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Article

Shaft Generator Design Analysis for Military Ships in Maritime Applications

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Abstract: Naval ships are of paramount importance to national security, culture and naval operations. A primary challenge for naval authorities is to balance the imperatives of maritime dominance with the operational demands of achieving sufficient sustainable reliability. Shaft generators (SGs) are crucial to the energy conversion systems on naval ships, functioning as part of the main power systems on board and providing both propulsion and power for various operational loads. In this sense, the design of shaft generators is an engineering element that has a major impact on the overall ship performance. The design process will be conducted within the MATLAB/Simulink environment, a platform that facilitates the study of the dynamic behavior of the system through simulation. The increasing demand for efficiency, reliability and sustainability in the military, along with the impact of emerging technologies, will further underscore the significance of shaft generators. Analyses carried out in MATLAB/Simulink demonstrate that the selection of the most suitable power system for naval ships is dictated by the system requirements and operational demands. The main construction is such that this work is the first of its kind in the field of shaft generator research for naval ships.

Keywords: shaft generator; military ships; design; MATLAB/Simulink; marine application; ANSYS/Maxwell

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1. Introduction

The maritime sector is of pivotal importance to global trade, with its significance showing no signs of abatement [1]. This heightened intensity is particularly evident over the past decade, as maritime trade has undergone significant expansion to meet the growing demands of the sector [2]. Marine energy systems represent a foundational component of the maritime industry, operating as the predominant source of energy for both propulsion systems and on-board power generation for commercial vessels, military vessels, and offshore vessels. These systems are of strategic importance, directly affecting the operational efficiency and sustainability of marine vessels [3] The power system is one of the most critical systems in a marine vessel, being autonomous in nature and affecting the entire life cycle of the vessel. This system is designed to provide energy generation to meet all the functional needs of the ship. In order to ensure safe and efficient operation of watercraft, it is essential that the electrical energy obtained from the power system is of a high quality, stable and continuous. The substandard quality of electrical energy has the potential to exert a detrimental effect on a number of factors, including the safety of navigation, the longevity of equipment, and the efficiency with which operations are carried out. It is therefore vital to emphasize the significance of the design, monitoring and control of the power system for the overall performance of marine vessels [4] The International Maritime Organization (IMO) has proposed a series of regulations with the objective of reducing emissions from this sector [5–7]. In an effort to adhere to the established regulatory frameworks, maritime enterprises within the designated sector have initiated a series of research and development initiatives [8]. While the IMO addresses the need for regulation by attempting to reduce this growth, shipping companies are conducting more R&D studies and taking energy efficiency measures to comply with these regulations. However, the implementation of new systems is often associated with significant financial investments, while a more cost-effective approach may involve the refurbishment of existing systems.

The utilization of shaft generators on board ships confers a dual benefit, both economically and environmentally, by enhancing energy efficiency. Consequently, these systems are being incorporated with increasing frequency in contemporary ship designs [9–11]. The integration of these generators on vessels leads to a reduction in fuel consumption and maintenance costs, while concurrently reducing cabin noise levels. This, in turn, facilitates the utilization of lower capacity diesel generators, thereby enhancing the overall efficiency of the vessel's energy management system. The operation of shaft generators is predicated on the direct extraction of power from the main engine. Maintaining constant voltage and frequency values at the stator output of the generator is imperative, even in conditions where the main engine speed fluctuates due to variations in sea conditions or propeller performance under water flow. In standard synchronous SG systems, an inverter is placed between the generator and the load, and this inverter is responsible for managing the entire output power of the system [12,13].

In this study, it is one of the SGs that play an appropriate role in increasing the energy efficiency of ships. They cover both mechanical and electrical loads, providing power for reliable operation of systems through high load variation periods, which is essential for military vessels. As for other power systems on military combat ships, this depends on their operational requirements and geographical location; the performance of the aforementioned power systems varies from region to region due to frequency and voltage level restrictions [14].

On naval vessels, 50 Hz and 60 Hz are the most commonly used system frequencies. However, the influence of different frequency levels on the performance and technical requirements of ship power systems at different efficiencies needs to be further investigated. A comparison of the advantages and disadvantages of 50 Hz and 60 Hz systems will help to develop better ship power systems that are more economically efficient.

This paper deals with a comprehensive assessment of SGs in naval vessels and looks into how different frequency systems could translate into a technical and energy efficiency. Analyses carried out in MATLAB/Simulink help to identify the best design solutions for each target system and thereby optimize system efficiency. For naval vessels the design and energy performance analysis of the shaft generator results in a reliable energy source becoming operational capabilities enhancement, mission duration extension and environmental friendliness through decreasing fuel consumption to describe this using proper metaphors; this study is going to propose frequency and voltage systems choice for naval vessels. The present paper is concerned with the following subjects:

- This study presents one of the first comprehensive analyses of shaft generator systems employed in naval ships.
- The study presents the findings obtained from investigations using real system data.
- Furthermore, the dynamic behavior of the system is simulated and evaluated by means of models developed in the MATLAB environment. As illustrated in Figure 1, the SG model under consideration is a prototypical representation of its kind.

(**a**) (**b**)

Figure 1. Model of shaft generator.

2. Ship Electrical Power System Structure

According to that, due to the continuous development and progress of electrical and electronic engineering on ships has changed to a great extent in ships electrical power systems installation. Figure 2 on the overview of three-phase ship's electrics power system includes diesel generators (DG), SG other type gensets, turbines generators, emergency gensets submersible transformer room, load center with relays and power cables as well as consumers [15].

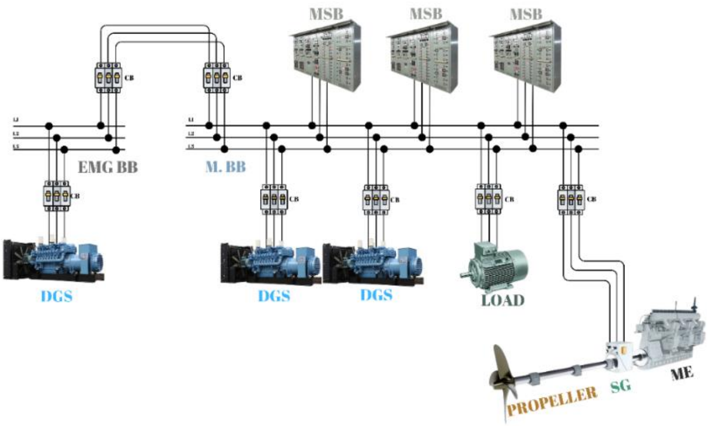

Figure 2. General diagram of the electrical power system of a three-phase vessel.

In ships that are equipped with electric propulsion systems, it is customary for the propulsion motors to be located at the main busbar systems. The utilization of power converters on such vessels magnifies the significance of power quality concerns in comparison to conventional ships [16]. The ship's power systems and terrestrial power distribution circuits negate many of the consequences of poor power management on the ship.

