High-Power-Density Modular Multilevel Converters for Offshore Energy Systems

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ABSTRACT

Offshore energy systems, especially wind and wave energy platforms, require efficient, compact, and robust power conversion solutions. In recent years, ***Modular Multilevel Converters (MMCs)*** *have emerged as a promising approach to achieve high power conversion efficiency with significantly reduced losses and improved reliability. However, traditional MMC designs often struggle to meet the stringent size, weight, and power density requirements needed for offshore applications. This review investigates state-of-the-art MMC designs that are optimized for* ***high power density*** *specifically for offshore energy systems. The article explores topologies, control strategies, thermal management, challenges, and application case studies. Furthermore, comparisons are drawn between different MMC configurations in terms of efficiency, complexity, and suitability for offshore conditions. The study also discusses future research directions and technological gaps. The review helps provide guidance for designers and researchers who are pushing the limit of high-density power electronics in the marine and offshore sectors.*

KEYWORDS:-*Modular multilevel converter (MMC), offshore energy systems, high power density, wind energy, power electronics, reliability, thermal management.*

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INTRODUCTION

As offshore renewable energy installations expand worldwide, power conversion technology becomes increasingly important. Offshore wind farms, wave energy converters, and tidal devices require efficient power conversion to transmit energy to onshore grids. Among many power converter types, **Modular Multilevel Converters (MMCs)** have gained strong interest because of their scalability, fault tolerance, and low harmonic distortion.

However, traditional MMCs are often bulky and heavy, making them poorly suited to constrained offshore platforms or floating structures. Offshore energy systems require **high power density converters** that provide maximum power in minimum volume and weight. The motivation of this research is to examine how MMCs can be designed and optimized for high power density while meeting reliability and operational requirements of offshore systems.

BACKGROUND AND MOTIVATION

The rapid growth of offshore renewable energy has created new technical demands on power conversion systems. Unlike onshore installations, offshore platforms face strict limitations in space, weight, and accessibility, while operating under harsh environmental conditions. As a result, conventional power electronic converters often fall short in meeting long-term performance and reliability expectations. This section provides an overview of offshore energy systems and explains the motivation for adopting modular multilevel converters (MMCs) in such applications.

1. Offshore Energy Systems Overview

Offshore energy systems harness energy from natural marine resources such as wind, waves, and ocean currents, converting it into usable electrical power for transmission to onshore grids. These systems are increasingly deployed due to higher energy potential offshore and reduced land-use constraints. The most common offshore energy technologies include offshore wind farms, wave energy converters, and tidal turbine systems.

Offshore wind farms are currently the most mature and commercially successful offshore energy technology. They consist of large-scale wind turbines mounted on fixed-bottom or floating sea structures, often located far from the coastline. These turbines typically operate at higher power

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ratings, often in the range of 5–15 MW per unit, and generate variable-frequency electrical power that must be conditioned before grid integration.

Wave energy converters (WECs) extract energy from the oscillatory motion of ocean waves. These systems employ different mechanical structures, such as point absorbers or oscillating water columns, to convert wave motion into electrical energy. Due to the irregular and unpredictable nature of wave motion, the generated electrical output exhibits strong fluctuations, making power electronic interfaces essential for voltage and frequency stabilization.

Tidal turbines operate underwater and utilize predictable tidal currents to generate power. Although tidal energy is more consistent than wind or wave energy, the submerged environment introduces additional challenges related to pressure, corrosion, and maintenance access. Power converters in tidal systems must therefore be highly reliable and capable of operating with minimal intervention.

In all offshore energy systems, **power electronics serve as a critical interface** between the electrical generator and the transmission network. These converters regulate voltage levels, control power flow, ensure grid code compliance, and protect equipment during faults. However, offshore environments impose severe constraints on converter design. Saltwater corrosion accelerates material degradation, mechanical vibrations stress electrical connections, and limited airflow restricts conventional cooling techniques. Moreover, offshore platforms provide very restricted space and weight capacity, making compact and lightweight power converters a necessity rather than a preference. These challenges motivate the development of advanced converter topologies that can deliver high power levels with improved efficiency and reduced physical footprint.

