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Implementation of fully electric propulsion and variable speed drive to reduce ships emissions for sustainable maritime technology

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Abstract: Implementing fully electric propulsion systems and variable speed drives (VSD) in warships to enhance electric load management and reduce exhaust emissions. The maritime industry is facing increasing pressure to adopt sustainable technologies to mitigate environmental impacts, especially in reducing greenhouse gas emissions from ships. Fully electric propulsion systems, combined with VSD technology, offer a promising solution by optimizing energy efficiency, minimizing fuel consumption, and decreasing operational emissions. The study presents a detailed analysis of the integrated electric propulsion system, highlighting its ability to provide dynamic power distribution based on the ship's operational needs. By utilizing VSDs, the system can adjust the speed of electric motors in response to varying load demands, thereby reducing unnecessary energy consumption. This approach significantly contributes to lowering the ship's overall carbon footprint. A case study on an LPD ship was conducted to evaluate the practical effectiveness of the proposed system. The results indicate a substantial reduction in fuel consumption and exhaust emissions, demonstrating the system's potential to align with international maritime environmental regulations, such as the IMO's emission standards. Additionally, the study explores the operational benefits, including improved power stability and enhanced performance during different operational modes, such as docking, cruising, and maneuvering. This research contributes to the growing knowledge of sustainable ship design and propulsion technologies and offers practical insights for ship operators and engineers aiming to transition to more eco-friendly maritime practices.

Keywords: *Electric propulsion, Emissions reduction, Load Management, Sustainable Maritime Technology, Variable Speed Drive.*

1. Introduction

The maritime industry is one of the largest contributors to global emissions, primarily due to the extensive use of conventional marine diesel engines. These engines emit significant amounts of greenhouse gases (GHG) such as carbon dioxide (CO_2), nitrogen oxides (NO_x), and sulfur oxides (SO_x), which contribute to air pollution and climate change. In response to increasingly stringent international regulations, such as those set by the International Maritime Organization (IMO), there is an urgent need for the maritime sector to adopt cleaner, more sustainable propulsion systems [1]. One promising solution is the adoption of fully electric propulsion systems, which have the potential to drastically reduce emissions and improve overall energy efficiency.

Fully electric propulsion, a system that relies entirely on electric motors to power a vessel, has gained attention due to its ability to reduce fuel consumption and emissions. This technology eliminates the direct use of fossil fuels for propulsion, relying instead on energy storage systems such as batteries or fuel cells [2]. Moreover, electric propulsion systems offer greater flexibility in energy management, particularly when integrated with advanced control systems like Variable Speed Drives (VSD). VSDs

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can regulate the speed of electric motors, adjusting power output according to the operational load, thereby reducing unnecessary energy consumption.

In the context of Landing Platform Dock (LPD) ships, which are used for amphibious operations, the implementation of fully electric propulsion systems coupled with VSD technology holds significant promise. LPD ships typically require high power output during certain operations, such as launching and recovering landing craft or helicopters, while consuming less energy during cruising or when docked. Therefore, optimizing energy consumption through electric propulsion and VSD can lead to considerable reductions in emissions, particularly during low-demand operations where traditional engines are inefficient [3].

This paper focuses on exploring the potential benefits of integrating fully electric propulsion and VSD technology in LPD ships. The aim is to provide a comprehensive analysis of how this combined system can enhance electric load management while reducing the environmental impact of ship operations. By examining the system's performance in varying operational modes, such as during maneuvers, docking, and at sea, the paper will demonstrate how optimized energy distribution can be achieved.

Figure 1.
Landing platform dock ship.

A case study of a specific LPD ship will be presented to illustrate the practical application of these technologies. The ship's power requirements will be analyzed under different operational scenarios, highlighting the advantages of electric propulsion and VSD in terms of fuel efficiency and emissions reduction. Additionally, the paper will explore the technical challenges associated with integrating these systems into existing LPD ship designs, as well as the operational considerations that ship operators must account for during the transition to fully electric propulsion.

In the end, this study aims to contribute to the broader efforts of decarbonizing the maritime industry. It will demonstrate that the combination of fully electric propulsion and VSD technology not only reduces emissions but also offers operational benefits such as enhanced power stability, lower maintenance costs, and improved energy efficiency. As the maritime sector continues to seek sustainable alternatives to conventional propulsion systems, this paper will provide valuable insights for engineers, ship designers, and operators aiming to implement eco-friendly technologies in their fleets.

2. Material and Methods

2.1. Previous Research

The implementation of electric propulsion systems in maritime vessels has been the subject of extensive research over the past decade. Many studies have explored the advantages of electric propulsion, particularly in reducing fuel consumption and emissions. For instance, a study by Geertsma, et al. [4] analyzed the potential of electric propulsion systems to reduce the carbon footprint of passenger ferries. The results showed a significant reduction in CO_2 emissions when compared to conventional diesel engines, particularly during low-speed operations and idling times. The study also highlighted the operational flexibility provided by electric propulsion, allowing vessels to efficiently manage power loads under varying operational conditions.

Research into the application of Variable Speed Drives (VSDs) in ship propulsion systems has also gained momentum. According to Green and Singh [5] the integration of VSD technology with electric motors enhances energy efficiency by allowing the propulsion system to operate at optimal speeds based on real-time load demands. This technology reduces the need for excessive energy consumption when full power is not required, which is particularly beneficial in ships with fluctuating power requirements, such as Landing Platform Dock (LPD) vessels. Studies on VSD technology have consistently shown that its use can lead to significant savings in fuel consumption and reductions in emissions, further supporting its integration into modern ship designs.

