HIGH-EFFICIENCY MODULAR CONVERTERS FOR MARITIME ELECTRIC PROPULSION

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ABSTRACT

Maritime electrification has become an essential focus within global efforts to reduce greenhouse emissions and improve energy efficiency in shipping. A central component of electric propulsion systems is the power converter, which bridges energy sources such as batteries or hybrid generators to propulsion motors. Traditional propulsion converters process the entire power and often suffer from high losses, limited reliability and scalability. To address these limitations, ***high-efficiency modular converters*** *are increasingly investigated and developed. This review discusses the architectures, technologies, benefits and challenges of modular converters tailored for maritime electric propulsion systems. Methods to achieve high efficiency such as partial power processing, modular multilevel topologies, and the use of wide-bandgap semiconductors are examined. The paper also reviews recent experimental results and commercial system trends. Modular solutions improve reliability, scalability, and maintainability — critical for the demanding operating environment of marine vessels. Finally, future research directions and technological gaps are outlined.*

KEYWORDS:- *Maritime electric propulsion; high-efficiency converters; modular converters; partial power processing; power electronics; reliability; wide-bandgap semiconductors.*

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INTRODUCTION

Maritime transport accounts for a significant fraction of global greenhouse gas emissions. Electrification of ship propulsion is now widely seen as a key solution to reduce environmental impact and improve operational efficiency. Traditionally, ship propulsion systems combine diesel engines with mechanical transmission or diesel-electric systems. By contrast, **electric propulsion** uses electrical energy — from batteries, generators or hybrid sources — to drive electric motors that turn ship propellers.

A critical component within this system is the **power electronic converter**, which conditions and transforms electrical energy between different voltage levels and waveforms to efficiently match source and load requirements. Conventionally, single large converters are used to process the full power flow (often in multi-megawatt range). These converters can be heavy, expensive, and present reliability concerns due to the entire system relying on one central unit. Thus, the focus on **modular converter topologies** is growing — to provide enhanced efficiency, fault tolerance and scalability. The maritime environment stresses hardware with vibration, temperature extremes and strict safety standards, so converter design plays a key role in system resilience.

Modern maritime electrical propulsion architectures benefit from modular approaches where multiple converter modules share power processing — referred to as **modular multilevel converters (MMC)**, **partial power processing** units, or hybrid modular converters using advanced semiconductor technology. These systems can increase efficiency, reduce losses and enhance flexibility across operating conditions.

This paper reviews the state-of-art in high efficiency converters with emphasis on modular structures and maritime electric propulsion requirements.

BACKGROUND: ELECTRIC PROPULSION AND POWER CONVERSION IN SHIPS

Electric propulsion in ships is a well-established concept, with its fundamental idea originating more than a century ago. The principle is based on **decoupling the prime mover (diesel engine, gas turbine, or alternative source) from the propeller shaft**, using electrical energy as the intermediate link. Early implementations were limited by the efficiency, size, and reliability of

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electrical machines and power electronics. However, recent advancements in semiconductor devices, digital control, and energy storage technologies have significantly renewed interest in electric propulsion systems.

The growing emphasis on reducing fuel consumption, greenhouse gas emissions, and underwater noise has accelerated the adoption of electric propulsion, particularly in passenger ferries, offshore support vessels, naval ships, and research vessels. International Maritime Organization (IMO) regulations on emissions, along with stricter port-based environmental norms, are pushing ship designers toward electrified propulsion architectures. Electric propulsion offers operational flexibility, improved efficiency at partial loads, and better integration of renewable and alternative energy sources compared to conventional mechanical propulsion systems.

1. Conventional and Modern Electric Propulsion Architectures

Traditional ship propulsion systems include **diesel-mechanical**, **diesel-electric**, and **hybrid diesel-electric** configurations. In diesel-electric propulsion, diesel generators produce electrical power that is converted and supplied to propulsion motors through power electronic converters. This arrangement allows engines to operate near optimal efficiency points, independent of ship speed. Hybrid systems extend this concept by adding batteries or other energy storage devices, enabling load leveling, peak shaving, and silent operation modes during low-speed navigation or port maneuvers.

More recently, **integrated electric propulsion systems** have gained attention, especially in naval and high-end commercial vessels. In such systems, propulsion loads and auxiliary ship loads are supplied from a common electrical distribution network, commonly referred to as an **Integrated Power System (IPS)**. Instead of dedicating generators solely for propulsion, the IPS allows dynamic allocation of electrical power depending on operational needs. This improves redundancy, survivability, and overall system utilization. Warships such as modern destroyers and large offshore vessels employ IPS architectures to support advanced radar, weapon systems, and hotel loads alongside propulsion.

