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TITLE in English

Electric motors used in marine electric propulsion, with particular reference to large ships.

TITLE in Italian

Motori elettrici utilizzati nella propulsione elettrica navale, con particolare riferimento alle grandi navi.

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Abstract

This thesis provides a multifaceted investigation into electric propulsion systems tailored for marine applications, with a specific focus on the rigorous requirements of high-displacement vessels such as cruise ships. Driven by the global imperatives of energy optimization, environmental sustainability, and heightened operational dependability, electric propulsion has transitioned from an elective feature to a cornerstone of modern naval architecture. The study commences with a systematic appraisal of diverse propulsion architectures encompassing conventional, hybrid, and all-electric ship (AES) configurations evaluating their respective merits in efficiency and system integration against the inherent risks of increased technical complexity and fault sensitivity.

A critical examination of electromechanical conversion technologies, including induction, permanent magnet synchronous, and multiphase machines, reveals that while traditional designs remain robust, multiphase architectures offer superior fault-tolerant characteristics through intrinsic hardware redundancy. This makes such machines indispensable for safety-critical maritime missions where propulsion continuity is paramount. Furthermore, the research explores the pivotal role of power electronic interfaces, specifically medium-voltage modular multilevel converters (MMC), which facilitate high-efficiency operation and minimized harmonic distortion. While these topologies offer significant scalability, the analysis also addresses the sophisticated control challenges they introduce regarding system-wide reliability.

A central contribution of this research lies in its comprehensive assessment of reliability and fault-tolerant methodologies, addressing a broad spectrum of failure modes ranging from semiconductor and sensor anomalies to open- and short-circuit faults. The work evaluates various mitigation strategies, including multiphase motor reconfiguration and current compensation methods, alongside advanced diagnostic frameworks. By reviewing model-based, signal-centric, and artificial intelligence-driven diagnostic approaches, the study highlights how AI-based methods provide transformative solutions for early-stage anomaly detection and predictive maintenance. The thesis concludes by assessing emerging paradigms such as digitalization and smart ship technologies, ultimately asserting that the resilience of next-generation marine propulsion depends on a holistic synergy between advanced hardware design, intelligent control algorithms, and data-driven diagnostic intelligence.

Contents

Chapter 1: General Introduction

1-1 Introduction

There is a steady shift toward electrification within the maritime industry today, largely due to tougher environmental regulations and the focus on improving energy efficiency [1], [2], [3]. In line with this trend, electric propulsion systems are now considered a fundamental solution for large-scale vessels, including naval ships and offshore platforms.

Unlike conventional mechanical propulsion systems, the use of electric propulsion allows for the decoupling of power generation and propulsion [3], [4], which provides much more flexibility in system design and operation. By using this approach, optimized energy management becomes easier to achieve. This leads to reduced fuel consumption and lower emissions [1], [5], both of which are necessary to meet the stringent requirements of international maritime regulations.

In many modern electric ships, propulsion usually relies on high-power electric motors, which are driven by power electronic converters as part of an integrated power system. These configurations, often known as AES or IPS [4], bring together generation, distribution, and propulsion into a single, unified electrical network. While this kind of integration improves both efficiency and operational control, it also creates some new technical challenges that need to be addressed.

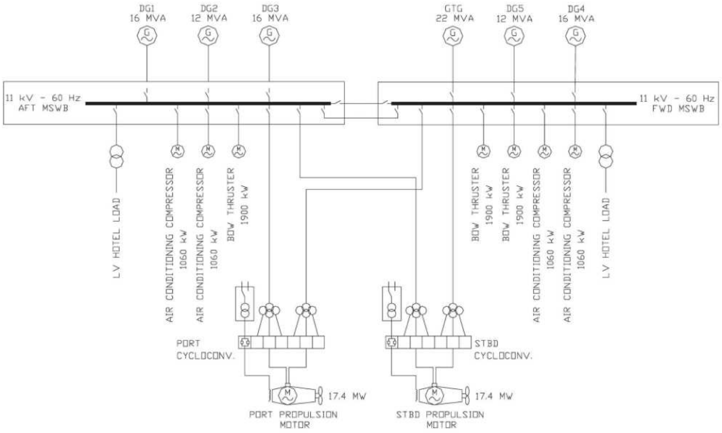

Figure (1-1): A simplified architecture of an electric ship propulsion system is shown [4].

Electric motors and the power converters connected to them are essential parts of any electric propulsion system [6], [7]. The efficiency, performance, and reliability of these specific units directly impact how the entire propulsion system functions. Specifically, high-power propulsion motors are required to work under tough conditions, such as variable loads, harsh environments, and long operational cycles.

Because of this, making sure electric propulsion systems are both reliable and robust has become a major focus in both research and industrial applications. If a propulsion motor or power converter fails, it can cause serious operational issues, such as loss of propulsion capability, reduced maneuverability, or even a complete system shutdown [3]. For large-scale vessels, these failures are not just expensive but also create significant safety risks.

To solve these problems, there is a growing interest in developing fault-tolerant propulsion systems [8]. These are designed to keep the ship running, at least partially, even when a fault occurs. Specifically, advanced motor topologies like multiphase and multi-winding machines [9], along with new control and converter strategies, are being used to improve system reliability and fault tolerance.

To solve these issues, there is a growing interest in developing fault-tolerant propulsion systems. The goal of these systems is to keep the ship running, even if only partially, during a fault. Specifically, advanced motor topologies, such as multiphase and multi-winding machines, along with new control and converter strategies, have been developed to improve both system reliability and fault tolerance.

The main objective of this thesis is to analyze the electric motors used in naval electric propulsion systems, with a particular focus on their reliability and fault-tolerant capabilities. Consideration is given to large-scale vessels, like cruise ships, where system dependability is critical.

1-2 Motivation

While the move toward electric propulsion systems has provided notable advantages in terms of efficiency [2], [10], flexibility, and environmental sustainability, it has also brought about new sets of difficulties. These challenges are mainly related to system reliability and operational safety, which are critical factors for large-scale vessels.

For vessels such as cruise liners and naval ships, the propulsion system is a mission-critical subsystem. Even a minor failure in the propulsion motor or the power electronic converter can lead to serious operational consequences. These might include loss of propulsion capability [3], reduced maneuverability, or failing to meet mission objectives. In the worst cases, such issues could threaten the safety of the vessel and its passengers. As pointed out in recent studies on shipboard IPS, reliability is much more than just a performance metric; it is a fundamental design requirement [3].

The importance of reliability is even higher due to the increasing complexity of modern electric ships. In IPS architectures, components for generation, distribution, and propulsion are all linked within a unified electrical network [4]. While this high level of integration is great for efficiency and control, it creates strong interdependencies between different parts of the ship. As a result, a fault in one part, like a converter switch or a motor phase, can spread through the network, potentially causing cascading failures across multiple subsystems [11].

Furthermore, electric propulsion systems must function under tough conditions, including high power levels, thermal stress, and variable loads over long operational lifetimes [11]. These factors naturally make component degradation and faults more likely over time. For instance, power electronic converters often face issues with semiconductor devices, such as thermal fatigue and aging [12], while electric machines are at risk of open-phase or short-circuit conditions. Research focused on power electronics reliability suggests that these failure mechanisms are often unavoidable and must be managed at both the design and control stages.

Historically, most efforts to improve reliability focused on fault prevention. However, in high-power marine propulsion, it is not always possible to avoid faults entirely. This has led to a growing focus on fault-tolerant system design, where the system can still provide acceptable performance even when a fault is present. This shift in perspective from avoiding faults to managing them (fault tolerance) is now a major research direction in this field.

Among the different fault-tolerant solutions discussed in literature, multiphase electrical machines have shown great potential [8]. By using more than three phases, these machines offer extra degrees of freedom that allow the system to redistribute currents and keep producing torque during a fault. Similarly, multi-winding and redundant converter configurations add structural redundancy [9], making the system more resilient. Studies on multiphase drives confirm their superior fault-tolerant capabilities compared to standard systems, particularly for reliability-critical applications.

Despite these improvements, there are still several open challenges. Implementing fault-tolerant solutions usually involves trade-offs between system complexity, cost, and efficiency.

Additionally, fitting these technologies into large-scale marine systems creates extra design constraints that need careful study.

Because of these factors, a detailed and critical analysis of electric motors and drive technologies, specifically focusing on reliability and fault tolerance, is needed. This necessity is what drives the research in this thesis.

1-3 Objectives and Scope of the Thesis

The primary goal of this thesis is to conduct a thorough and structured analysis of the electric motors used in naval propulsion systems, with a special focus on their reliability and fault-tolerant capabilities. The research is centered on large-scale marine applications, such as cruise ships and naval vessels, where the reliability of the propulsion system is an essential requirement.

To be more specific, this work examines the main types of electric motors commonly found in marine propulsion, including induction motors, permanent magnet synchronous motors, and wound rotor synchronous machines. Their operating principles, advantages, and limitations are analyzed, particularly for high-power and mission-critical scenarios.

Beyond just motor technologies, the thesis also looks into the role of power electronic converters and drive systems, which are critical for controlling these motors. Significant attention is given to medium voltage drives and multilevel converter topologies, as these are widely used in modern electric ships and have a major impact on how the system performs and how reliable it is.

A major part of this research is dedicated to analyzing reliability issues within electric propulsion systems. This involves identifying common fault types that affect both motors and converters, such as open-circuit, short-circuit, and thermal-related failures. The consequences of these faults on system performance and operational safety are also critically discussed.

Moreover, the thesis explores fault-tolerant design methods aimed at making the system more robust. In particular, advanced motor configurations, like multiphase machines and multi-winding systems are studied because of their ability to keep running even during a fault. At the same time, fault-tolerant control strategies and converter reconfiguration techniques are also reviewed.

In terms of methodology, this thesis follows a literature-based approach. It relies on the evaluation and comparison of recent scientific contributions, including journal articles and conference papers. The aim is not just to summarize previous work, but to critically assess their strengths, weaknesses, and how well they apply to marine propulsion.

Regarding the scope of the work, this study is limited to electrical propulsion systems and does not cover mechanical components or ship hydrodynamics. Additionally, while control strategies are discussed, their complex mathematical modeling is not the main focus, as the goal is to provide a system-level understanding and a comparative analysis.

Lastly, the thesis aims to provide a clear overview of current technologies and to point out potential paths for future research in the field of reliable and fault-tolerant electric propulsion systems.

1-4 State of the Art

1-4-1 Electric Propulsion Systems in Ships

Electric propulsion has emerged as a defining technology for modern maritime vessels, especially in the context of large-scale naval platforms and cruise ships. Over the past few decades, the industry has seen a gradual transition away from traditional mechanical setups toward these more efficient and versatile electric architectures.

In a conventional arrangement, the prime movers such as gas turbines or diesel engines are physically linked to the propeller shaft via mechanical transmission [10]. While this is a straightforward design, it lacks flexibility and often suffers from suboptimal efficiency when operating under varying loads. In contrast, electric propulsion decouples power generation from the actual propulsion mechanism. This allows energy to be distributed through an electrical network and utilized much more effectively across the vessel.

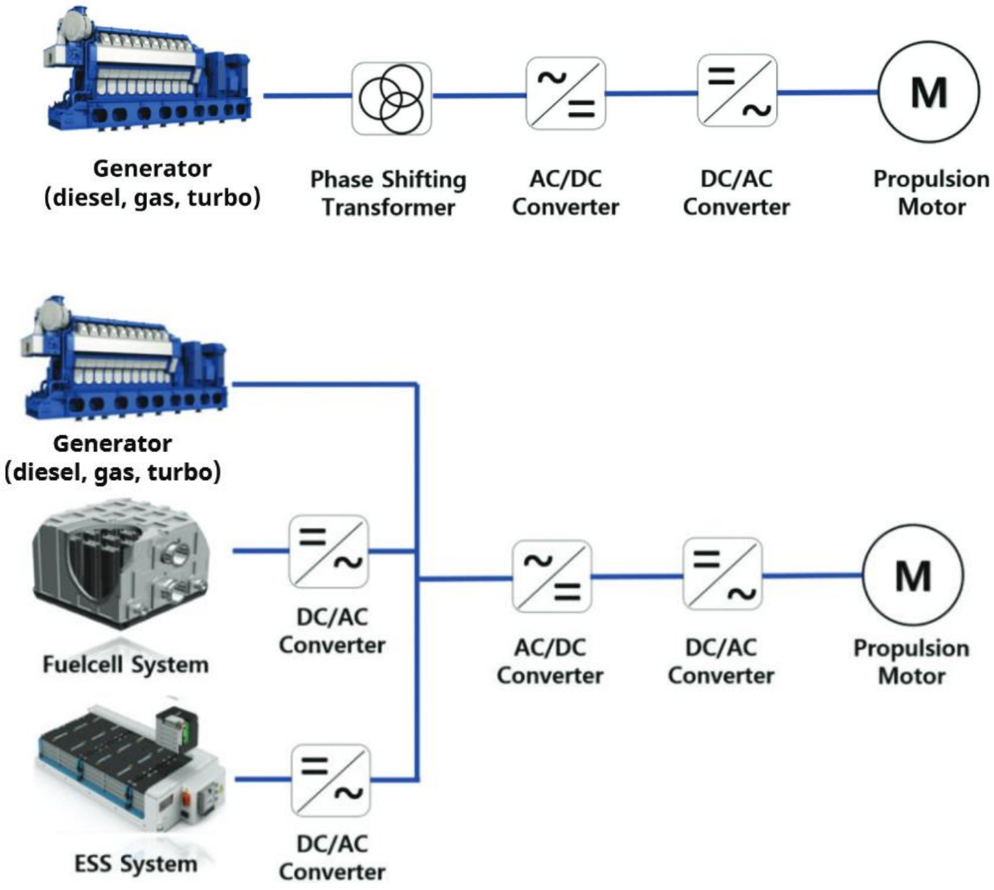

Figure (1-2): Different electric propulsion architectures used in modern ships are illustrated in [2].