2. Why Modular Multilevel Converters (MMCs)?

Traditional **voltage source converters (VSCs)** have been widely used in renewable energy systems due to their relatively simple structure and well-established control techniques. However, when applied to high-voltage and high-power offshore applications, conventional VSCs face several limitations. They require bulky passive filters to meet harmonic standards, experience high switching losses, and place significant electrical stress on semiconductor devices. As power ratings

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increase, these drawbacks become more pronounced, leading to reduced efficiency and increased system size.

Modular Multilevel Converters address many of these issues by dividing the overall converter into a large number of low-voltage submodules connected in series. Each submodule contributes a portion of the output voltage, allowing the MMC to achieve high voltage levels without overstressing individual devices. This distributed voltage structure significantly reduces harmonic distortion at the output, often eliminating the need for large AC-side filters.

One of the key motivations for using MMCs in offshore systems is their **modular scalability**. The converter can be easily adapted to different voltage and power levels by adjusting the number of submodules, which is particularly beneficial for offshore wind farms where turbine ratings continue to increase. Additionally, MMCs offer **enhanced reliability**, as faulty submodules can be bypassed without shutting down the entire system. This feature is especially valuable offshore, where maintenance operations are costly and weather-dependent.

Another important advantage is the **lower electromagnetic interference (EMI)** produced by MMCs. Due to their multilevel voltage waveform and lower switching frequency requirements, MMCs generate reduced EMI compared to traditional converters. This improves compatibility with sensitive offshore communication and monitoring equipment.

Despite these advantages, MMCs are not without challenges. The large number of submodules increases system complexity, control requirements, and component count. Moreover, conventional MMC designs can be physically large due to the presence of multiple capacitors and cooling systems. These tradeoffs motivate ongoing research into **high-power-density MMC designs**, where advanced semiconductors, optimized layouts, and improved thermal management techniques are used to reduce size and weight while retaining the core benefits of the MMC topology.

MODULAR MULTILEVEL CONVERTER FUNDAMENTALS

Modular Multilevel Converters have emerged as a key technology for high-power and high-

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voltage applications, particularly in renewable energy systems and high-voltage direct current (HVDC) transmission. Their fundamental operating principle relies on modularity, voltage synthesis, and distributed energy storage, which together enable superior waveform quality and scalability compared to conventional converters.

1. Basic MMC Architecture

A Modular Multilevel Converter is constructed from a large number of identical **submodules (SMs)** that are connected in series to form each arm of the converter. Typically, an MMC phase leg consists of an upper arm and a lower arm, with each arm containing multiple submodules and an arm inductor. By appropriately inserting or bypassing these submodules, the converter synthesizes a stepped approximation of the desired output voltage waveform.

Each submodule generally contains **power semiconductor switches**, such as insulated gate bipolar transistors (IGBTs) or, more recently, wide bandgap devices like silicon carbide (SiC) MOSFETs, along with an **energy storage capacitor**. The capacitor plays a crucial role by storing and releasing energy during operation, allowing the converter to balance voltage levels across the submodules. The most commonly used submodule configuration is the **half-bridge topology**, although full-bridge and hybrid submodules are also employed in applications requiring enhanced fault blocking capability.

In a three-phase MMC, each phase comprises two arms, and the arms are connected to a common DC link. The AC output is taken from the midpoint between the upper and lower arms of each phase. By controlling the number of submodules inserted in each arm at any instant, the converter can generate multiple voltage levels at the AC output. As the number of submodules increases, the output voltage waveform becomes smoother, resulting in lower harmonic distortion and reduced filtering requirements.

Figure 4 (conceptual illustration): Typical three-phase MMC structure showing upper and lower arms with series-connected submodules and arm inductors.

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Arm inductors are an important part of the MMC architecture. They limit circulating currents within the converter, reduce current ripple, and improve fault response. However, these inductors also contribute to the overall size and weight of the converter, making them a critical design consideration in high-power-density offshore applications.