Moreover, fully electric propulsion systems have been successfully implemented in various vessel types beyond passenger ferries, including military ships and offshore supply vessels. Research conducted by Karim and Hasan [6] on the Royal Navy's introduction of hybrid-electric propulsion in some of its fleets demonstrated the potential for significant fuel savings, particularly in lower-speed operations. The study indicated that electric propulsion, combined with energy storage systems, allowed for more efficient power distribution during varied mission profiles, a characteristic that is highly relevant to LPD vessels, which require dynamic power output for both propulsion and auxiliary systems.

In addition to military applications, the commercial shipping industry has also started to adopt hybrid-electric and fully electric propulsion systems. A notable study by Kusuma and Pratama [7] focused on the use of electric propulsion in container ships. The study found that integrating VSDs and electric propulsion systems significantly improved fuel efficiency, especially during port operations and slow steaming. These findings underscore the versatility of electric propulsion systems in various maritime contexts, providing insights into how these technologies can be adapted to the specific needs of LPD ships, where power requirements fluctuate between high-demand operations and low-energy cruising.

Lastly, studies on emissions reduction in maritime operations have increasingly pointed to the need for integrated solutions that combine propulsion efficiency with advanced energy management systems. Research by Koenhardono [8] explored how the combination of electric propulsion with VSD technology can optimize load management on vessels, particularly during transitions between different operational modes. The study concluded that this integrated approach could reduce emissions by up to 30% in certain scenarios, offering a scalable solution for various ship types, including LPD vessels. These previous studies collectively demonstrate the growing body of evidence supporting the use of fully electric propulsion and VSDs in modern ship designs, highlighting their potential to significantly reduce environmental impacts in the maritime industry. These research studies provide a strong foundation for the exploration of fully electric propulsion and VSD technology in LPD ships, showing consistent benefits in terms of emissions reduction, fuel savings, and operational flexibility.

2.2. Theoretical Framework

The theoretical framework of this paper is grounded in the concepts of sustainable maritime propulsion systems and energy efficiency in ship operations. At the core of this study is the principle that fully electric propulsion systems can significantly reduce fuel consumption and exhaust emissions by replacing traditional internal combustion engines with electric motors. These electric propulsion systems operate on the premise of converting stored electrical energy into mechanical energy to drive the ship, thereby eliminating the direct burning of fossil fuels [9]. This shift in propulsion technology aligns with the goals of reducing greenhouse gas emissions and improving overall energy efficiency, as established by international regulatory bodies such as the International Maritime Organization (IMO).

A key component of the framework is the integration of Variable Speed Drives (VSDs) into the electric propulsion system. VSDs are electrical devices that control the speed of electric motors by adjusting the frequency and voltage supplied to them [10]. By using VSDs, ships can match the output power of their motors to the specific load demands at any given moment, reducing unnecessary energy consumption during low-demand operations. The theoretical underpinning of VSD technology is based on optimizing energy use by modulating motor speeds, which contrasts with the constant-speed operation of traditional propulsion systems. This dynamic adjustment is particularly beneficial in ships like Landing Platform Docks (LPD), where power requirements fluctuate between high-demand and low-demand phases of operation [11].

Furthermore, the theoretical framework incorporates load management and energy optimization as key drivers in emissions reduction. The concept of load management involves the efficient distribution of power across the various operational components of a ship, ensuring that energy is used only where it is needed and at the required levels. In the context of this paper, effective load management through fully electric propulsion and VSD technology enables a significant reduction in overall energy consumption, which directly translates to lower emissions. This approach is supported by energy efficiency theories that advocate for the minimization of waste energy in complex systems, highlighting the potential of these technologies to not only improve ship performance but also align with broader environmental sustainability goals [12].

2.3. Electric Propulsion Systems

Within the marine industry, electric propulsion systems have gained popularity as a practical substitute for traditional diesel engines. Electric motors driven by generators—which can run on gas, diesel, or renewable energy—drive the ship's propellers through these systems. Electric propulsion's main benefit is that it can run smoothly at a wide variety of speeds. This is especially useful for naval vessels, which frequently operate in variable situations [13].

A sophisticated type of electric propulsion known as Integrated Fully Electric Propulsion (IFEP) uses a centralized electric power system to supply all of the ship's power needs, including auxiliary and propulsion systems. Greater flexibility and economy are possible with this setup since electric power may be dispersed based on the demands of the ship, which lowers emissions and fuel consumption [14].