A major milestone in this field is the AES concept, also known as the IPS [4]. In these architectures, every onboard energy consumer including the propulsion motors, auxiliary systems, and hotel loads is fed by a unified electrical network. This integration makes it easier to optimize energy management and improve overall fuel economy. However, this high level of interconnection brings its own set of risks. Unlike traditional designs where failures are usually localized, an integrated system involves strong interdependencies. As a result, a fault in one component can easily travel through the network, potentially impacting other subsystems and threatening the stability of the entire.

Table (1-1): A comparison of different propulsion architectures is provided.

Architecture	**Complexity**	**Efficiency**	**Flexibility**	**Reliability**
Mechanical	Low	Medium	Low	High
Diesel-electric	Medium	High	Medium	High
All-electric	High	Very High	Very High	Medium

1-4-2 Electric Motors for Marine Propulsion

At the heart of any electric propulsion system are the electric motors, which are responsible for converting electrical energy into the mechanical torque required to turn the propeller. Because they directly affect the ship's efficiency, power density, and reliability, selecting the right motor technology is essential.

Currently, several motor types are used in marine settings, most notably induction motors (IM), permanent magnet synchronous motors (PMSM), and wound rotor synchronous machines (WRSM). Each technology has a specific set of strengths and drawbacks [6]:

- IM: These have been the industry standard for years because they are rugged, simple, and cost-effective. They handle harsh environments well, but they generally cannot match the high-power density of more modern alternatives.
- PMSMs: These have gained significant traction recently due to their excellent efficiency and compact design. This makes them ideal for vessels like cruise ships, where space is at a premium. However, their higher cost and reliance on rare-earth materials remain notable challenges.
- WRSMs: Often used in high-power applications, these machines allow for controllable excitation and high efficiency without needing magnets, though they do require more intensive maintenance.

Beyond these standard three-phase options, there is a growing focus on multiphase electrical machines (those with more than three phases). These systems offer extra degrees of freedom that can be used to improve fault tolerance. Specifically, a multiphase machine can keep running even if a phase fails with only a minor reduction in performance [7], [8], [9], [13], [14].

Table (1-2): A comparison of the main motor technologies used in marine propulsion is presented.

Motor Type	**Efficiency**	**Power Density**	**Cost**	**Reliability**	**Fault Tolerance**
IM	*Medium*	*Medium*	*Low*	*High*	*Low*
PMSM	*High*	*High*	*High*	*Medium*	*Medium*
WRSM	*High*	*Medium*	*Medium*	*High*	*Medium*
Multiphase Motor	*High*	*High*	*High*	*Very High*	*Very High*

1-4-3 Power Electronics in Marine Drives

Power electronic converters serve as the vital interface between the ship's power grid and its propulsion motors. Their main task is to regulate voltage, current, and frequency, allowing for precise control over the motor's speed and torque. In marine applications, these converters must handle megawatt-level power, which places heavy demands on their reliability and thermal management [15].

While simple Voltage Source Inverters (VSI) are common, multilevel converters have become the preferred choice for high-power ships. Topologies such as the MMC offer several benefits, including reduced harmonic distortion and better scalability for high voltages [16]. The modular nature of the MMC is particularly useful for redundancy; if a submodule fails, it can often be bypassed to keep the system operational.

Nevertheless, semiconductor devices (like IGBTs) are recognized as some of the most vulnerable components in the system. Failures here are often driven by thermal stress and aging, which are intensified by the high-power demands of marine environments [11]. Because of this, reliability-oriented design has become a core focus, using techniques like fault detection and reconfiguration to minimize the impact of component failures.

1-4-4 Reliability and Fault-Tolerance Approaches

In modern shipping, reliability is a fundamental requirement, especially for large vessels where safety and operational continuity cannot be compromised. In this context, reliability means the system's ability to keep the ship moving even if certain components begin to degrade or fail.

Electric propulsion systems face various threats, from electrical faults (like short circuits) to thermal issues caused by overheating. In high-power systems operating in harsh seas, some level of failure is often unavoidable. This has pushed research away from simple fault prevention and toward fault-tolerant design, where the system is built to survive a fault and continue working, at least partially.

This fault tolerance is built into the system at several levels:

- Machine level: Using multiphase or multi-winding configurations to ensure the motor can still produce torque if a phase is lost.
- Converter level: Utilizing modular topologies that can reconfigure themselves after a hardware failure.
- Control level: Implementing smart algorithms that detect issues in real-time and adjust the system's operation to compensate.

Lately, AI and data-driven methods have also been proposed to help diagnose and even predict failures before they happen [17]. Overall, understanding these fault-tolerant strategies is key to developing the next generation of robust marine propulsion, and this forms the basis for the analysis in the chapters that follow.

Table (1-3): Classification of Faults in Electric Propulsion Systems.

Fault Category	**Example**	**Affected Component**	**Impact**
Electrical	Open circuit	Motor	Torque loss
Electrical	Short-circuit	Motor/Converter	Severe damage
Thermal	Overheating	Converter	Aging
Control	Sensor failure	Drive system	Instability

1-5 Thesis Structure

The research presented in this thesis is organized into five main chapters, each addressing a specific dimension of marine electric propulsion with a consistent focus on reliability and fault-tolerant design.

Chapter 1 serves as an introduction to the research field, detailing the primary motivations for the study. It also includes a comprehensive review of the state of the art, covering current propulsion systems, motor technologies, power electronics, and reliability-based approaches.

The second chapter is dedicated to the architecture of electric propulsion and the specific motor types used in maritime settings. Here, the operating principles, benefits, and drawbacks of various motor technologies are evaluated, alongside a comparative study of their suitability for different propulsion needs.

Building on this, Chapter 3 examines power electronic converters and drive systems, placing a particular emphasis on medium voltage drives and multilevel converter topologies. This section analyzes how power electronics control the propulsion system and the resulting impact on overall performance and reliability.

The core of the reliability analysis is found in **Chapter 4**, which investigates fault-tolerant techniques in detail. This chapter classifies the various faults that can affect motors and converters while discussing mitigation strategies at the machine, converter, and control levels.

Finally, Chapter 5 provides a comparative discussion of the technologies analyzed throughout the thesis, highlighting their respective strengths and limitations. It concludes by suggesting potential directions for future research in this area.

Chapter 2: Electric Motors and Propulsion Systems

2-1 Electric Propulsion Architectures

Over the last few decades, electric propulsion architectures have changed significantly. This evolution has been largely driven by the need for better energy efficiency, environmental sustainability, and more operational flexibility in modern shipping. Selecting the right architecture is a key factor that determines how well a vessel performs and how reliable it remains under different conditions.

Historically, marine propulsion relied on diesel-mechanical configurations, where diesel engines are directly connected to the propeller shaft. While these systems are known for being rugged and simple, they lack flexibility in power distribution. Because the engine speed is tied directly to the propeller, efficiency often drops when operating conditions change [10].

To solve these issues, diesel-electric propulsion systems became a popular choice, especially for larger ships like cruise liners and offshore vessels. In this setup, diesel generators produce power for an onboard grid that feeds the propulsion motors and auxiliary systems. This decoupling of power generation from the propulsion itself allows the engines to run at their most efficient points, providing much more freedom in the overall system design [2], [4].

Hybrid propulsion systems serve as a middle ground, blending traditional mechanical and electrical technologies. They offer multiple operating modes, allowing a ship to switch between diesel-mechanical or electric power based on the current mission. This versatility is particularly useful for vessels with variable load profiles, where cutting emissions and saving energy are top priorities.

The most sophisticated configuration is the fully electric propulsion system, often called the AES or IPS [4]. In this architecture, every energy consumer on the ship, from the propellers to the auxiliary services, is powered by one unified electrical network. This high level of integration is excellent for advanced energy management and overall operational flexibility [4], [10].

However, this high level of integration also makes the system more complex. Because components are so interconnected, a fault in one area can spread through the grid and affect other parts of the ship. This highlights why reliability, redundancy, and fault management have become such important considerations in modern design [18].

From a comparative standpoint, each architecture involves certain trade-offs. While diesel-mechanical systems are simple and robust, diesel-electric and fully electric designs offer far more control and efficiency, though they are more sensitive to faults. These factors show that choosing a propulsion architecture is about more than just raw performance; it requires a careful look at reliability and fault tolerance, especially for large-scale maritime applications.

Table (2-1): A comparative overview of the main propulsion architecture used in marine applications is presented.

Architecture	**Efficiency**	**Flexibility**	**Complexity**	**Reliability**	**Key Advantage**	**Main Limitation**
Diesel-Mechanical	Medium	Low	Low	High	Simple and robust design	Limited efficiency under variable load
Diesel-Electric	High	Medium	Medium	High	Decoupled generation and propulsion	Increased system complexity
Hybrid	High	High	Medium	Medium	Flexible operation modes	Complex control strategy
All-Electric (AES/IPS)	Very High	Very High	High	Medium	Optimal energy management	High fault sensitivity

2-2 Electric Motors Used in Naval Applications

Electric motors are the central components of modern propulsion systems, as they are directly responsible for converting electrical energy into the mechanical torque needed to drive the propeller. In maritime settings, these machines must satisfy rigorous standards, including high efficiency, high power capability, and long-term reliability while operating in harsh environments.

Currently, the most common motor technologies in naval propulsion are induction motors, permanent magnet synchronous motors, and wound rotor synchronous motors [6], [7], [19]. Each type offers a unique set of characteristics that determine its suitability for specific missions, particularly regarding cost, efficiency, and fault tolerance.

2-2-1 Induction Motors (IM)

The IM remains one of the most widely used machines in both industrial and marine sectors, primarily due to their straightforward construction and cost-effectiveness. Since their design does not require permanent magnets or complex external excitation, both manufacturing and long-term maintenance are simplified.

One of the greatest strengths of the IM is its operational durability in tough environments, making it a reliable choice for high-power marine systems. Furthermore, its rugged structure provides the mechanical strength needed for demanding maritime tasks. However, IMs generally have lower efficiency and power density compared to synchronous machines, especially when the ship is running under partial load conditions. This can be a significant drawback in applications where energy optimization is a top priority [6], [15].

2-2-2 Permanent Magnet Synchronous Motors (PMSM)

In recent years, PMSMs have gained a lot of traction in marine propulsion because of their exceptional efficiency and high-power density. These motors use permanent magnets on the rotor, which removes the need for rotor winding and effectively eliminates rotor copper losses.

The compact design and high efficiency of PMSMs make them ideal for vessels where space and weight are limited, such as cruise ships or advanced naval platforms. Nevertheless, these advantages come with challenges. The reliance on rare-earth materials increases the overall cost and raises concerns about long-term sustainability and supply. Additionally, the behavior of a PMSM during fault conditions can be less favorable than that of more traditional, robust motor types [7].

2-2-3 Wound Rotor Synchronous Motors (WRSM)

The WRSMs offer another viable solution, particularly for medium-to-high-power propulsion needs. Unlike the PMSM, these machines utilize rotor windings supplied through slip rings, allowing for controllable excitation.

The main benefit of WRSM is the ability to regulate the magnetic field through excitation control. This provides high efficiency across a broad operating range and offers great operational flexibility. Also, since they do not use permanent magnets, they are less dependent on rare-earth materials. On the other hand, the inclusion of rotor windings and slip ring assemblies adds to the system's complexity and increases the maintenance requirements. This can be a limiting factor in marine environments where access for maintenance is difficult [6].

These comparisons show that while traditional motor technologies offer various performance benefits, no single type perfectly meets all the requirements for efficiency, cost, and fault tolerance simultaneously. This gap highlights the need for more advanced motor solutions in modern naval research.

Table (2-2): A comparison of the main conventional *motor technologies used in marine propulsion systems is presented.*

Motor Type	**Efficiency**	**Power Density**	**Reliability**	**Maintenance**	**Key Advantage**	**Main Limitation**
IM	Medium	Medium	High	Low	High robustness and low cost	Lower efficiency and power density
PMSM	High	High	Medium	Low	High efficiency and compact size	High cost and magnet dependency
WRSM	High	Medium	High	High	Controllable excitation	Increased mechanical complexity

2-2-4 Typical Nameplate Data of Marine Propulsion Motors

The operational capabilities of marine propulsion motors are fundamentally defined by their nameplate data, which encompasses the critical electrical and mechanical parameters necessary for system integration, control design, and protective coordination. Unlike standard industrial machines, propulsion motors are engineered to withstand extreme power and torque envelopes, a requirement dictated by the hydrodynamic demands of driving large-scale ship propellers. To effectively displace high volumes of water, these systems must deliver immense torque at relatively low angular velocities, typically operating within the megawatt power range and utilizing medium-voltage drive architectures [6], Rated voltage in these maritime systems generally spans the medium-voltage spectrum, typically between 3.3 kV and 11 kV. The adoption of these higher voltage levels is a strategic design choice to minimize line currents, thereby reducing ohmic losses and enhancing the overall efficiency of the vessel's electrical network. However, this shift toward medium voltage necessitates advanced insulation systems and rigorous dielectric design to prevent premature failure. Conversely, the resulting rated current in high-capacity systems can still escalate to several hundred or even a few thousand amperes, necessitating the use of robust power electronic converters and sophisticated thermal management strategies to dissipate the significant heat generated during operation [12].

