Modular Multilevel Converter with Integrated Supercapacitor Energy Storage System for an Electric Tugboat

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***Abstract*—This paper presents the development of a drive system based on a Modular Multilevel Converter (MMC) with integrated supercapacitors for electric propulsion applications. Batteries, while capable of providing the required energy, have limitations related to cost, thermal management, and lifespan, especially in high-power, high-cycle applications. In this scenario, hybrid systems combining batteries and supercapacitors represent a promising solution, combining the high energy density of batteries with the rapid charge/discharge capability of supercapacitors. This paper investigates the integration of supercapacitors within an MMC (SC-ESS-MMC) and presents a control strategy validated through MATLAB/Simulink/SimScape, demonstrating the potential of this configuration for electric propulsion applications.**

***Index Terms*—Modular multilevel converter, supercapacitors, electric propulsion, energy storage systems, control strategy.**

I. Introduction

The increasing awareness of the impact of harmful emissions on climate change, human health, and the environment is driving the adoption of technological solutions capable of ensuring a climate-neutral future for the next generations. The maritime transportation sector contributes significantly to global greenhouse gas emissions, prompting the introduction of stringent regulations to reduce emissions. One promising solution is the electrification of maritime propulsion systems, which can be achieved through various approaches, including diesel-electric, hybrid, hydrogen and fully electric propulsion.

In this context, the Modular Multilevel Converter (MMC) has emerged as a key technology for high-voltage and high-power applications, such as electric propulsion systems and electric drive [1]–[4]. The MMC's modular architecture allows for scalability, efficiency, and fault tolerance, making it suitable for various applications, including electric ships and vessels.

A significant challenge in MMC applications is the management of voltage ripple across the submodule capacitors, which can lead to performance degradation and reliability issues. Traditional MMCs often require complex control strategies to balance the voltage across the submodule capacitors and manage circulating currents, especially during transient conditions such as startup or sudden load changes [5], [6].

Another interesting challenge is the handling of high current demands during transient conditions, such as startup or sudden load changes. This can lead to degradation of the battery pack, which is often used as the main energy source in electric propulsion systems [7], [8].

To address these challenges, this work proposes the integration of supercapacitors within the MMC submodules, creating a hybrid system (SC-ESS-MMC) that combines the high energy density of batteries with the rapid charge/discharge capability of supercapacitors. The proposed SC-ESS-MMC configuration allows for effective management of voltage ripple across the submodule capacitors and provides a mean to handle high current demands during transient conditions, thus improving overall system performance and reliability.

II. Modular Multilevel Converter

The Modular Multilevel Converter is an interesting solution for high-voltage and high-power applications. Thanks to its modular architecture, the MMC overcomes the limitations of traditional systems and offers significant advantages, such as high modularity, scalability, efficiency, and fault tolerance. A general MMC structure is shown in Fig. 1, where the submodules (SMs) are connected in series to form a three-phase converter. In particular, the MMC considered in this work is a three-phase full-bridge submodule topology, with four

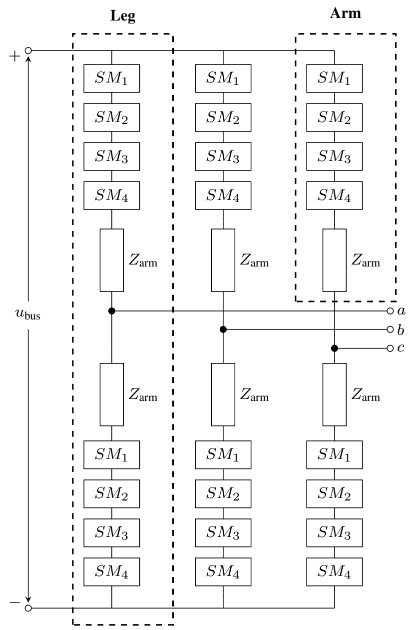

Fig. 1. Modular Multilevel Converter structure: 4 modules for each arm.

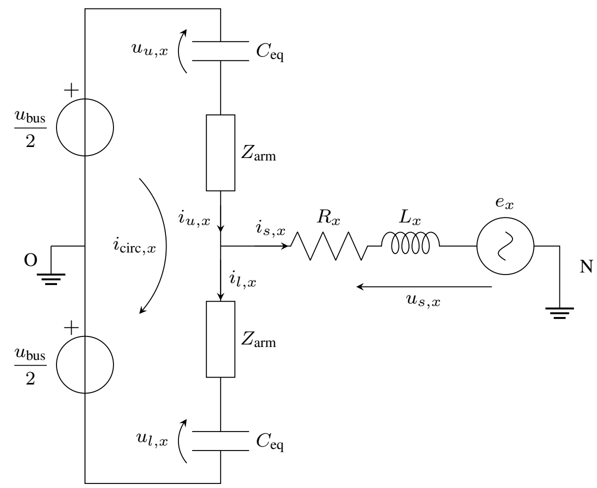

Fig. 2. MMC: single phase representation.