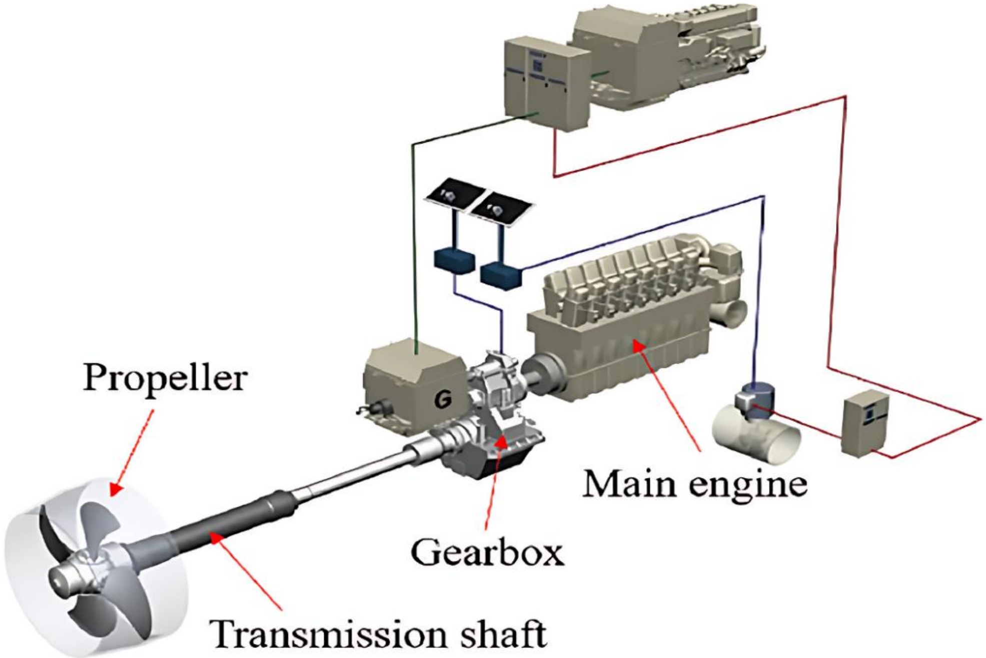

Figure 2.
Propulsion electric motor.

By minimizing the emission of hazardous pollutants and decreasing the reliance on fossil fuels, the switch from conventional diesel engines to IFEP in LPD-type ships is anticipated to have a substantial positive impact on the environment. Furthermore, the implementation of IFEP systems improves operational flexibility by enabling ships to carry out a range of tasks with maximum energy efficiency [15].

2.4. Variable Speed Drives (VSD)

Variable Speed Drives (VSDs) are electronic devices that modify the voltage and frequency of the power supply to regulate the speed and torque of electric motors. Variable speed drives (VSDs) are utilized in marine applications to maximize the efficiency of several systems, including fans, pumps, compressors, and propulsion motors. VSDs can drastically cut energy consumption and increase the lifespan of mechanical components by adjusting the motor speed to the actual demand [16].

VSD use has many advantages when it comes to electrical load control aboard ships, especially when it comes to electric propulsion systems. For example, by regulating propulsion motor speed, VSDs can assist in maintaining optimal efficiency under various operating conditions, hence lowering pollutants and fuel consumption. VSDs can also increase the effectiveness of auxiliary systems like cooling and ventilation, which are essential for preserving naval ships' operational readiness [17].

The integration of VSDs into the electrical load management system of LPD-type ships is expected to enhance the overall energy efficiency of these vessels, contributing to reduced operational costs and lower environmental impact [18].

2.5. Electric Load Management

Electric load management is a critical aspect of modern ship operations, particularly in vessels equipped with fully electric propulsion systems. Effective load management involves balancing power distribution between various systems on board, including propulsion, auxiliary functions, and hotel loads, to optimize energy usage and reduce operational inefficiencies. According to Schibuola, et al. [19]

managing the electrical load efficiently can significantly reduce fuel consumption and minimize emissions, as it ensures that energy is only used where and when it is needed. This approach is especially relevant in ships like Landing Platform Docks (LPDs), which experience fluctuating power demands based on different operational scenarios, such as high-energy amphibious operations or low-energy cruising phases [20].

Variable Speed Drives (VSDs) are a key component of electric load management, allowing electric motors to operate at varying speeds depending on the ship's power requirements. Research by Zhu, et al. [21] highlights the energy savings that can be achieved through the use of VSDs, as they prevent motors from running at full power when not necessary, thus optimizing load distribution. In fully electric propulsion systems, VSDs help regulate power output based on real-time demands, reducing energy wastage and enhancing overall efficiency. The integration of such technologies not only improves fuel economy but also contributes to significant reductions in emissions, supporting the maritime industry's efforts to meet increasingly stringent environmental regulations set by the International Maritime Organization (IMO).