A distinguishing characteristic of propulsion motors is their significantly lower rotational speed compared to conventional industrial counterparts, with typical values ranging between 60 and 180 rpm in direct-drive or podded configurations. This low-speed operation is vital to synchronize the motor’s output with the optimal hydrodynamic efficiency of the propeller. Consequently, to maintain the required power output at such low speeds, the motors must generate exceptionally high torque, often reaching magnitudes of several thousand kilo-Newton meters (kNm). Such high-torque requirements profoundly influence the rotor’s structural integrity and the design of the machine's cooling circuits [7]. While these machines are nominally rated for standard grid frequencies of 50 Hz or 60 Hz, the widespread implementation of variable-frequency drives allows for precise speed modulation and superior energy management throughout the vessel's operational profile.

Table (2-3): A summary of typical nameplate parameters for marine propulsion motors, based on reported industrial applications, is presented.

Parameter	**Typical Range**	**Unit**	**Description**
Rated Power	5 – 20	MW	Mechanical output power
Rated Voltage	3.3 – 11	kV	Medium-voltage operation
Rated Current	500 – 2000	A	Depends on rating and voltage
Speed	60 – 180	rpm	Low-speed propulsion
Frequency	50 / 60 (variable)	Hz	Converter-controlled
Torque	500 – 3000	kNm	High torque for propeller drive

As shown in Table 2-3, marine propulsion motors operate at significantly higher power and torque levels compared to conventional industrial machines, reflecting the demanding operational conditions of maritime applications. These characteristics highlight the importance of integrating appropriate motor design, power electronic converters, and control strategies to ensure reliable and efficient operation in marine propulsion systems.

2-3 Multiphase Electrical Machines

Lately, multiphase electrical machines have gained significant recognition as a viable solution for high-performance and safety-critical systems, including marine propulsion. Unlike the standard three-phase machines, these systems use more than three stator phases typically five, six, or more. This setup provides additional degrees of freedom in both how the machine is controlled and how it operates.

The growing interest in this technology is largely due to its enhanced reliability, superior fault-tolerant capabilities, and better overall performance under heavy loads. These features are especially valuable for marine propulsion, where ensuring continuous operation at sea is a top priority.

2-3-1 Definition and Basic Principles

By definition, a multiphase electrical machine is any machine featuring more than three stator phases. Having these extra phases allows the system to distribute power across multiple windings, which effectively reduces the current per phase and leads to better thermal performance. Different phase arrangements and spatial distributions of windings in multiphase machines are illustrated in Figure 2-1.

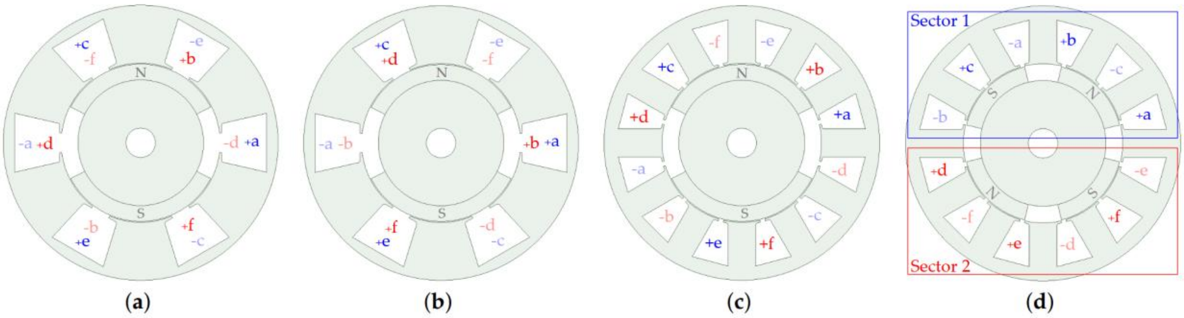

Figure (2-1): Phase distribution and spatial arrangement of stator windings in a multiphase electrical machine under different configurations [8].

As shown in Figure 2-1, the use of multiple phases enables more flexible current distribution and improved fault tolerance compared to conventional three-phase machines.

From a control standpoint, these additional phases offer extra degrees of freedom that can be used to optimize torque production, minimize torque ripple[8], [20], [21], [22], [23], [24], and boost system efficiency. This allows for much more versatile control strategies than what is possible with conventional three-phase systems [9], [20].

2-3-2 Advantages of Multiphase Machines

The most notable benefit of multiphase machines is their built-in fault tolerance. If a phase fails for instance, due to an open-circuit fault, the remaining healthy phases can still keep the machine running. This allows for torque production to continue, even if at a slightly reduced performance level. This capability is essential in marine settings, where an unexpected system shutdown could lead to dangerous situations [8], [22].

Beyond fault tolerance, these machines offer several other perks. These include lower current per phase, more even heat distribution, and less stress on the power electronic components. Together, these factors help improve the system's reliability and can extend its operational lifetime [9].

Table (2-4): The main advantages of multiphase electrical machines are summarized.

Feature	**Technical Benefit**	**Impact on Marine Systems**
Increased number of phases	Redundancy in operation	Enables continued operation under faults
Current redistribution	Reduced current per phase	Lower thermal stress
Additional control freedom	Advanced control strategies	Improved performance and stability
Fault tolerance capability	Operation under phase failure	Critical for safety applications

2-3-3 Multiphase Machine Configurations

Various multiphase configurations have been discussed in research, each offering a different balance of performance and reliability. The most common types include:

- Symmetrical Multiphase Systems: Such as five-phase machines, where phases are spaced evenly to ensure balanced operation and simpler control.
- Multiple Three-Phase Systems: Such as dual three-phase or six-phase machines. These consist of two or more independent sets of three-phase windings. Since these sets can be controlled separately, they provide higher redundancy and even better fault tolerance.

The choice between these configurations depends on the required level of redundancy, the complexity of the control system, and how well they integrate with the converter topology [20].

2-3-4 Challenges and Limitations

Despite their clear advantages, multiphase machines involve certain trade-offs that must be managed. Increasing the number of phases naturally requires more complex power electronic converters, which can raise the overall system cost and design difficulty.

Furthermore, controlling these machines is inherently more difficult. It requires managing multiple current components and ensuring that the current stays balanced across all phases. This often demands advanced control algorithms and more computational power than standard systems.

From a design perspective, optimizing a multiphase machine is also more demanding, particularly when it comes to electromagnetic design and reducing harmonics.

In summary, adopting multiphase machines is a balance between increased reliability and higher complexity. While they offer superior fault-tolerant performance, their implementation requires a careful look at cost, control, and system integration. These machines are not just a minor upgrade over conventional ones; they are a reliability-oriented solution specifically built for safety-critical applications.

2-4 Comparative Analysis of Motor Technologies

Selecting the right motor technology for a marine propulsion system is a complex process that depends on several key factors, including efficiency, power density, cost, reliability, and fault tolerance. Since no single technology can perfectly optimize all these variables at once, a comparative analysis is necessary to determine which solution best fits a specific maritime application.

In this section, the motor technologies discussed previously are evaluated based on their performance and their suitability for the demanding requirements of marine propulsion.

2-4-1 Performance Comparison

In terms of raw performance, PMSMs generally lead the way, offering the highest efficiency and power density among conventional options [7]. Their compact design and minimal losses make them a top choice for vessels where saving space and maximizing energy use are the main priorities.

IM, while not as efficient as PMSMs, still provide solid performance across a wide range of conditions. They remain a dependable solution for high-power systems. Their main appeal lies in their simplicity and ruggedness, making them ideal for environments where reliability is prioritized overachieving the highest possible efficiency [6].

WRSMs offer a middle ground between IMs and PMSMs by providing high efficiency and better control. However, their increased complexity and the need for regular maintenance can be a limiting factor in some cases.

Finally, multiphase machines can reach efficiency levels similar to PMSMs while offering much more operational flexibility. While their performance can be further boosted through advanced control, it is important to note that this adds to the system's overall complexity [9], [20].

Table (2-5): A comparative evaluation of motor performance characteristics is presented.

Motor Type	**Efficiency**	**Power Density**	**Control Flexibility**	**Suitability for Marine Applications**
IM	Medium	Medium	Low	Suitable for robust and cost-sensitive systems
PMSM	High	High	Medium	Suitable for high-efficiency and compact systems
WRSM	High	Medium	High	Suitable for controlled high-power applications
Multiphase	High	High	Very High	Suitable for advanced and safety-critical systems

2-4-2 Reliability and Fault-Tolerance Comparison

Reliability and fault tolerance are perhaps the most critical factors in marine propulsion, where the ship must always remain operational. IMs are widely respected for their robustness and ability to handle the tough conditions of the sea, making them a safe choice for many standard applications [6].

However, traditional three-phase machines, whether induction or synchronous, have limited fault-tolerant capabilities [8]. If a fault like an open-phase condition occurs, these machines often suffer from a major drop in performance or may stop working entirely.

Multiphase machines, on the other hand, offer superior fault tolerance due to their built-in redundancy [8]. Because they have extra phases, the system can redistribute current to keep producing torque even during a fault. This makes them a highly promising solution for safety-critical naval systems [8].

It is also worth noting the role of power converters. Technologies that require more complex drive systems, like multiphase machines, introduce more potential points of failure. These must be carefully managed through smart design and advanced control strategies.

Table (2-6): A comparison of motor technologies in terms of reliability and fault-tolerant capability is presented.

Motor Type	**Reliability**	**Fault Tolerance**	**Failure Behavior**	**System Impact**
IM	High	Low	Performance degradation under faults	Possible system shutdown
PMSM	Medium	Medium	Sensitive to certain fault conditions	Reduced performance
WRSM	High	Medium	Can operate with controlled excitation	Moderate impact
Multiphase	Very High	Very High	Continues operation under phase faults	Maintains propulsion capability

2-4-3 Trade-off Analysis

This comparison shows that choosing a propulsion motor is essentially a trade-off problem. While PMSMs are efficient and compact, they come with higher costs and potential risks during faults. IMs are affordable and tough but aren't the most efficient option available.

Multiphase machines represent a reliability-oriented solution; they provide excellent fault tolerance but require more complex converters and higher initial investment. Similarly, WRSMs offer flexibility but bring extra maintenance challenges.

Therefore, the final choice depends on the priorities of the specific project:

- If efficiency and space are the main concerns, PMSMs are usually the best fit.
- For cost-effective and rugged systems, IMs remain the standard.
- For missions where reliability and fault tolerance are the absolute priorities, multiphase machines are the most logical choice.

Ultimately, no single motor is the best for every ship. Instead, the most effective solution comes from a balanced evaluation of performance, cost, and operational safety. This confirms that selecting a propulsion motor is not just about one metric but is a multi-criteria optimization problem where reliability is becoming increasingly important.

2-5 Selection Criteria for Marine Propulsion Motors

Choosing the right electric motor for a marine propulsion system is a complex engineering task that involves evaluating various technical and operational factors. Unlike standard industrial applications, marine systems face unique challenges due to their immense power requirements, safety-critical nature, and the need for a very long operational lifespan.

Efficiency is a major driver in this selection process, given that propulsion accounts for the bulk of a vessel's total energy consumption. High-efficiency options, such as PMSMs, can effectively lower fuel use and operational costs, a factor that is especially important for massive vessels like cruise ships [1].

Another vital factor is reliability, which is a top priority in the unpredictable marine environment. Because a propulsion failure at sea can have serious safety and operational risks, the chosen motor must be durable enough to handle extreme conditions. This is why robust technologies, such as IMs, are frequently selected for their mechanical strength and ability to withstand environmental stress [18].

In recent years, fault tolerance has also become an increasingly important requirement. Rather than just trying to prevent faults, modern propulsion systems are now designed to stay operational even after a failure occurs. Multiphase machines and multi-winding setups have gained significant traction here because their built-in redundancy allows the ship to keep moving even under fault conditions [8].

Power density is another key consideration, particularly for large ships where space and weight must be managed carefully. Motors with high power density, like PMSMs, allow for a more compact propulsion setup and better integration into the ship's design.

However, these benefits must be weighed against cost and maintenance. While advanced motors perform better, they often come with higher initial prices such as the material costs for magnets in PMSMs or more frequent maintenance needs, as seen with the excitation systems in WRSMs.

Finally, the compatibility between the motor and its power electronic converters is essential. More advanced solutions, specifically multiphase machines, require specialized and more complex converter topologies, which can increase the overall system’s cost and design difficulty.

Ultimately, selecting a propulsion motor is a balancing act between efficiency, cost, and complexity. In modern marine engineering, where safety and operational continuity are the highest priorities, the ability to tolerate faults has become a dominant factor in the decision-making process.

Table (2-7): The main criteria influencing the selection of propulsion motors are summarized in.

Criterion	**Importance Level**	**Technical Role**	**Impact on System Design**
Efficiency	High	Reduces energy losses	Improves fuel economy
Reliability	Critical	Ensures continuous operation	Enhances safety
Fault Tolerance	Critical	Maintains operation under faults	Prevents system failure
Power Density	High	Reduces size and weight	Improves integration
Cost	Medium	Affects economic feasibility	Limits technology choice
Maintenance	High	Determines operational availability	Impacts lifecycle cost
Converter Compatibility	Medium	Affects control and integration	Influences system complexity

Chapter 3: Power Electronics and Drive Systems

3-1 Power Converter Technologies

Power electronic converters serve as an essential link in modern marine propulsion systems, acting as the bridge between the ship's power sources and its propulsion motors. Their main task is to transform electrical energy into the specific form the motor requires, which allows for precise management of voltage, current, and frequency.

In these maritime applications, propulsion systems often operate at medium- to high-power levels, sometimes reaching several megawatts. This scale of operation places strict demands on efficiency, thermal management, and overall reliability. Consequently, the choice of converter topology has a major influence on how the entire system performs [25].

Among the various technologies available, two basic types are commonly used in electric drives: VSIs and CSI. These two categories provide the foundation for the more advanced and complex topologies that will be discussed in the following section.

