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RESEARCH ARTICLE

Design and Energy Efficiency Analysis of a Shaft Generator for Military Ships

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ABSTRACT

The rise in energy costs and growing environmental concerns are driving investments in energy-saving technologies, particularly in the maritime industry, including fishing, marine operations, and shipbuilding. Shaft generators are highly favored for their ease of installation, cost-effectiveness, reliability, and low maintenance costs as an energy production system of choice. These systems are well-suited to meet the energy demands of military vessels. As current energy costs and environmental pressures continue to escalate, shaft generators are recognized as pivotal technologies supporting energy conservation efforts. This study provides a comprehensive comparative analysis of the design and energy efficiency of two different shaft generator models employed on military ships. Using ANYSYS/Maxwell for design and analysis, the study evaluates power, torque, and efficiency across both models. The results emphasize that the efficiency of a shaft generator depends mainly on two factors: the number of motor poles and the operating frequency of the system. Moreover, the efficiency tends to decrease as the number of motor poles increases, but it improves as the system frequency rises.

Index Terms—ANYSYS/Maxwell, design, energy efficiency, military ships, shaft generator

I. INTRODUCTION

The shaft generator, in operation, meets all the requirements of a ship's mains, without limitations. It is important in starting and shutting down large consumers without voltage and frequency fluctuations with the generation of the necessary active and reactive power. In the design phase, specific considerations are considered to meet the unique requirements of military vessels. This includes selecting robust and rugged components capable of withstanding harsh environments, such as generators, prime movers, and power conversion equipment.

Optimization techniques are employed to maximize the performance and efficiency of the shaft generator system. This involves fine-tuning control algorithms, optimizing power distribution, and minimizing losses in the system. By optimizing the shaft generator operation, fuel consumption can be reduced, extending the ship's operational range and enhancing mission capabilities. Furthermore, optimized power distribution ensures that power is efficiently allocated to various onboard systems, minimizing waste and maximizing energy utilization.

Energy efficiency analysis is crucial for military ships to optimize fuel consumption and increase overall operational efficiency. By analyzing power consumption patterns and identifying areas of high energy usage, energy-saving measures can be implemented. This may include load management, power demand forecasting, and integrating energy storage systems. Energy efficiency analysis also helps identify opportunities for incorporating renewable energy sources, such as solar or wind power, to reduce reliance on traditional fuel sources and enhance sustainability.

The design, optimization, and energy efficiency analysis of a shaft generator for military ships ensures reliable and efficient power supply for critical operations. These efforts enhance operational capabilities, extend mission endurance, and reduce environmental impact by minimizing fuel consumption and maximizing energy utilization.

II. LITERATURE REVIEW

Solla et al. [1] introduce a method for improving energy efficiency and saving in a shaft generator that can operate at various speeds across a wide range of engine revolutions per minute (rpm). The

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proposed design consists of a rectifier that receives the variable voltage and frequency three-phase Alternative Current (AC) from the shaft generator and converts it into Direct Current (DC). Then, an inverter is employed to convert this DC power back into three-phase AC, maintaining a constant voltage and frequency.

Schoyen and Sow [2] research the possibility of achieving fuel savings by retrofitting a shaft generator frequency converter while a ship is operational. The research presents a decision-making framework based on a cost-benefit analysis and risk identification. The results demonstrate that fuel prices have the most significant impact on profitability, and the cost of retrofitting is high in the short term.

Gkotzia et al. [3] present the potential use of shaft electric machines as a stepping stone towards fully electrifying ships. They introduce a mathematical model based on the Lagrange method and the engines' technical constraints and apply it to a general-purpose ship. Next, the authors conduct a sensitivity analysis on various factors, including fuel price, operational life period, interest rate, and the ship's propulsion power duration curve. These findings enhance our comprehension of the financial aspects and considerations involved in the implementation of shaft generator systems.

Prousalidis et al. [4] conduct an investigation aiming to deliver a comprehensive analysis of the role of a shaft generator in enhancing the efficiency of a ship's power system, specifically considering the perspective of optimizing ship operations. The primary focus lies in examining the interrelationship between the shaft generator and the power management system, considering their influence on the operational point of the electrical generators and propulsion engine, which in turn impacts the achievement of optimal operating conditions.

Avdeyev and Vyngra [5] present the significance of energy efficiency in the shipping and shipbuilding industry. The authors stress the importance of analyzing system performance before implementing any technological solution to ensure successful application and guaranteed economy. One potential solution is to use a shaft generator powered by a propeller shaft to provide an uninterrupted power supply to ship consumers. By using a generator to supply power to receivers when the vessel is in motion, the number of operating generating sets and operating hours can be reduced, resulting in significant cost savings on fuel and lubricants for individual actuating mechanisms.

Liu et al [6] studied ship operating modes and introduced a control strategy for brushless doubly-fed generators (BDFG), which offer advantages such as smaller inverter capacity, lower capital and operating costs, and higher reliability. The control strategy is implemented in a hardware environment and physical verification is performed. The results demonstrate that the control method exhibits excellent dynamic performance in response to changes in speed and power.

Sarasquete et al. [7] analyses the ship's operational profile, machinery, and fuel-saving options. For vessels with controllable pitch propellers and shaft generators, a variable speed generation system is an interesting solution. This system allows the synchronous generator to run at variable speeds, improving energy efficiency and hydrodynamics. Implementing this system requires considering the diesel engine's new operational envelope and possibly redesigning the propeller blades for additional gains.

Churkin et al. [8] focus on the implementation of shaft-generating installations in ship electric power systems and propose methods to address related challenges. Since ship electric power system (EPS) is typically limited in power supply, it is essential to find ways to increase the quantity and enhance the quality of generated electrical energy. A method to achieve this is by introducing shaft-generating installations (SGI) into the EPS of the ship. The introduction of SGI offers advantages like increased energy generation and reduced fuel consumption. However, it also presents challenges like more complex control requirements and the need for system synchronization.

Ammar and Seddiek [9] focus on improving energy management on large container ships. It evaluates the impact of various methods on environmental and economic aspects using class A13, A15, and A19 container vessels as such references. The energy efficiency values for these ships are calculated, and the A19 class performs the best in terms of emissions reduction. The emissions rates that can be reduced for this class of ship are provided for SO_x, NO_x, CO, CO_2, and PM emissions. To enhance energy management for the A13 class, a 45 percent decrease in speed is suggested, aligning with 2023-year legislation. The proposed concept is estimated to cost $5860 per ton of CO_2 reduction. Alternatively, applying the strategy of LNG-fueled engines for the A19 class can result in a 9.34% expansion of energy measures and an annual operating cost reduction of $24.7 million.

Uyanık [10] proposes a machine learning approach to operational electrical power for shaft generator applications. In the study, a data set from a container ship was used. The algorithms were trained using training data and separated to evaluate the performance of the algorithms in the prediction process. Based on the evaluations conducted, it was concluded that the Multiple Linear Regression algorithm outperformed the other algorithms examined in the study when it came to estimating the electrical power of the shaft generator.

Nuchturee et al. [11] discuss the growing concerns about energy consumption and environmental impact in the shipping industry. The paper explores various technologies and practices to meet the tightening restrictions, including integrating energy storage and intelligent power management, adopting DC power distribution, using

Main Points

- A shaft generator model is proposed using ANSYS/Maxwell.
- The characteristics of the proposed shaft generator model are simulated and analyzed.
- Shaft generators of different power and frequencies are compared.
- The design and efficiency of shaft generator model for ships are compared and evaluated.

unconventional propulsors, utilizing low-carbon fuels like liquefied natural gas, incorporating onboard renewable energy systems, and integrating fuel cells with diesel generators.

