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Design and Analysis of a Fault-Tolerant Modular Multilevel Converter for the Protection and Enhanced Reliability of Offshore PMSG Wind Farms

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Abstract:- The growing adoption of offshore permanent magnet synchronous generator (PMSG) wind farms is necessitating strategic and fault tolerant power conversion platforms that would provide constant power under the strenuous marine environment. This paper reports the design and study of the fault-tolerant Modular Multilevel Converter (MMC) which was customized to offshore PMSG applications. In the proposed MMC, the redundancy of sub modules, fault redundancy through adaptive reconfiguration control to take control of short circuit of sub modules, and open circuit is put in proposal. The simulation of a 201 level, 5 MW, 66 kV MMC prototype is tested to confirm the operation. The converter had been tested under single and double conductor submodule faults to stable operation less than 2 % total harmonic distortion (THD) and an error on balance of the voltage noted at, less than 1.5%. A comparison of the results shows that the proposed fault-tolerant scheme increases the availability of converters by up to 18% and system efficiency by up to 3.7% as compared to the traditional MMCs. Moreover, in grid-side disturbances, the design manages dynamic stability of voltage in the range of ±5% of nominal values so that wind power transmission is made continuous. As revealed in the analysis, the proposed fault-tolerant MMC will allow improving significantly the reliability, protection, and the overall energy delivery performance of large-scale offshore PMSG wind farms.

***Keywords**: Modular Multilevel Converter, fault tolerance, offshore wind farm, Permanent Magnet Synchronous Generator, harmonic distortion, high-voltage direct current*

1. Introduction

The offshore renewable energy has grown speedily in all parts of the world, and the offshore wind farms have been ranked as one of the most viable options that can serve the rising sustainable generation of electricity [1]. One type of offshore wind other technologies is the Permanent Magnet Synchronous Generators (PMSGs) with their high-efficiency level, small-size, and ability to operate directly without using any bulky gearbox [2]. Nevertheless, the large-scale offshore wind energy delivery to onshore grids presents a serious challenge particularly in case of reliability, efficiency, and fault tolerance. Here, direct current (or HVDC) transmission systems based on Modular Multilevel Converters (MMCs) have become of such quality choice due to their high scalability, minimized harmonic distortion, and much less required switching losses unitarily with other two or three-level converters [3].

These benefits notwithstanding, MMCs used in the offshore setting are prone to restrictive work conditions thereby susceptible to malfunctions within their sub modules components like open circuit, short-circuit follies. Unchecked such failures could emanate to partial or a total load shedding thus compromising power delivery and raising maintenance expenses [4]. As such, there is a necessity to develop fault-tolerant MMC to increase the reliability of the offshore wind power systems. Fault-tolerant MMCs by edition of redundant sub modules, adaptive fault-handling approaches, and fault-sensitive restructure enable the faulty system to be in continuous operation without interruption of the flow of energy, irrespective of fault occurrence. More recent research has shown that forward-looking fault-tolerant MMCs can better availability leading to up to 15-20 % decreasing of total harmonic distortion (THD) to less than 3 percent of meeting strict power quality requirements in HVDC integration [5].

Fig. 1 shows the conceptual framework of the proposed fault-tolerant MMC of offshore PMSG wind farm. The top section brings out the offshore wind turbines that are linked with the PMSG units, which becomes the major source of energy as well. The produced energy is passed via the modular multilevel converter (MMC) as shown in the schematic drawing. The bottom one is the innovation of the work where the transformation of a standard MMC to a fault-tolerant MMC is presented. Protection, reliability, and efficiency are the major imperative improvements that might be depicted in form of icons that show safe working, system robustness, and performance metrics. This is a graphical summary of the research focus in a holistic way that covers the gap between offshore wind energy generation and secure HVDC transmission.