3-1-1 Voltage Source Inverters (VSI)

The VSIs are the most frequently used converter topology in electric propulsion. The basic principle of a VSI involves converting a DC input voltage into an AC output with an adjustable frequency and amplitude. This capability is what allows for the precise management of motor speed and torque, making VSI-based drives a standard choice for maritime propulsion.

A major benefit of the VSI is its straightforward architecture and the flexibility it offers in terms of control [22], [25], [26]. These systems integrate well with modern techniques like pulse-width modulation (PWM), which ensures efficient operation across a wide range of speeds and loads.

However, when dealing with high-power applications, VSIs can encounter certain challenges. Specifically, they may face increased switching losses and harmonic distortion, both of which can lower the overall efficiency of the system. In many cases, these limitations require the addition of filtering components to maintain power quality [25].

3-1-2 Current Source Inverters (CSI)

The CSIs provide a distinct alternative to the more common VSI architectures, particularly in high-power scenarios. In a CSI-based setup, the input current is the primary regulated variable, which is then transformed into an AC output current to drive the propulsion motor.

A standout feature of the CSI is its built-in short-circuit protection, which naturally improves the system's overall robustness and reliability. This inherent safety mechanism makes the CSI a strong candidate for maritime missions where fault tolerance is a primary requirement.

On the downside, CSIs depend on large inductors to maintain a constant current flow, which can significantly increase both the physical footprint and the cost of the propulsion unit. Furthermore, their dynamic response tends to be slower than that of VSI-based drives, which may impact performance in operating conditions that require rapid changes in speed or torque [25].

Table (3-1): A comparison between voltage source and current source inverter technologies is presented.

Converter Type	**Control Variable**	**Efficiency**	**Complexity**	**Reliability**	**Key Advantage**	**Main Limitation**
VSI	Voltage	High	Low	Medium	Simple structure and flexible control	Harmonic distortion and switching losses
CSI	Current	Medium	Medium	High	Short-circuit protection capability	Large inductors and slower response

As shown in Table 3-1, VSIs offer higher efficiency and flexibility, while CSIs provide improved robustness and inherent fault protection. These conventional converter topologies provide the foundation for more advanced solutions, such as multilevel converters, which are discussed in the following section.

3-2 Multilevel Converters

Multilevel converters have established themselves as a core technology for medium- and high-voltage applications, particularly within the realm of marine propulsion. The defining difference between these and traditional two-level converters is their ability to generate output voltages using multiple discrete levels. This incremental approach to voltage synthesis results in a significantly cleaner waveform and a major reduction in harmonic distortion [3], [21].

By producing a more refined output, multilevel converters minimize the electrical and thermal stress placed on both the propulsion motors and the power electronic components. This reduction in stress leads to higher efficiency and improved system reliability, which explains why these topologies are increasingly favored for high-power maritime projects [16].

3-2-1 Modular Multilevel Converters (MMC)

The MMC stands as one of the most sophisticated and widely adopted topologies for high-power environments [16], [27], [28], [29]. The core of its architecture is the use of multiple submodules linked in series within each converter arm. This specific arrangement allows the system to synthesize a high-quality output voltage while keeping harmonic distortion to an absolute minimum.

A defining strength of the MMC is its modular nature, which directly enables scalability and hardware redundancy. In the context of marine propulsion where the ability to stay operational during a fault is a primary requirement, this redundancy makes the MMC an ideal candidate. Furthermore, when compared to more traditional converter designs, MMCs generally achieve lower switching losses and better overall efficiency most common faults [21].

That said, this level of performance comes with a trade-off in complexity. Operating an MMC requires highly sophisticated control strategies, particularly for managing capacitor voltage balancing across the various submodules. Additionally, the sheer number of semiconductor devices involved naturally adds to the overall complexity of the system, which is a factor that must be carefully managed during the design phase.

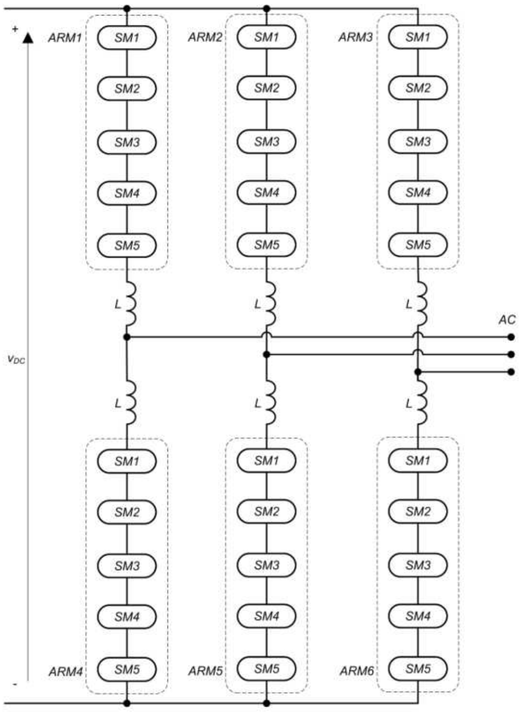

Figure (3-1): Structure of a MMC showing submodules and arm configuration [21].

As shown in Figure 3-1, the modular structure of MMCs enables flexible voltage scaling and improved harmonic performance.

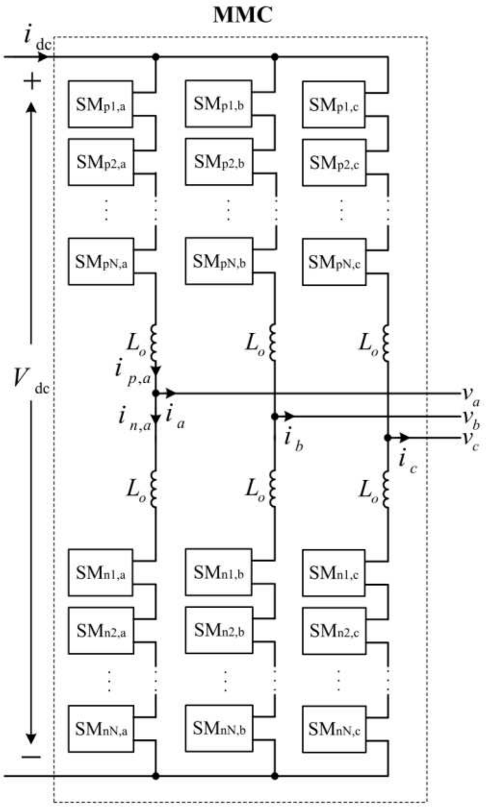

Figure (3-2): Detailed topology of a MMC, including submodules, arm inductors, and phase currents [16].

As shown in Figure 3-2, the MMC consists of multiple submodules connected in series within each arm, enabling high-voltage and scalable operation.

3-2-2 Cascaded Converters

Cascaded multilevel converters represent another significant topology frequently utilized in medium- to high-power drives. These systems are typically constructed from multiple H-bridge cells connected in series, where each individual cell is fed by its own independent DC source or capacitor bank.

This cascaded architecture is particularly effective at generating stepped output voltages, which results in a much cleaner waveform and a substantial drop in harmonic content. Beyond the electrical benefits, the modular nature of this design is a major advantage for high-power maritime systems, as it simplifies scalability and allows for better fault isolation if one cell fails.

However, the primary challenge with cascaded converters lies in the requirement for multiple isolated DC sources. Providing these independent sources adds a significant layer of system complexity and can be a limiting factor in certain marine applications where managing numerous isolated power inputs is not always practical [16].

3-2-3 Applications in Marine Propulsion

Multilevel converters have gained widespread acceptance in marine propulsion due to their ability to handle medium-voltage levels while delivering high-quality output waveforms. By significantly lowering harmonic distortion, these converters minimize electrical losses within the propulsion motors, which directly translates to better overall system efficiency.

In particular, the MMC is becoming a standard feature in modern IPS. Its architecture is highly valued for its scalability and inherent redundancy, providing the fault-tolerant capabilities that are essential for large-scale vessels like cruise ships and naval platforms.

This modular design also allows for effective fault isolation and system reconfiguration. These features are critical for maintaining operation during a component failure, ensuring that the ship remains maneuverable even under adverse conditions [4].

Table (3-2): A comparison of the main multilevel converter topologies is presented.

Topology	**Complexity**	**Scalability**	**Harmonic Performance**	**Reliability**	**Key Advantage**	**Main Limitation**
NPC	Medium	Medium	Good	Medium	Mature technology	Voltage balancing issues
Flying Capacitor	High	Medium	Good	Medium	Flexible control	Large number of capacitors
Cascaded H-Bridge	Medium	High	Good	High	Modular structure	Multiple DC sources
MMC	High	Very High	Excellent	High	Scalability and redundancy	Control complexity

As shown in Table 3.2, MMCs provide superior scalability and harmonic performance, making them particularly suitable for high-power marine propulsion systems. These advanced converter topologies form the basis of modern medium-voltage drive systems, which are discussed in the following section.

3-3 Medium-Voltage Drive Systems

The MV drive systems have become a standard fixture in modern marine propulsion, especially for large-scale vessels such as cruise liners, naval ships, and offshore support platforms. These systems typically operate within a range of several kilovolts (kV) and are engineered to handle power outputs that frequently reach the megawatt (MW) scale.

The shift toward medium-voltage levels is primarily driven by the need for efficient power transmission. By operating at higher voltages, the system can significantly reduce current levels. This reduction is vital because it minimizes conduction losses and boosts the overall energy efficiency of the ship. Consequently, MV drives are considered an indispensable technology for any high-power propulsion requirement [25].

3-3-1 Challenges in High-Power Applications

Operating MV drive systems at high power levels introduces several technical hurdles. A primary concern is the intense electrical stress placed on power electronic components, as they must constantly manage high voltage and current magnitudes.

Thermal management is equally critical. Because high-power converters generate a substantial amount of heat during operation, the system design must incorporate highly effective cooling mechanisms. Without proper thermal control, the safety and reliability of the drive cannot be guaranteed. Beyond heat, switching losses and electromagnetic interference (EMI) become far more pronounced as power levels rise, which can degrade the system's overall performance and stability.

Furthermore, insulation and dielectric stress require careful attention; as voltage levels increase, so does the risk of catastrophic insulation failure. These combined factors underline why robust engineering and the use of advanced converter topologies are necessary for any reliable medium-voltage application [25].

3-3-2 Industrial Solutions

To mitigate the difficulties associated with high-power maritime operations, several industry-standard strategies have been developed. Among the most effective is the implementation of multilevel converters, which allow for medium-voltage operation while simultaneously improving efficiency and delivering a much cleaner output with reduced harmonic distortion.

Specifically, MMCs have emerged as the preferred architecture for modern ship propulsion. Their popularity is driven by their inherent scalability, modularity, and superior fault-tolerant capabilities, all of which are essential for the rigors of the sea.

Beyond the converter topology itself, industrial systems utilize sophisticated thermal management techniques, such as liquid cooling, to effectively dissipate heat and manage thermal stress. Furthermore, the integration of robust insulation designs and advanced monitoring systems plays a vital role in enhancing system reliability and preventing catastrophic failures before they occur.

Ultimately, these solutions show that modern MV drive systems do not rely on a single component, but rather on a combination of advanced hardware and intelligent design. This integrated approach ensures that propulsion systems can remain reliable even in the most demanding marine environments [25].

Table (3-3): The main challenges and corresponding engineering solutions in MV drive systems are summarized.

Challenge	**Technical Issue**	**Engineering Solution**	**Impact**
High voltage stress	Insulation degradation	Advanced insulation design	Improved reliability
Thermal stress	Heat generation	Liquid cooling systems	Extended lifetime
Switching losses	Efficiency reduction	Multilevel converters	Improved efficiency
Harmonics	Motor stress	Advanced filtering and control	Better performance
EMI	Signal disturbance	Shielding and filtering	System stability

These considerations highlight the importance of reliability analysis in power electronic systems, which is discussed in detail in the following section.

3-4 Reliability of Power Electronics

Reliability stands as a cornerstone of power electronic design, particularly within the maritime sector where continuous operation and safety are non-negotiable. Despite their technological benefits, power electronic converters are frequently identified as the most susceptible elements in an electric propulsion architecture. This vulnerability is largely due to their intricate internal structures and the high density of semiconductor components required to manage high power levels.

In high-capacity environments such as medium-voltage marine drives the stakes are particularly high. A single converter failure can trigger a cascade of issues, ranging from severe performance degradation to a total system blackout, which could leave a vessel stranded.

Consequently, a deep-seated understanding of power electronics reliability is not merely a theoretical exercise; it is a practical necessity for the development of resilient, fault-tolerant propulsion systems [11], [30].

3-4-1 Failure Mechanisms

Power electronic components are vulnerable to several distinct failure mechanisms, which are largely driven by electrical, thermal, and mechanical stresses. Within this high-power environment, semiconductor devices such as IGBTs and diodes show a particularly high level of sensitivity to their specific operating conditions.

Frequent failure modes observed in these systems include bond wire lift-off, solder fatigue, and dielectric breakdown. These issues are typically triggered by the continuous thermal cycling and high current stress that occur during regular operation. Furthermore, exposure to overvoltage or overcurrent events can rapidly accelerate the degradation of a device, potentially leading to a catastrophic failure. Gaining a deeper understanding of these physical pathways is vital for enhancing overall system reliability and developing more effective protection strategies [12].

3-4-2 Thermal Stress and Lifetime

Thermal stress stands as a primary factor significantly influencing the operational life of power electronic components. Throughout their service, converters are subjected to continuous thermal cycling repeated heating and cooling which eventually triggers thermal fatigue and the progressive wear of internal materials. Specifically, the junction temperature of semiconductor units acts as a critical metric for predicting their longevity, as wide fluctuations in temperature tend to speed up the aging process and raise the likelihood of a system-level failure.

