The Next Generation of Marine Power Plants: Converter-Dominated Designs and VSM Integration

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Abstract—The adoption of zero-emission boats utilizing shipboard microgrids has increased significantly in shallow-water applications such as tugboats and ferries. However, deep-water operations—including cargo ships and offshore vessels—continue to rely on multi-fuel combustion engines. As land-based power grids transition towards converter-dominated systems incorporating renewable resources, this evolution presents both opportunities and challenges for marine power systems. This paper explores the potential of converter-dominated power systems to enhance marine power systems in demanding offshore environments characterized by large pulsed loads, limited space, and harsh maritime conditions. Key benefits include seamless blackout recovery, reduced system stress, and improved operability. Furthermore, energy storage systems managing peak consumption can free up valuable space for additional equipment, underscoring the critical role of converter technology in improving the resilience and efficiency of future marine power systems.

Keywords—*Converter-Dominated Power Systems, Grid-Forming Converters, Pulsed Power Load Compensation, Marine Power Systems*

1. Introduction

Marine power systems are characterized by their prevalence of pulsed power loads, resulting in significant load variations within the power plant. These loads commonly originate from propulsion systems, dynamic positioning systems, active heave compensators, and other marine offshore support equipment; essentially, any marine activity interacting with water, waves, or tides generates pulsed power demands.

Offshore installations often function as self-sufficient production or service facilities, generating power through onboard plants that may include diesel generators, gas turbines, or wind turbines. Compared to land-based grids, marine offshore power systems are typically smaller in scale, often providing energy equivalent to the needs of a town with approximately one hundred thousand residents and primarily operating in islanded mode.

The marine and offshore industry has experienced significant expansion in recent years, driven by increasing demand for energy resources and exacerbated by the pandemic and geopolitical events. This growth underscores the need for more reliable and environmentally sustainable power systems. Covering 71% of the planet's surface, seas and oceans host two primary categories of marine applications: shallow-water and deep-water, each presenting unique challenges to power generation requirements. Thrusters in these applications serve dual purposes: providing propulsion speed and maintaining stable positioning through dynamic positioning systems. A vessel's weight directly influences its ability to achieve speed or maintain stability.

While current research focuses on port logistics—with the implementation of shipboard microgrids and HVDC switchboard technologies aimed at achieving zero emissions —these applications represent only a fraction of the potential impact. The broader adoption of such technologies across global marine environments is crucial.

Modern land-based grids are undergoing a transition from synchronous to converter-dominated technologies, fundamentally shaping contemporary power systems and influencing marine power systems as well. This paper investigates how converter-based technologies can enhance the reliability of marine power systems, which are inherently challenged by pulsed power load dominance. Depending on sea conditions, thrusters can consume up to 85% of a plant's capacity, creating highly susceptible systems. These disturbances can be mitigated or eliminated through the strategic application of converter technologies—often without requiring modifications to existing marine power infrastructure. Furthermore, integrating grid-forming and virtual synchronous generator technologies can directly support the main power distribution busbar.

2. Marine Power System Load Distribution

Onboard-installed loads can occasionally exceed the power plant's generation capacity. In such instances, load scheduling is necessary to maintain balance between generation and consumption, particularly when addressing rapid fluctuations in demand caused by pulsed power loads.

To analyze the impact of pulsed power loads, we will compare a drillship's generation capacity with the available downstream system loads.

In Fig. 1, The installed equipment types, MVA values of the onboard load, and their corresponding percentages relative to the power generation capacity can be observed for a seventh-generation ultra-deepwater dual activity drillship. Within this configuration, non-periodic loads exhibiting rapid variation, alongside the thruster system, constitute the pulsed power load share within the distribution system.