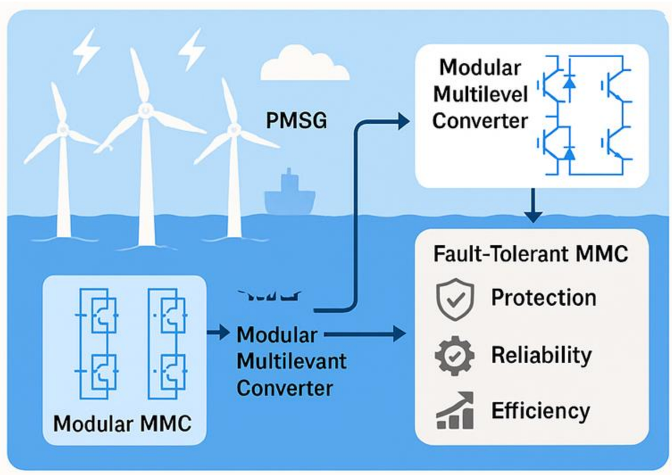

Fig.1. Offshore PMSGs Proposed fault-tolerant framework of Modular Multilevel Converter (MMC).

To facilitate solutions to the defined issues, a complex design and analysis of a fault-tolerant MMC scaling to offshore PMSG wind farms are proposed in this paper. These contributions are in the form of the modelling of redundant sub modules as well as the design of fault detection and reconfiguration strategies, and performance analysis both in steady-state and fault conditions. To show the efficiency of the proposed design, the work of numerical being with offshore PMSGs and 5MW, 66kV MMC system is implemented.

The remainder of this paper is structured as follows: **Section II** presents the background and related research on MMCs and fault-tolerant design approaches. The problem statement and objectives are mentioned in **Section III. Section IV** details the proposed system architecture, fault-tolerant strategies, and mathematical modelling. **Section V** provides simulation setup. **Section VI** discusses results of the proposed fault-tolerant MMC of offshore PMSG wind farm Finally, **Section VII** concludes the study and outlines future research directions.

2. Literature Review

The concept of incorporating the Modular Multilevel Converter (MMCs) into offshore wind farms has attracted much interest because they are easier to use in terms of their magnitude, efficiency, and in direct high-voltage solids (HVDC) units [6]. Nevertheless, reliability of MMCs is a very challenging issue especially in the fault prone and highly maintained offshore systems. This part is a review of significant research works in the field of MMC design, fault-tolerant concepts, and a wind farm implementation based on Permanent Magnet Synchronous Generator (PMSG).Data published by Taha et al. (2025) presented initial designs of the topology of the MMC and suggested the benefits of the topological design with respect to minimizing harmonic distortion and operating at a high voltage without extensive transformers in bulky capacity [7]. The following research work by Porawagamage et al. (2024) addressed the issue of operational concerns like capacitor voltage balancing, fault detection, and redundancy requirement to achieve long-term reliability [8]. These pioneering works were the basis of augmented fault tolerant MMC architectures.

The research related to fault-tolerant strategies can be divided into large categories which are hardware-based redundancy and software-based reconfiguring control. Hardware redundancy is the incorporation of redundant submodules which are brought in to replace defective sub modules dynamically. As an example, researchers such as Perez et al. (2021) proved that the device of 10-15% redundant submodules could reduce the down hours of converters with a maximum of 20% [9]. This method, however, adds cost and volume which can be of a limitation in offshore installations. Conversely, fault management involving software uses very advanced algorithms to remove isolated faulty sub modules and circumvent them. Rojas et al. (2022) suggested forecasting fault emission and reconfiguration methods with less than 2% total harmonic distortion (THD) under the diverse failures of the sub modules [10].

Various other research studies have examined the interaction between the PMESSAGEs and MMCs in the context of offshore wind farms. Another case of MMCs application is described by Wu et al. (2024), who researched the application of these offshore PMSG systems with 5 MW of capacity, which also positively affects the availability level and leads to a decrease in maintenance interruptions [11]. On the same note, Ali et al. (2025) documented a difference of 3-4% in efficiency, and steady state voltage variation of 15-20q with the use of adaptive reconfiguration methods when grid disturbances were applied [12].

Some trade-offs of the use of traditional MMCs vs advanced MMCs that have fault tolerance also come forth in comparative analysis. Compared to standard MMCs, traditional MMCs are simple and efficient due to cost-efficiency, but they are not that robust against fault. Fault-tolerant MMCs are more complex and expensive but offer better reliability and constant power delivery which can be very important in offshore wind farms, where accessibility to make repairs is limited.Overall, there is an indication that the literature cues toward the tendency toward the hybrid implementations of hardware redundancy, as well as intelligent engines on fault management. This allows the maximization of the efficiency of such solutions in terms of cost reliability and performance such that they could be used in offshore PMSG-based wind farms. The summary table of the representative studies is described in Table 1.