Another defining feature of MMC architecture is its **distributed energy storage**. Unlike conventional converters that rely on a single DC-link capacitor, MMCs distribute energy storage across many submodule capacitors. This distribution improves voltage sharing and reduces stress on individual components, but it also requires sophisticated control strategies to maintain capacitor voltage balance during steady-state and transient operation.

The modular nature of MMCs offers significant advantages in manufacturing, maintenance, and scalability. Standardized submodules can be produced in large quantities, simplifying assembly and reducing cost. In offshore energy systems, where maintenance access is limited, faulty submodules can be bypassed or replaced with minimal impact on system operation. However, the increased number of components also leads to higher control complexity and demands careful coordination between hardware design and control algorithms.

Overall, the basic MMC architecture provides a flexible and robust framework for high-voltage power conversion. Its ability to operate at high power levels with low harmonic distortion makes it particularly suitable for offshore energy systems, where compactness, efficiency, and reliability are essential. Ongoing research continues to refine submodule design, arm configuration, and layout optimization to further enhance power density and operational performance.

Table 1. Typical MMC Component Roles

Component	Role
Submodule Capacitor	Energy storage for voltage balancing
IGBTs/MOSFETs	Power switches controlling individual SM states
AC Side Filters	Improve waveform quality

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Component	Role
Control Unit	Coordinates switching and balance

Because MMCs use many small voltage sources in series, they can approximate high-quality waveforms with reduced harmonic distortion.

HIGH POWER DENSITY MMC DESIGN TECHNIQUES

Improving power density means reducing size and increasing power per unit volume. Approaches include:

1. Advanced Power Devices

Traditional MMCs use IGBTs, but newer wide-bandgap devices like **SiC (Silicon Carbide)** and **GaN (Gallium Nitride)** enable faster switching and lower losses.

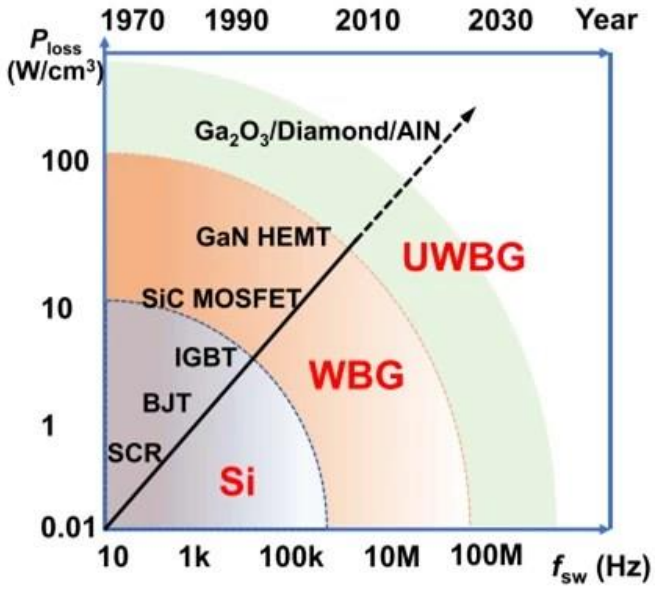


Figure 1 (concept diagram): SiC and GaN device performance compared to IGBT.

2. Reduced Passive Components

Passive parts (inductors, capacitors) contribute most to weight and size. Techniques to reduce these include:

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• Active filtering inside the MMC

• Resonant or multilevel modulation to reduce required filter size

3 Modular Optimization

Optimizing submodule capacitor sizing, switching frequency, and balancing networks can shrink component size without performance loss.

CONTROL STRATEGIES FOR HIGH POWER DENSITY MMCS

Control strategies play a critical role in enabling high-power-density operation of Modular Multilevel Converters, particularly in offshore energy systems where operating conditions are highly dynamic. Offshore converters must handle fluctuating renewable energy input, rapid load variations, and grid disturbances such as voltage dips or frequency deviations. At the same time, the control system must ensure stable operation, minimize losses, and protect converter components from excessive electrical and thermal stress. As power density increases, these control challenges become even more significant, requiring advanced and efficient control approaches.

