Fault tolerant control of modular multilevel shipboard storage system

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***Abstract*—This thesis focuses on the development of a fault-tolerant control system for multilevel modular storage systems. After studying potential failures and available fault-tolerant control methods, the necessary controls for the considered system were implemented using PLECS. Subsequently, the ability to ensure the required performance during faults was assessed.**

I. Introduction

In the current context of the maritime industry, electrification emerges as a key solution to address emissions challenges and improve energy efficiency. The International Maritime Organization (IMO) aims to reduce greenhouse gas emissions from maritime transport by 50% by 2050, driving towards more sustainable technologies. Shipboard Power Systems (SPSs) are evolving for greener and more efficient navigation, with particular attention to Direct Current Shipboard Microgrids (DC-SMGs) offering numerous advantages. However, their adoption presents challenges in designing protection and anomaly management systems. This thesis focuses on implementing fault-tolerant control of a multilevel modular storage system onboard ships, aiming to develop a robust and reliable system even in the presence of faults and interruptions.

II. Modular Multilevel Storage System

This thesis considers the multilevel modular storage structure such as in 1. This structure consists of a number of modules (i.e., battery and DC/DC converter) stacked in a string and a number of strings connected in parallel. This connection allows a tailored voltage and current output by changing the number of modules and strings. Additionally, both current and voltage control strategies are implemented to ensure the desired performance output from the system.

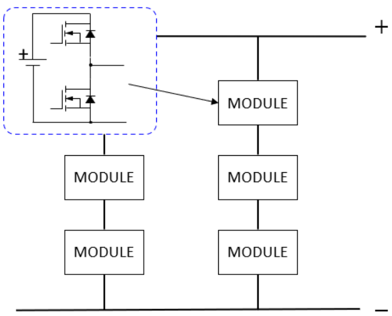

Figure 1: Diagram of the considered in MMC storage system.

III. Considered Fault Event

Faults in modular storage systems are mainly caused by open-circuit interruptions or short circuits in the switches. This thesis will address open-circuit faults in switches, particularly where faults manifest in both the upper and lower switches of the module.These faults can cause secondary damage to the device if not detected promptly, potentially leading to system failure. To ensure continuous operation of the modular multilevel converter (MMC), faulty modules need to be promptly identified, and fault-tolerant control is essential before replacing them.

IV. Fault Tolerant Control

In multilevel modular storage systems, the phase shift technique between carriers within the same string is commonly implemented to reduce the output harmonic content. When a module goes offline, this characteristic is lost, creating issues for the system. Furthermore, it's crucial to highlight that the failure of the transistor switch can lead to varying outcomes based on whether the system is in a charging or discharging state. While discharging, no issues typically arise as the current flows through the diode in anti-parallel with the low-side switch. However, during charging, the faulty switch may result in an uncontrolled charge of the battery in the affected module, thereby posing potential risks to the battery pack. To address this, two control methods have been implemented:

- phase-shift adjustment
- bypass of faulty module

V. Simulation Validation

Initially, the response to a fault occurring in one module within a system consisting of three modules arranged in series was analyzed, both during the discharge and charge phases. Afterwards, the behavior of a fault occurring in a string was investigated, considering a scenario with three parallel strings during the discharge phase when a fault happens at 0.1s. In Figure 2, a comparison is made during the discharge mode. The phase shift angle between the carriers is dynamically adjusted based on the number of active modules. This adjustment aims to achieve identical harmonic cancellation during switching operations. As it can been seen, the ripple current is reduced when the phase shift adjustment is implemented.

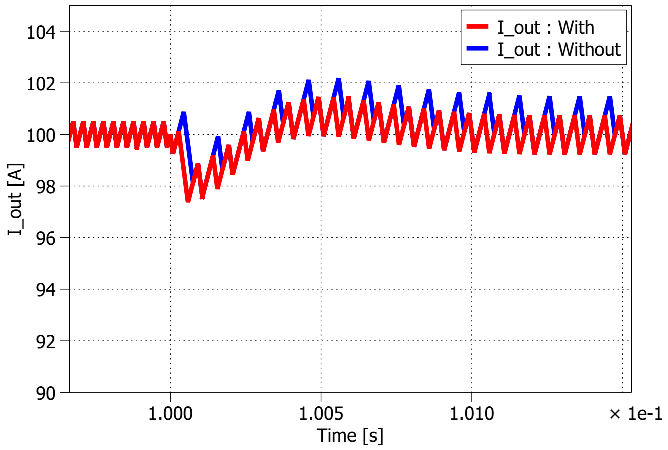

Figure 2: Comparison without (red line) and with phase shift adjustment (blue line).