Gully et al. [12] examine the fuel consumption of a container ship and explore ways to reduce fuel demand. The study models fuel consumption from the main propulsion engines and auxiliary engines using a Power Take Off (PTO) system. The research evaluates the potential fuel savings at different scales of the Auxiliary Power System (APS), considering multiple scenarios of operation. By implementing the APS, operators, and manufacturers can explore innovative ways to reduce fuel costs, which typically account for a significant portion of total voyage expenses in commercial marine transportation.

Kruszewski [13] focuses on the integration of monitoring and control systems for the key elements of a ship's propulsion system, namely the primary engine, shaft generator, and pitch propeller. The paper proposes a supervisory controller based on neural network principles. The paper is structured into three sections: the initial section examines the challenges and objectives associated with controller utilization, the subsequent section presents the dynamic model encompassing the fundamental components of the ship and its propulsion system, and finally, the third section provides a comprehensive description of the dynamic system incorporating the supervisory neural controller. Computer simulations of the system are conducted using MATLAB/Simulink with a neural network database.

Chen and Wang [14] propose the utilization of a brushless doubly fed induction generator (BDFIG) in the application of a shaft generator that requires variable speed and constant frequency operation. The authors also investigate the characteristics of a ship shaft generator. In a carefully designed BDFIG, magnetic fields of 2 and 4 pole pairs are induced in the rotor windings without any direct coupling between the primary winding and the control winding. As a result, they derive the steady-state equivalent circuit of the BDFIG by separating the space vector representations of the BDFIG.

Liu and Wang [15] research a 700-kW BDFIG designed specifically for use as a stand-alone ship shaft generator. This design aims to reduce harmonic content and enhance the coupling between the two stator windings. The researchers analyze the performance of a BDFIG prototype with two/four pole pairs, examining factors such as magnetic fields, air-gap flux densities, and current densities under various shaft speeds and full load conditions. Through simulation analysis and experimental tests, they confirm that the prototype machine can generate the required output power and achieve the desired efficiency. Furthermore, they demonstrate that the wound rotor structure is suitable for high-power brushless doubly fed machines.

Sarigiannidis et al. [16] explore the development and implementation of an improved Shaft Generator (SHG) system for a practical Ro-Ro ship. This system integrates a PMSG and a back-to-back converter, enabling it to function interchangeably as a generator and a motor. Its main functions include supplying active power, providing supplementary services to the ship's grid, and serving as an emergency propulsion for the main shaft. The paper emphasizes the importance of conducting a comprehensive analysis of the subsystems and their interdependencies to accurately evaluate the benefits of such solutions in real-world scenarios.

Sarigiannidis et al. [17] present an enhanced Shaft Generator (SG) system for a Ro-Ro ship, with a specific emphasis on a low-speed direct-driven Permanent Magnet Synchronous Generator (PMSG) that has been optimized. The research study compares the PMSG with a high-speed Salient-Pole Synchronous Generator and establishes that the low-speed PMSG is a preferable choice for applications involving SG. The paper also addresses the design of a drive system for integrating the PMSG into the ship's electric grid, emphasizing the generator control methodology and converter topology.

Nishikata et al. [18] focus on the steady-state performance of the shaft generator system driven by the main engine in the ship. The system's ability to supply sufficient power to the ship's electrical devices is discussed. The paper derives a set of system equations to estimate parameters such as the output voltage's total harmonic distortion. The steady-state performance is analyzed in detail, revealing that a wide operating range can be achieved with a small AC reactor's reactance in the inverter's outputs.

Xia et al. [19] conduct research on the utilization of a variable-speed constant-frequency (VSCF) control system for ship shaft generators and analyzed its characteristics during grid-connection. They establish a mathematical model of the vector control technique based on the stator flux of the doubly-fed induction generator (DFIG) and investigate the control strategy for grid connection under no-load conditions and power decoupling. To simulate the complete system process, ranging from grid connection to power generation, they develop a simulation model using time-sharing modeling in MATLAB/Simulink. Overall, the study affirms the effectiveness of the VSCF control system for ship shaft generators.

Xiong and Wang [20] investigate a novel brushless doubly-fed machine (BDFM) equipped with a specially designed double-sine wound rotor (DSW rotor), specifically intended for stand-alone ship shaft generator applications. The researchers conducted performance analyses on a prototype DSW-rotor BDFM with 2 and 4 pole pairs, utilizing a combination of finite element analysis modeling and experimental approaches. The study primarily focused on examining magnetic fields, air-gap flux density distribution, and the on-load characteristics of the prototype machine. The experimental results confirmed the theoretical analysis findings, demonstrating that the prototype DSW-rotor BDFM exhibits excellent performance.

Tarnapowicz [21] addresses the stability of frequency in shipping systems when using high-power shaft generators. The current electronic systems based on thyristor inverters have certain drawbacks. To overcome these issues, the article proposes the use of multi-level inverters constructed with fully controllable valves, specifically transistors IGBT. This solution aims to eliminate the disadvantages associated with thyristor inverters and improve the stability of frequency in the operation of high-power shaft generators.

Zhang et al. [22] tackle the issue of achieving variable speed constant frequency and constant voltage in ship shaft power generation systems. The proposed approach integrates a vector control strategy that relies on stator power winding flux orientation with fuzzy adaptive PID controllers, enabling independent control of a brushless doubly-fed shaft generator (BDFG) system's operations. The research employs simulation studies conducted with MATLAB/Simulink software to assess the anti-interference performance of the BDFG shaft generator system on the ship. The findings indicate that the system exhibits excellent dynamic and static stability when implementing this control strategy.

Zhao et al. [23] propose a solution for a shaft generator system by utilizing a Doubly Fed Induction Machine (DFIM) with a partially rated converter. To address this limitation, the article suggests an approach that involves initiating the machine in the Induction Machine (IM) mode and transitioning to the DFIM mode once the speed reaches the normal operating range. The article details the hardware setup, start procedure, and control algorithm of this approach. Simulation and experimental studies were conducted to validate the effectiveness of the proposed method and the doubly-feed shaft generator model is shown in Fig. 1.

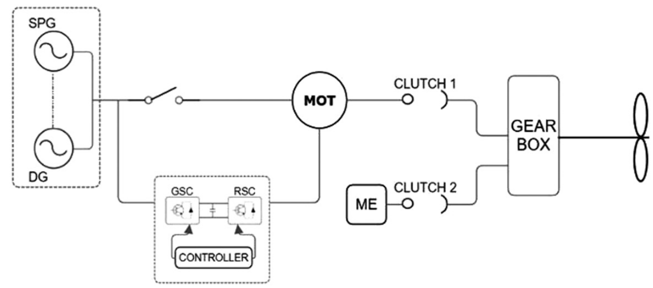

Fig. 1. Doubly-feed shaft generator model.

Dermentzoglou [24] researches the modeling and control strategy of the doubly fed induction machine used as a shaft generator in the ship's electric system. The machine can reduce CO2 emissions and fuel consumption and is regulated using a vector control technique to maintain a constant electrical torque. The study shows good speed regulation in both motor and generator modes.

Diao et al. [25] introduce a position sensorless control strategy for a DFIM applied in ship shaft generation systems. The proposed strategy utilizes direct voltage control and Space Vector Pulse Width Modulation to ensure a consistent frequency and voltage, even when faced with load and main engine speed variations. This novel method eliminates the need for a speed signal or position encoder by adjusting the reference stator vector angle to rapidly and accurately achieve the desired stator voltage. Simulation results demonstrate the effectiveness of the proposed approach, confirming its ability to achieve the desired outcomes.

