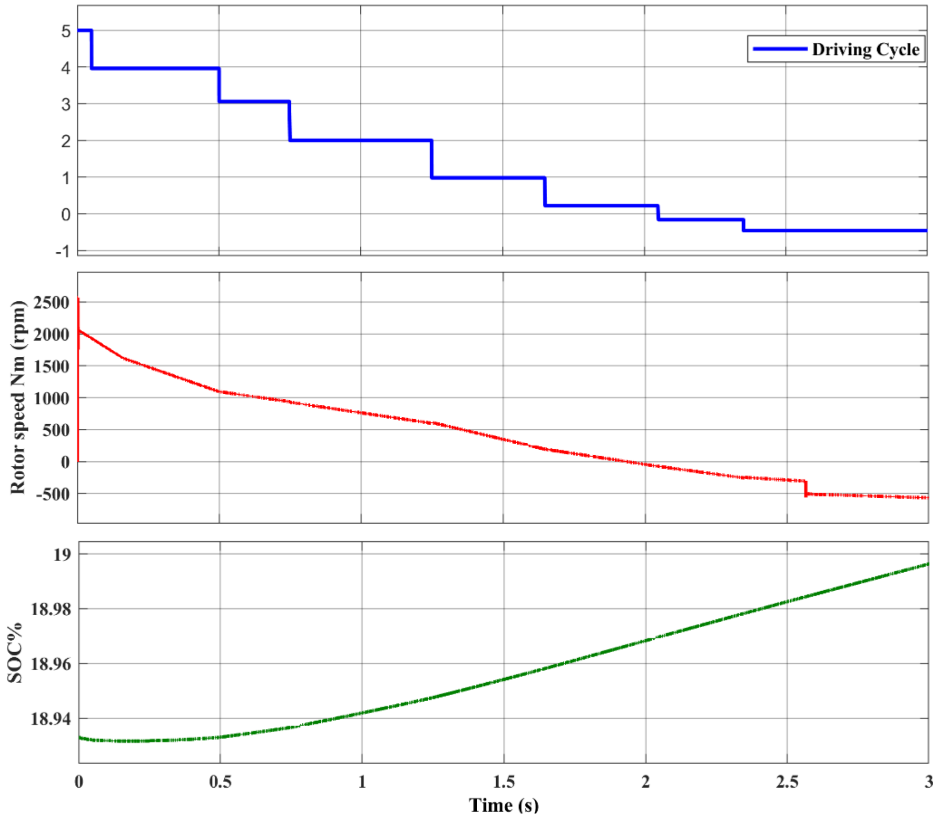

Figure 8: Driving behavior, motor speed, and SOC waveforms of the ultracapacitors (charging mode)

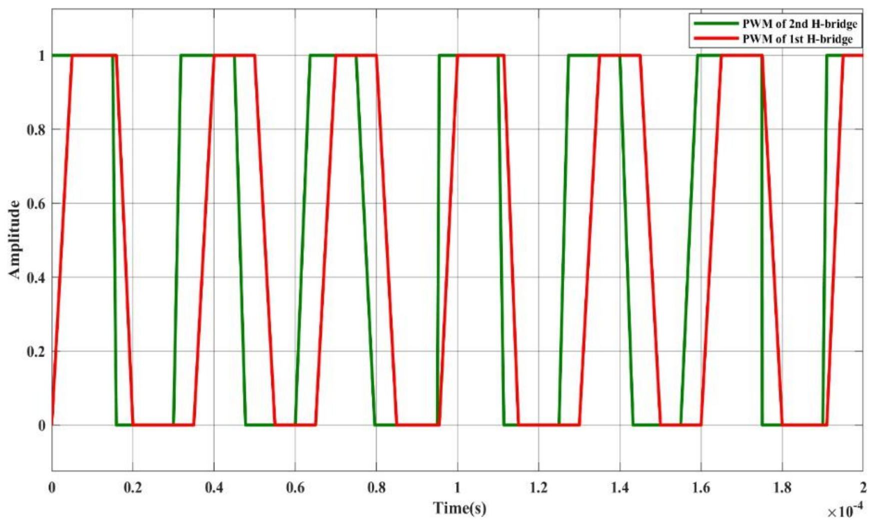

Figure 9. Gate pulses of the DAB (charging mode)

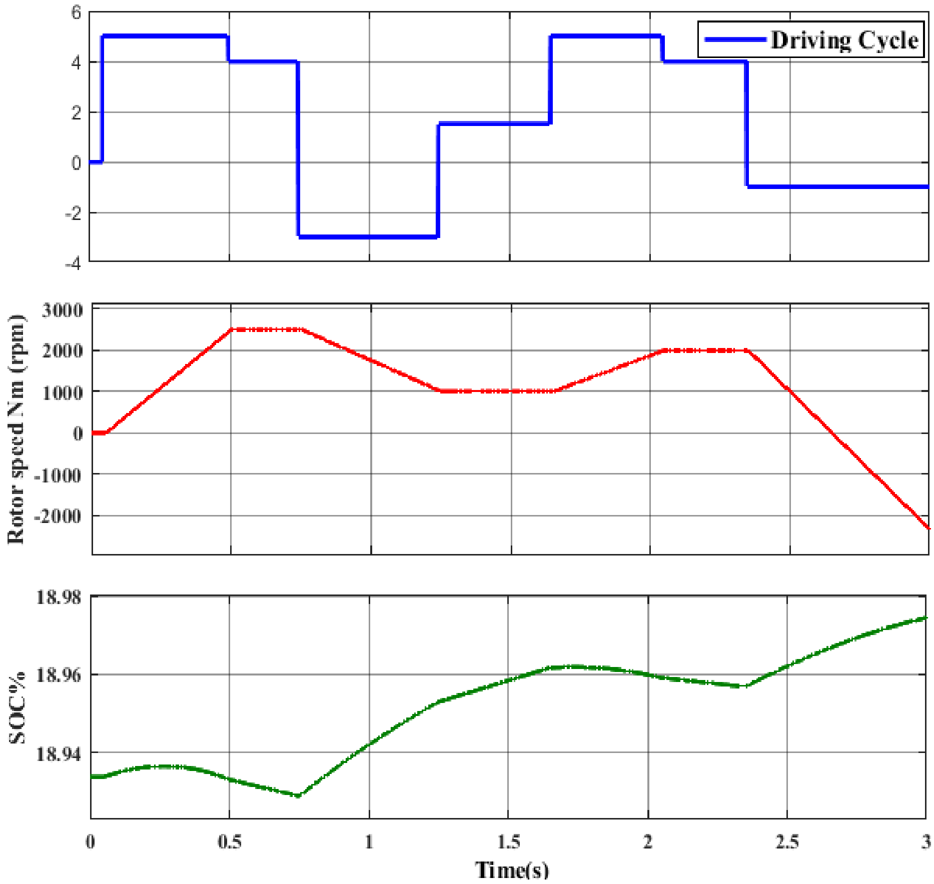

Figure 10. Driving behavior, motor speed, and SOC waveforms of the ultracapacitors (hybrid mode)

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