In the charge mode, the faulty module is bypassed, while in the case of systems with parallel strings, the contactors are opened at both ends.

Simulations have been conducted to observe how the system behaves in reality after the following events:

- Single fault module when discharging (Fig.3).
- Single fault module when charging (Fig.4).
- Disconnection of one out of three strings (Fig.5).

Fig. 3 demonstrate the system's capability to maintain performance and service continuity during discharge mode until the healthy modules are nearly fully discharged.

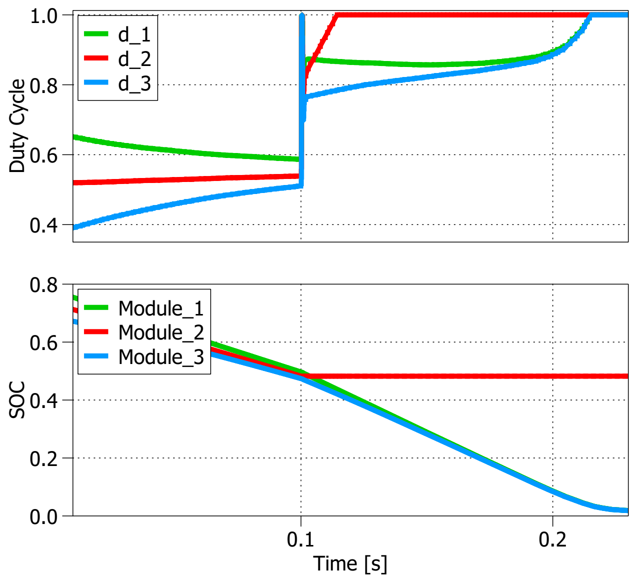

Figure 3: Duty cycle and SOC in discharge mode.

Similarly, in figure 4, performance and continuity of service are ensured, except for the faulty module, which is bypassed to preserve the component.

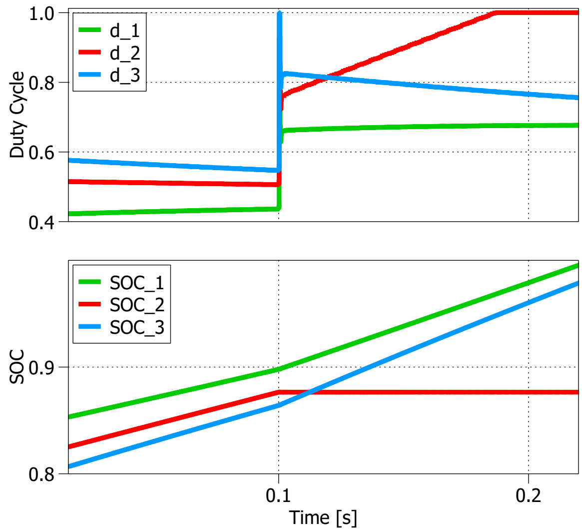

Figure 4: Duty cycle and SOC in charge mode.

Finally, the fault in a string was analyzed. Fig.5 presents the main results, showing that continuity of service and that the performance cannot be ensured after the fault, if the healthy two strings lack sufficient energy to restore the system to supply the load.

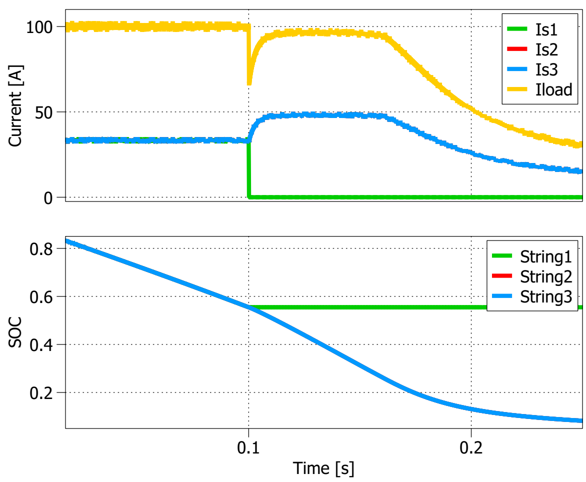

Figure 5: Currents and SOC in parallel string.

VI. Conclusion

The simulations showcase the system's ability to dynamically respond to faults, ensuring efficient distribution of energy among intact modules. Moreover, the system's adaptive behavior in both discharge and charge modes underscores its resilience in maintaining essential performance metrics despite unexpected disruptions. The parallel string configuration enables uninterrupted system operation, even as there is a fault in one string. However, to further enhance safety measures, it is prudent to oversize the battery packs. This approach not only ensures operational continuity but also enhances vessel and crew safety in the event of module failures, advancing reliability and sustainability in naval applications, thereby contributing to the overall resilience of maritime operations.