The following is a list of some of the most salient features of ship power systems:

- The utilization of on-board generators imposes constraints on the available space, thereby restricting potential for expansion.
- The system under discussion must include power converters and transformers, which are essential components in the modification of voltage and frequency levels. The system incorporates a limited number of distinct capacity generators, in conjunction with major starter-control systems. The system has been engineered to ensure peak performance and efficiency.

- It is imperative to acknowledge that certain power loads possess sufficient capacity to surpass the aggregate output of all installed generators when operated in conjunction.
- It is evident that the short circuit impedance of ship generators is relatively high.
- Non-linear loads are a common occurrence in ship power systems.
- Parallel operation of generators is possible.
- Installed loads show higher sensitivity to power quality compared to terrestrial power systems [17].

It is also important to note that ship generators have relatively high short circuit impedance. The utilization of non-linear loads has become a customary aspect in the domain of ship power systems, facilitating parallel generator operation. Installed loads show higher sensitivity to power quality compared to terrestrial power systems. These factors require the development of special engineering approaches in the design, operation and management processes of vessel electrical power systems.

In the domain of vessel propulsion systems, generators connected to the main propulsion shaft play a pivotal role in conjunction with generator sets, providing supplementary energy. In fixed propeller systems, the generators function at a constant speed during the operation of the main engine, thereby ensuring stable energy production, particularly in cruising mode. In propeller pitch-controlled systems, the generators can be utilized during maneuvers, provided that the engine speed remains constant.

This paper provides an introduction to the fundamental principles and historical development of shipboard electrical systems that utilize three-phase synchronous generators, diesel engine-driven sets. The system is powered from two bus sections with differing voltages by three DGs. This configuration has been designed to enhance the robustness and efficiency of marine power systems. The efficacy of this configuration is determined by conducting a performance evaluation, as it is imperative that the most efficient machine in power generation and distribution is identified.

As illustrated below, a standard ship's electrical system typically consists of a three-phase genset, driven by diesel engines, serving as the primary power source. It is important to note that the voltage rating of the two busbar sections powered by these generators is different. The DGs, in this configuration, are responsible for the generation of the requisite power. As demonstrated in Figure 3, the system under consideration involves the generation of electricity by a generator set comprising a shaft generator and three DGs.

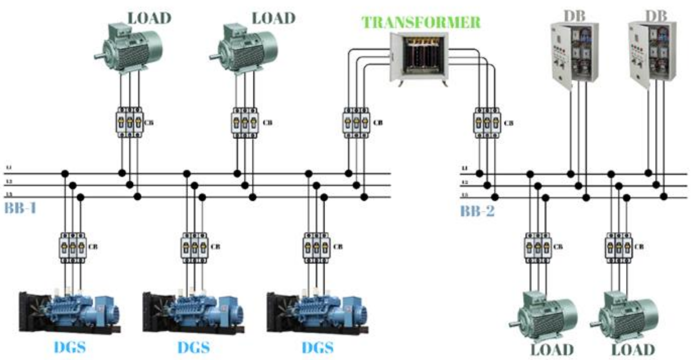

Figure 3. The conventional electrical structure is a ship electrical energy system structure.

Shaft generator systems have been shown to be fuel-efficient and to generate electrical power, thereby reducing the operational costs of ships. In comparison with conventional fuel-fired marine engine-generator sets, these systems offer a number of advantages in a variety of applications. These systems enhance the efficiency of the ship during operation at sea, thereby ensuring superior performance and reducing future operating costs. This paper investigates the architecture of ship energy systems with respect to shaft generator cycles for a comprehensive analysis and comparative evaluation of such systems with the operating conditions [18]. As illustrated in Figure 4, a system is presented in which electricity is generated by a generator set consisting of a SG and three DGs.

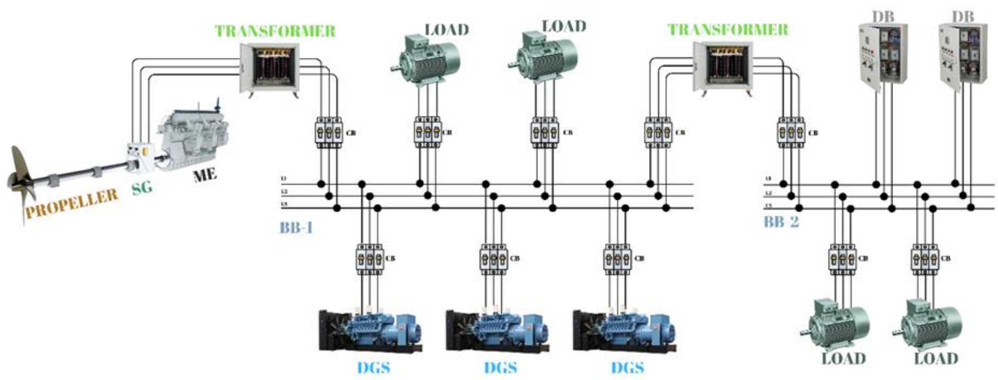

Figure 4. The shaft generator structure is defined as the ship electric power system structure.

3. Shaft Generator System

3.1. General Specifications of Shaft Generators

Energy efficiency in the field of shipbuilding continues to be a matter of concern. The high cost of energy has prompted ship owners to purchase new vessels or upgrade existing ones in order to reduce fuel consumption [11]. Prior to the implementation of technological solutions, it is imperative to assess the efficacy of such systems. The present study hypothesizes that ship consumers driven by the propeller shaft and powered by a shaft generator is a solution to this issue. It is acknowledged that different configurations can be used for different ship types and power plants. A generator-based solution, in particular, has been identified as a means of powering receivers, with the potential to significantly reduce fuel and operating costs by minimizing the number and hours of genset usage. [19].

The advantages of integrating a SG within the vessel's power generation system, as contrasted with the conventional reliance on a single main engine for propulsion, are becoming clearer. This approach also offers distinct technical and economic advantages, including the utilization of the main engine in conjunction with alternative power sources to drive the generator. [20].

The introduction of the ship's SG system dates back to its inception in 1982, with MAN B&W being among the early pioneers to explore its practical applications. Over the years, numerous models of shaft power generation systems have been developed and successfully employed in maritime operations. This innovative approach has garnered widespread interest and approval from ship owners and shipyards across the globe. The merits of integrating a SG into a vessel's power generation system, as against relying on just a single main engine for propulsion, have become more apparent. The integration of a SG into the ship's power generation system enables the utilization of the main engine's power to drive the generator in combination with other power sources, thus providing both technical and economic benefits [20].

This integration is particularly valued during extensive sea voyages, where the installed SG operates at peak efficiency. Remarkably, the power demand of a ship at sea typically accounts for only 5-10% of the main engine's capacity. Consequently, the shaft generator optimizing surplus power reduces the workload on the diesel driven generators and hence the fuel consumption. This contributes to the promotion of sustainability and extends the operational lifespan of the auxiliary generators. A notable advantage of shaft generators is that the cost of power production is only half that of a DG, making it a highly cost-effective and eco-friendly choice for the marine industry. [20].