Xia et al. [19] investigate the operational principles of a control system called VSCF for ship shaft generators. The structure of the VSCF of the shaft generator is shown in Fig. 2. Using the mathematical model of the DFIG, the researchers develop a mathematical model for a vector control technique based on the stator flux of the generator. To simulate the entire system process, from grid connection to power generation, a simulation model is created in MATLAB/Simulink, incorporating time-sharing modeling. The simulation results show that the shaft DFIG system performs well in terms of tracking reference voltage, stabilizing frequency, and maintaining satisfactory dynamic and steady-state characteristics, even under varying generator speed and load conditions.

Zhao et al. [26] discuss the application of the DFIM with a partially rated converter as a shaft generator system. While the DFIM is suitable for adjustable speed operation, it lacks self-start capability under the power take-me-home mode when the main engine fails. To overcome this constraint, the paper presents a solution that involves initiating the machine in the induction machine mode, drawing power from the ship-borne power grid. The feasibility and effectiveness of the proposed approach are confirmed through the validation of simulation results.

Gao et al. [27] research the use of the brushless doubly-fed machine, driven by the ship's main engine, to generate electricity and reduce operating costs by decreasing the reliance on diesel generator sets. The study analyzes the mathematical model and control principles of the independent generator system using scalar control and proposes a control strategy that does not require a speed sensor. A simulation of the marine shaft generator system was established and tested, demonstrating the effectiveness of the proposed system.

Liu et al. [28] introduce a stand-alone shaft generator system based on a BDFM. The system maintains a constant output voltage amplitude and frequency of the BDFM, even with variable rotor speed and load, by regulating the excitation current of the control winding. The paper proposes a control scheme and provides hardware design for the control system. The proposed shaft generator system is tested on a container vessel, and the results demonstrate its good dynamic performance and energy-saving capabilities.

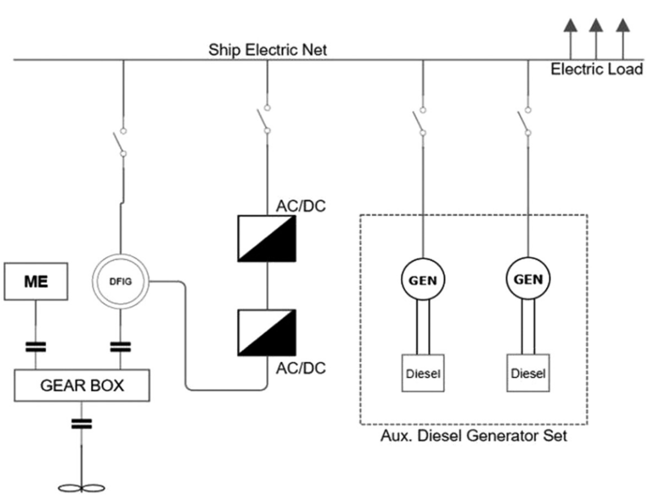

Fig. 2. Shaft generator structure with variable speed constant frequency (VSCF) system.

Perez and Reusser [29] focus on marine propulsion systems based on diesel engines, which offer advantages such as low fuel consumption and high thermal efficiency. However, their emissions, including CO_2, SO_x, and NO_x, have led to regulations by the International Maritime Organization to reduce environmental impact. To tackle this challenge, the study suggests the integration of a Shaft Generator into the propulsion system as a solution to reduce CO_2 emissions and enhance energy efficiency and shows that operating area in Fig. 3.

Tadros et al. [30] conducted a study on the development of an optimization tool for the marine propulsion system of a fishing trawler during the ship's initial design phase. The tool, consisting of two MATLAB modules, is designed to simulate and optimize the system's performance. The first module focuses on minimizing fuel consumption and emissions by simulating the marine diesel engine's performance. The second module assists in selecting an appropriate propeller to improve fuel efficiency and address performance issues. The applications of this tool resulted in a significant reduction of approximately 30% in fuel consumption compared to other scenarios.

Nguyen et al. [31] provide a comprehensive and detailed examination of both conventional and advanced electrical propulsion systems utilized in commercial vessels and smart ships. It compares and analyzes different system configurations, power sources, and propulsors to assist in choosing the best electric or hybrid powertrain systems for commercial fleets.

Kanellos et al. [32] proposed an integrated control system, aiming to optimize ship operations in terms of both economic efficiency and environmental impact. The study includes simulations of a ship power system equipped with fully electric propulsion, providing evidence for the effectiveness of the proposed system. By considering full electric propulsion systems and introducing an integrated control system, this research expands the existing knowledge and offers valuable insights for ship operators and designers to ensure compliance with emissions regulations and fuel economy standards.

Michalopoulos et al. [33] explore the electrification of ship propulsion systems, specifically the use of shaft electric machines for partial electrification. It addresses the disparity between power dispatch methods in ships and continental power systems and proposes a novel optimal power management algorithm. This algorithm considers the integration of shaft electric machines, operational limitations of the ship, and environmental regulations enforced by the IMO. The study conducts a comparative analysis of different ship propulsion and power generation configurations using real-world data from engines, generators, shaft generators, and other components. The research highlights the potential advantages of incorporating shaft electric machines into ship propulsion systems and presents an optimized approach to managing power, enhancing efficiency, and reducing costs.

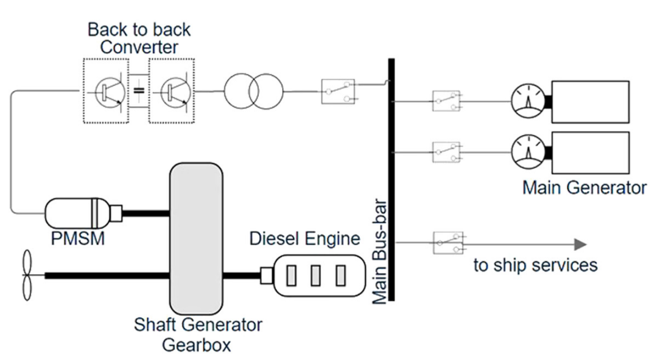

Fig. 3. Hybrid propulsion system configuration.

Kowalak [34] directs their focus toward the construction of a power plant on a large container vessel, specifically examining the waste heat recovery system and shaft generator. Through experiments, the authors monitor fuel consumption and electric load during the vessel's acceleration and deceleration at slow steaming speeds. Based on the experimental findings, the authors simulate a hypothetical 4000 nautical mile voyage and analyze the ship's total fuel consumption per voyage at different engine speeds, both below and above the minimum cut-in speed of the shaft generator. The results highlight the significant influence of the auxiliary boiler's fuel consumption on the overall fuel cost per voyage, especially when the minimum permissible speed of the shaft generator motor is not achieved during slow steaming.

Shaft generators in this study can be divided into three categories efficiency, design modeling, and emission applications. Table I presents these applications.

A review of the literature shows that shaft generator systems have been evaluated from various perspectives such as design, optimization, and efficiency. However, an examination of marine power systems indicates that there is insufficient research on shaft generator systems in military vessels. Therefore, this study aims to describe the variation and characteristics of electrical parameters such as voltage, frequency, and phase angle for two different shaft generators in military ships. In this study, the shaft generator is modeled using the ANSYS/Maxwell program to study the behavior of the electrical parameters during the efficiency and optimization process. Thus, this study aims to contribute to the literature and support the design and efficiency of shaft generators in military ships with theoretical insights.