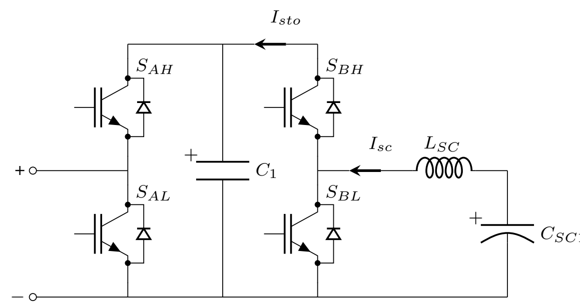

Fig. 3. Structure of cell 1 of the MMC (see Fig. 1, where C_{SC} is the supercapacitor.

submodules connected in series for each arm. The structure of the submodule is discussed in detail in Sect. II-B.

Among the various topologies, the solution considered in this work is the full-bridge submodule topology. The MMC consists of multiple submodules connected in series, each containing a capacitor, a supercapacitor, an inductor and four power electronic switches. The submodules can be configured to operate in different modes, such as charging, discharging, or bypassing, allowing for flexible control of the output voltage and current. The submodules structure is discussed in detail in Sect. II-B.

In order to simplify the analysis, the MMC can be represented as a single-phase equivalent circuit, as shown in Fig. 2, [6]. With reference to the single-phase representation, the MMC consists of two arms, each containing a number of submodules connected in series. The following equations represent the Kirchhoff's voltage law of the circuit in Fig. 2:

$$u_{\text{bus}} = u_{u,x} + u_{l,x} + 2L_{\text{arm}}\frac{di_{\text{circ}}}{dt} + 2R_{\text{arm}}i_{\text{circ}} \tag{1}$$

$$u_{s,x} = \frac{u_{l,x} - u_{u,x}}{2} - 2\frac{L_{\text{arm}}}{2}\frac{di_{\text{circ}}}{dt} - R_{\text{arm}}i_{\text{circ}} \tag{2}$$

where u_{bus} is the bus voltage, $u_{u,x}$ and $u_{l,x}$ are the upper and lower arm voltages, respectively, L_{arm} is the arm inductance, R_{arm} is the arm resistance, and i_{circ} is the circulating current.

The circulating current of a generic leg x is defined as:

$$i_{\text{circ},x} = \frac{i_{u,x} + i_{l,x}}{2} \tag{3}$$

where $i_{u,x}$ and $i_{l,x}$ are the upper and lower arm currents, respectively.

A. Voltage Ripple Across Submodule Capacitors

It is possible to calculate the voltage ripple across the submodule capacitors using the following equation, see [9]:

$$\Delta u_{\text{C}} = \frac{I_{\text{M}}}{2\omega_{\text{me}}C} \tag{4}$$

where I_{M} is the maximum current flowing through the submodule, ω_{me} is the fundamental frequency, and C is the capacitance of the submodule capacitor. Equation (4) shows that the voltage ripple across the submodule capacitors is inversely proportional to the capacitance and the fundamental frequency, and directly proportional to the maximum current flowing through the submodule. This means that in applications with high current demands, the operations of the MMC are not guaranteed. For instance, during startup operations of an electric propulsion system, the electric speed ω_{me} is low and the current draw by the motor I_{M} is high, leading to a significant voltage ripple across the submodule capacitors.

The traditional MMC faces challenges related to voltage balancing by injecting a high-frequency circulating current in the MMC arms to ensure that the voltage across the submodule capacitors remains within acceptable limits, [5].

B. Integrated Supercapacitor Energy Storage System

To address the voltage ripple issue in MMCs, this work proposes the integration of supercapacitors directly within the submodules of the MMC, creating a hybrid system (SC-ESS-MMC), [10]. Supercapacitors, with their high power density and rapid charge/discharge capability, can effectively manage high current demands and protect the battery from excessive stress, improving overall system efficiency. The proposed SC-ESS-MMC configuration is shown in Fig. 3, where the supercapacitor is integrated into the submodule structure. The supercapacitor C_{SC1} transfers energy to and from the main output capacitor C_1 by proper driving switches S_{BH} and S_{BL}, allowing to quickly respond to transient power demands while the battery provides the necessary energy for longer-term operation.