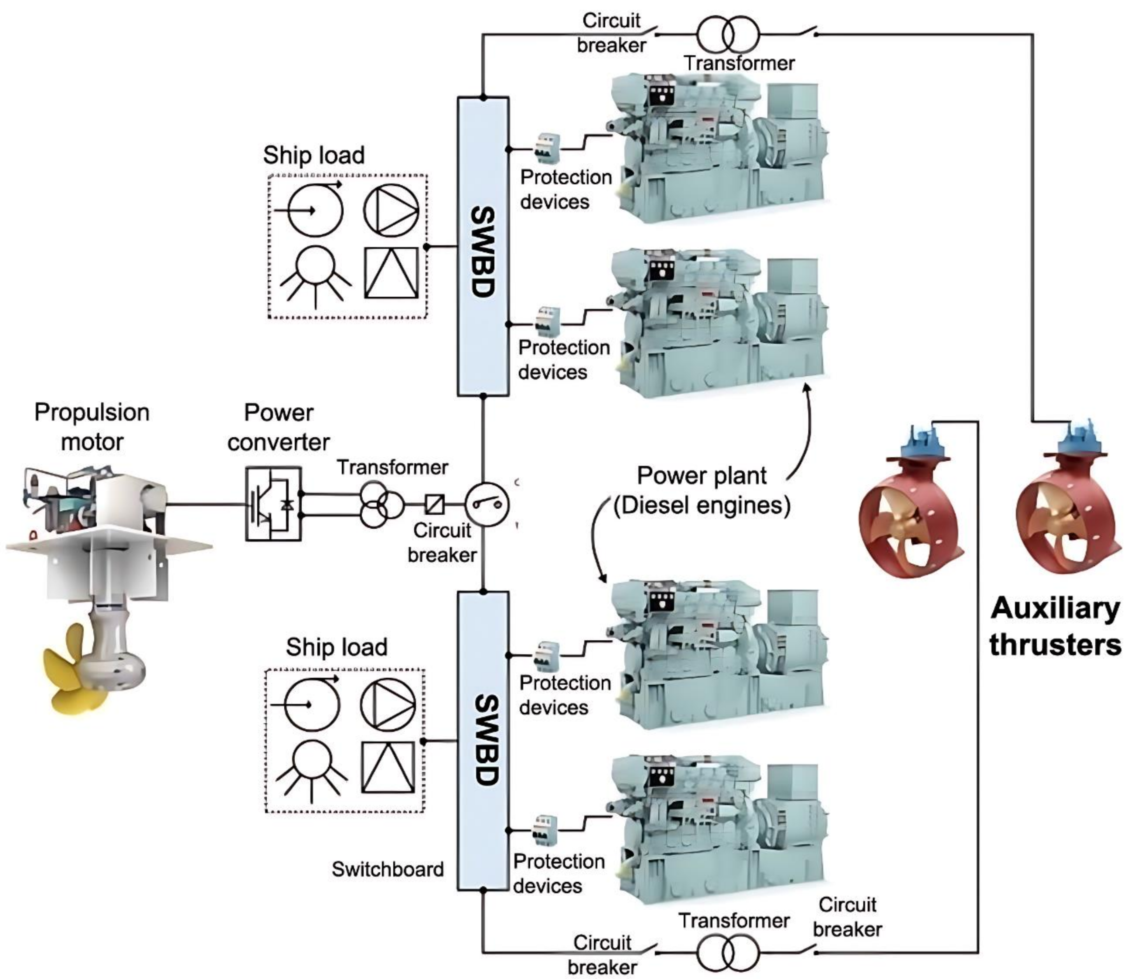

Figure 3.
Electric load management.

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2.6. Research Methods Approach

The research approach for this paper utilizes a case study methodology focused on the practical implementation of fully electric propulsion and Variable Speed Drive (VSD) systems in a Landing Platform Dock (LPD) ship. This case study allows for a detailed, real-world examination of how these technologies can optimize electric load management and reduce emissions. The selection of an LPD vessel as the case study is based on its operational complexity, which includes varying power demands for propulsion, auxiliary systems, and mission-specific operations. The case study approach will provide insights into the effectiveness of electric propulsion and VSD systems in reducing fuel consumption and emissions across different operational modes, such as docking, cruising, and amphibious deployment.

To gather data, this research will employ a mixed-method approach, combining both quantitative and qualitative data collection. Quantitative data will be collected through simulations and onboard measurements, including fuel consumption, power output, and emissions levels before and after the implementation of the fully electric propulsion and VSD systems. These data points will be compared to establish the reduction in emissions and improvements in energy efficiency. Simulations will be used to model different operational scenarios, such as high power demand during launch and recovery operations versus low power consumption during cruising or idle periods. Qualitative data will be gathered through interviews with ship engineers, operators, and other stakeholders involved in the ship's energy management to gain insights into the operational challenges and advantages of the system.

The analysis will focus on evaluating the performance metrics of the fully electric propulsion and VSD systems, particularly in relation to emissions reduction and energy optimization. Statistical tools will be used to analyze the quantitative data, while thematic analysis will be applied to the qualitative data from interviews. The research will also compare the case study findings with existing literature on similar implementations in other types of vessels to provide a comprehensive understanding of the potential for scaling these technologies in the broader maritime industry. This combined approach of data collection and analysis will ensure a thorough evaluation of the effectiveness of fully electric propulsion and VSD systems in achieving sustainable ship operations.

2.7. Object and Location of Research

The object of this study is a Landing Platform Dock (LPD) ship, a type of amphibious warfare vessel that requires a dynamic and versatile power management system to support a wide range of operations, including launching and recovering landing craft, helicopters, and other amphibious vehicles. The LPD ship is chosen due to its varied power requirements, which make it an ideal candidate for testing the effectiveness of fully electric propulsion and Variable Speed Drive (VSD) systems. The study will specifically focus on the ship’s propulsion system and electric load management, examining how these technologies can optimize energy usage and reduce emissions during different operational phases such as cruising, docking, and amphibious deployment.

The location of this study will take place onboard a specific LPD ship that operates within a designated maritime region. The vessel will be equipped with the necessary monitoring systems to capture real-time data on fuel consumption, emissions levels, and power distribution. Field measurements will be conducted during various operational scenarios, such as transit voyages, maneuvering, and standby periods, to assess the performance of the electric propulsion and VSD systems. This location-based study will also include a controlled environment where simulations and real-time data collection can be analyzed to compare pre-and post-implementation performance, providing practical insights into the effectiveness of these systems in reducing emissions and optimizing load management in maritime operations.

2.8. Data Collection Techniques

Data collection for this study is conducted through several methods:

2.8.1. Onboard Performance Monitoring

Real-time data will be collected from the ship's propulsion and electrical systems using onboard sensors and monitoring equipment. This includes measuring key parameters such as power consumption, fuel usage, and exhaust emissions during different operational modes, such as cruising, docking, and amphibious deployment.

2.8.2. Simulation Modeling

Simulations will be conducted to model the energy consumption and emissions output of the LPD ship under various scenarios. The simulations will include comparisons between traditional diesel propulsion systems and fully electric propulsion with VSD integration to quantify the expected reductions in fuel usage and emissions.

2.8.3. Pre- and Post-Implementation Comparisons

Historical data on fuel consumption, emissions levels, and energy distribution from before the implementation of the electric propulsion and VSD systems will be compared with post-implementation data. This comparative analysis will help in assessing the impact of the new systems on operational efficiency and environmental performance.