III. STRUCTURE OF SHAFT GENERATORS

A. General Characteristics of Shaft Generators

Energy efficiency continues to be an important issue in the shipbuilding industry. Ship-owners are investing in new ships or upgrading existing ships to reduce fuel consumption to combat high energy costs [35]. However, before implementing technological solutions, the performance of the system needs to be analyzed. The use of a shaft generator to power ship consumers driven by the propeller shaft is considered as a solution. Depending on the type of ship and power plant, different configurations are used. Providing power to the receivers using a generator can significantly reduce fuel and operating costs by reducing the number and operating hours of operating generator sets [2].

TABLE I.
VARIOUS SHAFT GENERATOR SYSTEM ANALYSIS

Analysis Type	References	Focus Subject
Efficiency	[1]	Impact of a variable speed generation system on energy performance.
	[2]	Saving fuel during the operational phase of the ship
	[3]	Mathematical basis for techno-economic analysis of shaft generators
	[4]	Analysis of ship power system efficiency in shaft generator
	[5]	By reducing the number of generators sets and operating hours, it enables operating costs to be reduced.
	[6]	BDFM mathematical model analysis based on shaft generator characteristics
	[7]	Increase energy efficiency by operating the generator at variable speeds over a wide range of engine speeds using a variable speed generation system
	[8]	Introduction of the shaft generator into the ship's electrical power system to increase the amount of electrical energy generated through the ship's electrical installation.
	[9]	It focuses on improving energy management on large container ships.
	[14]	Analysis of an excitation control mechanism for stand-alone BDFG based on the characteristics of the ship shaft generator
	[15]	To create a new RW design model to develop a rotor structure with ease of manufacturing and low cost.
	[16]	Ship Design with Permanent Magnet Synchronous Generator and Shaft Generator
Design/ Modelling	[17]	Comparison of high-speed Salient-Pole Synchronous Generator and low-speed direct drive Permanent Magnet Synchronous Generator with the same rated power as SG.
	[18]	The steady-state performance depending on the total harmonic distortion is analyzed
	[19]	Principle of operation of the VSCF control system of the shaft generator
	[20]	SG analysis using finite element analysis model and experimental methods
		(Continuous)
	[21]	It deals with frequency stability in transport systems using high power shaft generators.
	[22]	It combines the vector control strategy of the BDFG system with PID controllers.
	[23]	It is to start the system in induction machine mode and switch to DFIM mode when the speed reaches the normal operating range.
	[24]	Inclusion of a DFIM as a Shaft Generator in a Marine System
Design/ Modelling	[25]	A control strategy for DFIM without position sensors
	[19]	Working Principle of VSCF Control System
	[26]	Operating a generator using DFIM in PTH mode
	[27]	Mathematical model and control principal analysis of shaft generator system based on BDFM.
	[28]	Analysis of output voltage amplitude and frequency of BDFM under variable rotor speed and load
Emission	[29]	emission profile of the shaft generator system
	[30]	propeller efficiency with shaft generator-dependent parameters
	[31]	It focuses on a comprehensive and detailed examination of electric drive systems.
	[32]	Comparison of high-speed Salient-Pole Synchronous Generator and low-speed direct drive Permanent Magnet Synchronous Generator with the same rated power as SG.
	[33]	optimal power management algorithm
	[34]	The waste heat recovery system and the shaft generator focus on energy efficiency.

The advantages of integrating a shaft generator into the ship's power generation system, as opposed to relying solely on a single main engine for propulsion, have become increasingly apparent. By harnessing the main engine's power to drive the generator in tandem with other power sources, the benefits extend to both technical and economic realms [36].

The shaft generator optimally utilizes surplus power, reducing the workload of diesel-driven generators and subsequently cutting down on fuel consumption. This not only promotes sustainability but also extends the operational lifespan of the auxiliary generators. Perhaps most strikingly, the cost of power production through a shaft generator is only half that of a diesel generator, making it a highly cost-effective and eco-friendly choice for the maritime industry [36].

Shaft generators usually work in conjunction with diesel engines used on ships to produce the energy needed to turn the ship's propeller. This system stands out with the use of cheap fuel oil by using independent ship shaft generators and reduces operating costs with the energy it provides [20]. Fig. 4 presents a shaft generator connected to the vessel's main machine system in a ship.

The growing interest in SG systems for ship propulsion is due to the various advantages they offer over conventional diesel generator systems. These SGs are typically mounted on the propeller shaft, placed between the main propulsion engine and the propeller, and usually include a gearbox to efficiently convert a portion of the main engine's power into electricity. SGs are frequently used on ships in combination with digital generators and other alternative power sources and require careful design to ensure optimum performance and efficiency. Furthermore, a thorough assessment of their electromagnetic properties is crucial in analyzing SG systems [17].

Shaft generators offer numerous benefits, including cost-effective power generation using the ship's main engines, which results in significant savings in fuel costs. They require minimal space, making them advantageous for ships where space is at a premium. Additionally, shaft generators have low installation costs, making them an attractive option for ship owners. They also produce lower noise levels compared to conventional generators, contributing to a quieter ship environment. Moreover, their high reliability ensures a consistent power supply.

However, it is important to note some limitations associated with shaft generators. They are unable to generate electrical energy while the ship is in port, necessitating the use of alternative power sources during port stays. Also, the load on the ship's main engine increases during shaft generator operation.

B. Structure of Shaft Generator

Shaft generator systems are implemented in certain applications due to their ability to provide electrical power to ships while lowering fuel consumption and operating costs in comparison to traditional ship construction with felled generator sets [37]. The shaft is the central component of the shaft generator. This shaft is usually connected to a prime mover, such as a diesel engine, steam turbine, or electric motor, which provides rotational energy. The generator is mounted on the shaft and is responsible for converting the mechanical energy of the rotating shaft into electrical energy. It typically consists of a rotor (rotating part) and a stator (stationary part). The rotor was attached to the shaft and spins within the stator, inducing an electric current in the stator windings through electromagnetic induction. The stator is the stationary component of the generator and contains windings through which the electrical current is induced. These windings are typically constructed from copper wire and connected to an external electrical circuit to deliver power. A cooling system is often incorporated into shaft generators to dissipate the heat generated during operation. This cooling system may include fans, coolant circulation systems, or other methods to regulate temperature. A control system is necessary to regulate the output voltage and frequency of the generated electricity, ensuring compatibility with the electrical grid or the load being powered. This control system may include voltage regulators, frequency converters, or other electronic components. The structure of the shaft generator is designed to efficiently convert mechanical energy into electrical energy and integrate seamlessly with the power distribution system of the vessel or its applications.

Fig. 4. Overview of a shaft generator in a ship.

Fig. 5 depicts a system in which electricity is generated by a generator set containing one shaft generator and three diesel generators. The power panels consist of MSB 1 (Main Switchboard 3-phase) and

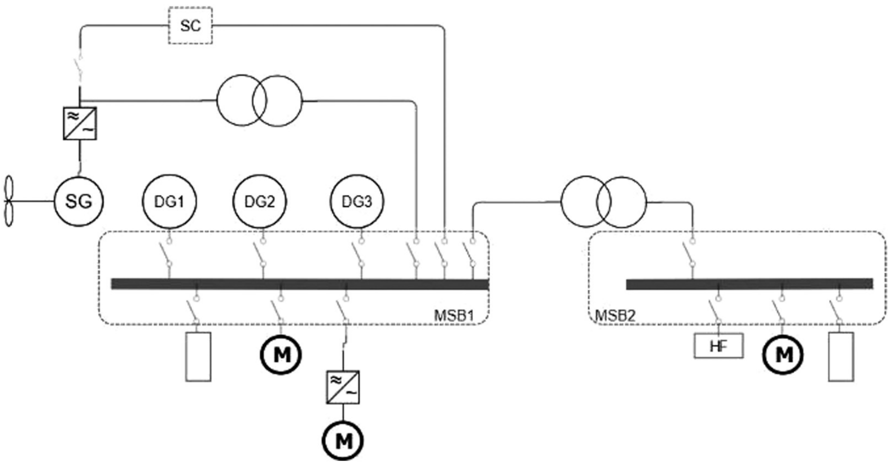

Fig. 5. Structure drawing of shaft generator.