III. Control Strategy

The control strategy aims to decouple the energy provided by the supercapacitors and the battery, allowing the supercapacitors to handle transient high-power demands while the battery gradually recharges the supercapacitors during steady-state operation. The control strategy is implemented in MATLAB/Simulink/SimScape, where the MMC is modeled with the integrated supercapacitors. The control loops are designed to ensure that the supercapacitors can quickly respond to changes in power demand, while the battery operates at a more stable rate, thus prolonging its lifespan and improving overall system performance.

The modulation strategy for the MMC is based on the phase-shifted carrier pulse width modulation (PWM) technique, which allows for efficient control of the submodule switches and ensures that the output voltage is balanced across the submodules. The control strategy is of hierarchical nature, with a high-level control loop managing the overall system performance and a low-level control loop managing the individual submodule operations. In particular, the hierarchical control strategy consists of the following control loops:

- Speed control loop
- (Output) Current control loop
- Circulating current control loop
- Supercapacitor state-of-charge (SoC) control loop
- Submodule capacitor voltage control loop

The speed control loop regulates the motor speed by adjusting the reference current, which is then used in the current control loop to manage the output current of the MMC. The field orient control (FOC) technique is employed to control the motor current, ensuring that the motor operates efficiently and effectively.

A. Circulating Current Control Loop

The circulating current control loop is designed to manage the circulating currents within the MMC arms. With reference to Fig. 2, the circulating current can be expressed as:

$$L_{\text{arm}} \frac{di_{\text{circ},x}}{dt} + R_{\text{arm}} i_{\text{circ},x} = \frac{1}{2}\left(u_{\text{bus}} - u_{u,x} - u_{l,x}\right) \quad (5)$$

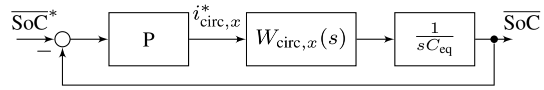

Fig. 4. Control of the average SoC of the supercapacitors.

Therefore, the circulating current can be controlled by imposing a certain voltage across the upper and lower arms of the MMC. A proportional-integral (PI) controller is used to regulate the circulating current with respect to a reference value. Its role is important since the circulating current is responsible for balancing the state of charge of the supercapacitors in the arms of the MMC. In particular, the dynamics of the circulating current affects the current draw from the battery pack, which is important to keep it at low gradients to prolong its lifespan.

B. Supercapacitor State-of-Charge (SoC) Control Loop

The average SoC of the supercapacitors decreases/increases due to the power demand of the load. Therefore, the average SoC can be regulated by controlling the circulating current of each leg of the MMC. This is a distinctive feature of the proposed SC-ESS-MMC configuration, which allows for the regulation of the average SoC of the supercapacitors by adjusting the circulating current. In this work, a proportional controller is used to regulate the average SoC of the supercapacitors with respect to a reference value, which is set to 0.5, that is the average SoC of the supercapacitors at the beginning of the simulation. The average SoC of the supercapacitors $\overline{\text{SoC}}$ can be expressed as:

$$\overline{\text{SoC}} = \frac{1}{2N} \sum_{i=1}^{2N} \text{SoC}_i \quad (6)$$

where N is the number of supercapacitors in the arm and SoC_i is the state of charge of the i-th supercapacitor.

The SoC of the supercapacitors is controlled by adjusting the circulating current of each leg of the MMC, which in turn affects the power flow between the supercapacitors and the submodule capacitors. The control scheme is reported in Fig. 4.

C. Submodule Capacitor Voltage Control Loop

The submodule capacitor voltage control loop is designed to regulate the voltage across the submodule capacitors. In particular, the voltage over the capacitors is controlled by means of the supercapacitors connected to the submodule capacitors through a half bridge. This configuration allows the bidirectional power flow between the supercapacitors and the submodule capacitors, enabling the supercapacitors to charge or discharge as needed to maintain the voltage across the submodule capacitors within acceptable limits.

By taking advantage of the bidirectional power flow capability of the supercapacitors, the proposed MMC configuration can handle the power going in/out of the battery during transient conditions, such as during startup or sudden load changes. The voltage of each capacitor is controlled by

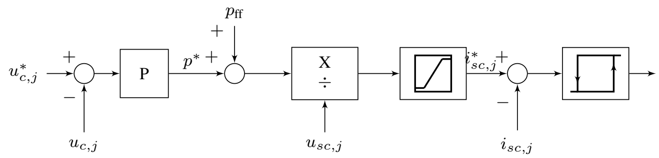

Fig. 5. Capacitor voltage control via bidirectional converter.

TABLE I
MAIN PARAMETERS OF THE MMC USED IN THE SIMULATION.