Shaft generator systems have witnessed a surge in popularity within the domain of marine propulsion, attributable to the numerous advantages they offer in comparison to conventional DG systems. The majority of SGs are mounted on the prop shaft, situated between the main propulsion engine and the propeller gearbox. A proportion of engine power is converted to electricity by some SGs. The integration of SG systems with both DG systems and other forms of alternative power sources has the potential to enhance the energy efficiency of ships. It is imperative that SG systems are meticulously designed to ensure optimal performance and efficiency. A comprehensive evaluation of the electromagnetic properties of these systems is also a crucial aspect of their assessment. [14]. As illustrated in Figure 5, the SG is situated on a ship and is connected to the relevant systems.

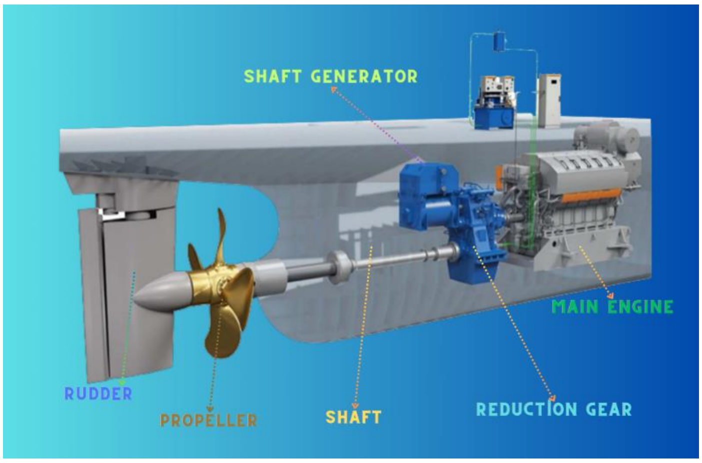

Figure 5. Ship structure consisting of shaft generator structure.

Systems incorporating SGs are favored for their energy efficiency and operational advantages, offering significant benefits for ships. These systems generate electricity in a cost-effective manner by utilizing the vessel's main engines, thereby reducing fuel consumption. The systems' compact design offers a distinct advantage in vessels where space is at a premium. In addition, the SG system offers ship owners a cost-effective solution, with low installation costs, while its lower noise levels compared to conventional generators allow for quieter operation in the vessel environment. A notable advantage of SG systems is their ability to provide uninterrupted power supply, a crucial aspect for operational continuity, due to their high reliability [14].

However, it should be noted that SG systems are not without their limitations. Primarily, as the ship is unable to generate electrical energy during port stays, alternative power sources are required. Additionally, the operation of the SG places an additional load on the ship's main engine, which necessitates meticulous management. Failure to do so may result in adverse effects on engine performance and operational efficiency. Consequently, a meticulous design and management process is imperative, taking into account the limitations and advantages inherent to SG systems [14].

3.2. Structure of Shaft Generator

Shaft generator systems are utilized as an efficient alternative in ship energy systems, with lower fuel consumption and operating costs when compared to conventional stationary diesel generator sets. This is due to their ability to generate electricity by taking mechanical energy directly from the main propulsion machine [21]. In the marine industry, the term 'shaft generator' is used to denote an alternating current (AC) generator, otherwise referred to as an alternator. This component is powered by the ship's primary engine. The vessel's propulsion system comprises a drive shaft connected to the propeller, which engages a large gearbox. The gearbox is capable of accommodating supplementary auxiliary shafts, the function of which may be to drive various pieces of equipment, including compressors, hydraulic pumps or alternators. In the context of marine engineering, it is pertinent to note that the alternator is frequently designated as a shaft generator.

Shaft generators are complex systems that convert mechanical energy into electrical energy, and their operating principles are based on certain physical principles to ensure that this conversion process takes place efficiently. Basically, SGs are based on the principle of electromagnetic induction, where the rotary motion of a motor is converted into an electric current by a combination of a magnetic field and a conductive coil. This process is based on the fact that, according to Faraday's law of induction, a conductor will produce an electric current when passed through a time-varying magnetic field.

During operation, the motor rotates the shaft and this rotation creates an interaction between the coils and the magnetic field of the installed rotor. The magnets on the rotor create the desired magnetic field as it rotates. This process causes the field to be interrupted by the coils, producing AC. The generated electrical current is then passed through a power electronics circuit to bring it to the required voltage level. The efficiency of these systems depends on the quality of the materials used, the design of the rotor and stator, and their placement and assembly.

In addition, SGs are supported by various control devices that provide the ability to optimize the system on the fly. For example, automatic control systems that regulate the output voltage and current increase the efficiency of SGs and provide protection in overload situations. In summary, the operating principle of SGs is both a reflection of the laws of physics and a product of modern engineering practice. In this way, the process of converting mechanical energy from both industrial and renewable sources into electrical energy is carried out with high efficiency.

As illustrated in Figure 6, the general structure and connection details of a typical SG are demonstrated. This generator is mechanically connected to the main propulsion system and generates electricity with the rotational motion it receives from the ship's main engine. It is evident that the SG depicted in Figure 6 is prepared for immediate utilization, with all necessary connections having been established on board.

(**a**) (**b**)

Figure 6. Typical shaft generator structure of military vessels.

3.3. Shaft Generator Model and Analysis

The purpose of this study is to analyze the performance of the SG under different voltage levels, output frequencies and pole numbers in the MATLAB/Simulink environment. The analysis will encompass the electrical characteristics of the generator, with a particular focus on how parameters such as output voltage, frequency stability, power quality, efficiency, and torque generation are influenced by alterations in the number of poles and system frequency. The objective of this analysis is to ascertain the most suitable configuration of SG for use in specialized applications, such as military ships, and to optimize the system according to the operating conditions. The simulation

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results under different scenarios will shed light on the strategies to be followed in system design and contribute to the balance between energy efficiency and performance.

Figure 7 shows a three-dimensional model of the SG structure from multiple angles.