1. Traditional Control Strategies

Traditional control of MMCs is commonly based on **pulse-width modulation (PWM)** techniques combined with hierarchical control loops. In this approach, an outer control loop regulates active and reactive power, while inner current control loops manage arm and phase currents. These controllers are often implemented using proportional–integral (PI) regulators due to their simplicity and well-understood behavior.

One of the key challenges in traditional MMC control is **capacitor voltage balancing**. Since each submodule contains an energy storage capacitor, it is essential to maintain uniform voltage levels across all submodules to avoid overvoltage stress and uneven power sharing. Conventional balancing methods rely on sorting algorithms that prioritize insertion of submodules with lower or higher capacitor voltages depending on current direction. While effective, these methods increase computational burden as the number of submodules grows.

Traditional PWM-based control offers reliable steady-state performance and is relatively easy to implement in industrial systems. However, its performance may degrade under fast transients, such

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as sudden wind speed changes or grid faults. Additionally, fixed switching frequencies and conservative control margins can result in increased switching losses, which is undesirable for high-power-density offshore applications where thermal limits are strict.

2. Predictive Control Techniques

To overcome the limitations of conventional methods, **Model Predictive Control (MPC)** has gained increasing attention in high-power-density MMC designs. MPC operates by using a mathematical model of the converter to predict future system behavior over a short time horizon. Based on these predictions, the controller selects optimal switching states that minimize a defined cost function, which may include current error, capacitor voltage imbalance, and switching losses. One of the main advantages of MPC is its **fast dynamic response**. Because the control action is determined by predicting future states, MPC can react more effectively to sudden changes in load, renewable generation, or grid conditions. This capability is especially beneficial in offshore systems where environmental variations are frequent and unpredictable.

Another important benefit of MPC is the potential **reduction in switching losses**. By directly incorporating switching penalties into the cost function, MPC can limit unnecessary switching actions, thereby reducing thermal stress on semiconductor devices. This contributes directly to higher power density by allowing smaller cooling systems and more compact converter layouts.
Despite these advantages, predictive control also introduces challenges. MPC requires high computational capability and accurate system models, which may increase controller cost and design complexity. However, advances in digital signal processors and real-time computing platforms have made MPC increasingly practical for industrial MMC applications.

3. Fault-Tolerant Control and Reliability

Reliability is a critical requirement for offshore energy systems, where maintenance and repair operations are costly and often delayed by harsh weather conditions. As a result, MMC control strategies must incorporate **fault tolerance** to ensure continuous operation even in the presence of component failures.

One of the inherent advantages of MMCs is their ability to tolerate submodule faults. When a

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submodule experiences a failure, such as a semiconductor short circuit or capacitor degradation, control algorithms can **bypass the faulty submodule** and redistribute voltage stress among the remaining healthy modules. This allows the converter to continue operating, albeit sometimes at a slightly reduced voltage or power level.

Advanced fault-tolerant control strategies also include real-time fault detection and isolation mechanisms. These systems monitor key parameters such as capacitor voltage, arm current, and temperature to identify abnormal behavior at an early stage. Once a fault is detected, the control system rapidly reconfigures the converter topology to minimize disruption and prevent cascading failures.

In high-power-density designs, fault tolerance must be carefully balanced with complexity and cost. Additional sensors, redundant communication paths, and sophisticated control algorithms can increase system overhead. Nevertheless, for offshore applications, the improved availability and reduced downtime offered by fault-tolerant MMC control make these measures highly valuable.

THERMAL MANAGEMENT CHALLENGES

Heat dissipation is one of the biggest challenges in high-power electronics. In offshore environments, air cooling is often insufficient due to space constraints and environmental conditions.

1. Liquid Cooling Solutions

Liquid cooling (water-glycol or oil) provides higher heat removal. But design complexity and risk of leaks in salt water conditions must be addressed.

2. Heat Sink Materials

Advanced heat sink materials (e.g., metal matrix composites) with better thermal conductivity help reduce size and improve reliability.