Compared to mechanically coupled propulsion, electric systems provide better torque control at

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low speeds, reduced vibration, and improved maneuverability. These features are particularly important for dynamic positioning vessels and naval ships, where precise speed and thrust control is critical.

2. Role of Power Conversion in Shipboard Electric Systems

Power electronic converters are the backbone of electric propulsion systems. They serve as the interface between power generation units, energy storage devices, and propulsion motors. The primary functions of these converters include **AC–DC rectification, DC–AC inversion, voltage regulation, frequency control, and bidirectional power flow**. Depending on the system architecture, converters may operate at low voltage (below 1 kV) or medium voltage levels reaching several kilovolts.

In traditional AC distribution systems, propulsion converters receive power from synchronous generators through transformers and controlled rectifiers. In contrast, modern shipboard systems increasingly adopt **DC distribution architectures**, where multiple sources and loads are connected to a common DC bus. DC systems reduce the number of conversion stages, eliminate reactive power issues, and simplify integration of batteries and renewable sources. However, they rely heavily on efficient and reliable DC–DC and DC–AC converters to maintain voltage stability and safe operation.

Bidirectional converters are particularly important in hybrid and battery-electric ships, where energy must flow both to and from the storage system. During regenerative braking or propeller-assisted deceleration, propulsion motors can operate as generators, feeding power back to the DC bus. This recovered energy can be stored or redistributed to onboard loads, improving overall energy efficiency.

3. Efficiency and Reliability Considerations

The operating profile of marine vessels is highly variable, involving frequent changes in speed, load, and environmental conditions. As a result, propulsion converters must maintain high efficiency over a wide operating range. Losses in power electronic devices directly impact fuel

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consumption, cooling requirements, and system lifetime. Even small efficiency improvements can lead to significant fuel savings over long voyages.

Reliability is equally critical, as converter failures at sea can compromise safety and mission success. Shipboard converters are exposed to harsh conditions including humidity, salt mist, vibration, and temperature fluctuations. Therefore, converter designs must prioritize robust thermal management, fault tolerance, and redundancy. Modular and distributed converter architectures have emerged as a practical solution to address these requirements, allowing continued operation even if individual modules fail.

In summary, the background of electric propulsion and power conversion in ships highlights a clear transition from centralized, mechanically dominated systems toward **electrically integrated and converter-intensive architectures**. The central challenge remains achieving high efficiency and reliability while meeting the demanding operational and environmental constraints of maritime applications.

MODULAR CONVERTER ARCHITECTURES

Modular converter architectures represent a significant shift from traditional centralized power electronic systems used in maritime propulsion. Instead of relying on a single high-power converter to handle the entire propulsion load, modular designs distribute the power processing task among multiple smaller and often identical converter units. This approach improves scalability, enhances reliability, and allows flexible system expansion based on vessel size and power demand.

From a maritime perspective, modularity offers several practical advantages. It enables easier maintenance and replacement of faulty units, reduces downtime, and supports redundancy, which is crucial for ship safety and mission continuity. Furthermore, modular converters are well suited for integration with modern DC distribution systems and hybrid energy sources such as batteries and fuel cells.

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1. Modular Multilevel Converters (MMC)

Modular Multilevel Converters (MMC) are among the most widely adopted modular topologies for high-power and medium-voltage applications. An MMC is composed of a large number of submodules (SMs), each typically consisting of a capacitor and semiconductor switching devices. These submodules are connected in series and parallel arrangements to form converter arms capable of handling very high voltage and power levels.

One of the key advantages of MMCs is their ability to generate near-sinusoidal output voltages with very low harmonic distortion. This significantly reduces the need for bulky output filters, which is especially beneficial in space-constrained shipboard environments. The stepped voltage waveform produced by MMCs also lowers switching losses, thereby improving overall efficiency. For maritime electric propulsion, MMCs are attractive because they scale naturally from a few hundred kilowatts to multi-megawatt levels. They are commonly considered for large cruise ships, naval vessels, and offshore platforms where propulsion motors operate at medium voltage levels. In addition, MMCs offer inherent fault tolerance. If one submodule fails, it can often be bypassed without shutting down the entire converter, allowing continued operation at slightly reduced performance.