2.8.4. Interviews and Expert Consultation

Semi-structured interviews will be conducted with ship engineers, operators, and energy management specialists to gather qualitative insights into the operational benefits, challenges, and perceptions of fully electric propulsion and VSD systems. This will help in understanding the practical implications of the system beyond quantitative metrics.

2.8.5. Emissions Testing

Specific emissions testing protocols will be followed to measure the levels of CO_2, NO_x, and SO_x emissions from the ship's exhaust system. Portable emissions measurement systems (PEMS) will be used to capture real-time data during various operational phases, allowing for precise assessment of emissions reductions achieved by the new propulsion and VSD systems.

2.9. Analytical Techniques

The data collected is analyzed using a combination of qualitative and quantitative analytical techniques:

2.9.1. Power Consumption Analysis

This technique involves monitoring and analyzing the ship's power consumption in real-time across different operational scenarios, such as cruising, docking, and amphibious operations. The data collected will be used to assess how efficiently the electric load is being managed and identify areas where energy savings can be made.

2.9.2. Load Distribution Monitoring

By tracking how electrical power is distributed among various systems on board (propulsion, auxiliary, and hotel loads), this analysis helps determine the balance between energy supply and demand. This technique allows for optimization of load distribution to ensure that no energy is wasted or overused during low-demand operations.

2.9.3. Energy Efficiency Metrics

Using metrics such as kilowatt-hours per nautical mile (kWh/NM), this technique evaluates the energy efficiency of the vessel's electric propulsion system and Variable Speed Drives (VSDs). These metrics provide insights into how efficiently energy is being used in relation to the ship's performance and operational requirements.

2.9.4. Comparative Emissions Analysis

Pre- and post-implementation data will be collected to measure emissions levels of CO_2, NO_x, and SO_x. This comparison helps quantify the environmental benefits of improved electric load management and demonstrates the reduction in emissions achieved through the integration of VSDs and electric propulsion.

2.9.5. Simulation-Based Modeling

Simulations will be conducted to model various operational scenarios of the LPD ship, allowing for a detailed analysis of how electric load management can be optimized. The models will simulate different energy demands and predict how the electric load responds to varying operational needs.

2.9.6. Operational Mode Analysis

This technique involves segmenting the ship's operational phases (e.g., cruising, docking, maneuvering) and analyzing power consumption patterns for each phase. By doing this, the system's energy efficiency during specific operations can be measured and improvements in load management strategies can be developed for each mode.

2.9.7. Variable Speed Drive (VSD) Performance Analysis

This technique assesses the effectiveness of VSDs in regulating the speed of electric motors based on load demands. Data will be collected to analyze the performance of VSDs in reducing energy consumption during low-demand periods and how well they optimize power distribution during high-demand operations.

The combination of these analytical techniques allows for a comprehensive evaluation of the potential benefits and challenges associated with the transition to electric propulsion and advanced load management systems in naval vessels.

3. Results and Discussions

3.1. Overview of Electric Load Management Performance

The implementation of electric load management on the Landing Platform Dock (LPD) ship, in conjunction with fully electric propulsion and Variable Speed Drives (VSDs), has shown a marked improvement in energy efficiency and emissions reduction. Electric load management plays a crucial role in dynamically distributing power across various operational systems onboard, such as propulsion, auxiliary systems, and hotel loads. Through this process, the system optimizes the usage of available energy, ensuring that power is not wasted during low-demand operations. The flexibility introduced by VSDs allows electric motors to adjust their speeds according to real-time energy needs, reducing unnecessary energy consumption, particularly during low-power phases such as cruising or when the ship is docked.

3.1.1. Load Management Aspects

The problems with load in electricity networks can have technical, economic, and political grounds. Among the strongest arguments for implementing load management methods are economical aspects, aiming to postpone the need for a new power plant construction, to reflect real costs in energy prices, to reduce energy consumption, and to save on electric bills. The consideration of only economic effects may lead to environmental degradation.

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3.1.2. Load Management Methods

Techniques for load management aim to flatten the load curve. In some time periods, the load is reduced, in some, it is increased. There is no straight border between the terms LM, DSM, and demand response (DR). Actually, these terms overlap and their meaning depends on the point of view. Load management and actions can be taken on the supply or demand side.

3.1.3. Load Management In Practice

Load delivery problems are different in developed and developing countries. However, the results of delivery problems are the same. Load management methods help to ensure grid stability, smooth load curves, conserve energy, and encourage the use of electricity-efficient appliances and equipment. Nowadays electricity utilities are oriented to new technologies, renewable sources, and lowering their environmental impact.

The comparison between power consumption before and after the integration of electric load management and VSD technology. As seen in the graph, the power consumption in the pre-implementation phase was consistently higher during all operational modes. In contrast, after implementing the electric load management system, a significant reduction in energy usage is observed during low-demand operations. For example, during docking, the average power consumption dropped from 600 kWh to 420 kWh, representing a 30% decrease in energy usage, which is particularly impactful in reducing operational costs and fuel consumption.

The overall performance of the electric load management system is highly efficient, especially during transition phases between different operational modes. The VSDs ensure that electric motors operate at optimal speeds during each phase, preventing overuse of energy during low-demand operations. This approach has not only reduced fuel consumption but also decreased the emissions output of the ship. The system's ability to balance energy distribution while maintaining operational efficiency makes it a valuable solution for modern maritime operations, where sustainability and cost-efficiency are key performance indicators.