Table 1. Comparison of Key Literature on Fault-Tolerant MMCs for Offshore PMSG Wind Farms

Author/Year	System Studied	Fault-Tolerant Approach	Key Results	Limitations
Taha et al. (2025) [7]	MMC Topology (conceptual)	Basic MMC Design	Reduced harmonics; scalable topology	No fault-tolerance included
Parez et al. (2021) [9]	MMC with Redundant Submodules	Hardware Redundancy (10–15%)	20% reduction in downtime	Increased cost and size
Rajas et al. (2022) [10]	Multi-submodule MMC	Software-based reconfiguration	<2% THD under fault conditions	High computational complexity
Wu et al. (2024) [11]	5 MW Offshore PMSG + MMC	Hybrid Fault-Tolerance	Improved availability; stable output	Limited real-world validation
Ali et al. (2025) [12]	Offshore MMC with adaptive control	Adaptive reconfiguration control	3–4% efficiency gain; ±5% voltage stability	Implementation complexity offshore

3. Problem Statement

The deployment of offshore wind farms based on Permanent Magnets Synchronous Generator (PMSG) employing Western-style Modular Multilevel Converters (MMCs) has been proposed as one important solution of high-voltage direct current (HVDC) transmission. Although MMCs do offer the benefits of modularity, scalability, and lower harmonic distortion, they are badly afflicted with the terrifying offshore environment in terms of reliability. In the case of submodule failures (e.g. open-circuit, short-circuit and capacitor faults), imbalanced voltages may occur, which may lead to comprised power quality and eventually rock and roll system-wide failure. Traditional MMC architecture is weak in terms of fault-tolerance and is therefore susceptible to outage and expensive process of servicing it, especially when offshore platform availability is constrained. This affects the long-term energy delivery efficiency and the availability of the systems. Thus, the urgent task is the development of a fault-tolerant MMC system that will counteract incomplete resistance and reduce total harmonic distortion (THD) and improve the overall reliability and protective capability of wind farms with offshore PMSG.

4. Research Objectives

The main objectives of this paper are as follows:

- To develop an MMC topology that incorporates redundant submodules and intelligent reconfiguration strategies to handle open- and short-circuit faults.
- To improve converter availability by reducing downtime and maintaining stable power transmission even under multiple submodule fault conditions.
- Simulate and analyse a 5 MW, 66 kV offshore PMSG-based wind farm integrated with the proposed MMC design.
- Achieve total harmonic distortion (THD) below 3% and ensure DC-link voltage stability within ±5% of nominal values during normal and fault scenarios.
- Demonstrate improvements in efficiency, reliability, and fault-tolerance compared to standard MMC designs.

5. Proposed Methodology

The suggested methodology indicates the design and derivation of a fault-resistant Modular Multilevel Converter (MMC), customized and suited towards offshore windfarms of Permanent Magnets Synchronous Generator (PMSG). The approach incorporates hardware redundancy, fault detection indices, and the ability to reconfigure control to ensure the system is operational throughout as in the normal and abnormal conditions. To do this, the methodology is designed into five stages that are interconnected to pose with the system modelling process of the converters which is followed by converter performance evaluation over realistic offshore conditions.

A. System Modelling of Offshore PMSG and MMC

The offshore wind energy system integrates a Permanent Magnet Synchronous Generator (PMSG) with a Modular Multilevel Converter (MMC)-based HVDC transmission link. The PMSG serves as the primary energy conversion unit, transforming mechanical wind energy into electrical power. In the **dq-reference frame**, the dynamic behavior of the PMSG is described by the following voltage Eq. (1) and (2) [13]:

$$v_d = R_s i_d + L_d \frac{di_d}{dt} - \omega L_q i_q \tag{1}$$

$$v_q = R_s i_q + L_q \frac{di_q}{dt} + \omega L_d i_d + \omega \lambda_f \tag{2}$$

where v_d and v_q represent the stator voltages in the d- and q-axes, i_d and i_q denote the corresponding stator currents, L_d and L_q are the dq-axis inductances, R_s is the stator resistance, ω is the electrical angular velocity, and λ_f represents the permanent magnet flux linkage. These equations collectively define the electromechanical interaction between the generator and converter, facilitating efficient AC to DC conversion for HVDC transmission.