However, MMCs also introduce challenges related to control complexity. Issues such as circulating currents between converter arms and voltage imbalance across submodule capacitors must be carefully managed. Recent research has proposed advanced modulation and control strategies to minimize these effects. Reducing circulating currents not only improves efficiency but also decreases thermal stress on semiconductor devices, thereby extending converter lifetime and improving reliability in marine applications.

2. Partial Power Processing (PPP) Converters

Partial Power Processing (PPP) converters represent a different modular philosophy focused primarily on maximizing efficiency. In PPP systems, each converter module handles only a fraction of the total power instead of processing the entire energy flow. The remaining power is transferred directly, without conversion, which significantly reduces overall conversion losses.

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This approach is particularly advantageous in shipboard DC systems, where voltage adaptation or balancing is required between sources and loads with similar voltage levels. Since only partial power is processed, semiconductor devices experience lower current and voltage stress, resulting in reduced conduction and switching losses. Consequently, cooling requirements are relaxed, and converter efficiency can exceed that of conventional full-power converters.

PPP architectures are increasingly explored for battery integration in electric and hybrid ships. Experimental studies have demonstrated efficiencies above 99% using series-connected PPP modules, making them highly suitable for energy storage interfaces and auxiliary propulsion systems. Such high efficiency is especially valuable in maritime applications where energy losses directly translate into higher fuel consumption or reduced operational range.

Most PPP converters employ **dual-active-bridge (DAB)** topologies due to their bidirectional power flow capability and inherent galvanic isolation. DAB converters support soft-switching over a wide operating range, which further improves efficiency and reduces electromagnetic interference. However, PPP systems require precise coordination among modules to maintain voltage stability and ensure safe operation, particularly during transient conditions.

3. Hybrid Modular Converters

Hybrid modular converters combine the strengths of different modular concepts to meet the demanding requirements of advanced maritime propulsion systems. These converters may integrate features of MMC and PPP architectures, along with intelligent control algorithms and adaptive power sharing techniques. The goal is to achieve high efficiency, high reliability, and flexible operation under varying load conditions.

A key enabler of hybrid modular converters is the use of **wide-bandgap (WBG) semiconductor devices**, such as Silicon Carbide (SiC) MOSFETs and Gallium Nitride (GaN) transistors. These devices support higher switching frequencies, lower losses, and higher temperature operation compared to conventional silicon-based devices. As a result, hybrid modular converters can achieve higher power density and improved efficiency, which are critical for weight- and space-constrained marine vessels.

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Hybrid solutions are of particular interest for naval and high-performance commercial ships, where fault tolerance and survivability are essential. By combining modular redundancy with advanced semiconductor technology, hybrid converters can continue operating even under partial system failures. Defense research programs and industrial collaborations are actively developing such converter systems to support future all-electric and hybrid-electric ships.

In summary, modular converter architectures — including MMC, PPP, and hybrid solutions — provide a strong foundation for next-generation maritime electric propulsion. Each architecture offers unique advantages, and the choice of topology depends on factors such as power level, system voltage, efficiency targets, and operational requirements.

HIGH-EFFICIENCY TECHNIQUES

Achieving high efficiency in modular converters for maritime electric propulsion is a multi-dimensional challenge that involves semiconductor selection, converter topology, control strategy, and thermal design. Since propulsion systems operate continuously for long durations, even small improvements in converter efficiency can lead to noticeable reductions in fuel consumption, emissions, and operational costs. Modular architectures provide a strong foundation, but high efficiency is realized only when combined with carefully selected design techniques.

1. Use of Wide-Bandgap Semiconductors

The adoption of **wide-bandgap (WBG) semiconductor devices**, particularly Silicon Carbide (SiC) MOSFETs and Gallium Nitride (GaN) transistors, has played a major role in improving converter efficiency. Compared to conventional silicon-based IGBTs, WBG devices offer significantly lower switching and conduction losses, as well as the ability to operate at higher switching frequencies and elevated temperatures.

In maritime propulsion systems, these characteristics are especially beneficial. Higher switching frequencies allow the use of smaller passive components such as inductors and filters, which reduces overall converter size and weight. This is important for vessels where space and mass constraints directly affect payload capacity and vessel stability. Moreover, the reduced losses of SiC-based converters lead to lower heat generation, improving system reliability and simplifying

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thermal management.

Medium-voltage propulsion drives based on SiC technology are increasingly being introduced by marine power electronics manufacturers. These converters demonstrate higher efficiency across a wide load range, including partial-load operation, which is common in real ship operating profiles. Additionally, WBG devices exhibit faster switching transitions, enabling advanced modulation techniques that further reduce harmonic distortion and improve motor performance.