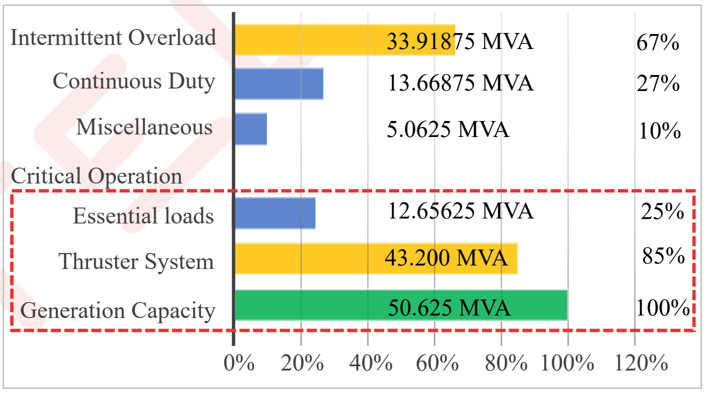

Figure 1. Installed Load Distribution

To illustrate the relationship between installed load and generation capacity, Fig. 2 presents the onboard equipment available for connection to the distribution systems, revealing a total capacity of 214% relative to the power generation capacity. This discrepancy is typically managed through load scheduling during operation, which can create fluctuating load conditions on the power plant. For the purposes of this document, we will focus on the thruster system and essential loads—those connected and operating continuously throughout the process.

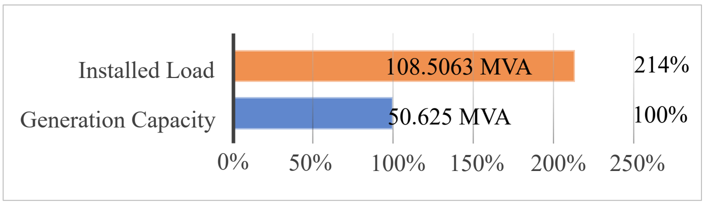

Figure 2. Generation vs Installed Load

2.1. Pulsed Power Loads Predominance

Among pulsed power loads in marine power systems, thrusters are particularly prominent due to their widespread use in maritime applications. Thruster systems typically serve dual purposes of propulsion and dynamic positioning, often representing approximately 70% of the total generation capacity. This substantial consumption relative to the power plant's generation capacity poses a challenge when maintaining dynamic positioning stability in rough sea conditions. For drillships, which primarily operate by drilling at fixed locations, service capacity is directly dependent on the remaining generation capacity after accounting for thruster consumption required for position maintenance. As illustrated in Fig. 1, limiting the generation capacity to that needed to sustain essential loads and thruster systems under high-demand conditions reveals that the load exceeds the available generation capacity. In such scenarios, the ship's chain of command—typically including the captain, chief mate, and dynamic positioning officer—determines acceptable operational tolerances to ensure safety. Consequently, thruster consumption serves as a key indicator for decision-making, providing insight into the power system's operating status and potential risk level based on its percentage of total generation capacity.

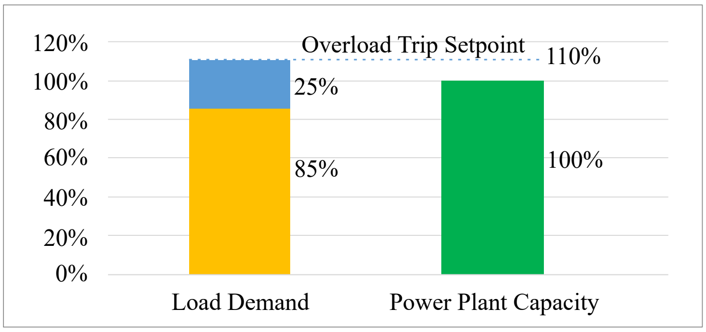

Figure 3. Generation vs Thruster System-Percent

Fig. 3 illustrates how the combined essential load and thruster system demand can exceed generation capacity by 10%, reaching a critical 110% threshold, potentially triggering a generator breaker trip. To prevent this protective action, smart loads—which dynamically adjust their power limit setpoints based on voltage or frequency—have been implemented to ensure continuous power plant operation. However, even with this mitigation strategy, blackouts remain a possibility due to the inherent nature of pulsed power loads. Converter-based technologies offer complementary solutions that can support, compensate for, and mitigate the effects of these pulsed power loads without requiring modifications to the existing marine power system architecture.