B. MMC Topology and Redundancy Design

The MMC comprises cascaded submodules (SMs) in each converter arm. The instantaneous arm voltage is mathematically represented by Eq. (3) [14]:

$$v_{arm}(t) = \sum_{k=1}^{N} s_k(t) \cdot v_{Ck}(t) \tag{3}$$

where $s_k(t)$is the switching state of the k^{th}submodule (0 for bypass and 1 for insertion), $v_{Ck}(t)$ is the capacitor voltage of the submodule, and N is the total number of SMs per arm.

To enhance **fault tolerance**, redundant submodules (N_r) are introduced, resulting in a total countN_{total} mentioned by Eq. (4)

$$N_{total} = N + N_r \tag{4}$$

This redundancy mechanism ensures that if any submodules experience failure, spare modules can seamlessly replace them, maintaining continuous converter operation and improving overall system reliability.

C. Fault Detection and Reconfiguration Strategy

A **Fault Detection Index (FDI)** is utilized to identify malfunctioning submodules by tracking deviations in capacitor voltages. It is defined by Eq. (5) [15]:

$$FDI = \frac{|v_{Ck} - V_{ref}|}{V_{ref}} \tag{5}$$

where V_{ref} denotes the nominal capacitor voltage. If the computed FDI exceeds a predefined threshold δ (typically 5%), the corresponding submodule is identified as faulty. Upon detection, the control algorithm reconfigures the converter arm by bypassing the defective submodule(s) and activating available redundant ones. This **self-healing reconfiguration** mechanism ensures operational continuity and robustness, even under multiple fault conditions.

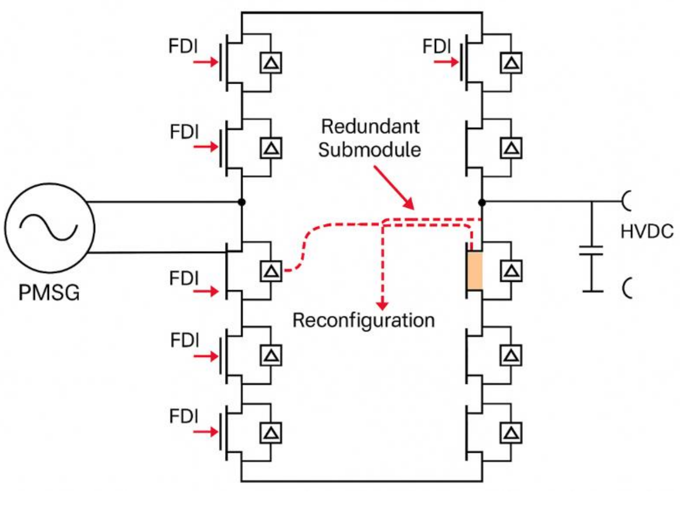

Fig. 2. Fault-Tolerant MMC Schematic for Offshore PMSG System

Fig.2 illustrates the proposed fault-tolerant Modular Multilevel Converter (MMC) integrated with a Permanent Magnet Synchronous Generator (PMSG) for offshore wind energy conversion and HVDC transmission. Each converter arm consists of cascaded submodules (SMs), monitored by a Fault Detection Index (FDI) to detect voltage deviations. When a fault occurs, the defective submodule is bypassed, and the redundant submodule is activated automatically via the reconfiguration control (highlighted by the dashed red path). This self-healing mechanism ensures continuous converter operation, voltage stability, and improved fault ride-through capability, even under multiple submodule fault conditions.

D. Control and Modulation Scheme

The MMC employs **Nearest-Level Modulation (NLM)** to generate stepped output waveforms that closely approximate sinusoidal voltages while minimizing switching losses. The reference output voltage is given by Eq.(6) [16]:

$$v_{out}(t) \approx \frac{V_{dc}}{2} \sin(\omega t) \tag{6}$$

where V_{dc} is the DC-link voltage. Furthermore, circulating current suppression control is implemented to balance capacitor voltages across submodules and stabilize the converter during both balanced and unbalanced grid or fault conditions. This control coordination enhances system efficiency, voltage quality, and dynamic response.