To counteract these effects, modern designs integrate sophisticated cooling technologies and thermal management protocols. These solutions often involve liquid cooling architectures, high-performance heat sinks, and the implementation of real-time thermal monitoring systems to ensure that the devices remain within safe operating limits [31].

3-4-3 Reliability Modeling Approaches

Reliability modeling serves as an indispensable tool for forecasting the operational lifespan and failure probabilities of power electronic systems. Over the years, several distinct methodologies have emerged to address this need, most notably statistical models, physics-of-failure (PoF) approaches, and mission profile-based analyses.

Statistical models are primarily built on historical failure data to derive key reliability metrics, such as Mean Time to Failure (MTTF). While their simplicity makes them relatively easy to implement, these models often fall short because they fail to account for the actual physical degradation occurring within the components. In contrast, physics-of-failure models offer a much more granular perspective by examining the specific physical and chemical processes that drive material wear. This depth allows for far more precise lifetime predictions, especially when operating conditions are constantly shifting.

Taking this a step further, mission profile-based strategies incorporate the specific real-world operating conditions of the system, such as fluctuating loads, thermal cycles, and environmental stressors. This comprehensive approach is particularly valuable for marine propulsion systems, where the operating environment can vary drastically depending on the mission or sea conditions. By aligning the reliability model with the actual demands of the vessel, engineers can achieve a much more realistic assessment of the system's long-term durability [28].

Table (3-4): A comparison of the main reliability modeling approaches is presented.

Method	**Approach**	**Accuracy**	**Complexity**	**Key Advantage**	**Limitation**
Statistical	Data-driven	Medium	Low	Simple implementation	Limited physical insight
Physics-of-Failure	Physical modeling	High	High	Accurate lifetime prediction	Complex modeling
Mission Profile-Based	Real operating conditions	High	Medium	Realistic evaluation	Requires detailed data

These reliability considerations highlight the importance of fault-tolerant design strategies, which are discussed in detail in the next chapter.

Chapter 4: Reliability and Fault-Tolerant Techniques

4-1 Reliability in Shipboard Power Systems

Reliability remains a foundational requirement for maritime power architecture, particularly for vessels utilizing electric propulsion systems. Unlike terrestrial grids, shipboard networks operate in isolated, self-sufficient environments where access to external support is restricted; consequently, ensuring continuous operational availability is a matter of necessity rather than a preference.

In the context of modern AES, the consolidation of propulsion, auxiliary loads, and hotel services into a single, unified power network has significantly boosted both energy efficiency and operational versatility. Nevertheless, this deep level of system integration creates complex interdependencies between various subsystems. Such coupling means that faults or disturbances in one area can easily propagate, making reliability a critical design challenge for the entire IPS [4], [32].

4-1-1 Dependability Requirements

Within the context of shipboard power systems, reliability is often viewed as part of a more comprehensive framework known as dependability. This concept encompasses several interconnected attributes: reliability, availability, maintainability, and safety (RAMS). Collectively, these factors define a system's capacity to deliver an acceptable level of performance, not only during standard operations but also when faced with abnormal or unforeseen conditions.

To distinguish these attributes, reliability is defined as the system's ability to function without failure over a specific timeframe, while availability measures its constant state of readiness for deployment. Maintainability refers to the efficiency and speed with which a system can be restored to full operation following a malfunction. Finally, safety ensures that the system's operation even in a degraded state does not lead to hazardous outcomes for the vessel or its environment.

In marine propulsion applications, these requirements are exceptionally rigorous. A failure in the propulsion line is never a minor issue; it can lead to a total loss of maneuverability, the immediate interruption of a mission, or significant risks to the lives of the passengers and crew. Consequently, modern shipboard architectures must be engineered with a dual focus: they must not only aim to prevent failures through robust design but also possess the inherent ability to tolerate and recover from them effectively [4].

Table (4-1): The main dependability requirements in shipboard power systems are summarized.

Requirement	***Description***	***Importance in Marine Systems***
Reliability	Operation without failure	Ensures propulsion continuity
Availability	Readiness for operation	Minimizes downtime
Maintainability	Ease of repair	Enables fast recovery
Safety	Avoidance of hazardous conditions	Protects crew and vessel
Fault Tolerance	Operation under faults	Maintains system functionality

As shown in Table 4.1, dependability in marine systems involves multiple interconnected requirements beyond reliability alone.

4-1-2 System-Level Reliability Considerations

In the context of shipboard power networks, reliability cannot be viewed in isolation; it must be evaluated at both the component and system levels. Because modern electric propulsion systems are so deeply integrated, a failure within a single subsystem is rarely contained. Instead, these faults have a high tendency to propagate, potentially destabilizing other interconnected parts of the vessel. For instance, a malfunction in a power converter can directly compromise the performance of the propulsion motor, while a fault within the distribution grid might simultaneously disrupt multiple auxiliary loads. This interdependent behavior underscores why a comprehensive, system-level reliability analysis is an absolute necessity for modern naval architecture.

To mitigate these complex risks, shipboard systems are engineered with a heavy emphasis on redundancy, modularity, and robust fault isolation. By utilizing parallel configurations and redundant hardware, the system can maintain its primary functions even when specific components fail. Furthermore, advanced protection and control strategies are employed to detect abnormalities in real-time, isolate the faulty sections, and reconfigure the power flow to preserve operational continuity. Such strategies are particularly crucial for marine propulsion, where a total system shutdown is considered an unacceptable risk to the safety of the crew and the vessel [18], [33]. These considerations highlight that reliability in marine propulsion systems is inherently a system-level property, which necessitates the adoption of fault-tolerant design strategies discussed in the following sections.

4-2 Types of Faults in Electric Propulsion Systems

Electric propulsion systems are susceptible to a wide array of operational failures, largely due to the inherent complexity of their hardware and the rigorous environments in which they function. These faults can manifest within several critical subsystems, most notably the electric machines, power electronic converters, sensors, and central control units. Developing a comprehensive understanding of the origins and system-wide consequences of these malfunctions is a vital prerequisite for engineering resilient and fault-tolerant propulsion architectures.

In a general sense, these failures are categorized into four primary groups: open-circuit faults, short-circuit faults, converter-specific anomalies, and sensor-related errors. Each of these categories presents unique challenges for detection and mitigation, necessitating a targeted approach to monitoring and system protection to ensure the vessel remains operational under adverse conditions [8].

4-2-1 Open-Circuit Faults

Open-circuit faults manifest when one or more phases within the motor or the power converter become disconnected, leading to a direct interruption of the current path. Within the architecture of electric propulsion, these events are among the most frequently encountered failures and are typically triggered by semiconductor switch malfunctions, compromised electrical connections, or physical damage to the cabling. In conventional three-phase machines, the onset of an open-circuit fault is particularly disruptive, often resulting in substantial torque reduction, heightened mechanical vibration, and severely unbalanced phase currents. In the most severe cases, these imbalances can render the entire system inoperable, forcing a complete emergency shutdown.

In contrast, multiphase machines offer a significant inherent advantage in these scenarios. Unlike their three-phase counterparts, multiphase systems are engineered with the capability to maintain continuous operation even under open-circuit conditions. By intelligently redistributing currents among the remaining healthy phases, these machines can preserve propulsion power and stability. This specific ability to mitigate the impact of phase loss makes multiphase drives a cornerstone technology for fault-tolerant maritime applications, where mission continuity is paramount [8], [13], [14].

4-2-2 Short-Circuit Faults

Short-circuit faults represent one of the most critical and potentially catastrophic failure modes within electric propulsion systems. These events manifest when unintended, low-resistance paths are established within the electrical network, triggering a sudden and massive surge in current flow.

Such malfunctions can originate in several key areas, including the stator windings, the semiconductor junctions of power electronic switches, or within the primary cabling. Due to the extreme magnitudes of the resulting currents, the affected components experience a rapid and intense thermal rise. Without immediate and precise intervention, this thermal stress can lead to permanent hardware destruction and a complete, system-wide shut down.

Given their inherently destructive potential, the management of short-circuit faults necessitates the integration of high-speed protection mechanisms. Reliable operation in these high-power environments depends on a combination of robust hardware solutions such as current limiting devices and circuit breakers alongside sophisticated fault detection algorithms designed to identify and isolate the fault before it can propagate or cause irreversible damage [18], [34]. The failure mechanisms associated with short-circuit conditions in power semiconductor devices are illustrated in Figure 4-1.

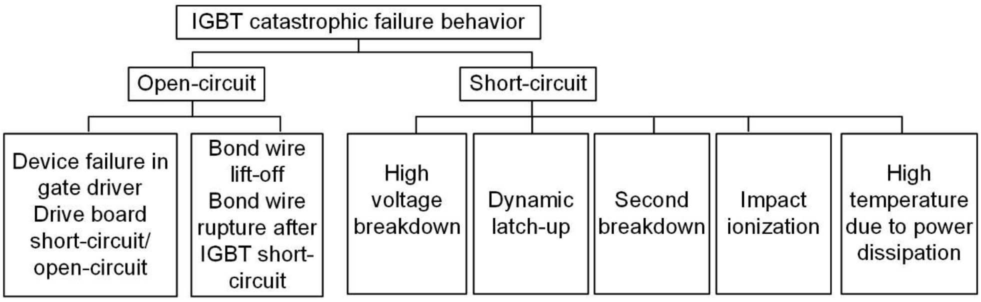

Figure (4-1): Cascading failure mechanisms in IGBT devices under open-circuit and short-circuit fault conditions [12].

As shown in Figure 4-1, short-circuit faults can trigger multiple degradation mechanisms, potentially leading to catastrophic device failure.

4-2-3 Converter Faults

As a cornerstone of the electric propulsion chain, power electronic converters represent a significant point of vulnerability. Their complexity, largely stemming from the high density of semiconductor components within their architecture, makes them particularly susceptible to operational failures.

Typical failure modes in these units include semiconductor switch malfunctions, gate driver anomalies, and the progressive degradation of DC-link capacitors. When these faults occur, they often manifest as distorted voltage and current waveforms, leading to a noticeable drop in efficiency and a heightened risk of system-wide instability. These converter-specific failures are notably critical because they rarely remain isolated; instead, they have a strong tendency to propagate throughout the network, directly compromising motor dynamics and the total performance of the propulsion system [11], [28].

Table (4-2): The main types of converter faults are summarized.

Fault Type	**Cause**	**Effect**	**Severity**
Switch failure	IGBT damage	Loss of control	High
Gate driver fault	Control failure	Incorrect switching	Medium
Capacitor degradation	Aging	Voltage ripple	Medium
DC-link fault	Overvoltage	System instability	High

As shown in Table 4.2, converter faults can significantly impact system performance and must be carefully managed.

4-2-4 Sensor Faults

Sensor faults occur when the measurement devices responsible for monitoring the system's state such as current, voltage, or position sensors deliver inaccurate, noisy, or entirely missing data. In the sophisticated environment of an electric propulsion unit, these anomalies can mislead the central control unit, triggering incorrect control actions that inevitably lead to degraded system performance.

For modern maritime propulsion, the integrity of sensor data is non-negotiable. High-performance control algorithms, such as field-oriented control (FOC), as well as the system's own fault detection layers, depend on precise feedback to function. Consequently, a sensor failure is not merely a data error; it can result in dynamic instability, incorrect torque production, or a complete, forced system shutdown. To counteract these vulnerabilities, engineers often integrate hardware redundancy alongside advanced estimation techniques. These typically include observer-based methods, which allow the system to synthesize virtual sensor data, ensuring that the propulsion remains under control even if a physical sensor fails [17], [35].

4-3 Fault-Tolerant Motor Design

Fault-tolerant motor design serves as a fundamental pillar in the reliability of electric propulsion systems, particularly within safety-critical maritime environments. Rather than relying exclusively on reactive fault detection and protection layers, contemporary motor architectures are engineered to sustain functionality even when internal faults occur.

This methodology represents a significant paradigm shift from pure fault prevention toward active fault tolerance. In this framework, the system is designed to provide acceptable performance levels despite the failure of specific components. To achieve this resilience, several hardware-level strategies have been pioneered, most notably the use of multiphase machines, multi-winding configurations, and highly redundant system architectures [8].

4-3-1 Multiphase Machines

Multiphase machines stand out as a premier architecture for achieving high-level fault tolerance within electric propulsion systems. By extending the stator phase count beyond the conventional three-phase limit, these machines introduce a degree of inherent redundancy that allows for continued operation even under adverse fault conditions. In the event of a phase failure such as an open-circuit fault the system does not suffer a total loss of functionality. Instead, the remaining healthy phases can intelligently reconfigure their current distribution to maintain torque production. While this may result in slightly reduced performance levels, the ability to avoid a complete shutdown significantly bolsters system reliability, making multiphase drives an ideal choice for the rigorous demands of marine propulsion [8], [20], [22].

Beyond their fault-tolerant capabilities, multiphase machines offer several auxiliary benefits, including improved thermal performance due to the lower current density per phase and a broader range of control flexibility. These features allow for a more optimized design of the electric drive train. However, these advantages come with a distinct trade-off in system architecture; implementing a multiphase drive requires more complex converter topologies and sophisticated control algorithms to effectively manage the increased number of degrees of freedom. Despite this added complexity, the drive toward more resilient shipboard power systems continues to favor multiphase technology as a standard for high-power applications.

4-3-2 Multi-Winding Configurations

Multi-winding configurations represent a sophisticated architectural strategy for enhancing the fault tolerance of high-power electric machines. In this design, the stator is structured with multiple independent winding sets, with each set typically supplied by its own dedicated power electronic converter. This decoupled arrangement creates a highly modular power path, ensuring that the machine is not dependent on a single electrical channel for its entire torque production. A typical configuration of a double-winding motor supplied by parallel converters is illustrated in Figure 4-2.