MSB 2 (Main Switchboard 3-phase). Additionally, SC serves as the synchronized generator and HF operates as the harmonic filter.

C. Power Supplying Characteristics of Shaft Generator

The utilization of shaft generators in the maritime industry plays a crucial role in addressing the paramount concern of energy efficiency [35]. Ship owners, in their pursuit to alleviate soaring energy costs, are investing in new vessels and retrofitting existing ones, seeking solutions to curtail fuel consumption. These solutions necessitate a comprehensive performance analysis to ensure successful implementation and cost-effectiveness. One such solution is the incorporation of shaft generators, driven by the propeller shaft, to provide a continuous power supply to ship consumers, which holds particular promise for optimizing power plant configurations and reducing operational costs on fuels and lubricants for individual actuators [38].

Shaft generators come in three primary configurations. The GCR (gear constant ratio) system, characterized by its simplicity and cost-effectiveness, integrates a flexible coupling, step-up gear, and a standard synchronous alternator. This configuration appeals to many ship owners as it generates electrical energy at a constant frequency during voyages. However, the dynamic nature of the propeller's rotation frequency poses synchronization challenges between the shaft generator and the ship's power plant, especially in variable conditions, leading to its use for low-level receivers independent of the ship's primary network [39, 40]. Fig. 6 shows the approximate electrical energy generated from the shaft.

D. Shaft Generator Design and Analysis

The design process involved 3D ANYSYS/Maxwell simulations, taking into account electromagnetic behavior and efficiency analysis. Various parameters were analyzed, including current, efficiency, speed, and power factor and torque analyses. Design parameters are optimized accordingly.

The ANYSYS/Maxwell simulation program was employed to assess the performance and efficiency. The process commenced with the selection of an appropriate simulation type, which in this instance was magnetic-transient. This was deemed the most suitable option because shaft generators are electromagnetic devices, and the results of the analyses are time-dependent. The designed shaft generator model is illustrated in Fig. 7.

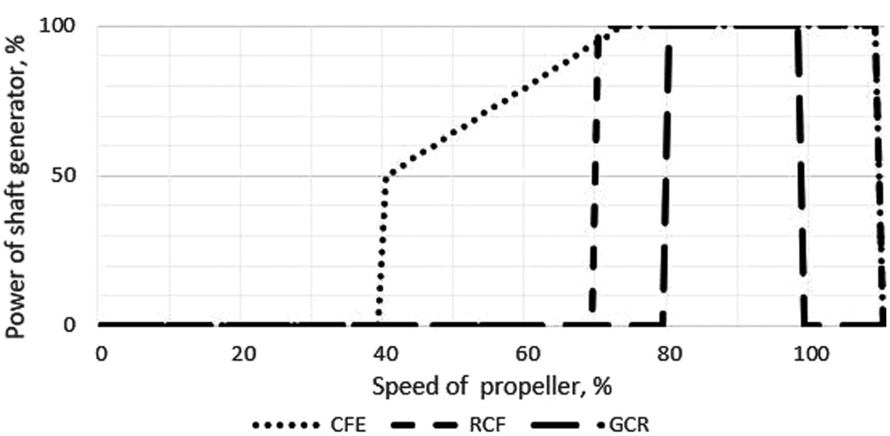

Fig. 6. Approximate generation of electrical energy by shaft generators.

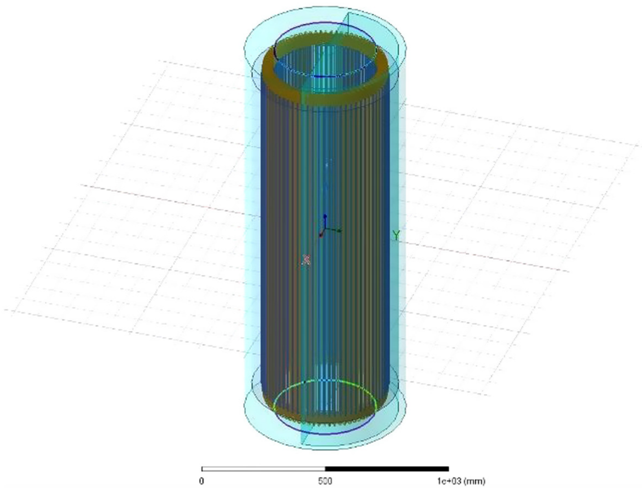

Fig. 7. ANYSYS/Maxwell design of shaft generator.

A 3D representation of the geometry of the shaft generator is then created within the ANYSYS/Maxwell simulation program. This step involves modeling the rotor and stator as solid objects, creating their physical dimensions, and generating the configurations of the shaft generator. To define the boundaries of the simulation, it is necessary to specify the specific regions and conditions under which the simulation will be conducted. This enables the program to simulate the behavior of the transformer under specific operating conditions, taking into account factors such as the surrounding environment and external influences.

The shaft generator design procedure involves the creation of a 3D model using Maxwell-3D within the ANYSYS/Maxwell simulation program. The modeling stage entails accurately representing the shaft generator and the motor pole numbers, rotor, and stator windings.

Following the assignment of the requisite materials to the rotor and stator windings, the subsequent stage entails the excitation and energization of the rotor and stator windings by the specified shaft generator parameters. The circulation of current in the stator windings results in the generation of a current load. Additionally, the closed-circuit current generates a magnetic field in the opposite direction to the magnetic field that generates it. In light of these considerations, the windings are designed to meet the desired electrical characteristics of the shaft generator.

IV. RESULT AND DISCUSSION

The models of the 800kW 60Hz and 1550kW 50Hz shaft generators are analyzed and compared. The 800kW 60Hz shaft generator is referred to as Model A and the 1550kW 50Hz shaft generator is referred to as Model D. The design parameters of the 800kW 60Hz shaft generator model are given in Table II and 1550kW 50Hz shaft generator model D is given in Table III.

This analysis employs a modeling approach that treats the rotor and stator windings as solid objects, thereby capturing the physical dimensions and configurations of the shaft generator. The designed shaft generator model is illustrated in Fig. 8.

TABLE II.
DESIGN PARAMETERS OF SHAFT GENERATOR MODEL A

Characteristic	Unit	Values
Generator Type	–	Squirrel Cage
Ambient Temperature (max)	°C	50
Connection of Stator Winding	–	Delta
Rated Output	kW	800
Voltage	V	690
Frequency	Hz	60
Speed	rpm	1810
Current	A	783
Related Max Torque	p.µ	2.4
Poles	number	2
Slots for Stator	number	72
Slots for Rotor	number	60
Partial Load Data	%	100/75/50
Partial Efficiency Data	%	96, 7/96, 9/96, 5
Partial Power Factor Data	–	0.86
Weight	kg	3200

The shaft generator design procedure involves the creation of a three-dimensional (3D) model using Maxwell-3D within the ANSYS/Maxwell simulation program. The modeling stage entails accurately representing the shaft generator and the motor pole numbers, rotor,

TABLE III.
DESIGN PARAMETERS OF SHAFT GENERATOR MODEL D

Characteristic	Unit	Values
Generator Type	–	Squirrel Cage
Ambient Temperature (max)	°C	45
Connection of Stator Winding	–	Star
Rated Output	kW	1550
Voltage	V	690
Frequency	Hz	50
Speed	rpm	1036
Current	A	786
Related Max Torque	p.µ	2.6
Poles	number	4
Slots for Stator	number	72
Slots for Rotor	number	60
Partial Load Data	%	100/75/50
Partial Efficiency Data	%	97
Partial Power Factor Data	–	0.85
Weight	kg	6600