3. Integration of Synchronous-Dominated Marine Power Systems

This section provides an overview of the marine power system configuration aboard a drillship.

The schematic in Fig. 4 illustrates an equivalent marine system divided into sections. Drillships are typically segmented into three separate zones—a design feature intended to mitigate the risk of losing the entire power plant due to operational integrity events such as fire, water ingress, or loss of position. Each section is capable of providing full or partial power supply for the vessel's demands.

Table 1. Three Section Equivalent Distribution

Equipment	*Apparent Power (S)*
Generator	8.43 MVA
Equivalent Generator per Section	16.87 MVA
Generation Capacity	50.62 MVA
Thruster	7.2 MVA
Thruster per Section	14.4 MVA
Thruster System	43.03 MVA

Table 1 presents the equivalent generation capacity and load for

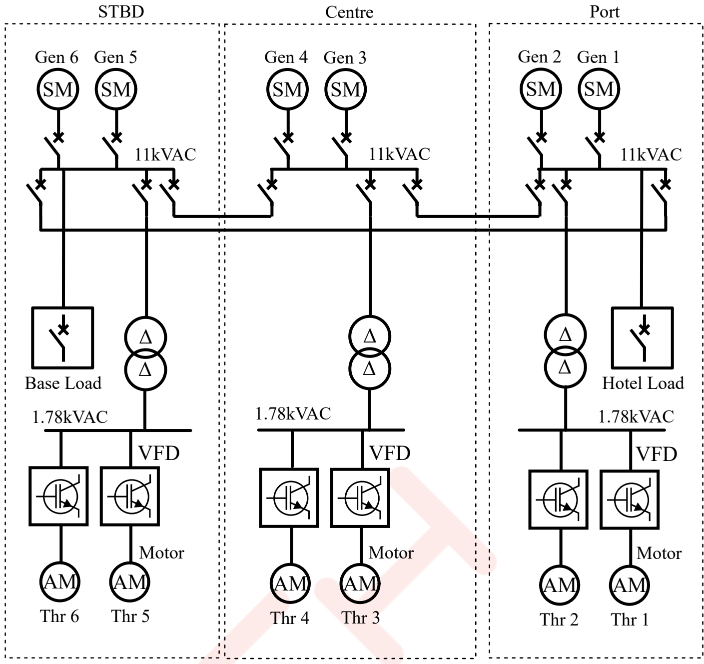

Figure 4. Three-Section Distribution Schematic

each section. In a dynamic positioning system, each thruster generates a thrust vector to counteract movement caused by water flow, wind, and waves—factors that affect the vessel's ability to maintain position. Furthermore, in a propulsion system, the load on a thruster varies depending on the required thrust vector to achieve the speed setpoint dictated by the propulsion system controller.

Table 2. Operational Limits

Setpoint	*Value*
Over-voltage	106%
Under-voltage	80%
Over-current	122%
Over-frequency	105%
Under-frequency	95%
Overload	110%

Table 2 lists the operational limits used to configure the generator protection system in a marine power system. Thrusters are frequently employed as indicators of safe operating status because, due to their pulsed power load characteristics, demand peaks that could trigger the protection system are more likely to occur when thruster consumption approaches 80% of their capacity.

3.1. Synchronous Machines and Rapid Demand Changes

In a marine power system utilizing multiple synchronous machines, frequency is controlled by the governor, while Automatic Voltage Regulators (AVRs) maintain output voltage magnitude. When operating under frequency drooping—a requirement for generator load sharing—the governor plays a crucial role in restoring stability following disturbances, such as those caused by pulsed power loads. Rapid changes can create imbalances between generation and consumption.

Fig. 5 presents a simplified model of a synchronous machine, illustrating how rapid load changes can result in:

- Rapid increase in load can cause drop of frequency.
- Rapid decrease in load can cause a frequency spike.