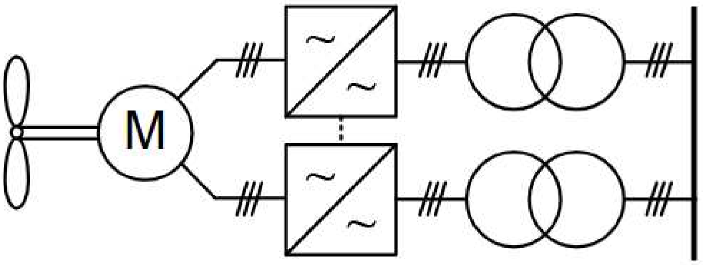

Figure (4-2): Parallel converter configuration supplying a double-winding motor, enabling redundancy and enhanced fault-tolerant operation [3].

As shown in Figure 4-2, the use of multiple windings and parallel converters allows continued operation even in the presence of faults in one converter.

The primary strength of the multi-winding approach is its capacity for partial or degraded-mode operation. If a failure occurs within one winding set or its corresponding converter, the remaining healthy windings can continue to function independently. While this inevitably results in a reduced power capacity, it prevents a total loss of propulsion, thereby significantly increasing the overall system availability. This level of hardware redundancy and inherent fault isolation makes multi-winding machines an ideal solution for megawatt-class marine propulsion systems, where mission-critical reliability and safety are the top priorities [15].

4-3-3 Redundant Systems

Redundancy stands as a fundamental pillar of fault-tolerant design, shifting the engineering focus from absolute fault prevention toward operational continuity through the use of auxiliary components. By incorporating subsystems that can seamlessly take over during a failure, the architecture ensures that a single point of failure does not result in a total loss of mission capability. In shipboard environments, this redundancy is typically implemented across multiple hierarchical stages ranging from the power supply and converter units to the propulsion motors themselves. For instance, the adoption of dual-motor setups or parallel-connected drive systems provides a robust safety net, allowing the vessel to remain maneuverable even if a major drive unit goes offline.

However, the benefits of increased availability and reliability are inherently accompanied by significant practical challenges. The integration of redundant hardware inevitably adds to the system's total physical footprint and weight, while also driving up capital expenditure and the complexity of the underlying control logic. Consequently, the design of modern marine propulsion systems requires a meticulous multi-objective optimization process. Engineers must strive to achieve an optimal balance where the gains in resilience and safety are not overshadowed by excessive system weight or a reduction in overall energy efficiency [3].

Table (4-3): The main fault-tolerant motor design strategies are summarized.

Strategy	**Principle**	**Fault Tolerance Capability**	**Advantage**	**Limitation**
Multiphase machines	Increased number of phases	High	Continues operation under phase faults	Complex control
Multi-winding	Independent windings	High	Fault isolation	Increased hardware
Redundancy	Parallel systems	Very High	High availability	Increased cost and weight

As shown in Table 4.3, fault-tolerant motor design relies on redundancy and structural modifications to maintain operation under fault conditions. These design approaches demonstrate that fault tolerance can be embedded at the machine level, complementing control-based strategies discussed in the following section.

4-4 Fault-Tolerant Control Strategies

Fault-tolerant control strategies serve an indispensable function in maintaining the continuity of electric propulsion systems under adverse conditions. While structural motor design focuses on building a resilient physical architecture, FTC strategies are designed to dynamically reconfigure the system’s behavior in real-time. This algorithmic approach allows the controller to compensate for internal malfunctions such as sensor inaccuracies or semiconductor failures without requiring immediate human intervention or a total system restart.

In the high-stakes environment of marine propulsion, where an unexpected shutdown can lead to a loss of maneuverability or mission failure, these advanced control techniques are paramount. The process typically involves a sophisticated sequence of fault detection, isolation, and reconfiguration. By identifying the anomaly early, the control system can mask the fault's impact, redistributing the load or updating control gains to preserve operational integrity. This ensures that the vessel remains capable of delivering acceptable performance, effectively bridging the gap between a hardware failure and the successful completion of a maritime mission [8].

4-4-1 Reconfiguration Techniques

Reconfiguration techniques serve as a pivotal response within fault-tolerant frameworks, providing the necessary logic to sustain operation after a failure has been isolated. These strategies involve the dynamic modification of the control laws or the physical system configuration to bypass the compromised elements. In the context of electric propulsion, this reconfiguration often manifests as the immediate disconnection of faulty phases, the intelligent redistribution of current across the remaining healthy channels, or a strategic transition to alternative operating modes. By shifting the control objective from full performance to maximum available performance, these techniques allow the vessel to maintain a degraded mode of operation, prioritizing safety and maneuverability over a complete and potentially dangerous system shutdown.

The effectiveness of these reconfiguration strategies is exponentially higher in multiphase and multi-winding systems. Because these architectures possess inherent hardware redundancy, they offer the control degrees of freedom required for flexible adjustments. When a fault occurs in such a system, the controller does not simply fail; it re-maps the torque and flux commands to the functioning phases, ensuring that the magnetic field remains balanced and torque ripples are minimized. This synergy between advanced hardware and reconfigurable software is what defines a truly resilient marine drive, ensuring that mission-critical propulsion remains available even under significant internal stress [8].

4-4-2 SVPWM-Based Strategies

Space Vector Pulse Width Modulation (SVPWM) stands as a premier control methodology in power electronics, valued for its superior voltage utilization and minimized total harmonic distortion (THD). Within the context of fault-tolerant systems, the standard SVPWM algorithm can be significantly enhanced to maintain functionality during component failures by dynamically modifying the switching strategy. These adapted fault-tolerant SVPWM schemes aim to preserve a balanced output voltage even when specific phases or semiconductor switches become unavailable. This is typically achieved by redefining the operational space vector set and meticulously recalibrating the modulation index and dwell times to account for the lost degrees of freedom. Such reconfigurable modulation techniques prove exceptionally effective in multiphase and multilevel converter topologies, where the increased number of switching states provides the necessary flexibility to synthesize the required voltage vectors despite the presence of internal faults [28], [36].

4-4-3 Current Compensation Methods

Current compensation methods represent a critical algorithmic layer in fault-tolerant drives, specifically designed to alleviate the performance degradation caused by phase losses or semiconductor failures. By dynamically adjusting the current references and redistributing the electrical load among the remaining healthy phases, these techniques ensure that the machine continues to produce steady electromagnetic torque. The primary objective is to shift the operational burden away from the faulty component, thereby mitigating mechanical stress and preventing the high-frequency torque ripples that typically follow a phase interruption.

In multiphase architectures, these methods are particularly potent due to the increased degrees of freedom available for control. The inherent redundancy of the stator allows for the injection of specific current components into the functioning phases to compensate for the missing Magnetomotive Force (MMF) of the lost phase. This reconfiguration of the current space vectors ensures that the air-gap magnetic field remains as balanced as possible, even under asymmetrical fault conditions. When integrated with advanced control frameworks such as Model Predictive Control (MPC) or robust observers current compensation strategies can significantly optimize the post-fault efficiency and dynamic stability of the entire propulsion unit, ensuring mission-critical reliability in maritime environments [14], [37]. A typical model predictive control (MPC) strategy for multiphase motor drives is illustrated in Figure 4-3.

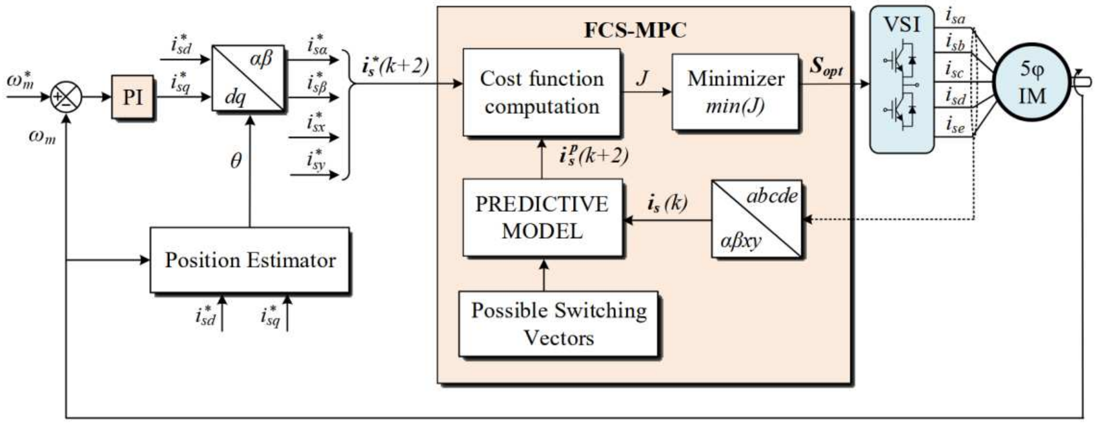

Figure (4-3): Finite control set model predictive control (FCS-MPC) scheme for multiphase motor drives, including prediction model, cost function evaluation, and optimal switching selection [13].

As shown in Figure 4-3, predictive control strategies enable optimal switching decisions, improving system performance and enhancing fault-tolerant operation.

Table (4-4): A comparison of the main fault-tolerant control strategies is presented.

Strategy	**Principle**	**Response Speed**	**Complexity**	**Application**	**Key Advantage**
Reconfiguration	System restructuring	Medium	Medium	Multiphase systems	Maintains operation
SVPWM-based	Modified switching	High	Medium	Converter control	Improved voltage quality
Current compensation	Current redistribution	High	High	Multiphase drives	Maintains torque

As shown in Table 4-4, different control strategies offer trade-offs between complexity, response speed, and performance under fault conditions. These control strategies demonstrate that fault tolerance can be achieved not only through system design but also through advanced real-time control techniques.

4-5 Fault Diagnosis Techniques

Fault diagnosis techniques constitute a pivotal component in the enhancement of reliability and operational safety within electric propulsion architectures. The ability to achieve early detection and precise identification of anomalies is fundamental, as it facilitates the implementation of proactive mitigation strategies that prevent localized malfunctions from escalating into catastrophic system failures.

In the demanding environment of modern marine propulsion, the integration of real-time diagnostics is no longer optional but essential. Given the high degree of system complexity and the mission-critical nature of maritime operations, a diverse array of diagnostic methodologies has emerged, specifically tailored to monitor the health of electric machines, power converters, and the extensive network of sensors that drive the system's control logic. These diagnostic layers serve as the sensory system of the vessel, providing the necessary data to trigger fault-tolerant control actions and ensuring that the propulsion remains available even under adverse conditions [18].

4-5-1 Model-Based Methods

Model-based fault diagnosis methods leverage analytical representations of a system to detect deviations between expected and actual performance. By continuously comparing real-time measured signals against the predictions generated by a high-fidelity mathematical model, it becomes possible to characterize anomalous operational states with high precision. This comparison typically produces a residual signal, which ideally remains near zero during healthy operation and deviates significantly when a component fails or degrades.

In practice, these methodologies often utilize observers, estimators, or state-space models to monitor the internal dynamics of the propulsion system. When the resulting discrepancies between the physical hardware and its mathematical digital twin surpass established deviation thresholds, a fault is officially triggered and isolated. While model-based approaches are highly regarded for their accuracy and their ability to pinpoint the specific root cause of a failure, their performance is intrinsically tied to the fidelity of the underlying system model. Any significant mismatch between the mathematical abstraction and the physical plant often caused by parameter drift or unmodeled environmental dynamics can lead to false alarms or missed detections, necessitating robust parameter estimation to maintain the integrity of the diagnostic layer [11], [12], [35].

4-5-2 Signal-Based Methods

Signal-based fault diagnosis methods involve the direct analysis of measured physical variables such as phase currents, terminal voltages, and mechanical vibrations to identify underlying system anomalies. Unlike model-based approaches, these methodologies do not require an explicit mathematical representation of the propulsion system’s dynamics, which significantly simplifies their implementation within real-time embedded controllers. By focusing exclusively on the observed output data, signal-based techniques can effectively detect a wide range of malfunctions without the necessity for complex parameter estimation or high-fidelity modeling of the motor and converter. A thermal and state-of-health monitoring system based on loss and temperature estimation is illustrated in Figure 4-4.

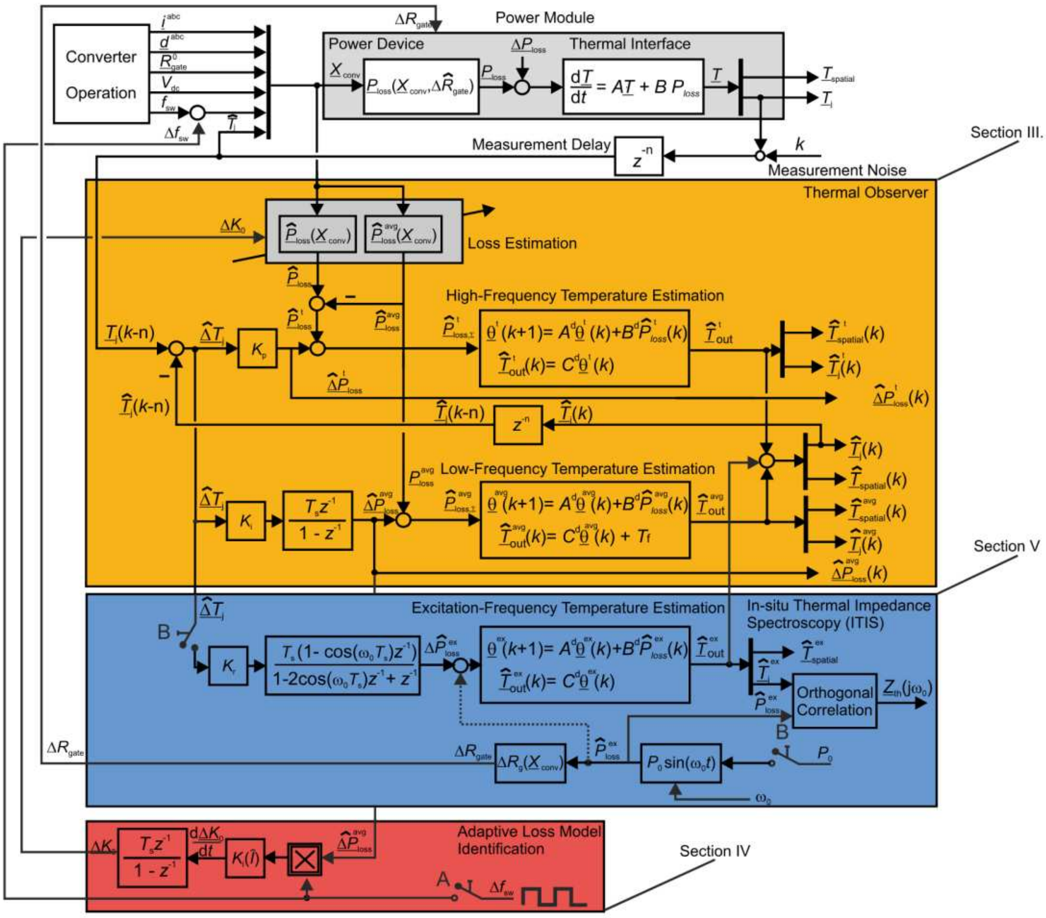

Figure (4-4): Thermal and state-of-health monitoring framework for power electronic systems, including loss estimation, temperature observation, and adaptive model identification [31].