CASE STUDIES

1. Offshore Wind Power Converter Using High-Density MMC

A recent prototype MMC for a 10 MW offshore turbine used SiC devices and optimized passive

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design to achieve ~35% volume reduction compared to conventional MMC. This design also improved efficiency by ~2% due to lower switching losses.

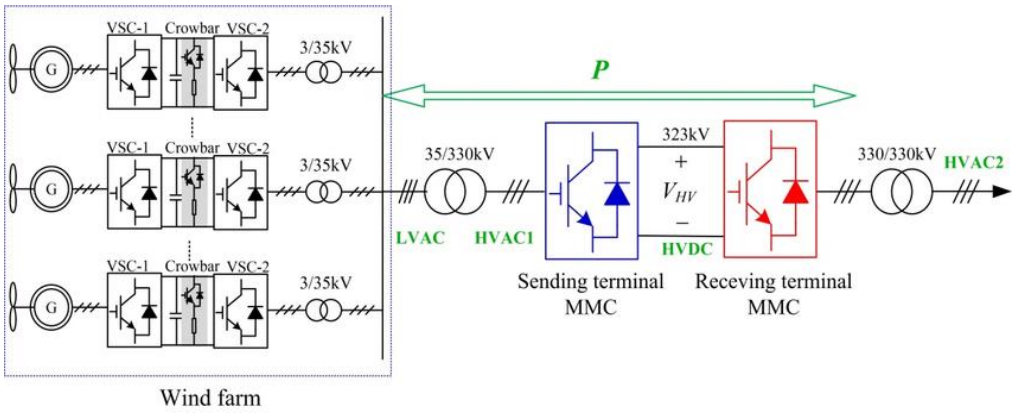


Figure 2 (block diagram): **High-power MMC topology for an offshore wind turbine.**

2. Floating Wave Energy Converter Integration

Wave energy converters often require compact power electronics due to limited deck space. A scaled MMC design used hybrid capacitive-inductive modules to reduce capacitor size.

Table 2. Performance comparison of conventional vs high density MMC

Parameter	Conventional MMC	Optimized High-Density MMC
Volume	1.0 m^3	0.65 m^3
Weight	900 kg	600 kg
Efficiency	97.1%	98.5%
Cooling Method	Air + Oil	Liquid + optimized fins

This shows how design choices can significantly impact overall size and performance.

COMPARISON WITH OTHER CONVERTER TYPES

1. Traditional VSC

Voltage Source Converters are simpler but suffer from higher harmonic distortion and lower efficiency at high power levels, making MMCs preferable for ≥5 MW systems.

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2. Cascaded H-Bridge Converters

H-bridge multilevel converters are competitive but typically require larger passive filters.

CHALLENGES AND LIMITATIONS

While high power density MMCs are promising, several challenges remain:

- **Control complexity** — advanced control adds cost and requires high-speed processors
- **Thermal issues** — liquid cooling increases system complexity
- **Cost** — wide-bandgap devices and advanced materials can be expensive
- **Marine environment durability** — salt corrosion and humidity require rugged packaging

Despite these challenges, research and industrial implementations continue to advance.

FUTURE RESEARCH DIRECTIONS

Emerging topics include:

- **Integrated passive components** – embedding power inductors into structural supports
- **AI-assisted control** – machine learning to adapt to varying offshore conditions
- **Fault prediction** – using sensor networks to predict component degradation
- **High-temperature semiconductors** – improving junction temperature tolerance to reduce cooling needs

These areas promise further gains in size, efficiency, and reliability.

CONCLUSION

Modular Multilevel Converters provide a scalable, low-harmonic, and reliable solution for high-power offshore energy systems. Transitioning MMCs to high power density designs involves innovations in semiconductor choices, thermal management, control strategies, and passive component optimization. While challenges like system complexity and environmental ruggedness persist, ongoing research and field demonstrations show strong potential for MMCs to become standard in offshore wind and wave energy platforms.

This review summarized key design principles, presented recent case examples, and outlined future research priorities. The overall trajectory of MMC research suggests a promising role in enabling efficient, compact, and resilient offshore energy systems.

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