Generators equipped with governors adjust their output speed to help balance grid frequency; however, the response time and capacity

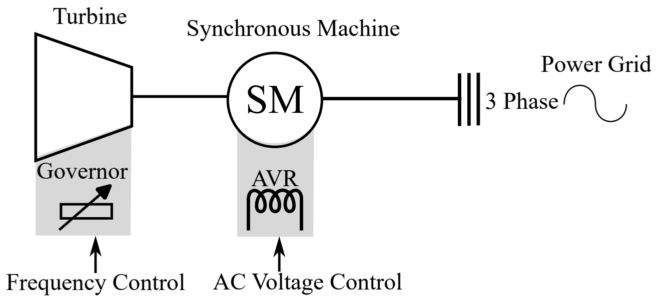

Figure 5. Scheme of the energy conversion for synchronous machine

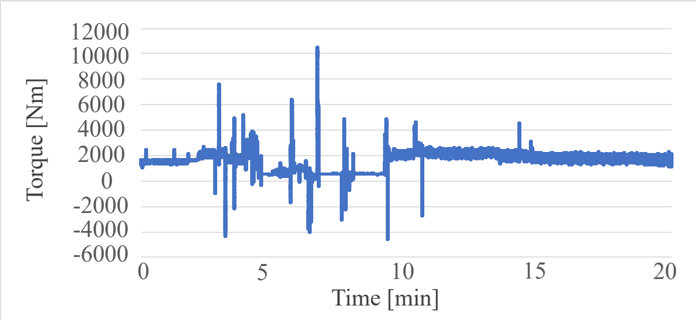

Figure 6. Pulsed Power Load - Motor Torque

of these governors are finite. Large or rapid load variations can exceed the governor's ability to respond effectively.

This limitation on the governor can manifest as frequency drift—an imbalance between generation and consumption. The generator compensates for this difference by drawing upon its kinetic energy, which can be quantified using the following equation: Eq. 1:

$$\text{K.E.} = \frac{1}{2} J \omega_{sm}^2 \times 10^{-6}\ \text{MJ} \tag{1}$$

Where:

- J rotor moment of inertia in $kg - m^2$
- ω_{sm} synchronous speed in rad (mech)/s

A generator's capacity to respond to an imbalance is determined by its critical inertia—the minimum kinetic energy that must be maintained within the generators to ensure frequency stability. This value is calculated when the available inertia response equals the expected energy imbalance resulting from the contingency, as shown in Eq. 2:

$$\text{K.E.}_{con} = \frac{1}{2} J (\omega_0^2 - \omega_{min}^2) \times 10^{-6}\ \text{MJ} \tag{2}$$

Where:

- K.E._{con} the expected energy imbalance due to the contingency
- ω_0 is the initial angular velocity (rotational speed) of the rotor
- ω_{min} is the minimum allowable angular velocity (rotational speed) of the rotor

The prevalence of pulsed power loads and the increasing integration of converter-based technologies in marine power systems present challenges when designing and implementing a power plant with sufficient inertia for typical operational scenarios, particularly given constraints like limited space and harsh maritime conditions.

3.2. Pulsed Power Loads and Converter-based technologies

Converter-based technologies have been integrated into marine power systems for thruster systems, propulsion and dynamic positioning systems, and offshore applications such as active heave compensation. These systems interact with maritime conditions, often resulting in rapid consumption changes—pulsed power loads—during rough sea conditions.

Fig. 6 illustrates the torque variation of a pulsed power load. Generally, high-frequency switching can introduce disturbances that potentially compromise marine power system stability.

Furthermore, Fig. 7 demonstrates that torque variation in continuous loads can also arise from converter-based technology controllers. Aggressive controller settings can introduce disturbances into the islanded system, adding complexity to safely regulating the marine power system.

Fig. 8 illustrates the per unit speed-frequency response of three generators, demonstrating rotor speed variations during large demand transients caused by pulsed power loads and converter-based technologies.