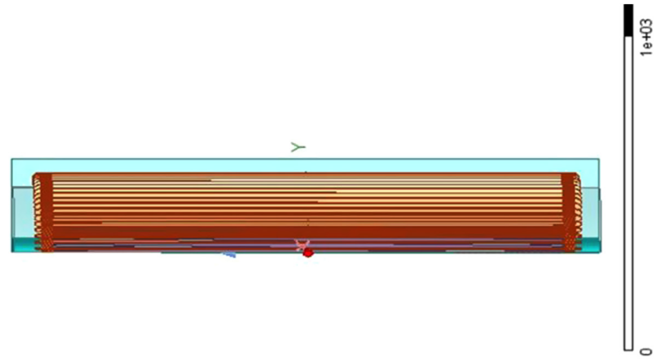

Fig. 8. ANYSYS/Maxwell design of shaft generator.

and stator windings. The resulting 3D model of the shaft generator, as depicted in Fig. 9, provides a visual representation of the configuration of the rotor and stator windings within the design. This representation facilitates an understanding of the physical layout and alignment of the design components.

The simulation program enables the analysis of electromagnetic fields and behavior within the shaft generator, employing Maxwell-3D for the design of the shaft generator system.

This enables a comprehensive evaluation of factors such as magnetic fields, torque value, and current value, thereby providing insights into the performance and efficiency of the transformer design.

Following the modeling of the induction motor and its windings, the subsequent step is to select the most appropriate material types for these components. The selection of the appropriate material types for these components is performed using the material property panel within the ANSYS/Maxwell simulation program, as illustrated in Fig. 10 and 11.

During the design process, copper was selected as the optimal material for the rotor and stator of the shaft generator. This

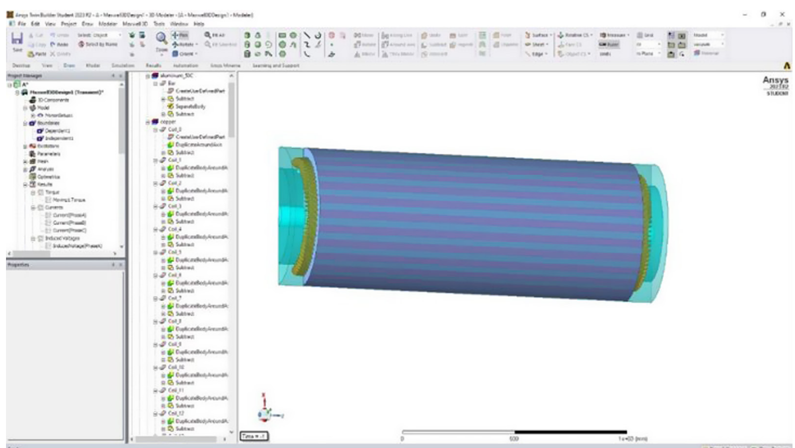

Fig. 9. ANYSYS/Maxwell 3D design operation panel.

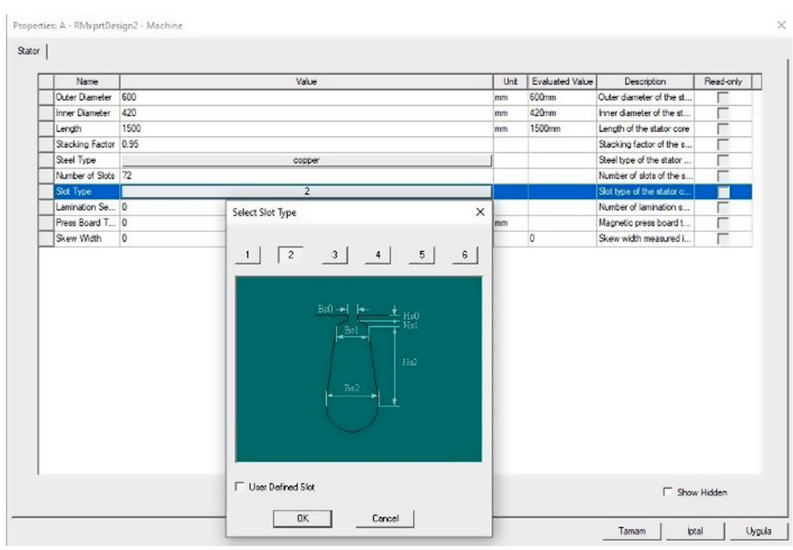

Fig. 10. Creating specific properties for stator.

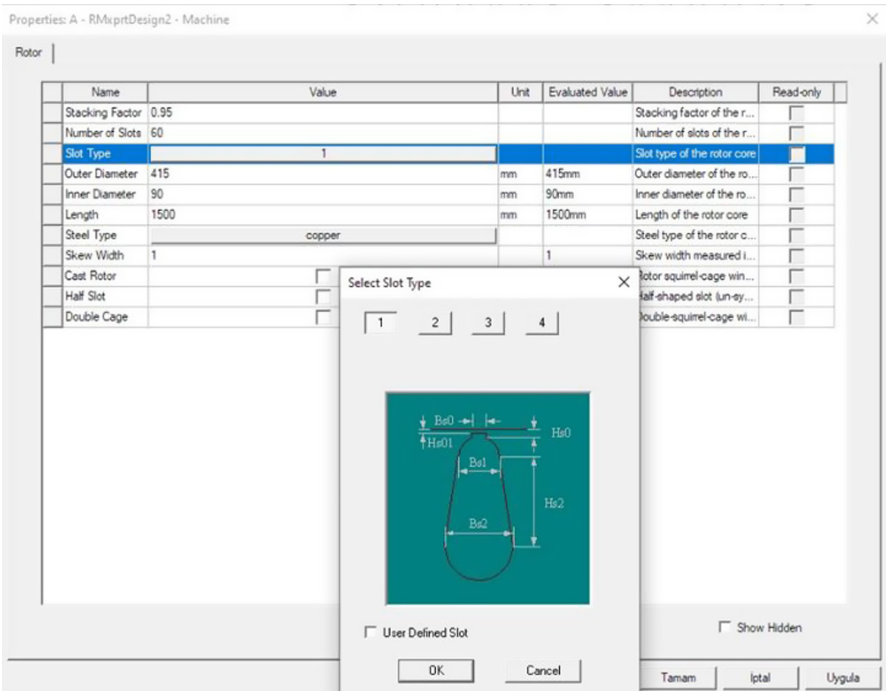

Fig. 11. Creating specific properties for rotor.

selection was based on the superior characteristics of copper. Copper is particularly suited to the manufacture of transformer cores and other similar applications due to its specific electromagnetic properties.

Following the assignment of the requisite materials to the rotor and stator windings, the subsequent stage entails the excitation and energization of the rotor and stator windings by the specified shaft generator parameters. The circulation of current in the stator windings results in the generation of a current load. Additionally, the closed-circuit current generates a magnetic field in the opposite direction to the magnetic field that generates it. In light of these considerations, the windings are designed to meet the desired electrical characteristics of the shaft generator.

The assignment of excitations to the windings is illustrated in Fig. 12, which provides a visual representation of the connections and energization of the windings within the shaft generator design.

The ANYSYS/Maxwell program facilitates the accurate simulation and evaluation of the electromagnetic transient behavior of the shaft generator when the appropriate analysis parameters are set. This enables the study of fundamental electrical quantities, such as current, voltage, and efficiency values, over the defined analysis time interval. Subsequently, the analysis results are obtained based on the defined analysis time.