Description	Symbol	Value
Number of submodules per arm	N_{SM}	4
Submodule capacitance	C	$1\,\text{mF}$
Arm inductance	L_{arm}	$1\,\text{mH}$
Arm resistance	R_{arm}	$0.02\,\Omega$
DC bus voltage	u_{bus}	$5000\,\text{V}$
Supercapacitor capacitance	C_{SC}	$0.2\,\text{F}$

calculating the power that the supercapacitor has to provide. The power is proportional to the difference between the measured voltage and the reference voltage of the capacitor. An additional feedforward term p_{ff} is added to the power reference to account for the power demand of the load. The feedforward term is calculated as the product of the desired voltage that the cell has to provide and the measured current of the arm.

The power requested to the supercapacitors is then converted into a current reference by dividing the power by the voltage of the supercapacitor. In this way, the current reference for the supercapacitors can be limited within a certain range, which is defined by the maximum current that the supercapacitors can provide. Once the current reference is calculated, it is compared with the measured current of the supercapacitors. A bang-bang controller is used to control the switches of the half-bridge configuration, allowing the supercapacitors to charge or discharge as needed to guarantee the desired current reference. The bang-bang controller results in a non-fixed switching frequency, which is not a problem for the supercapacitors, since they can handle high switching frequencies; however, this could represent a drawback when it comes to size the converter filters. Furthermore, the adoption of a bang-bang controller allows for a simple implementation and fast response time, which is crucial for the control of the supercapacitors during transient conditions.

IV. Simulation and Results

The proposed control strategy is validated through simulations performed in MATLAB/Simulink/SimScape. The case study considered in this work is an electric tugboat with a propulsion system based on a Modular Multilevel Converter (MMC) with integrated supercapacitors. The motor and battery pack data are the same as those used in the IEEE VTS Motor Vehicle Challenge 2025, [11], [12]. The characteristic parameters of the MMC are summarized in TABLE I.

The simulation is performed for a mission profile of 7 minutes, which includes a startup phase, a steady-state phase, and a shutdown phase. The simulation time was reduced to 7 seconds, applying a scale factor of 1 minute per second. The simulation was performed with a time step of $1\,\mu\text{s}$, and an ODE 2 solver was used to solve the differential equations of the system.

The first goal of the proposed control strategy is to ensure that the voltage across the submodule capacitors is within acceptable limits, which is achieved by means of the supercapacitors aiding the submodule capacitors in the power demand handling during the mission profile, which is reported in Fig. 7. The voltage across the submodule capacitors is shown in Fig. 6, in particular the voltage of capacitor 1 (leg A) is shown. The difference of the remaining three voltage capacitors with respect to the voltage of capacitor 1 is negligible, since the supercapacitors are able to balance the voltage across the submodule capacitors as demonstrated in Fig. 6 by means of the voltage differences Δu.

Another goal of the proposed control strategy is to smooth the power flow requested to the battery pack, which is achieved by means of the supercapacitors aiding the battery in the power demand handling during the mission profile. The results of the power flow are shown in Fig. 7. It is interesting to note that the supercapacitors are able to handle the power demand during the startup phase, and the battery pack intervenes smoothly without sudden changes in the power flow. The SoC of the supercapacitors, shown in Fig. 9, is initially suffering a drop due to the high power demand during the startup phase, but it is able to recover as soon as the power flow from the battery pack is sufficient to recharge the supercapacitors. This characteristic is inherent to the proposed control strategy, which allows the supercapacitors to handle the power demand during transient conditions, while the battery pack operates at a more stable rate, thus prolonging its lifespan and improving overall system performance. The rate of intervention of the battery pack is regulated by means of the circulating current control loop, which is discussed in Sect. II-B.

The importance of the proposed control strategy of the average SC of the supercapacitors is inferable from the results reported in Fig. 8. The higher the gain of the control action discussed in Sect. III-B, the more the power requested from the battery rather than the supercapacitors.

The SoC of the supercapacitors is shown in Fig. 9, where it can be seen that the SoC of the supercapacitors is able to recover after the startup phase, and it remains within acceptable limits during the steady-state phase. Furthermore, all the supercapacitors are able to balance their SoC, which is a key feature of the proposed control strategy.