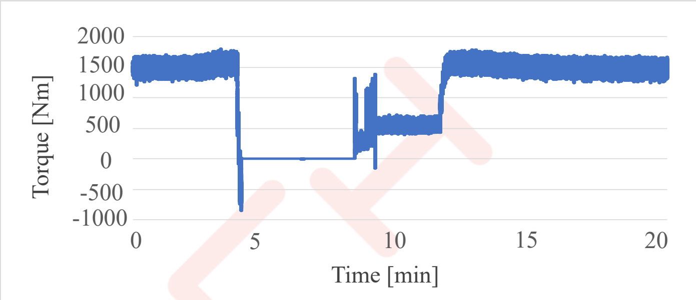

Figure 7. Continuous Load - Motor Torque

4. Converter-Dominated Marine Power Systems

Rapid response pulsed load compensation can be achieved through the implementation of converter-based technologies **i**. These technologies compensate for large transient load disturbances, thereby enhancing power plant reliability by effectively managing kinetic energy Eq. 3.

$$\text{K.E.}_{max} = \text{K.E.}_{con} + \text{K.E.}_{vsm} \tag{3}$$

Where:

- K.E._{max} The total kinetic energy obtained from the system and the compensator.
- K.E._{con} the expected energy imbalance due to the contingency
- K.E._{vsm} The kinetic energy that can be added by the converter-based compensator.

K.E._{vsm} represents the additional energy required to compensate for transient demand peaks. Any solution must meet two conditions: sufficient energy density to provide a large amount of energy, and speed to overcome the generator's mechanical reaction. Alternatively, the approach could focus on enhancing the system's equivalent inertia.

4.1. Converter-Based Solution for a Converter-Based Problem

A Virtual Synchronous Machine (VSM) is a control algorithm designed to enable power electronic converters (PEC), such as inverters, to emulate the behavior of conventional electromechanical synchronous machines. The primary goal of a VSM is to replicate the inertia and damping characteristics of traditional synchronous generators. By mimicking the dynamics of a rotating synchronous generator, VSMs can provide virtual inertia and support the grid during power imbalances, thereby reducing frequency change rates and enhancing overall system stability.

Fig. 9 presents a simplified model of an inverter that converts DC power to AC and connects to the grid. To ensure system robustness, grid-forming capabilities are essential. Grid-forming Virtual Synchronous Generators (VSGs) can operate independently and enhance grid stability by emulating the behavior of traditional synchronous generators; they are particularly valuable in microgrids and systems

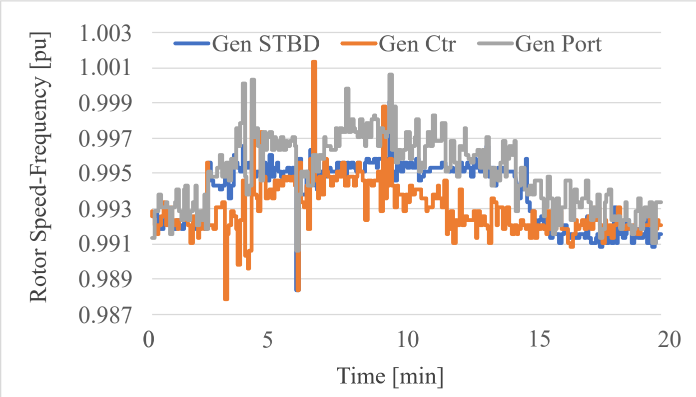

Figure 8. Rotor Generator - Speed Frequency (pu)

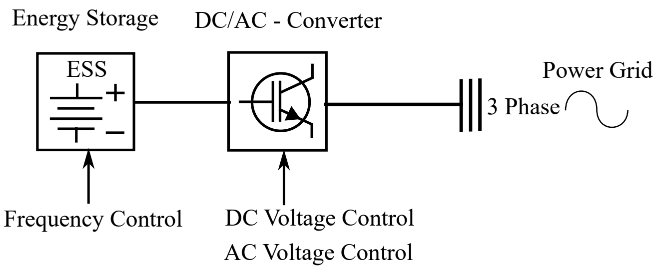

Figure 9. Scheme of the energy conversion for PEC

with a high penetration of renewable energy sources. In marine power systems, VSGs with grid-forming capabilities can serve as reference generators, absorbing much of the transient load during rapid demand changes due to their ability to adjust inertia characteristics.