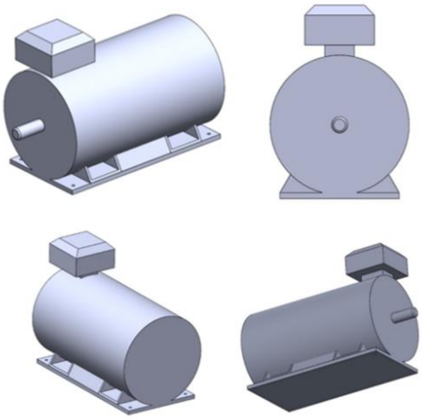
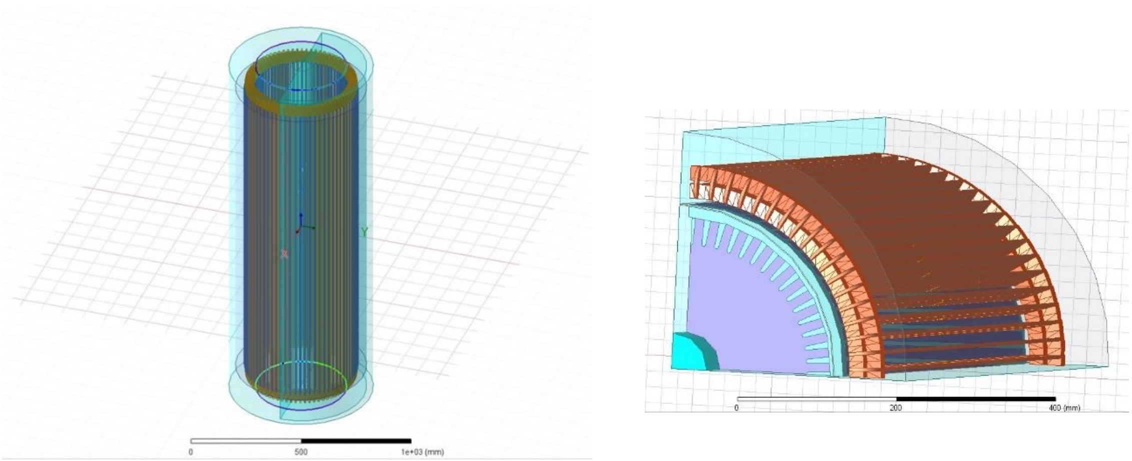


Figure 7. 3D model of the shaft generator structure.

In addition, the shaft generator was modelled for electromagnetic analysis in the ANSYS/Maxwell environment for better analysis. This was deemed the most suitable option due to the fact that shaft generators are electromagnetic devices, and the results of the analyses are time dependent. The designed shaft generator model is illustrated in Figure 8.



(**a**) (**b**)

Figure 8. ANSYS Maxwell design of the shaft generator structure.

The rotor rotating field always moves behind the stator rotating field and is less than the rotating field speed. Stator rotating field speed is called synchronous speed (n_s), rotor speed is called asynchronous speed (n_r). The speed difference between two revolutions is called slip (s). It can be demonstrated that, in the event of the total number of poles of the stator being *2P*, the number of double poles is *P* and the frequency of the applied voltage is *f*, the synchronous speed of an asynchronous motor is n_s. This equation is shown in equation 1.

$$n_s = \frac{120f}{2p} d/d \quad (1)$$

The angular velocity equation is expressed as follows

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$$\omega_s = \frac{120f}{2p} \cdot \frac{2\pi}{60} rad/s \tag{2}$$

Expressing the slip speed using these values

$$s = n_s - n_r (d/d) = \omega_s - \omega_r (rad/s) \tag{3}$$

Expressing the slip as a percentage

$$s = \frac{n_s - n_r}{n_s} = \frac{\omega_s - \omega_r}{\omega_s} \tag{4}$$

The rotor frequency is given as

$$f_r = s.f = \frac{n_s - n_r}{n_s} .f \tag{5}$$

The shaft generator model presented in Figure 9, which was created in MATLAB/Simulink environment based on real system data, allows the basic parameters such as stator and rotor currents, voltage characteristics, rotational speed and torque to be analyzed under varying power levels, frequency values and operating conditions. The developed model facilitates more effective decision-making in design and optimization processes by enabling comparative analysis of the effects of parameter variations on system performance. The overarching objective of the model is to enhance operational efficiency by facilitating a more comprehensive analysis of the dynamic response of SGs, particularly within the domains of marine engineering and electrical power generation systems.

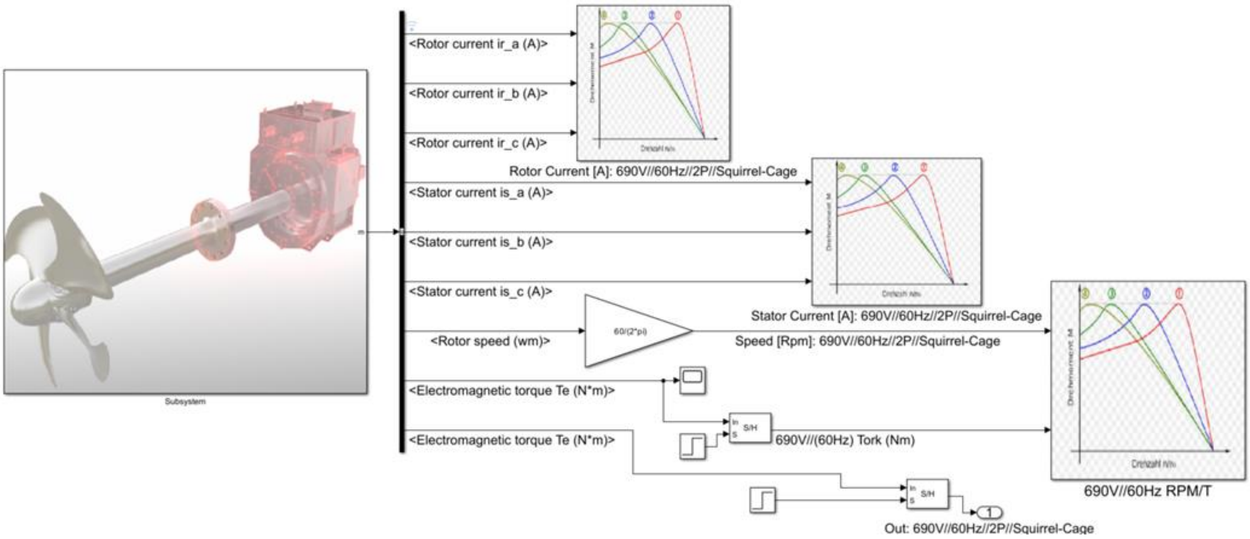

Figure 9. MATLAB/Simulink analysis depending on shaft generator, power and frequency parameters.

The analyses provided by the SG model developed using MATLAB/Simulink are as follows:

The analysis of stator and rotor currents is a method by which to understand the electrical performance of the system under a number of operating conditions. Within this framework, variations in current magnitudes, frequency content and harmonic levels are subjected to detailed analysis, with the effect of deviations and harmonics on system performance being rigorously evaluated. These analyses yield critical insights pertaining to system reliability and efficiency.

A detailed analysis has been conducted on the 690 V, 440 V, 400 V and 380 V systems, which are commonly utilized in ship electrical systems. In the course of the investigation, a range of parameters are evaluated, including harmonic content, current fluctuations, torque and speed stability. In addition, the system's behavior under a number of different operating conditions is observed and opportunities for improving performance are identified.

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The present study analyses the speed and torque behavior of shaft generator systems at frequencies of 50 Hz and 60 Hz for different power ratings. The investigation evaluates the dynamic response, stability and efficiency of the system and provides comprehensive insights into the effects of sudden load variations, as well as important performance criteria such as energy losses and mechanical stability.