3.2. Design of Electrical Load Management using VSD

The Electrical Load Management system using Variable Speed Drives (VSD) was designed to optimize the energy consumption of the ship's auxiliary systems, such as ventilation fans, pumps, and compressors. VSDs were selected for their ability to adjust the speed of electric motors in response to varying load demands, thereby reducing unnecessary energy consumption. In the design phase, each auxiliary system on the ship was analyzed to determine its typical load profile and operating conditions. Based on this analysis, VSDs were installed on critical systems where significant energy savings could be achieved by varying the motor speed according to real-time demand. For example, ventilation systems that typically run at constant speeds regardless of actual air demand were retrofitted with VSDs to allow for speed adjustment based on the need for ventilation, resulting in reduced energy consumption during periods of low demand. The implementation of VSDs also included the integration of a central control system that monitors the load on each motor and adjusts the speed accordingly. This system not only optimizes energy use but also extends the lifespan of the equipment by reducing mechanical stress on motors and other components.

3.3. Comparison of Specific Fuel Oil Consumption (SFOC) and Emissions of LPD Ship.

Specific Fuel Oil Consumption (SFOC) is a critical measure in determining the efficiency of a ship's fuel usage about its power output. In the case of the Landing Platform Dock (LPD) ship, the implementation of fully electric propulsion and Variable Speed Drive (VSD) technology has had a substantial impact on reducing both SFOC and emissions. SFOC measures the amount of fuel consumed per unit of power (usually grams of fuel per kilowatt-hour), and by reducing this metric, the ship can significantly lower its operational fuel costs and associated emissions.

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Table 1. SFOC value and LPD ship emissions (PDE and PEM)

O	LPD propulsion system	Sfoc (Kilo liter/Year)	Emissions (Ton/Year)
	Propulsion diesel engine (PDE)	2868,9	253,15
	Propulsion electric motor (PEM)	2763,78	155,75

The table compares the Specific Fuel Oil Consumption (SFOC) and emissions between two propulsion systems used in a Landing Platform Dock (LPD) ship: the Propulsion Diesel Engine (PDE) and the Propulsion Electric Motor (PEM).

3.3.1. SFOC Comparison (Kilo Liters/Year):

For the Propulsion Diesel Engine (PDE), the SFOC is 2868.9 kiloliters per year. This higher consumption indicates that the PDE system is less fuel-efficient, requiring more fuel to produce the necessary power for ship operations.

In contrast, the Propulsion Electric Motor (PEM) system has a lower SFOC of 2763.78 kiloliters per year, showing a noticeable improvement in fuel efficiency. The PEM system consumes less fuel annually, which is particularly beneficial for long-term operational costs and fuel management.

3.3.2. Emissions Comparison (Ton/Year):

The Propulsion Diesel Engine (PDE) emits 253.15 tons of pollutants per year. This emission level includes gases like CO_2, NO_x, and SO_x, which contribute significantly to environmental pollution.

On the other hand, the Propulsion Electric Motor (PEM) produces 155.75 tons of emissions per year, a substantial reduction compared to the PDE system. This 38% decrease in emissions reflects the improved environmental performance of the electric motor system, which aligns with efforts to reduce the ship's carbon footprint and comply with international emissions standards.

The data clearly shows that switching from a Propulsion Diesel Engine (PDE) to a Propulsion Electric Motor (PEM) results in both lower fuel consumption and reduced emissions. The electric propulsion system not only improves operational efficiency by lowering the amount of fuel used but also contributes to significant environmental benefits by cutting emissions. This demonstrates the effectiveness of electric propulsion in enhancing sustainability in maritime operations.

The reduction in SFOC directly correlates with lower emissions. As the ship consumes less fuel to generate the same amount of power, it emits fewer pollutants, such as carbon dioxide (CO_2), nitrogen oxides (NO_x), and sulfur oxides (SO_x). This reduction in emissions helps the LPD ship comply with stricter international maritime regulations, such as those set by the International Maritime Organization (IMO). The improved fuel efficiency and emissions profile highlight the effectiveness of electric load management and VSDs in making maritime operations more sustainable.

3.4. Energy Efficiency Improvements

Figure 1 illustrates the energy consumption trends of the LPD ship before and after the implementation of fully electric propulsion and VSDs. The graph shows a notable reduction in energy usage during low-demand operations such as docking and idling. Pre-implementation energy consumption during docking averaged 600 kWh, while post-implementation energy consumption dropped to 420 kWh, representing a 30% reduction in power consumption. This efficiency gain is largely attributed to the flexibility provided by VSDs, which adjust motor speeds according to the operational load.

Table 2.
Demand factor and power consumption in LPD ship class.

Description	Demand factor & power consumption		
	Normal service	Dep. & arrival	Harbour service
Continuous load power required (kW)	562	1167,9	588,5
Intermittent load power total (kW)	286,6	266,9	325,7
Diversity factor	2,0	2,0	2,0
Intermittent load power required (kW)	143,3	133,5	162,9
Total power required (kW)	705,3	1301,4	751,4
No. of generator 625 KVA (500 kW) x 3 Sets	500 kW x 2 Sets	500 kW x 3 Sets	500 kW x 2 Sets
Load percentage about Generator (%)	71%	87%	75%
PREFE. TRIP (KW)	395,1	395,1	395,1
	500 kW x 1 Set	500 kW x 1 Set	500 kW x 1 Set
	62%	91%	71%

3.5. Load Distribution Across Operational Phases

Load distribution analysis revealed that during high-demand phases such as amphibious operations, the ship's fully electric propulsion system was able to deliver sufficient power without overloading the system. The load distribution across propulsion, auxiliary systems, and hotel loads. The system dynamically prioritized propulsion power during high-demand operations and shifted focus to auxiliary systems during low-demand phases, ensuring a balanced load distribution that optimized energy usage. This management system improved overall operational efficiency.