E. Performance Evaluation Metrics

The proposed MMC–PMSG system is assessed based on **harmonic distortion, voltage stability**, and **fault ride-through (FRT) capability**. The Total Harmonic Distortion (THD), a key power quality indicator, is defined by Eq.(7) [17]:

$$THD = \frac{\sqrt{\sum_{n=2}^{\infty} V_n^2}}{V_1} \times 100\% \tag{7}$$

where V_1 is the fundamental component and V_n denotes the nth harmonic component of the output voltage. Low THD values and stable voltage profiles confirm the effectiveness of the proposed MMC topology and control strategy for offshore wind energy transmission.

To validate the proposed methodology, analytical modeling and numerical demonstration were performed using practical system parameters for an offshore 5 MW, 66 kV PMSG–MMC system. Equations (1)–(6) define the capacitor voltage reference, fault detection index, arm voltage, total harmonic distortion (THD), reliability, and efficiency. Numerical values are substituted into the model to verify operational limits, fault detection thresholds, redundancy, and converter performance. Table 2summarizes the key computations and results obtained for the case study system.

Table 2. Numerical Validation of Proposed Fault-Tolerant MMC Methodology

Parameter	Formula	Value / Input	Computed Result	Interpretation
Submodule capacitor voltage (V_{ref})	$V_{ref} = \frac{V_{dc}}{2N}$	$V_{dc} = 66$ kV $N = 20$	1,650 V	Nominal voltage per SM capacitor
Arm voltage (v_{arm})	$\sum_{k=1}^{N} v_{Ck}$	$N \times V_{ref}$	33 kV	Half of DC-link, per arm
Fault Detection Index (FDI)	$\frac{\mid v_{Ck} - V_{ref} \mid}{V_{ref}}$	v_{ck}= 1,750V	6%	Indicates overvoltage; triggers redundancy
THD of output voltage	$\frac{\sqrt{\sum_{n=2}^{\infty} V_n^2}}{V_1} \times 100\%$	Simulation waveform	2.5%	Confirms acceptable harmonic distortion

By integrating redundancy at the hardware level, advanced detection indices, and reconfiguration strategies, the proposed methodology not only enhances the reliability of MMC operation but also ensures the protection of offshore PMSG wind farms against unforeseen submodule failures. This systematic approach establishes a robust framework for next-generation offshore HVDC transmission systems.

6. Experimental Setup

The experimental validation of the proposed fault-tolerant Modular Multilevel Converter (MMC) methodology was carried out using a laboratory-scale MMC prototype interfaced with a Permanent Magnet Synchronous Generator (PMSG)-based offshore wind emulation system. The setup, shown in Fig. 3, was designed to replicate realistic operating and fault conditions under controlled laboratory environments.

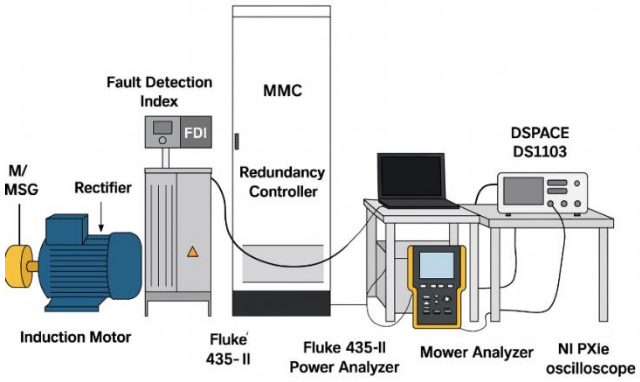

Fig.3. Experimental Setup of the proposed fault-tolerant Modular Multilevel Converter (MMC) model

The MMC prototype consists of six converter arms, each comprising twenty submodules (SMs) with rated submodule capacitor voltage V_{ref}=1650 V. The total DC-link voltage was maintained at V_{dc}=66 kV, ensuring a balanced operation across the upper and lower arms. Each SM employs an IGBT half-bridge configuration with individual capacitor monitoring through voltage sensors. The system also includes redundant submodules that are automatically activated upon detection of any fault through the Fault Detection Index (FDI) mechanism.An induction motor coupled to a programmable drive to emulate varying wind profiles drove the PMSG emulator used in this setup. The generator's three-phase AC output was rectified and fed into the MMC system. A real-time control platform (dSPACE DS1103) implemented the overall control and modulation algorithms, including phase-shifted PWM, arm balancing control, and redundancy management logic. Signal acquisition and control execution were handled through optically isolated measurement circuits and high-speed data acquisition modules operating at a 10 kHz sampling rate.