These analyses facilitate the comparable valuation of basic electrical parameters such as stator and rotor currents, voltage profiles, speed and torque behavior of SG systems as a function of different power, frequency and operating modes. The data obtained is of significant importance for the more effective design and optimization of such systems in the marine industry. The selection of appropriate equipment and components during the design process can be made in a more informed manner thanks to these multifaceted analyses, and the system can operate at maximum efficiency. Furthermore, the analysis provides a strategic framework to increase energy efficiency and reduce operational costs in the long term by preparing the ground for further studies on harmonic components and the overall stability of the system.

4. Result and Discussion

This study involves a detailed, comparative analysis of two different shaft generator systems one with a 2-pole Squirrel Cage configuration and the other with a Double Squirrel Cage configuration that operate under 690 V voltage and 60 Hz frequency values. This analysis is conducted within the MATLAB/Simulink environment, with the primary objective of assessing the performance criteria of the two generator types and unveiling their dynamic responses under various operational conditions.

The investigative process commences with the analysis of the rotor and stator currents, followed by a comparative evaluation of their amplitudes, ripple levels and harmonic contents. An exhaustive analysis of the electrical behavior of both systems is conducted, with particular emphasis on the differences between the response time of the rotor current and the stability of the stator current. The results obtained from this study offer significant insights into the assessment of the systems' impact on energy efficiency and operational stability, thereby serving as a valuable reference point in the design process.

This analysis focuses on the behavior of speed and torque, which are of key importance in this study. The responses of both generator systems under various load scenarios are analyzed in detail by means of speed-torque curves obtained through simulations. Comparisons, especially in terms of speed variability and torque stability, clearly reveal the operational advantages and disadvantages of Squirrel Cage and Double Squirrel Cage structures. These analyses provide an in-depth evaluation of the responsive behavior of the systems to sudden load changes and their performance under constant operating conditions.

4.1. Shaft Generator Type Analysis

As demonstrated in Figure 10, the torque value of the Double Squirrel Cage shaft generator model decreases over time. The high torque value initially obtained is subject to a gradual decline as the generator accelerates. This observation indicates that this configuration offers a distinct advantage, particularly in applications such as heavy lifting operations and crane systems that necessitate high initial torque. However, in scenarios requiring uninterrupted and consistent speed operation, it is evident that the performance is constrained due to the decline in torque values.

Conversely, the Squirrel Cage SG model exhibits an increase in torque over time, reaching a maximum level. This maximum torque, estimated at approximately 2600 Nm, is attained at approximately 12 seconds, which is earlier than the 10 second mark for the Double Squirrel Cage model. Despite its initial lower torque output, the model's ability to steadily increase torque over time makes it an optimal choice for systems that demand sustained and consistent speed.

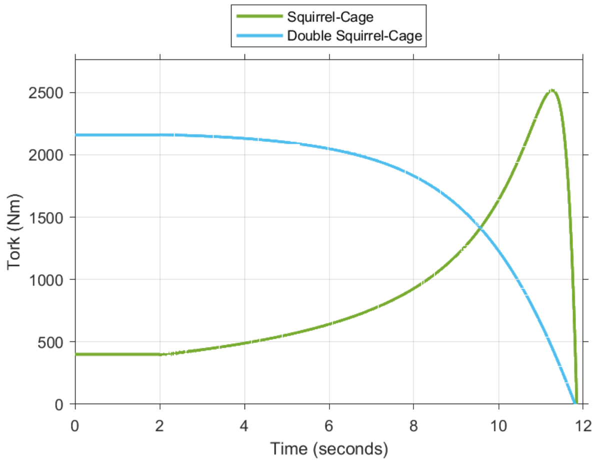

Figure 10. Comparative torque graph of Squirrel Cage ang Double Squirrel Cage system.

A thorough analysis of the data presented in Figure 11 reveals that the torque value remains constant at low speeds, signifying that the generator functions with high efficiency within this speed range. At medium speeds, the decline in torque is more regulated, indicating that the system maintains its operational balance. However, the rapid decrease in torque at high speeds suggests that the operation of the generator at these speeds is not efficient and that the optimal operating speeds should be reduced.

The analysis indicates that double squirrel cage SGs demonstrate optimal performance, particularly in systems necessitating high starting torque. This efficacy is attributed to the generator's capacity to generate substantial initial torque while sustaining a balanced acceleration. Conversely, the decline in torque with increasing speed signifies that this system is more appropriate for applications requiring low torque and consistent speed. This evaluation underscores the necessity for a judicious selection of the application domains of double squirrel cage shaft generators, in alignment with the prevailing parameters of operation.

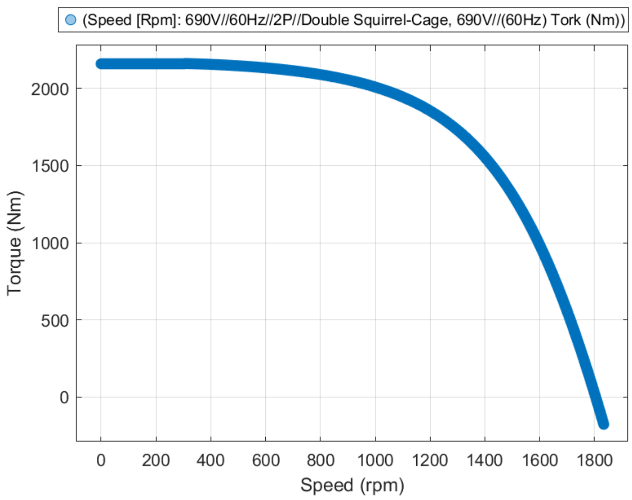

Figure 11. Speed / torque graph of Double Squirrel Cage model.

The high initial torque of the SG facilitates efficient operation of heavy loads, while the steady increase in speed over time demonstrates a balanced and controlled acceleration process. However, the observed decrease in torque as the speed increases indicates that the generator operates with optimal efficiency within a specific speed range. Double Squirrel Cage SGs offer an ideal solution for systems requiring large initial loads due to their high starting torque and stability as the speed

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increases. The negative correlation between torque and speed indicates that this type of generator is particularly effective in applications with constant speed and low torque requirements. The graphs in Figure 12 clearly demonstrate the necessity of careful evaluation when selecting SGs suitable for specific application areas.