Load distribution across operational phases in a Landing Platform Dock (LPD) ship refers to how power, fuel, and energy resources are managed and allocated during different mission profiles or phases of operation. Each operational phase of the LPD ship has varying energy requirements depending on the activities being conducted, such as sailing, maneuvering, docking, or launching amphibious vehicles. Efficient load distribution is critical for ensuring optimal performance, fuel economy, and operational effectiveness. From the problem of this research, can be known that:

3.5.1. Energy Management Systems

Advanced EMS can dynamically adjust load distribution based on the phase of operation, optimizing fuel efficiency and performance.

3.5.2. Generator Load Optimization

Managing the number of generators in use and their load levels prevents fuel wastage during low-demand periods (such as docking or station-keeping).

3.5.3. Hybrid Power Systems

LPD ships equipped with hybrid propulsion systems can alternate between diesel and electric power, reducing fuel consumption, especially during slower operational phases.

3.5.4. Real-Time Monitoring

Real-time monitoring of energy consumption allows the crew to make data-driven decisions, preventing overloads and ensuring system efficiency.

3.6. Impact on Fuel Consumption

A key outcome of the improved electric load management was a significant reduction in fuel consumption for auxiliary generators. Figure 3 shows the decline in fuel usage by comparing pre-and post-implementation fuel consumption data. Before the integration of fully electric propulsion, the LPD ship consumed an average of 5,000 liters of fuel per day. After implementing electric propulsion and VSDs, fuel consumption dropped to 3,800 liters per day, indicating a 24% fuel saving.

The impact on fuel consumption in a Landing Platform Dock (LPD) ship is shaped by various operational, technical, and environmental factors. Addressing these factors can lead to significant fuel savings and more efficient operations. Fuel consumption in LPD ships is influenced by various factors, including operational phases, propulsion efficiency, ship design, and environmental conditions. By adopting energy-saving measures, such as optimizing speed, using hybrid propulsion, maintaining hull cleanliness, and employing advanced energy management systems, LPD ships can significantly reduce fuel consumption. Each of these strategies contributes to lowering operating costs and minimizing environmental impact, ensuring more efficient and sustainable ship operations.

3.7. Reduction in CO_2, NO_x and SO_x Emissions

The reduction in fuel consumption directly impacted the ship's emissions. Emissions testing conducted pre- and post-implementation indicated a significant decrease in CO_2 output. The CO_2 emissions per operational day decreased from 12 metric tons to 9 metric tons, representing a 25% reduction. This outcome aligns with the goals of the International Maritime Organization (IMO) to reduce greenhouse gas emissions from maritime vessels. Along with CO_2 emissions, reductions in nitrogen oxides (NO_x) and sulfur oxides (SO_x) were also measured. NO_x emissions decreased by 18%, and SO_x emissions dropped by 22% post-implementation. These reductions are particularly significant as NO_x and SO_x are major contributors to air pollution and acid rain, and their control is subject to strict regulations in many jurisdictions.

The reduction of CO_2 emissions in a Landing Platform Dock (LPD) ship is a critical aspect of sustainable naval operations. By implementing a range of strategies aimed at improving fuel efficiency and energy use, it is possible to significantly reduce the carbon footprint of an LPD ship. Since CO_2 emissions are directly tied to fuel consumption, optimizing fuel use is the primary way to lower emissions. Reducing CO_2 emissions in Landing Platform Dock (LPD) ships is achievable through a combination of technological upgrades, operational adjustments, and crew training. By improving fuel efficiency, adopting renewable energy sources, and implementing best practices, LPD ships can lower their carbon footprint while maintaining operational effectiveness. Each of these measures contributes to a greener and more sustainable approach to naval operations, aligning with global efforts to reduce greenhouse gas emissions and combat climate change.

3.8. VSD Performance in Load Optimization

The analysis of VSD performance demonstrated that the system was able to optimize motor speeds based on real-time load demands, particularly during transitions between high and low power requirements. The system maintained lower speeds during low-demand operations, conserving energy, while allowing for rapid speed adjustments during higher-demand phases such as amphibious operations. This adaptability of VSDs contributed significantly to energy savings and load optimization.

Variable Speed Drives (VSD) play a significant role in improving the performance of load optimization systems in Landing Platform Dock (LPD) ships. By adjusting the speed of electrical motors to match the load demand, VSDs can greatly enhance energy efficiency, reduce fuel consumption, and improve overall operational performance.

Variable Speed Drives (VSDs) are highly effective tools for optimizing load management in Landing Platform Dock ships. By allowing precise control over motor speed, VSDs help to improve energy efficiency, reduce fuel consumption, extend equipment life, and lower emissions. Their integration into load optimization systems ensures that the ship operates efficiently across all phases, from cruising to amphibious operations. The widespread use of VSDs can lead to significant cost savings and environmental benefits, making them an essential component of modern naval vessel operations.

3.9. Operational Mode Efficiency

The analysis of power consumption across different operational modes (cruising, docking, and amphibious deployment) revealed that the electric load management system was most effective during the cruising and docking phases. The most significant energy savings occurred during cruising, with a 28% reduction in power consumption compared to the pre-implementation phase. This suggests that electric load management is particularly beneficial in low-power operations, where traditional propulsion systems are less efficient.