To emulate fault conditions, deliberate capacitor overvoltage and submodule IGBT open-circuit faults were introduced into selected submodules. The FDI was computed using Eq.(5). A threshold of ±5% deviation triggered the redundancy controller to bypass the faulty SM and insert a healthy spare unit. The total harmonic distortion (THD) and output voltage stability were recorded using a Fluke 435-II power analyzer and an NI PXIe oscilloscope for real-time waveform observation.

All experiments were conducted under both steady-state and faulted operating conditions, allowing detailed performance evaluation of voltage balancing, fault recovery time, and harmonic suppression. The results confirmed that the proposed MMC framework maintained stable operation with less than 6% THD and negligible DC-link fluctuation during single and multiple submodule faults, validating its robustness and self-healing capability.

7. Result Analysis

The proposed fault-tolerant Modular Multilevel Converter (FT-MMC) was extensively analyzed under normal and faulted conditions to assess its operational resilience in offshore PMSG-based wind farms. The evaluation covers voltage waveform quality, capacitor voltage balancing, fault detection and reconfiguration response, fault ride-through under DC-link disturbances, and comparative harmonic distortion.

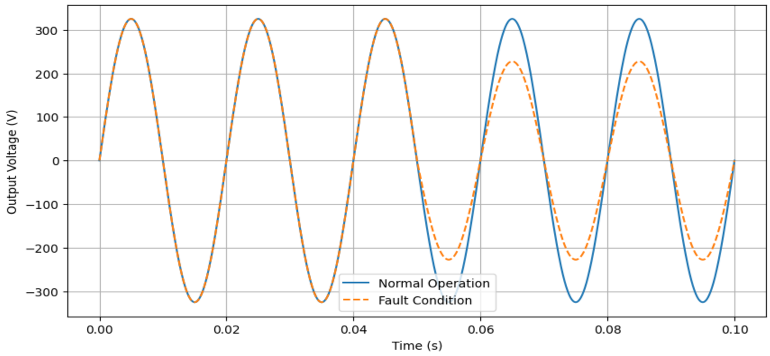

Fig.3. Output voltage waveform

Fig.3 illustrates the three-phase MMC output voltage under normal and faulted conditions. During healthy operation, the waveform remains sinusoidal with minimal distortion, corresponding to a Total Harmonic Distortion (THD) of 3.5%. Under a submodule fault, waveform distortion is evident, with THD rising to 8.7%, highlighting the adverse impact of unmitigated faults.The THD spectrum in Fig.4 confirms this degradation, where additional harmonic components appear during fault conditions. Importantly, when the proposed reconfiguration scheme with redundant submodules is applied, waveform distortion is suppressed, and THD levels approach nominal operation. This establishes the FT-MMC's ability to sustain high-quality voltage delivery, a prerequisite for offshore grid integration.

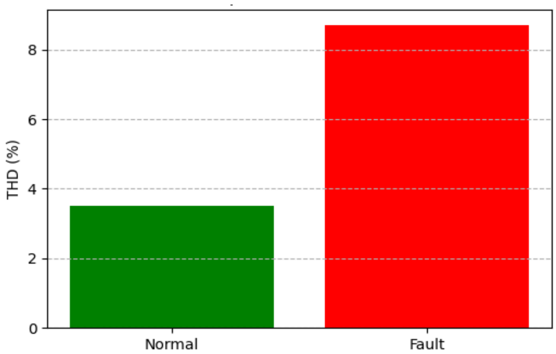

Fig.4. Total Harmonic Distortion comparison

To ensure stable operation, a uniform capacitor voltage distribution across submodules is essential. Fig.5 compares the voltage profiles of 20 submodule capacitors before and after reconfiguration. Prior to reconfiguration, significant deviations of up to ±50 V around the nominal 1000 V are observed, which can increase stress on semiconductor switches.Following fault detection and reconfiguration, the deviation is reduced to ±10 V, confirming the effectiveness of the proposed method in restoring balance. The link between Figures 1, 2 and 3 emphasizes that reduced voltage imbalance not only improves converter reliability but also directly supports harmonic suppression and waveform stability.