5. Validation & Inertia Control Performance

The role of inertia in mitigating frequency variations caused by pulsed power loads is critical. This section analyzes two scenarios designed to test the performance of the inertia control loop, based on the synchronous machine rotor response, through simulation.

- Case Study 1 (CS1): Response with default inertia.
- Case Study 2 (CS2): Response integrating VSM inertia.

As a disturbance response test, Fig. 10 illustrates a sequence of pulsed power load disturbances applied to the system. Each disturbance is separated by sufficient time to allow the system to reach a steady state. The disturbances consist of single, double, and triple pulses occurring at times [27, 51, 54, 81, 84, 87] with magnitudes [1.01, 1.01, 1.16, 1.01, 1.16, 1.40].

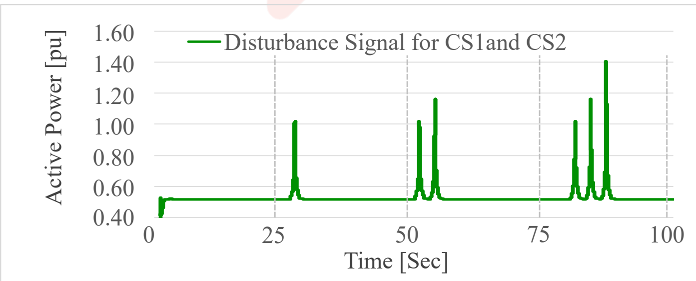

Figure 10. Active Power - Pulsed Power Load Simulation

Fig. 11, shows the frequency responses of the CS1 and the CS2 to the same pulsed load disturbance observed in Fig. 10. The CS1 scenario, using default inertia, exhibits an oscillation characteristic of an underdamped controller as it reaches a steady state—a behavior

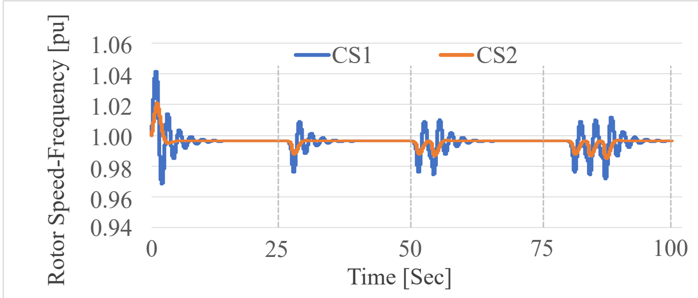

Figure 11. Rotor-Speed Frequency (pu) - Synchronous Machine Response

correlated with the frequency variations shown in Fig. 8. In contrast, the CS2 scenario, which utilizes increased machine inertia through a VSM converter, demonstrates improved settling time and enhanced frequency response performance compared to CS1.

6. Conclusion: Realizing the Potential of VSM Inertia Control for Next-Generation Vessels

This study demonstrates that rapid changes in power demand caused by pulsed power loads in marine power systems can be effectively absorbed or damped using inertia controllers based on VSMs. Our innovative VSM technology offers unparalleled ability to manage both traditional and emerging power demands, directly contributing to significant emissions reductions – a key advantage for environmentally conscious operators.

The implications are profound, particularly for navigation in challenging environments like the Arctic and North Sea, where our solutions provide critical protection against blackout conditions and ensure safer operations.

We see tremendous improvement potential as we adapt our inertia controllers to even more diverse power system configurations. This study lays the groundwork for a new generation of vessel power plant designs – optimized for converter-dominated environments and ready to meet the demands of tomorrow's maritime industry.

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