V. Conclusion

The integration of supercapacitors within the MMC, along with the proposed control strategy, offers a promising solution for electric propulsion applications. The SC-ESS-MMC addresses the voltage ripple issue faced by traditional MMCs while optimizing the utilization of batteries and supercapacitors. Future work includes further optimization of the control strategy, such as by replacing the bang-bang controller with

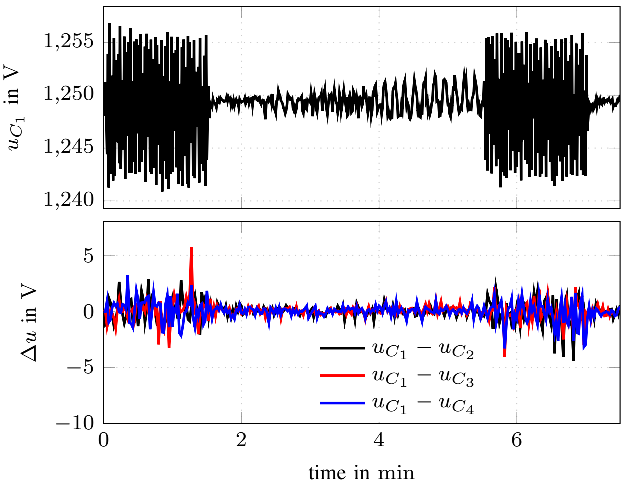

Fig. 6. Voltage of capacitor 1 (leg A), $u_{C,1}$, during the mission profile as well as arm capacitor voltage unbalances.

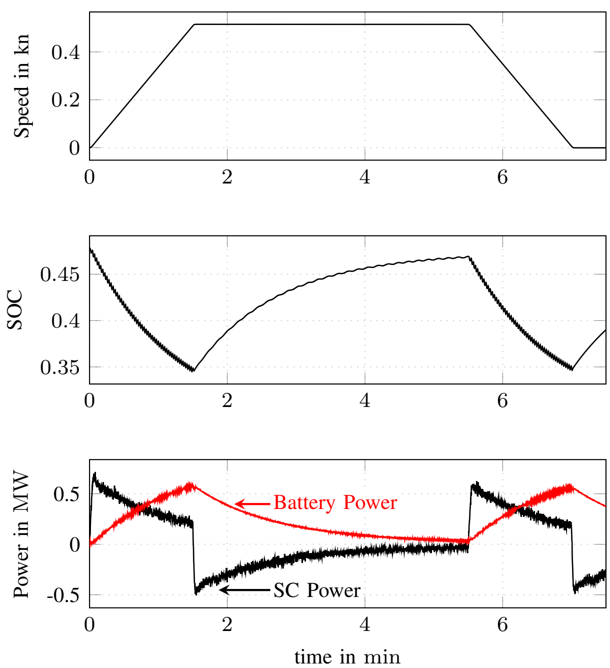

Fig. 7. SoC of the capacitors (leg A) during the mission profile. The speed profile of the considered mission and the requested battery and SC power are reported, as well.

a fixed switching frequency strategy, thermal analysis, and potential applications in on-board charging systems.

VI. Acknowledgments

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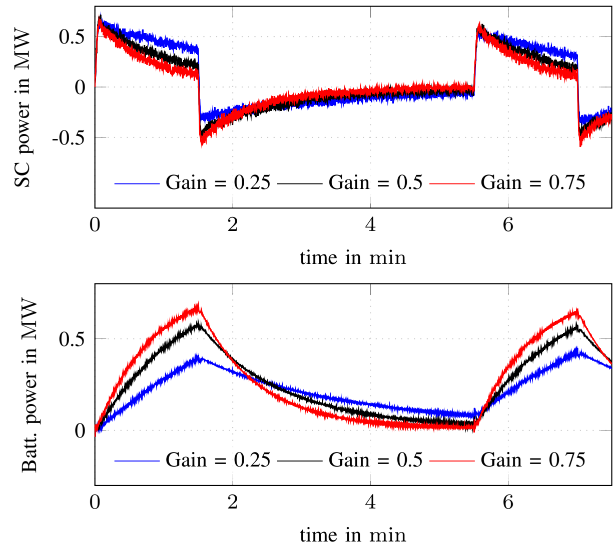

Fig. 8. Effect of the proportional gain P in Fig. 4 on the power flows.

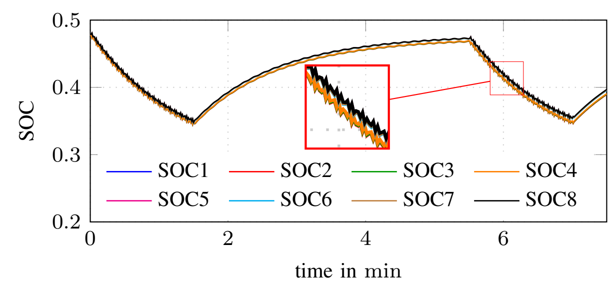

Fig. 9. SoC of the capacitors (leg A) during the mission profile.

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