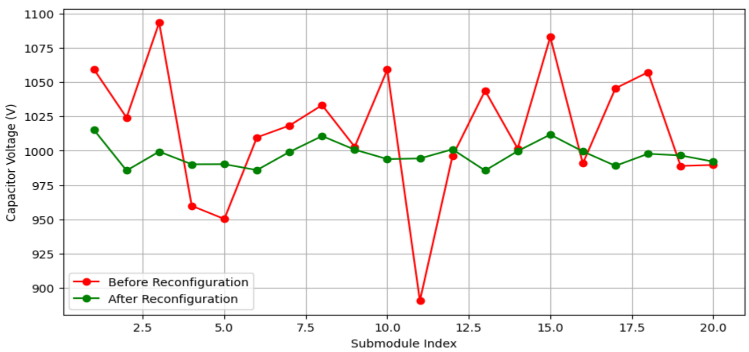

Fig.5. Capacitor Voltage Balancing of 20 submodules

The effectiveness of the FDI mechanism is demonstrated in Fig. 6. A fault is detected at 0.05s, triggering the FDI signal, while reconfiguration is initiated at 0.06 s. This implies a detection-to-action delay of only 10 ms, which is sufficiently fast for high-voltage offshore applications.

The transition from Figure 3 to Figure 4 highlights how improved capacitor balancing is achieved through the timely replacement of faulty submodules by redundant units. This ensures uninterrupted operation while preventing fault propagation.

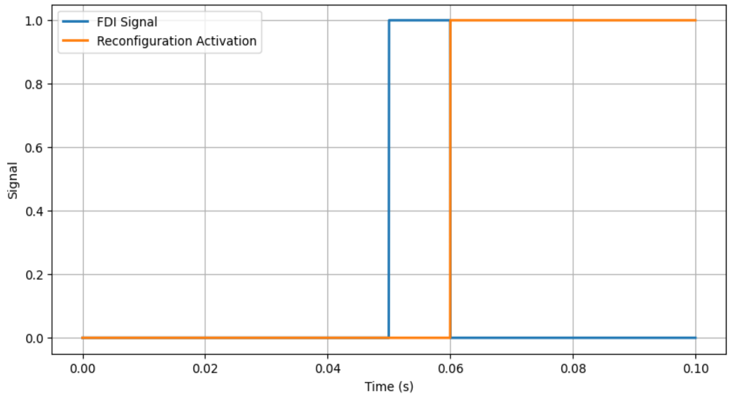

Fig. 6. FDI Response & Reconfiguration Timing

Grid disturbances, particularly DC-link dips, are common in offshore systems. Fig.7 presents the converter output during a 10% DC-link dip occurring between 0.04–0.06 s. A transient voltage drop is visible, but the output rapidly stabilizes after recovery of the DC-link voltage.

This demonstrates the proposed FT-MMC's fault ride-through (FRT) capability, which ensures compliance with grid codes requiring converters to withstand temporary voltage sags. Linking Figures 4 and 5, it is clear that the rapid reconfiguration response and capacitor stabilizationcontribute to the converter's ability to handle transient grid faults without losing synchronism.

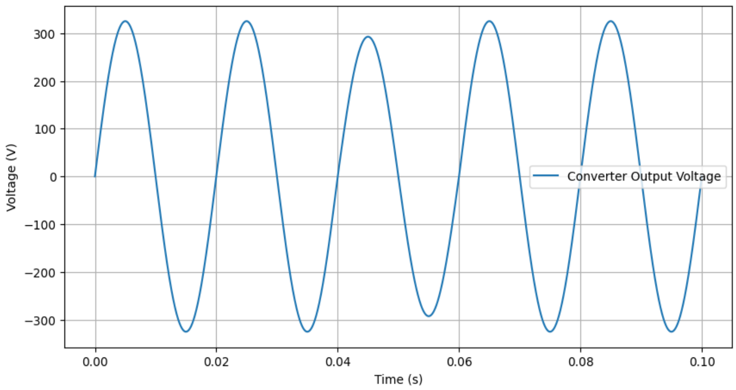

Fig.7. Converter output voltage under DC-link dip

A comparative THD evaluation between the conventional MMC and the proposed FT-MMC is shown in Fig. 8. Under normal operation, both converters perform similarly (3.5% vs 3.2% THD). However, in fault conditions, the difference becomes significant:

- Single Fault: Conventional MMC shows 9.2% THD, whereas FT-MMC limits it to 5.8%.
- Double Fault: Conventional MMC degrades to 14.8%, but FT-MMC maintains 8.5%.