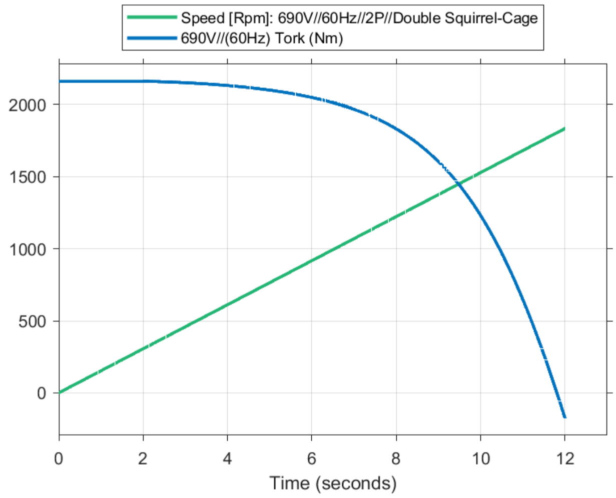

Figure 12. Double Squirrel Cage speed and torque graph on time.

As demonstrated in Figure 13, the SG displays consistent and balanced performance during operation, with the rotor currents aligning with the theoretically anticipated behavior of the three-phase system. This validates the model's precision. The operating voltage of 690 V instigates high-amplitude currents in the rotor windings, leading to the generation of a substantial magnetic field. This, in turn, facilitates the generator's capacity to produce high torque. The transient regime at start-up is rapidly damped, enabling the system to reach a steady state. The data thus demonstrate that the shaft generator is both design efficient and operationally reliable.

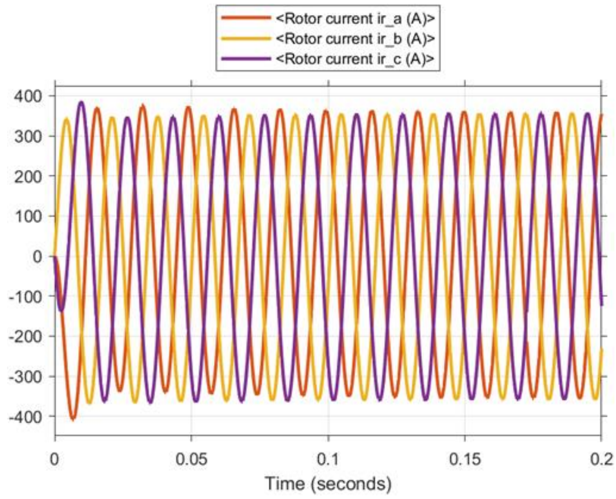

Figure 13. Rotor current graph of double squirrel cage system.

As illustrated in Figure 14, the SG functions within its nominal parameters, with the loads being connected to the SG in a balanced manner. When a system is connected to the grid, successful synchronization between the SG and the grid is indicated, thereby demonstrating that the SG is operating in a stable mechanical and electrical state. Consequently, the current operating state of the system is reliable, and efficient energy production is ensured.

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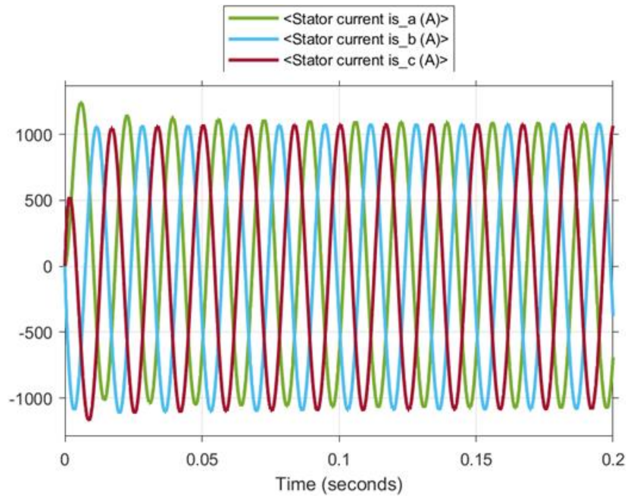

Figure 14. Stator current graph of double squirrel cage system.

As illustrated in Figure 15, the maximum torque is attained at a speed of approximately 1800 rpm, signifying that the SG has attained its maximum mechanical load capacity. It is noteworthy that an increase in load can precipitate instability in the system. Beyond this speed, the torque undergoes a rapid decline, which can be attributed to the mechanical stability of the SG. It is evident that by surpassing the synchronous speed of 1800 rpm, the generator experiences a decline in mechanical stability, leading to a reduction in torque production. The shaft generator's stable operating point is identified at speeds that are marginally below the maximum torque. This speed range corresponds to the operational range of the SG under conditions of rated load.

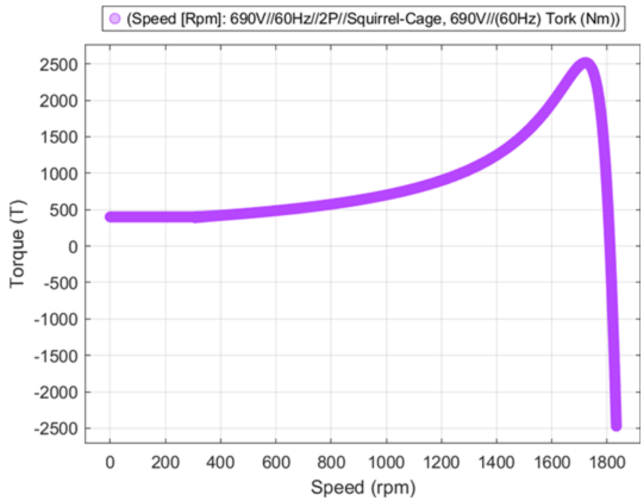

Figure 15. Squirrel Cage speed/torque graph.

As demonstrated in Figure 16, the variation of speed (rpm) and torque (Nm) of a 690 V, 60 Hz, 2-pole squirrel cage induction SG with respect to time is illustrated. In the time period of approximately ten seconds the speed approaches a constant value. This finding suggests that the SG has attained synchronous speed and stabilized in relation to the load torque.

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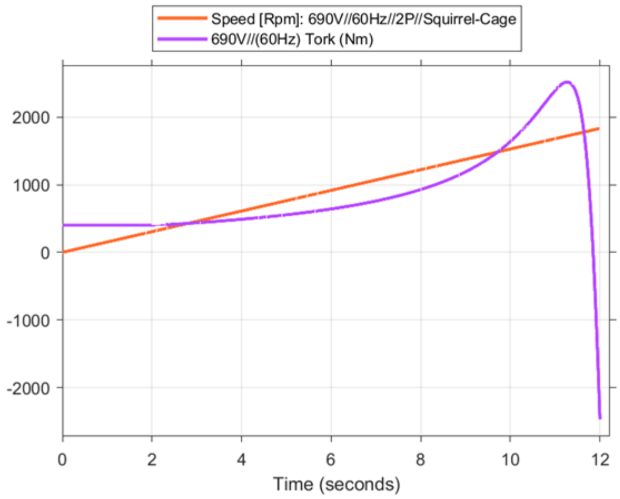

Figure 16. Squirrel Cage speed and torque comparison graph.