As shown in Figure 4-4, advanced monitoring systems can estimate internal temperature and losses, enabling early fault detection and improved system reliability.

Within this diagnostic framework, common analytical tools include Fast Fourier Transform (FFT) for spectral analysis, wavelet transforms for time-frequency localization, and various statistical signal processing algorithms. These techniques are particularly adept at identifying the unique spectral signatures associated with unbalanced phase currents, increased harmonic distortion, and mechanical eccentricities. By monitoring the deviation of these signal patterns from a known baseline, the diagnostic unit can detect faults such as broken rotor bars or switch failures through the emergence of specific frequency components. However, while these methods offer high computational efficiency and model independence, they are often susceptible to measurement noise and may require adaptive thresholding to remain reliable across the vessel's diverse range of operating speeds and load conditions [38].

4-5-3 AI-Based Approaches

In recent years, artificial intelligence-driven methodologies have emerged as a transformative force in the fault diagnosis of electric propulsion systems. Leveraging robust machine learning architectures including Artificial Neural Networks (ANNs), Support Vector Machines (SVMs), and Deep Learning (DL) models these approaches excel at identifying the subtle, non-linear signatures associated with complex faults. By shifting the diagnostic burden from manual feature engineering to automated pattern recognition, AI-based systems can effectively categorize various failure modes with a high degree of precision that was previously difficult to achieve using purely analytical models.

A primary advantage of these AI-based approaches lies in their ability to ingest and process vast streams of high-dimensional sensor data, uncovering intricate fault patterns that often elude traditional signal-processing or model-based observers. This capability is especially synergistic with modern AES, where the high density of onboard data-logging infrastructure provides the necessary information "fuel" for data-driven diagnostics. By learning from historical performance data, these systems can adapt to the unique operational nuances of a specific vessel, allowing for more nuanced detection of gradual degradation or interdependencies between subsystems.

Despite their predictive power, these techniques are not without significant engineering hurdles. They remain inherently data-intensive, requiring comprehensive training sets that accurately represent both healthy and various faulty states across different operating points. Furthermore, the computational overhead required for real-time inference and the sensitivity to data quality represent critical design constraints. If the training dataset lacks diversity or contains noise, the diagnostic accuracy can diminish rapidly, making the quality of the dataset as important as the architecture of the model itself in safety-critical maritime missions [17].

Table (4-5): A comparison of the main fault diagnosis techniques is presented.

Method	**Principle**	**Accuracy**	**Complexity**	**Data Requirement**	**Key Advantage**	**Limitation**
Model-based	Mathematical model	High	Medium	Low	Accurate detection	Model dependency
Signal-based	Signal analysis	Medium	Low	Medium	Easy implementation	Noise sensitivity
AI-based	Data-driven learning	High	High	High	Detects complex patterns	Requires large datasets

As shown in Table 4.5, AI-based methods provide high accuracy and flexibility, while model-based methods offer strong analytical reliability. As shown in Table 4.5, AI-based methods provide high accuracy and flexibility, while model-based methods offer strong analytical reliability.

4-6 Fault-Tolerant Power Converter Strategies

Power electronic converters represent one of the most critical, yet inherently vulnerable, links within the electric propulsion chain. Their susceptibility to failure is primarily driven by the high density of semiconductor devices and their extreme sensitivity to fluctuating operating conditions, such as high-frequency switching stresses and thermal cycles. Because a single component failure within a converter can propagate and lead to a total loss of propulsion, these units are often the focal point of reliability assessments in maritime engineering. The challenge lies in the fact that these semiconductors must operate in a rigorous environment where voltage transients and load variations are frequent, necessitating a design approach that anticipates and mitigates potential failure modes at the junction level.

To bolster system reliability and guarantee uninterrupted operation during a malfunction, fault-tolerant strategies must be deeply integrated into the converter’s architectural design. This shift toward enhanced resilience is typically achieved through a combination of hardware redundancy, modularity, and reliability-oriented design methodologies. By employing modular topologies such as the MMC or cascaded H-bridge structures the system gains the ability to isolate faulty sub-modules while maintaining the required output voltage. These proactive design approaches ensure that the propulsion system remains mission-capable, transforming a potentially catastrophic semiconductor failure into a manageable, degraded mode of operation that preserves the vessel's safety and maneuverability .

4-6-1 Redundancy in Converters

Redundancy constitutes one of the most effective methodologies for achieving fault tolerance within power converter architectures. By integrating auxiliary components or establishing parallel converter topologies, the system is engineered to sustain operational continuity despite the failure of individual elements. This architectural resilience ensures that a localized malfunction does not lead to a total system shutdown, effectively bridging the gap between a component-level failure and the maintenance of overall system availability. In these configurations, the control logic is often designed to automatically bypass the faulty segment while redistributing the load to the functioning hardware, ensuring that the propulsion chain remains active.

Within the specific context of marine propulsion, redundancy is typically realized through the deployment of parallel-connected converters, redundant switching devices, or dedicated backup power paths. Such configurations allow for a seamless transition to a degraded or full-capacity operating mode in the event of a fault. By distributing the electrical load across multiple redundant channels, the system can isolate faulty semiconductors or modules without compromising the vessel's maneuverability. This multi-path approach is particularly vital for safety-critical missions where the safe return to port capability depends on the hardware's ability to tolerate significant internal stress.

Nevertheless, the integration of redundant hardware is inherently associated with increased system cost, physical weight, and control complexity. These factors represent significant constraints in naval design, where hull space and weight distribution are at a premium. Consequently, a meticulous multi-objective optimization process is required to strike a definitive balance between the desired level of reliability and the overall efficiency of the propulsion system. This ensures that the benefits of fault tolerance are achieved without incurring prohibitive increases in capital expenditure or weight-related performance penalties, leading to a more sustainable and resilient shipboard power network [3].

4-6-2 Modular Converter Structures

Modular converter structures, most notably MMCs, provide a high degree of inherent fault tolerance as a direct consequence of their distributed and decentralized architecture. Unlike traditional two-level converters where a single switch failure can be catastrophic, MMCs distribute the total DC-link voltage across a large number of independent, low-voltage submodules. This granular structure ensures that the failure of a single semiconductor device or a specific power cell does not necessitate a complete system-wide shutdown. Instead, the voltage stress is partitioned, allowing the system to absorb localized failures without compromising the insulation or the operational limits of the remaining healthy components.

In the event of a submodule failure, the control system can activate high-speed bypass mechanisms such as thyristor-based switches or mechanical contactors to effectively isolate the compromised unit from the power string. Following this isolation, the converter can continue to synthesize the required output voltage waveforms using the remaining active submodules. While this "degraded mode" might result in a slightly reduced performance envelope or a marginal increase in total harmonic distortion (THD), the ability to maintain continuous propulsion is a significant advantage. This specific resilience makes modular converters exceptionally suitable for marine propulsion systems, where the capability to "limp home" or maintain station-keeping after a hardware failure is a critical safety requirement.

Beyond the immediate benefits of fault tolerance, the modular nature of these converters introduces significant advantages in terms of maintenance and scalability. Because the system is composed of identical, interchangeable units, repairs can often be performed by replacing specific submodules rather than the entire converter assembly, which reduces the mean time to repair (MTTR). Furthermore, the architecture allows for easy scalability; additional power capacity can be integrated by simply adding more submodules to the existing phases. This flexibility not only simplifies the initial design and installation phase for various vessel classes but also drastically improves the long-term operational availability and lifecycle costs of the shipboard power system [21].

4-6-3 Reliability-Oriented Design

Reliability-oriented design (ROD) constitutes a proactive engineering framework dedicated to enhancing the operational lifespan and physical robustness of power electronic converters. This methodology prioritizes the rigorous selection of high-grade components with superior Mean Time Between Failures (MTBF) ratings, alongside the meticulous optimization of thermal management systems to mitigate localized heating and junction temperature fluctuations. A fundamental pillar of this approach is the application of derating strategies, wherein semiconductor devices are operated significantly below their maximum rated electrical and thermal thresholds. By increasing these design margins, the cumulative stress on power modules is reduced, thereby exponentially lowering the probability of random hardware failures. The main failure mechanisms affecting power semiconductor devices are illustrated in Figure 4-5.

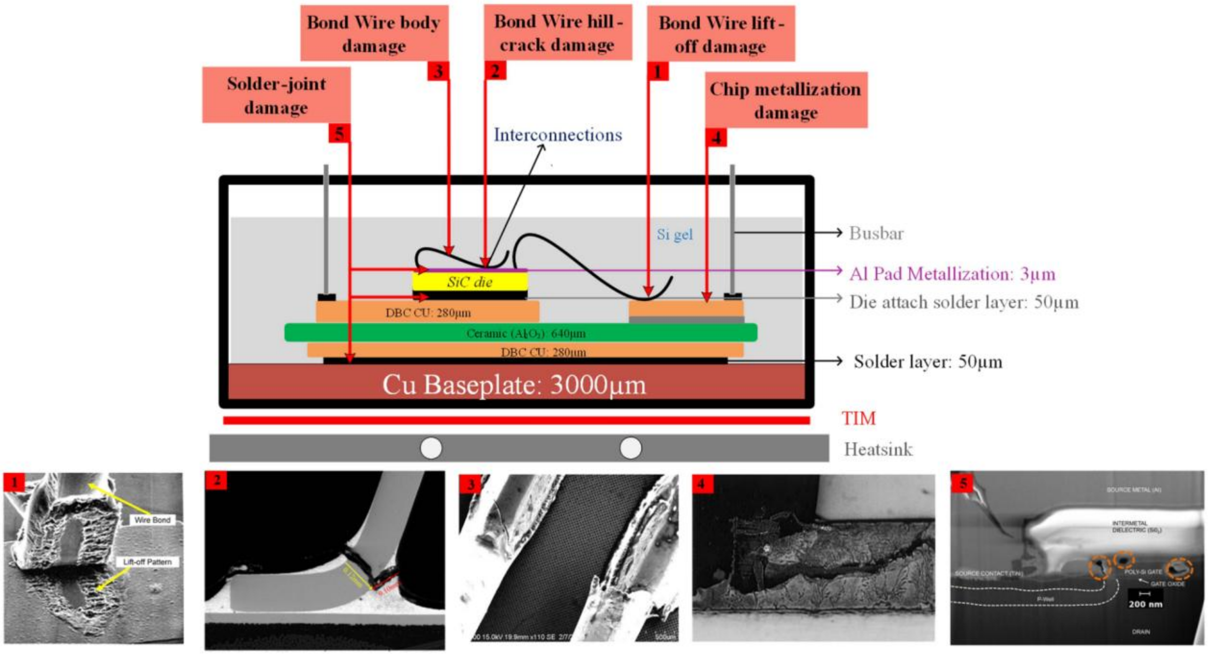

Figure (4-5): Common failure mechanisms in power semiconductor devices, including bond wire lift-off, solder joint degradation, and chip metallization damage under thermal stress [32].

As shown in Figure 4-5, thermal and electrical stresses can lead to multiple degradation mechanisms, significantly impacting the reliability and lifetime of power converters.

Furthermore, the integration of advanced monitoring systems facilitates the continuous acquisition of high-fidelity telemetry, including junction temperatures, DC-link voltages, and transient currents. These diagnostic layers provide the necessary data for predictive maintenance and early-stage prognostic identification, allowing operators to detect incipient degradation such as capacitor aging or solder joint fatigue long before a critical failure occurs. Ultimately, ROD serves as a vital companion to redundancy and modularity; while the latter provide the system with the capacity to survive failures, reliability-oriented design actively minimizes the fundamental likelihood of failure occurrence, ensuring a holistic extension of the propulsion system's total lifecycle and mission availability [12].

Table (4-6): The main fault-tolerant strategies for power converters are summarized.

Strategy	Principle	Reliability Impact	Advantage	Limitation
Redundancy	Parallel components	High	Maintains operation	Increased cost
Modularity	Distributed structure	Very High	Fault isolation	Complex control
Reliability-oriented design	Stress reduction	High	Longer lifetime	Design complexity

As shown in Table 4.6, combining redundancy, modularity, and reliability-oriented design provides a comprehensive approach to improving converter reliability. The combination of fault-tolerant motor design, advanced control strategies, fault diagnosis techniques, and converter-level resilience forms the foundation of reliable electric propulsion systems in modern marine applications.