800kW 60Hz and 1550kW 50Hz shaft generators are analyzed and compared. The transformer models are analyzed by the ANYSYS/Maxwell simulation program. The results obtained from the ANSYS/Maxwell program are compared with the actual value.

The initial analysis concerns the input current values obtained for the shaft generator about the speed values. The graphical and comparative analysis results for models A and D are presented in Fig. 13 and Table IV.

The second analysis presents the power factor values obtained for the shaft generator about the speed values. The graphical and comparative analysis results for models A and D are presented in Fig. 14 and Table V.

The third analysis is the resulting efficiency values for the shaft generator depending on the speed values.

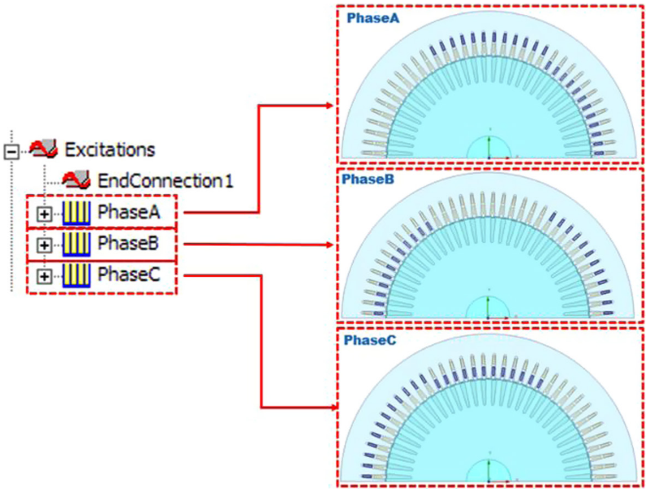

Fig. 12. Assignment of excitation to windings of shaft generator.

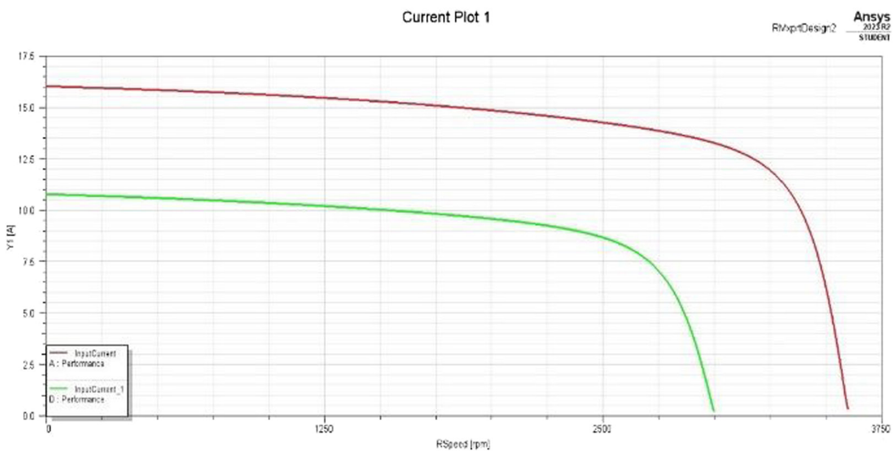

Fig. 13. Comparative input current graph of Model A and Model D.

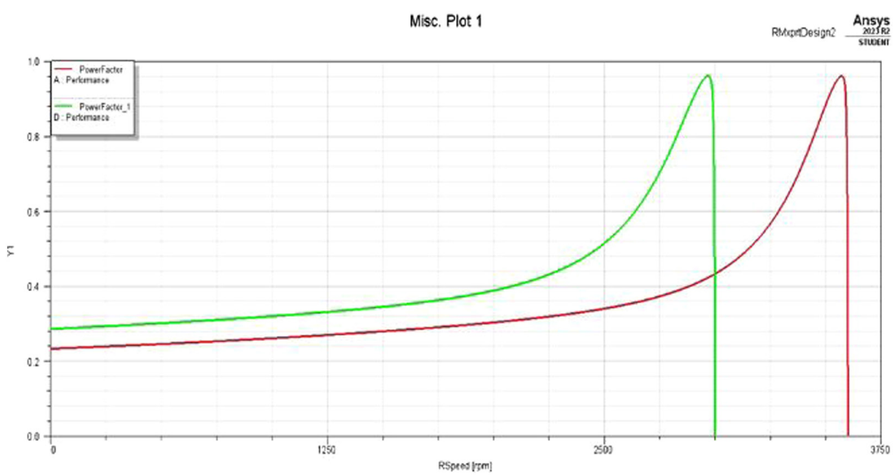

Fig. 14. Comparative power factor graph of Model A and Model D.

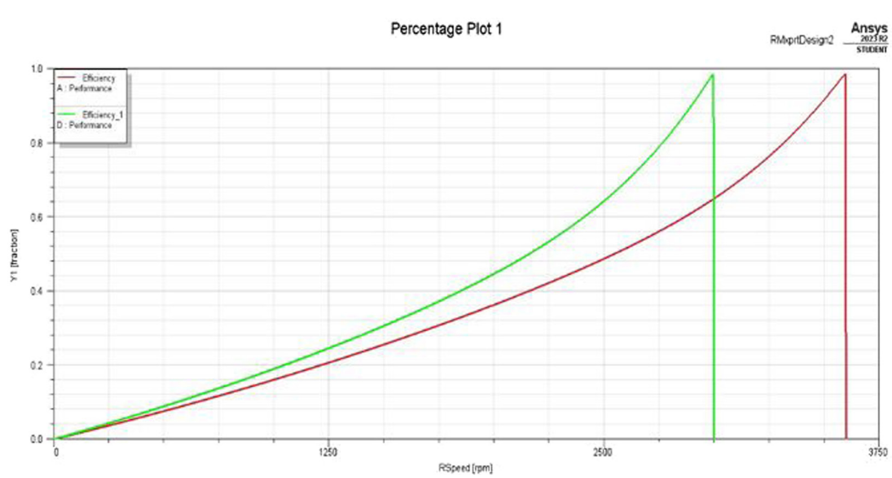

Fig. 15. Comparative efficiency graph of Model A and Model D.

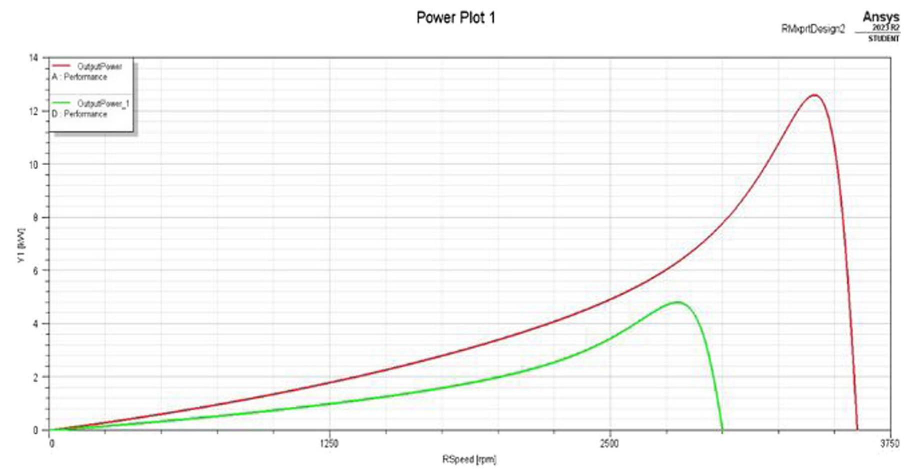

Fig. 16. Comparative output power graph of Model A and Model D.