Figure 17 illustrates the time-dependent fluctuation of the currents in the rotor windings (ir_a, ir_b, ir_c) of a 690 V, 60 Hz, 2-pole squirrel-cage asynchronous shaft generator. These currents initially exhibit a rapid increase, eventually attaining a constant value. This phenomenon is known as the starting current effect of the shaft generator. It is evident that, in the absence of rotor rotation during the initial start-up phase, the currents within the rotor circuit exhibit elevated values. Over a brief period, these currents attain a constant amplitude and transition into a stable, sinusoidal configuration. The maintenance of the three-phase sinusoidal structure signifies the preservation of symmetry between the phases, thereby indicating the absence of any imbalance.

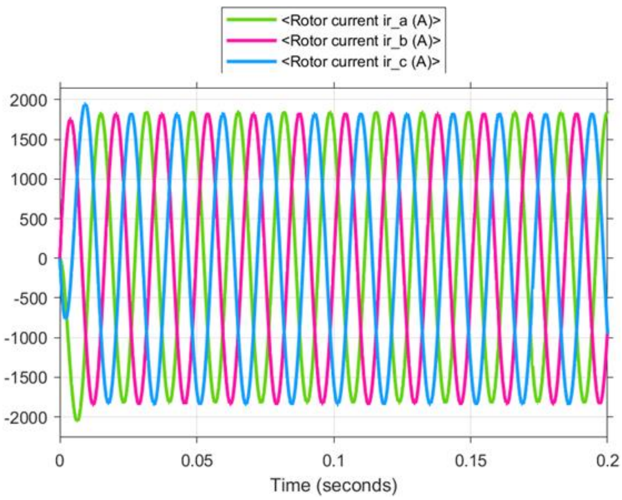

Figure 17. Squirrel Cage rotor current graph.

As illustrated in Figure 18, the stator currents of the shaft generator are generated in a smooth manner, and the generator operates in synchrony with the grid. The absence of any distortion in the current suggests that the SG is operating efficiently. However, the evaluation of high magnitudes of inrush currents may necessitate precise adjustments to the overcurrent protection systems, emphasizing the necessity for caution in this regard.

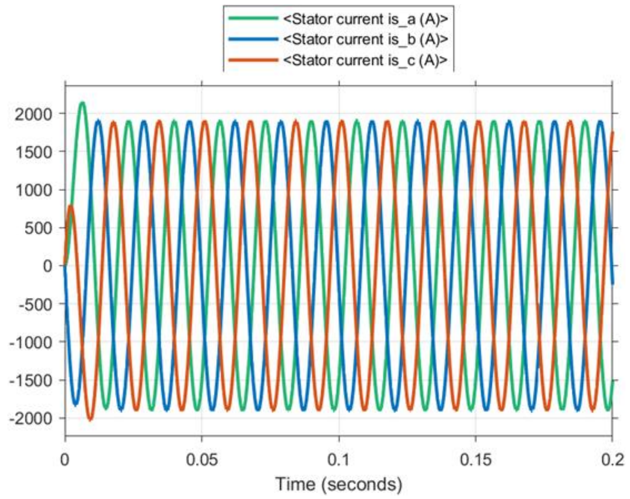

Figure 18. Squirrel Cage stator current graph.

4.2. Number of Poles Analysis

This study investigates the characteristic behavior of a squirrel cage SG operating at 690 V voltage and 60 Hz frequency for five different pole values. For this purpose, the torque values of the generator for different configurations of 2, 4, 6, 8 and 12 poles are measured and analyzed. The study investigates the effects of each pole number on the performance of the generator, with a particular focus on torque generation. Furthermore, the analysis encompassed a comprehensive evaluation of the disparities in generator efficiency and torque values across various pole numbers.

As demonstrated in Figure 19, Increasing the number of poles in a generator can result in alterations to the power generated. Specifically, SGs with a high pole number generally necessitate larger mechanical forces due to their operation at low speeds, which can potentially lead to power losses. Conversely, SGs with a higher pole count tend to exhibit higher torque at low speeds. Additionally, SGs operating at low speeds typically demonstrate reduced efficiency due to increased electrical losses and heat generation.

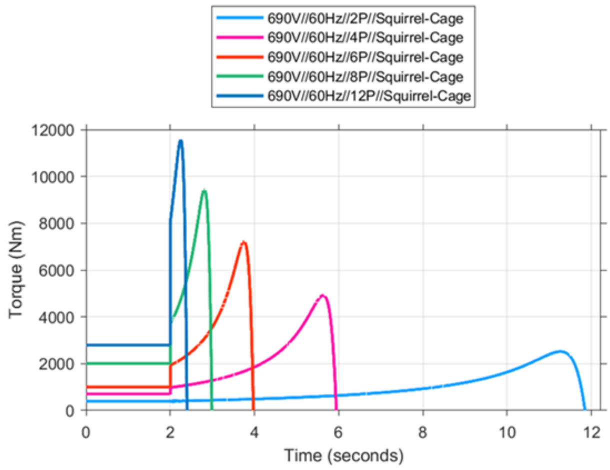

Figure 19. Torque/time graph according to number of poles.

The high torque capacity of 12-pole SGs is attributable to their capacity to operate at low speeds, a feature that is particularly advantageous in systems operating with heavy loads. Conversely, SGs with a reduced pole count, such as 2-pole generators, are favored in compact and efficient systems that operate at higher speeds.

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4.3. Voltage Characteristic Analysis

This research presents a comparative analysis of the effects on the rotor and stator, time-dependent analysis of the torque, and general performance characteristics of 2-pole squirrel-cage SG systems operating at 60 Hz. The analysis is conducted at different voltage levels, including 690 V, 440 V, 400 V, and 380 V, which are commonly utilized in ship applications. The objective of this analysis is to comprehensively evaluate the effects of each voltage level on rotor dynamics and stator voltages.

As demonstrated in Figure 20, the shaft generator operating at 690V exhibits the highest torque capacity and the most rapid in-crease in torque, at which point it attains its maximum torque value. In generators operating at lower voltage levels, torque is limited and the increase in torque is more gradual. Evidently, an augmentation in voltage gives rise to a proportional escalation in the shaft generator's torque capacity. This lends weight to the notion that the torque curve serves as a pivotal performance indicator, exhibiting a direct correlation with the applied voltage. At a voltage of 690 V, the SG demonstrates optimal torque output and efficiency. Conversely, a decline in voltage to levels ranging from 380 V to 400 V results in a reduction in efficiency and the observation of torque limitations. This observation suggests that lower voltage levels have a detrimental effect on the efficiency of the SG.

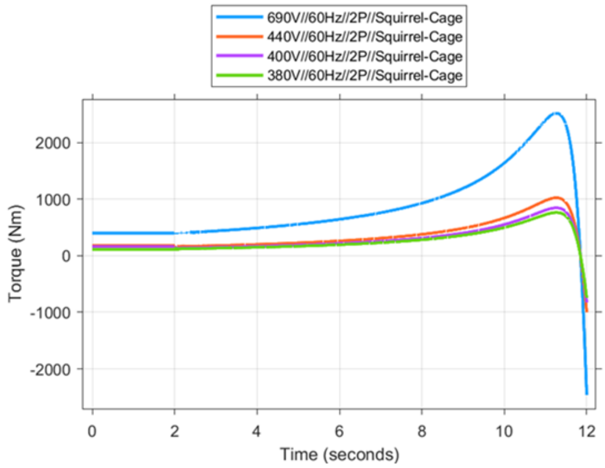

Figure 20. Torque/time graph for voltage characteristics.