Chapter 5: Discussion

5-1 Comparative Analysis of Technologies

This section presents a comprehensive comparative evaluation of the core technologies underpinning modern marine electric propulsion architectures. By systematically analyzing diverse motor configurations, power electronic converter topologies, and specialized fault-tolerant strategies, the discussion emphasizes their respective performance metrics, operational reliability, and overall viability for large-scale maritime applications. The objective of this comparison is to highlight the trade-offs between system complexity and resilience, providing a technical basis for selecting the most appropriate configurations that meet the stringent safety and efficiency requirements of contemporary naval engineering.

5-1-1 Motor Technologies Comparison

A diverse array of motor technologies has been integrated into modern marine propulsion architectures, most notably Ims, PMSM, and multiphase machines. Each of these electromechanical conversion systems presents a distinct operational profile, characterized by specific merits and drawbacks regarding efficiency, power density, and resilience. IMs remain a cornerstone of the maritime industry due to their inherent mechanical ruggedness and economic viability; however, they generally exhibit a lower efficiency gradient compared to permanent magnet alternatives. While PMSMs deliver superior power-to-weight ratios and high-performance efficiency making them ideal for specialized naval applications they are often constrained by their dependence on volatile rare-earth material markets and a comparative lack of fault tolerance in standard three-phase configurations.

To address these limitations, multiphase machines have emerged as a pivotal solution for safety-critical maritime propulsion. By expanding the phase count beyond the traditional three-phase limit, these architectures introduce a level of inherent hardware redundancy that allows for continued thrust generation even under significant fault conditions, such as an open-circuit phase. This capability to maintain a symmetrical magnetic field through the redistribution of currents among healthy phases ensures that the vessel remains maneuverable, effectively bridging the gap between a component-level failure and a total system shutdown [8]. Consequently, the transition toward multiphase technology represents a fundamental shift in marine engineering, prioritizing mission availability and the preservation of propulsion integrity over conventional design limits.

Table (5-1): A comparison of the main motor technologies used in marine propulsion systems is presented.

Motor Type	***Efficiency***	***Power Density***	***Reliability***	***Fault Tolerance***	***Cost***	***Key Advantage***
IM	Medium	Medium	High	Low	Low	Robust and simple
PMSM	High	High	Medium	Low	High	High efficiency
Multiphase	High	Medium	High	High	Medium	Fault-tolerant operation

As shown in Table 5.1, multiphase machines provide superior fault tolerance, while PMSMs offer the highest efficiency.

5-1-2 Converter Technologies Comparison

Power converter technologies serve as a fundamental pillar in determining the operational performance and reliability of electric propulsion systems. Conventional converter topologies, such as VSIs and current source CSI, are recognized for their established reliability; however, these designs often reach their physical and technical limits when applied to high-power, megawatt-scale marine environments. Consequently, multilevel converter architectures and MMCs in particular have been widely adopted as the superior alternative for medium-voltage propulsion. The MMC's modular design provides unparalleled scalability, minimizes total harmonic distortion without the need for extensive filtering, and delivers optimized efficiency, solidifying its role as the preferred solution for the power demands of modern large-scale vessels [21].

Table (5-2): A comparison of the main converter technologies is presented.

Converter	***Efficiency***	***Complexity***	***Harmonics***	***Reliability***	***Application***
VSI	High	Low	Medium	Medium	General drives
CSI	Medium	Medium	Low	High	High-power systems
MMC	High	High	Very Low	High	Marine propulsion

As shown in Table 5.2, MMCs provide the best performance in terms of harmonic reduction and scalability.

5-1-3 Fault-Tolerant Approaches Comparison

Achieving high-level operational resilience in electric propulsion systems necessitates a synergistic integration of structural design strategies, sophisticated control techniques, and robust diagnostic methodologies. Each of these pillars contributes distinct advantages to the system's overall reliability, varying in terms of computational complexity, temporal response speed, and corrective effectiveness. By layering these approaches, engineers can move beyond simple fail-safe mechanisms toward a holistic framework that ensures the vessel remains mission-capable even under significant component stress or failure.

Architectural design-based approaches, characterized by the deployment of multiphase machines and hardware redundancy, establish the system's inherent capacity for fault survival. These "passive" measures provide the physical degrees of freedom required to maintain thrust without immediate intervention. Conversely, control-based methods represent an "active" layer of defense, enabling real-time algorithmic adaptation and the dynamic reconfiguration of power flow to compensate for identified anomalies. Supporting these layers are advanced diagnostic techniques, which act as the system's prognostic sensors; by facilitating early fault detection and continuous condition monitoring, these diagnostic tools provide the critical data necessary to trigger timely and effective fault-tolerant control actions before localized malfunctions escalate into system-wide failures.

Table (5-3): A comparison of fault-tolerant approaches is presented.

Approach	***Type***	***Response***	***Complexity***	***Advantage***
Multiphase	*Design*	*Medium*	*High*	*Built-in fault tolerance*
Redundancy	*Design*	*High*	*High*	*High availability*
Reconfiguration	*Control*	*Medium*	*Medium*	*Maintains operation*
AI Diagnosis	*Monitoring*	*Fast*	*High*	*Early detection*

5-2 Critical Discussion

Despite the substantial technological evolution witnessed in the field of electric propulsion, several critical challenges persist, primarily revolving around the inherent trade-offs between performance metrics, system complexity, and overall reliability. Modern engineering solutions often necessitate a delicate balancing act; for instance, high-performance architectures such as those utilizing PMSMs and multilevel converter topologies deliver superior efficiency and power density but simultaneously introduce a higher degree of architectural complexity and elevated capital expenditure. In contrast, simpler, more conventional systems provide a reliable baseline of ruggedness, yet they frequently fail to meet the rigorous performance and efficiency benchmarks required by contemporary large-scale vessels.

Furthermore, while fault-tolerant methodologies significantly bolster the resilience of the propulsion chain, their integration typically entails a substantial increase in hardware overhead, the development of more sophisticated control algorithms, and the allocation of greater computational resources. This creates a fundamental optimization challenge: achieving an equilibrium between peak performance and operational dependability. In maritime propulsion, reliability is prioritized above all other factors, as system failures can lead to mission-critical consequences and jeopardize the safety of the vessel. Consequently, the optimal design of these systems must be grounded in a meticulous evaluation of these trade-offs, ensuring that performance enhancements are never achieved at the expense of the vessel’s fundamental operational integrity.

5-3 Future Trends

The future development of marine electric propulsion systems is strongly driven by the increasing demand for higher efficiency, enhanced reliability, and reduced environmental impact. Emerging technologies such as digitalization, artificial intelligence, and advanced energy systems are expected to significantly reshape the design and operation of next-generation propulsion architectures.

5-3-1 Smart Ships and Digitalization

A defining evolution in contemporary marine engineering is the transition toward smart ship architectures, characterized by the deep integration of digital technologies across all operational strata. Within these sophisticated environments, propulsion units, power electronic converters, and shipboard electrical grids are no longer isolated components but are instead seamlessly embedded within extensive sensing and communication infrastructures. This interconnectedness ensures that every facet of the power chain is subject to continuous, high-fidelity monitoring, transforming the vessel into a data-driven entity capable of unprecedented self-awareness and operational transparency.

The implementation of digitalization facilitates real-time data acquisition and holistic, system-wide monitoring, empowering operators to optimize performance parameters dynamically while identifying incipient anomalies with high precision. Furthermore, the convergence of Internet of Things (IoT) technologies and cloud-based analytical platforms enables a paradigm shift toward remote diagnostics and comprehensive fleet-level performance benchmarking. By leveraging these globalized data streams, maritime organizations can transcend traditional localized maintenance models, utilizing aggregated insights to enhance the reliability of propulsion systems across diverse operating environments and load profiles.

A foundational element of this digital transformation is the digital twin, which serves as a dynamic virtual mirror of the physical propulsion system. By continuously synchronizing this mathematical representation with real-time operational data, it becomes possible to simulate complex system behaviors under varying conditions, enabling the proactive prediction of potential failures before they manifest physically. This prognostic capability allows for the precise optimization of maintenance schedules based on actual component health rather than arbitrary intervals. Ultimately, the adoption of digital twin technology significantly bolsters system reliability and reduces long-term operational expenditures, solidifying its status as a critical asset in the modern quest for resilient and efficient maritime propulsion.

5-3-2 AI-Based Fault Detection

Artificial intelligence is anticipated to exert a transformative influence on the future of maritime propulsion, particularly within the domains of fault diagnosis and prognostic health management. In contrast to traditional model-based or signal-processing methodologies, AI-driven approaches possess the unique capacity to ingest and synthesize vast volumes of multidimensional operational data, facilitating the identification of intricate patterns associated with gradual component degradation and incipient failure. This shift from reactive to proactive monitoring allows for a deeper understanding of system health, moving beyond the limitations of fixed mathematical models to capture the non-linear dynamics inherent in complex marine power networks.

Advanced machine learning algorithms encompassing artificial neural networks and deep learning architectures are particularly adept at discerning subtle behavioral anomalies that often remain undetectable through conventional diagnostic frameworks. This enhanced sensitivity not only permits significantly earlier fault detection but also provides a more precise estimation of the system's remaining useful life (RUL), thereby optimizing the lifecycle management of mission-critical assets. Furthermore, the fusion of AI with established control architectures paves the way for the development of adaptive and self-optimizing propulsion systems. Such autonomous frameworks can dynamically recalibrate their operational parameters in response to real-time telemetry, simultaneously bolstering performance efficiency and structural reliability under varying sea states and load conditions.

However, the widespread deployment of AI-based solutions is accompanied by significant engineering hurdles that must be addressed to ensure maritime safety. These challenges include the prerequisite for extensive, high-fidelity datasets for training, the necessity for substantial onboard computational resources, and the requirement for rigorous validation protocols to guarantee deterministic behavior in critical environments. Ensuring the safe and transparent operation of these "black-box" algorithms remains a primary area of concern, as the consequences of system failure in a maritime context can be catastrophic. Consequently, the future of smart propulsion depends on balancing the predictive power of AI with robust verification and validation strategies to ensure total operational integrity.

5-3-3 Next-Generation Propulsion Systems

The evolution of next-generation marine propulsion is fundamentally anchored in the global paradigm shift toward decarbonization and the adoption of sustainable, low-emission technologies. Future architectures are anticipated to move beyond traditional fossil-fuel reliance, incorporating a synergistic blend of renewable energy harvesting, advanced energy storage systems (ESS), and complex hybrid configurations. This transition represents a transformative step in naval architecture, necessitating a complete reimagining of the shipboard power balance to accommodate diverse energy sources and variable load profiles.

Hybrid propulsion frameworks integrating high-density batteries and fuel cell technologies alongside conventional prime movers provide a versatile solution for enhancing energy efficiency while significantly mitigating the environmental footprint of maritime transport. The efficacy of these hybrid systems is inherently tied to the sophistication of advanced Energy Management Systems (EMS), which utilize intelligent control laws to orchestrate the optimal distribution of power among disparate energy sources. By dynamically balancing load demands with available generation, these systems ensure that the vessel operates at its peak efficiency point, thereby reducing fuel consumption and minimizing operational emissions.

Concurrently, the adoption of fully electric and zero-emission vessels is gaining significant momentum, particularly within the domains of short-range transit and coastal navigation. These architectures rely on a robust technological foundation consisting of high-efficiency power converters, state-of-the-art electromechanical conversion units, and resilient energy storage solutions. For such systems to be viable, the power electronics interface must achieve exceptional power density and minimal losses, ensuring that stored energy is utilized with maximum effectiveness to extend the vessel's operational range and mission capabilities.

For large-scale, high-displacement vessels, escalating power requirements necessitate continued advancements in medium-voltage and high-power drive technologies. This development involves the engineering of more resilient modular converter topologies, the implementation of advanced thermal management strategies to mitigate high heat fluxes, and the realization of inherently fault-tolerant system architectures. Ultimately, the trajectory of marine propulsion will be defined by the seamless convergence of environmental sustainability, pervasive digitalization, and reliability-oriented design, establishing a new standard for resilient and ecologically responsible maritime transport.

Chapter 6:

Conclusions

In conclusion, this research has delivered a holistic analysis of electric propulsion frameworks tailored for maritime environments, prioritizing the critical nexus of reliability and fault-tolerant architecture. By synthesizing the comparative merits of electromechanical conversion units, power electronic topologies, and resilience-based control laws, this work underscores the necessity of an integrated, multidisciplinary engineering paradigm. The findings indicate that the concurrent optimization of performance, efficiency, and reliability is not attainable through a singular technological solution; rather, system design must be navigated as a sophisticated balancing act dictated by the unique operational constraints of the marine sector. In this regard, multiphase machines and MMCs have been identified as fundamental enabling technologies, offering the inherent redundancy and architectural scalability required to meet contemporary maritime safety standards.

Moreover, the investigation demonstrates that fault tolerance is a multi-layered concept that transcends physical hardware design, encompassing advanced control logic and robust diagnostic methodologies. The seamless integration of these layers ensures that propulsion remains viable even under significant failure conditions, a non-negotiable requirement for safety-critical maritime operations where maneuverability is essential for the preservation of life and property. The exploration of future trajectories suggests that the convergence of digitalization and artificial intelligence will catalyze a transformative shift in propulsion intelligence, fostering the development of adaptive, self-healing systems capable of meeting increasing demands for sustainability and operational efficiency. Ultimately, this study concludes that the future of marine electric propulsion is defined by a synergistic merger of advanced engineering, cognitive control, and data-centric technologies, establishing a resilient foundation for the next generation of global maritime transportation.

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