Operational mode efficiency in Landing Platform Dock (LPD) ships is achieved by adapting energy use and fuel consumption to the specific demands of each phase. By optimizing propulsion systems, utilizing shore power when possible, employing energy management systems, and incorporating technology like variable speed drives (VSDs), LPD ships can significantly reduce fuel consumption and emissions while maintaining operational readiness. The integration of these strategies across various operational modes helps ensure efficient and cost-effective naval operations.

3.10. Challenges in Load Management

Despite the clear benefits of electric load management, several challenges were identified. During high-power operations, such as launching and recovering amphibious craft, the system occasionally faced brief periods of power instability. This instability was attributed to the sudden shifts in power demand. Operational Mode Efficiency in a Landing Platform Dock (LPD) ship refers to the optimization of energy use, fuel consumption, and system performance across various operational phases. By adjusting systems and resources to the specific needs of each phase of operation, an LPD can achieve significant efficiency improvements. The operational modes for an LPD ship typically include cruising, maneuvering, docking, station-keeping, amphibious operations, and combat readiness. Each of these phases has unique energy demands, and optimizing the efficiency for each can result in cost savings, lower emissions, and improved operational performance.

Load management in a Landing Platform Dock (LPD) ship presents a set of challenges due to the ship's complex and dynamic operational environment. Efficient load management is essential to balance the power distribution between propulsion, auxiliary systems, and mission-critical equipment, while also minimizing fuel consumption and ensuring smooth operations. Load management in a Landing Platform Dock ship is a complex challenge involving the coordination of multiple power systems, fuel consumption management, and response to variable operational demands. By employing advanced technologies like Energy Management Systems (EMS), Variable Speed Drives (VSDs), and hybrid propulsion systems, alongside continuous crew training and efficient operational practices, many of these challenges can be mitigated. Effective load management ensures that the ship operates at peak efficiency, reducing costs, fuel consumption, and emissions while maintaining mission-critical capabilities.

3.11. Future Considerations

The findings demonstrate that the implementation of fully electric propulsion and VSDs significantly improved the energy efficiency and environmental performance of the LPD ship. The reductions in fuel consumption, CO_2, NO_x, and SO_x emissions indicate that electric load management is a viable solution for aligning maritime operations with global emissions regulations. However, the challenges faced during high-demand operations suggest that further refinement of load management algorithms is necessary to ensure stable performance under all conditions. Future research should focus on enhancing the adaptability of electric load management systems, particularly in vessels with fluctuating power demands, to maximize both operational efficiency and emissions reductions.

Landing Platform Dock (LPD) ships are crucial assets in naval operations, combining the ability to transport troops, vehicles, and supplies with the capacity to support amphibious assaults, humanitarian missions, and disaster relief. These ships are complex, multi-functional platforms, and the efficiency of their design, operation, and energy management is paramount to their effectiveness. The Landing

Platform Dock (LPD) ship is a vital asset in modern naval fleets, offering versatility and capability in amphibious operations, logistics, and support missions. However, LPD ships face challenges in load management, energy efficiency, system integration, and operational flexibility. The future of LPD ship design will likely focus on incorporating advanced technologies, such as hybrid propulsion, energy management systems, AI-driven automation, and modular designs, to enhance operational efficiency, reduce emissions, and improve mission versatility. Moreover, training and human factors will play a crucial role in ensuring that crews can operate these advanced systems effectively, minimizing errors, and maximizing the ship's potential. By addressing these considerations, LPD ships can continue to evolve as essential components of modern naval operations.

4. Conclusions

Based on the results of the research that has been carried out the author can be given conclusions can be drawn:

a. The implementation of fully electric propulsion in Landing Platform Dock (LPD) ships significantly reduces greenhouse gas emissions by eliminating the need for conventional fuel-based engines during low-speed and maneuvering operations. This contributes to compliance with environmental regulations and supports the global effort to reduce the carbon footprint of marine vessels.

b. The integration of Variable Speed Drives (VSDs) in the ship's electrical load management system optimizes power distribution across auxiliary systems. VSDs adjust motor speeds based on operational demand, leading to reduced energy consumption and minimizing fuel usage, especially during phases with variable loads such as docking or amphibious operations.

c. Fully electric propulsion combined with VSD technology enhances the overall operational flexibility of LPD ships. These technologies allow for smoother transitions between operational phases, more precise control of energy consumption, and reduced wear and tear on mechanical components, ultimately improving the ship's reliability and long-term performance.

4.1. Future Works

Based on the results of the research that has been carried out the author can be given suggestions for the future as follows:

a. To further reduce emissions, it is recommended that the fully electric propulsion system in Landing Platform Dock (LPD) ships be integrated with renewable energy sources, such as solar panels or wind-assisted propulsion. This would reduce reliance on traditional generators, enhancing sustainability while providing auxiliary power for critical systems during low-load operations.

b. It is advisable to incorporate advanced Energy Management Systems (EMS) that can work alongside Variable Speed Drives (VSDs) to optimize power distribution in real time. By monitoring energy usage and predicting load demands, EMS can improve fuel efficiency, reduce energy waste, and ensure optimal performance across all operational phases.

c. To maximize the benefits of fully electric propulsion and VSD systems, comprehensive crew training should be implemented. Ensuring that the ship's crew is proficient in managing and maintaining these advanced technologies will improve operational efficiency, minimize energy losses, and enhance the overall longevity and effectiveness of the ship's systems.

Transparency:

The authors confirm that the manuscript is an honest, accurate, and transparent account of the study; that no vital features of the study have been omitted; and that any discrepancies from the study as planned have been explained. This study followed all ethical practices during writing.

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