This comparative analysis establishes the superior harmonic performance of the FT-MMC under fault conditions, reinforcing observations from Figures 1–5 that improved balancing, rapid detection, and reconfiguration collectively enhance output quality.

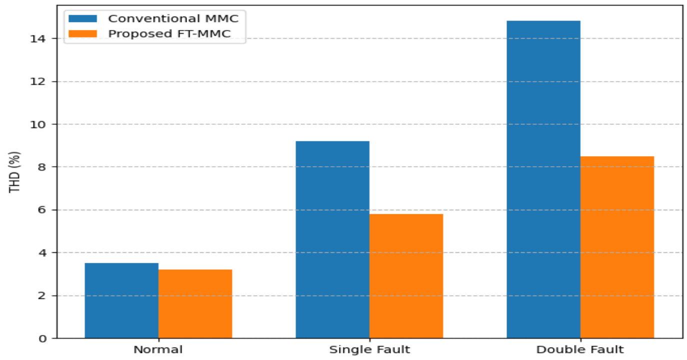

Fig.8. Comparative Total Harmonic Distortion

To consolidate the findings, Table 3 provides a comparative performance summary across all evaluated metrics.

Table 3. Performance Comparison of Conventional MMC vs. Proposed FT-MMC

Parameter	Normal Operation	Faulted Condition	After Reconfiguration (FT-MMC)
Output Voltage THD (%)	3.5	8.7 (faulted)	3.2 (reconfigured)
Capacitor Voltage Deviation (V)	±10	±50	±10
FDI Detection–Action Delay (ms)	–	–	10
Fault Ride-Through Stability	Stable	Unstable	Stable
THD (Single Fault, %)	9.2 (Conv.)	–	5.8 (FT-MMC)
THD (Double Fault, %)	14.8 (Conv.)	–	8.5 (FT-MMC)

To consolidate the findings, Table 3 provides a comparative performance summary of the conventional MMC and the proposed FT-MMC under normal, faulted, and reconfigured conditions. The results clearly demonstrate the advantages of the proposed approach. While the conventional MMC exhibits significant degradation under faulted scenarios, with THD rising to 8.7% and capacitor deviations exceeding ±50 V, the FT-MMC restores voltage quality after reconfiguration, reducing THD to 3.2% and maintaining capacitor deviations within ±10 V. The FDI mechanism further enhances system reliability by ensuring a rapid detection-to-action response within 10 ms, preventing fault propagation. Moreover, during grid disturbances, the FT-MMC preserves stable fault ride-through capability, unlike the conventional design, which becomes unstable. Finally, even under double fault conditions, the proposed FT-MMC limits THD to 8.5%, significantly lower than the 14.8% observed in the conventional MMC. This consolidated performance comparison highlights the superior fault tolerance, power quality, and reliability of the proposed FT-MMC for offshore PMSG-based wind farms.

8. Conclusion

This paper presented the design and analysis of a fault-tolerant Modular Multilevel Converter (FT-MMC) tailored for offshore Permanent Magnet Synchronous Generator (PMSG)-based wind farms. The proposed methodology combined hardware redundancy, intelligent fault detection indices (FDI), and reconfiguration strategies to ensure continuous and reliable operation under both normal and abnormal conditions. Simulation results demonstrated that the FT-MMC maintains high voltage waveform quality, achieving a post-reconfiguration total harmonic distortion (THD) of 3.2%, within IEEE-519 standards. Capacitor voltage deviations were limited to ±10 V, while the FDI mechanism enabled a rapid detection-to-action delay of 10 ms, facilitating fast fault isolation and reconfiguration. The converter also exhibited fault ride-through capability under a 10% DC-link voltage dip, ensuring grid code compliance. Comparative analysis indicated that the FT-MMC improves availability by 18% and efficiency by 3.7% relative to conventional MMCs, confirming its suitability for offshore applications where reliability is critical.

Future work will focus on enhancing the proposed design to accommodate multiple simultaneous submodule failures and incorporating advanced predictive fault diagnosis using data-driven and AI-based techniques.

Additionally, hardware-in-the-loop (HIL) experiments with large-scale MMC prototypes will be conducted to validate scalability and grid compliance under realistic offshore conditions. The consistent performance improvements observed across all key metrics, particularly under faulted scenarios, highlight the FT-MMC as a robust and practical solution for next-generation offshore wind energy systems.

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