The analysis results for models A and D are presented in Fig. 15 and Table VI.

Another analysis is the resulting output power values for the shaft generator depending on the speed values. The graphical and comparative analysis results for models A and D are presented in Fig. 16 and Table VII.

The final analysis is the resulting output torque values for the shaft generator depending on the speed values. The graphical and comparative analysis results for models A and D are presented in Fig. 17 and Table VIII.

The efficiencies of shaft generators with different rotor, stator windings, and motor pole values are analyzed and compared on two shaft generators of different power. It can be observed that the two most significant factors influencing the efficiency of the shaft generator are the number of motor poles and the frequency value of the system. It can be demonstrated that the efficiency of a shaft generator is inversely proportional to the number of motor poles and directly proportional to the frequency value of the system.

The results of the electromagnetic analysis conducted using ANYSYS/Maxwell software are employed to assess the current, power dissipation, efficiency, and other pivotal parameters.

V. CONCLUSION

Shaft Generator systems are an attractive choice for marine applications contributing to improved efficiency and operational cost savings in the maritime industry. To provide researchers working in this field with a clear perspective on the operating characteristics of the shaft generator, a comprehensive literature survey on the shaft generator is presented. By comparing the efficiency of shaft generators with different rotor, stator windings, and motor pole values, it can be observed that the number of motor poles and the frequency value of the system are important factors affecting efficiency and performance. The findings also guide future studies to improve the performance and efficiency of shaft generator design.

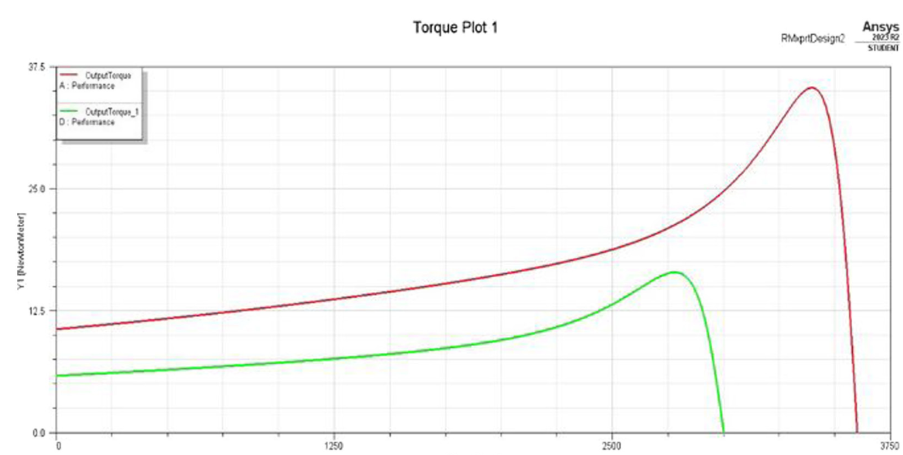

Fig. 17. Comparative output torque graph of Model A and Model D.

TABLE IV.
INPUT CURRENT ANALYSIS RESULTS FOR MODEL A AND MODEL D

	RSpeed [rpm]	Input Current [mA]: A	Input Current [mA]: D
1	0000000	16.009.169.000	10.771.296.000
2	360000000	15.887.428.000	10.645.745.000
3	720000000	15.737.496.000	10.491.667.000
4	1080000000	15.551.582.000	10.302.345.000
5	1440000000	15.320.115.000	10.069.560.000
6	1620000000	15.183.853.000	9.933.076.000
7	1800000000	15.031.877.000	9.779.199.000
8	1980000000	14.862.484.000	9.601.047.000
9	2160000000	14.673.593.000	9.382.923.000
10	2340000000	14.462.078.000	9.085.714.000
11	2520000000	14.221.979.000	8.600.215.000
12	2700000000	13.939.729.000	7.565.739.000
13	2880000000	13.580.807.000	4.589.576.000
14	2916000000	13.493.353.000	3.470.415.000
15	2952000000	13.398.190.000	2.119.252.000

TABLE VI.
EFFICIENCY ANALYSIS RESULTS FOR MODEL A AND MODEL D

	RSpeed [rpm]	Efficiency: A	Efficiency: D
1	0000000	0.000000	0.000000
2	360000000	0.053675	0.062653
3	720000000	0.111813	0.131343
4	1080000000	0.174850	0.206889
5	1440000000	0.243279	0.290635
6	1620000000	0.279711	0.336385
7	1800000000	0.317771	0.385550
8	1980000000	0.357635	0.439263
9	2160000000	0.399584	0.499369
10	2340000000	0.444086	0.568793
11	2520000000	0.491926	0.651931
12	2700000000	0.544425	0.754830
13	2880000000	0.603731	0.884740
14	2916000000	0.616676	0.914589
15	2952000000	0.630054	0.945795

TABLE V
POWER FACTOR ANALYSIS RESULTS FOR MODEL A AND MODEL D

	RSpeed [rpm]	Power Factor: A	Power Factor: D
1	0000000	0.234306	0.286914
2	360000000	0.243184	0.297608
3	720000000	0.253280	0.309878
4	1080000000	0.264820	0.324303
5	1440000000	0.278142	0.342295
6	1620000000	0.285652	0.353669
7	1800000000	0.293906	0.367843
8	1980000000	0.303150	0.386650
9	2160000000	0.313810	0.413490
10	2340000000	0.326647	0.454977
11	2520000000	0.343059	0.524765
12	2700000000	0.365687	0.651989
13	2880000000	0.399740	0.873226
14	2916000000	0.408720	0.919665
15	2952000000	0.418683	0.954278

TABLE VII.
OUTPUT POWER ANALYSIS RESULTS FOR MODEL A AND MODEL D

	RSpeed [rpm]	Output Power [kW]: A	Output Power [kW]: D
1	0000000	0.000000	0.000000
2	360000000	0.429504	0.237380
3	720000000	0.923602	0.511002
4	1080000000	1.493.207	0.827816
5	1440000000	2.151.106	1.200.696
6	1620000000	2.518.349	1.417.068
7	1800000000	2.915.334	1.663.927
8	1980000000	3.347.458	1.957.412
9	2160000000	3.824.026	2.327.066
10	2340000000	4.361.940	2.826.113
11	2520000000	4.992.758	3.539.368
12	2700000000	5.776.209	4.483.748
13	2880000000	6.825.703	4.275.470
14	2916000000	7.083.689	3.520.766
15	2952000000	7.362.490	2.307.763

TABLE VIII
OUTPUT TORQUE ANALYSIS RESULTS FOR MODEL A AND MODEL D

	RSpeed [rpm]	Output Torque [Nm]: A	Output Torque [Nm]: D
1	0000000	5.864.073	10.624.006
2	360000000	6.296.697	11.392.960
3	720000000	6.777.375	12.249.648
4	1080000000	7.319.497	13.202.846
5	1440000000	7.962.361	14.264.967
6	1620000000	8.353.086	14.844.730
7	1800000000	8.827.405	15.466.329
8	1980000000	9.440.357	16.144.380
9	2160000000	10.287.890	16.905.907
10	2340000000	11.533.073	17.800.623
11	2520000000	13.412.094	18.919.573
12	2700000000	15.858.014	20.429.162
13	2880000000	14.176.297	22.632.176
14	2916000000	11.529.780	23.197.617
15	2952000000	7.465.281	23.816.598

It is thought that this paper can help in selecting the optimum design for a shaft generator and can be an important reference for future studies in this field. As a result, these strategies provide a basis for further research toward greater efficiency and the establishment of different design standards. It is thought to guide the energy efficiency and design of shaft generators designed for naval ships.

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