However, the use of WBG semiconductors also introduces challenges, such as higher device cost and sensitivity to electromagnetic interference. Careful layout design, shielding, and gate-drive optimization are therefore essential to fully exploit their benefits in shipboard environments.

2. Partial Power Processing Balance

Partial Power Processing (PPP) is a powerful technique to improve efficiency by minimizing the fraction of power that is actively converted. In PPP-based modular systems, only the difference between input and output power is processed by the converter modules, while the remaining energy flows directly. This significantly reduces switching and conduction losses, especially in applications where the voltage difference between source and load is relatively small.

For maritime electric propulsion, PPP is particularly attractive in DC-based architectures used for battery integration, auxiliary propulsion, and power sharing between multiple DC buses. By ensuring that each module processes only the required portion of power, overall system efficiency can be increased beyond what is achievable with conventional full-power converters.

A critical aspect of PPP systems is **proper power and voltage balancing** among modules. In series or parallel configurations, uneven power sharing can lead to overloading of certain modules, increasing losses and reducing reliability. Advanced control algorithms are therefore required to dynamically regulate current and voltage levels across modules, especially during transient operating conditions such as acceleration, deceleration, or load switching.

Balancing strategies also play a key role in maintaining long-term reliability. Unequal thermal

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stress among modules can accelerate aging of power devices and passive components. By distributing power evenly and minimizing unnecessary conversion, PPP systems help maintain uniform thermal profiles and extend converter lifetime.

3. Thermal Management and Cooling

Thermal management is closely linked to converter efficiency and overall system reliability. High-efficiency converters generate less heat, which reduces thermal stress on semiconductor devices and passive components. However, given the high power levels involved in maritime propulsion, effective cooling remains essential even for highly efficient modular converters.

Liquid cooling has become the preferred solution for marine power electronic converters due to its superior heat removal capability compared to air cooling. Liquid-cooled systems enable higher power density by maintaining device temperatures within safe operating limits, even under heavy load conditions. This allows converters to be more compact, which is valuable for integration into confined shipboard spaces.

In modular converter architectures, thermal management can be optimized at the module level. Each converter module can be equipped with dedicated cooling paths, ensuring uniform temperature distribution and preventing localized hotspots. This modular thermal design also simplifies maintenance and improves fault tolerance, as individual modules can be isolated without affecting the entire cooling system.

Furthermore, advanced thermal monitoring and control systems are increasingly integrated into marine converters. Real-time temperature feedback allows adaptive power derating or load redistribution among modules, enhancing both efficiency and reliability. Overall, effective thermal management not only supports high efficiency but also plays a vital role in ensuring safe and long-term operation of maritime electric propulsion systems.

RELIABILITY AND FAULT TOLERANCE

Reliability and fault tolerance are among the most critical design requirements for maritime electric propulsion systems. Ships often operate for long durations in remote locations where

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immediate technical support is unavailable. Any failure in the propulsion converter can lead to serious safety risks, mission interruption, or significant economic losses due to downtime and towing costs. Therefore, converter systems must be designed not only for high efficiency but also for robust and continuous operation under fault conditions.

Modular converter architectures provide inherent advantages in terms of reliability compared to conventional monolithic converters. By dividing the total power rating among multiple converter modules, the failure of a single module does not necessarily lead to a complete system shutdown. Instead, faulty modules can be electrically isolated or bypassed, allowing the remaining modules to continue supplying power to the propulsion motor, albeit at a reduced capacity. This degraded-mode operation is often sufficient to maintain safe navigation until the vessel reaches port.

1. Redundancy and Fault Isolation in Modular Systems

Both Modular Multilevel Converters (MMC) and Partial Power Processing (PPP) topologies naturally support redundancy. In MMCs, each arm consists of a large number of submodules. If a submodule experiences a fault, bypass switches can remove it from operation without significantly affecting the output voltage quality. This feature enhances system availability and minimizes the risk of cascading failures.

In PPP-based systems, multiple modules share the power processing task. A fault in one module can be managed by redistributing power among the remaining modules. While this may reduce maximum power capability, the system remains operational. Such fault isolation strategies are particularly valuable in maritime propulsion, where maintaining even partial thrust is preferable to a complete loss of propulsion.

Advanced protection schemes are required to detect faults rapidly and respond appropriately. These include overcurrent protection, voltage imbalance detection, thermal monitoring, and insulation fault detection. Modern modular converters often employ digital control platforms that allow fast fault identification and coordinated isolation of faulty modules, ensuring system stability and safety.

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2. Maintainability and Modular Replacement

Another major advantage of modular converters is improved maintainability. In traditional large-scale converters, maintenance often requires shutting down the entire propulsion system, which can be impractical during voyages or costly in commercial operations. Modular systems, by contrast, allow individual converter units to be serviced, repaired, or replaced independently.

This design approach significantly reduces maintenance time and complexity. Crew members or service engineers can replace a faulty module using standardized procedures, without the need for specialized heavy equipment. Spare modules can be stored onboard, enabling quick restoration of full power capability once the fault is addressed. This approach aligns well with the operational requirements of commercial shipping, offshore vessels, and naval fleets.

3. Hot-Swap Capability and Reduced Downtime

Some modern modular propulsion converters support **hot-swap capability**, where individual modules can be removed and replaced while the system remains energized. Although hot-swapping is typically performed during port dwell times rather than at sea, it offers a substantial reduction in vessel downtime. This capability is especially valuable for vessels with tight operational schedules, such as ferries and offshore support ships.

Market studies and industrial reports indicate that modular electric shaftline drives equipped with hot-swappable converter modules are gaining adoption. These systems enable ship operators to perform maintenance without taking the vessel out of service, leading to improved availability and lower lifecycle costs. Additionally, hot-swap designs encourage proactive maintenance strategies, where modules showing early signs of degradation can be replaced before failure occurs.

4. Long-Term Reliability and System Lifetime

Beyond immediate fault tolerance, modular converters also contribute to improved long-term reliability. By distributing electrical and thermal stress across multiple modules, component aging is more uniform, reducing the likelihood of premature failures. In combination with advanced condition monitoring and predictive maintenance techniques, modular systems support longer service intervals and extended system lifetime.

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In summary, reliability and fault tolerance are key drivers for adopting modular converter architectures in maritime electric propulsion. Redundancy, fault isolation, ease of maintenance, and hot-swap capability collectively enhance system availability and safety. These benefits make modular converters particularly well suited for the demanding and remote operating conditions encountered in marine environments.

Table 1: Comparison of Converter Types for Maritime Propulsion

Feature	MMC	PPP Modules	Hybrid Modular
Scalability	High	Moderate	Very High
Efficiency	High	Very High	Very High
Fault Tolerance	Moderate	High	Highest
Control Complexity	High	Moderate	Very High
Typical Use	Medium-High Power	Battery/DC link	All ranges

COMMERCIAL TRENDS AND REAL DEPLOYMENTS

Marine power electronics companies are increasingly offering solutions optimized for maritime electric propulsion:

- **Kongsberg Maritime's propulsion drives** featuring active front ends, low harmonic distortion and bidirectional power flow are engineered for marine environments.
- **Danfoss's iC7-Marine converters** use liquid cooling and compact modular designs to occupy less space onboard vessels while delivering high efficiency.
- **DEIF marine power converters** provide flexible AC/DC conversion with galvanic isolation useful for hybrid shipboard systems.

CHALLENGES AND FUTURE WORK

Despite advances, several challenges remain:

1. Control and Balancing of Modular Systems

Distributed modules require sophisticated control to ensure balanced current sharing and voltage stability. This is particularly important when modules operate under varying load conditions, such as during rapid changes in ship speed or power demands.

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2. Standardization and Marine Certification

Maritime electrification standards (e.g., IEC 62619 and 62620 for battery systems) are evolving. Converter standards specific to marine electric propulsion remain under development.

3. Integration with Hybrid Energy Storage

Converters must seamlessly integrate with batteries, fuel cells, supercapacitors and other storage elements — a complex optimization problem that must consider lifetime, efficiency and safety. Future research should address improved control algorithms for power distribution among modular units, and further advancements in WBG semiconductor reliability in harsh marine environments.

CONCLUSION

High-efficiency modular converters are a cornerstone technology for maritime electric propulsion. Their benefits include enhanced efficiency, scalable architecture, reliability and maintainability — all crucial for modern vessels aiming for zero-emission operation. Advanced modular topologies such as MMC and partial power processing units, especially when combined with wide-bandgap devices, help reduce losses and enable better control of power flows. However, challenges such as sophisticated control needs and standardization must still be addressed. Continued research and commercial development will accelerate deployment of modular converter systems across a wide range of ship types. The future of marine propulsion is electric, and modular high-efficiency converters will play a vital role in that transformation.

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