4.4. Poles Characteristic Analysis

The 2-pole squirrel cage shaft generator system is analyzed in order to ascertain its characteristics at a 50 Hz frequency, with various voltage levels being considered, including 690 V, 440 V, 400 V and 380 V, which are widely utilized in ship applications.

As demonstrated in Figure 21, the SG exhibits an increased torque output at higher voltage levels. This indicates that squirrel cage SGs exhibit substantial performance characteristics contingent on the voltage level. The study demonstrates that maximum torque is attained at 690 V, while performance diminishes at reduced voltage levels. It is evident that for a constant initial torque value, higher voltage levels yield significantly higher and more rapid torque development. In summary, it is evident that when higher torque and acceleration performance are requirements, elevated voltage levels, such as 690 V, yield more efficient results.

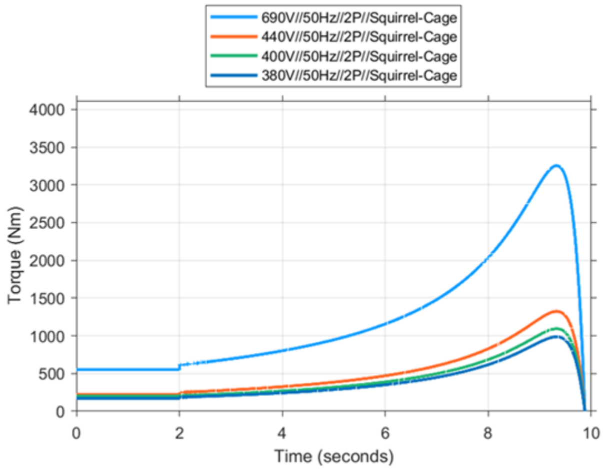

Figure 21. Poles Characteristic Analysis.

4.5. Frequency Characteristic Analysis

Figure 22 shows the time dependent variations of torque in a squirrel cage generator operating at 690 V and 60 Hz. Figure 21 demonstrates that, at both frequencies, the initial torques are negligible and almost equal (approximating 500 Nm). A shaft generator functioning at 50 Hz exhibits a significantly more rapid torque curve increase than a SG operating at 60 Hz. This is attributable to the fact that, at 50 Hz, the rotor operates at a lower synchronous speed, resulting in a higher slip rate.

As illustrated in Figure 22, the torque output at 50 Hz is notably higher than that at 60 Hz. It is crucial to acknowledge that a decline in frequency concomitantly leads to an enhancement in the slip ratio. Evidently, a reduction in frequency that is, from 60 Hz to 50 Hz results in a diminution in the slip rate of the SG and consequently an augmentation in torque. Notably, the torque production at 50 Hz exceeds by more than 75% of that attained at 60 Hz. Consequently, the effect of low frequency on shaft generator performance can be considered favorable. Conversely, low frequencies have the potential to negatively affect efficiency levels, which may lead to increased losses. The decline in instantaneous torque may be attributed to inherent limitations in mechanical or electrical systems. It is evident that at 50 Hz, the torque capacity of the shaft generator is amplified, which is instrumental in meeting the demands of high loads.

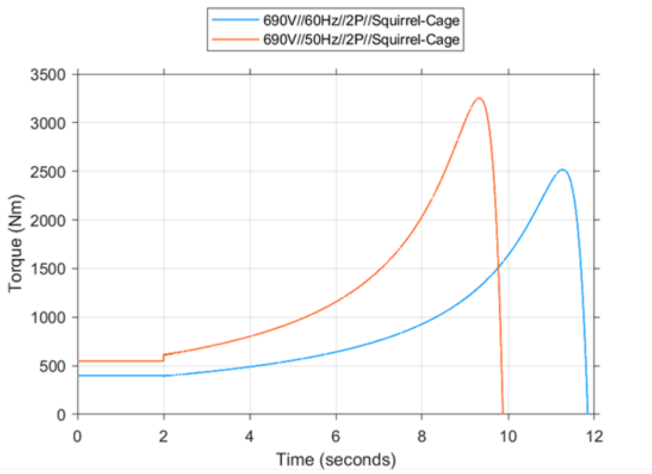

Figure 22. 690 V torque/time graph for 50 Hz and 60 Hz frequency values.

As illustrated in Figure 23, the torque-time variations of a squirrel cage generator operating at 440 V 50 Hz and 60 Hz show that initial torque values are approximately the same at these

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frequencies. This finding indicates that the frequency difference has a minor effect on the initial torque of the SGs. The torque curve of the SG operating at 50 Hz demonstrates that it rises more rapidly than at 60 Hz. The phenomenon under investigation can be attributed to the operating conditions of the rotor. Specifically, these conditions consist of a reduced synchronous speed and an elevated slip ratio at 60 Hz in comparison to 50 Hz. This results in an increased magnetic flux, which consequently leads to elevated torque production. The results obtained in the present study demonstrate that decreasing the operating frequency results in an augmentation in the torque capacity of the SG.

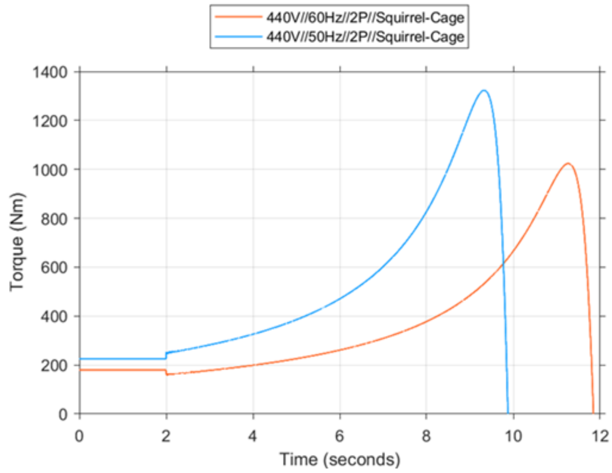

Figure 23. Torque/time graph for 440 V 50 Hz and 60 Hz frequency values.

The torque/time plot in Figure 24 provides significant data for comprehending the response of the SG at 400 V, 50 Hz and 60 Hz frequencies to frequency-dependent alterations. It is also noteworthy that, at a frequency of 50 Hz, after the maximum torque is reached, the torque undergoes a rapid decline. This phenomenon could be indicative of the loss of shaft generator stability under load at a certain point. In contrast, at 60 Hz, the fall after the maximum torque is more gradual and occurs over a longer period of time, as does the rise.

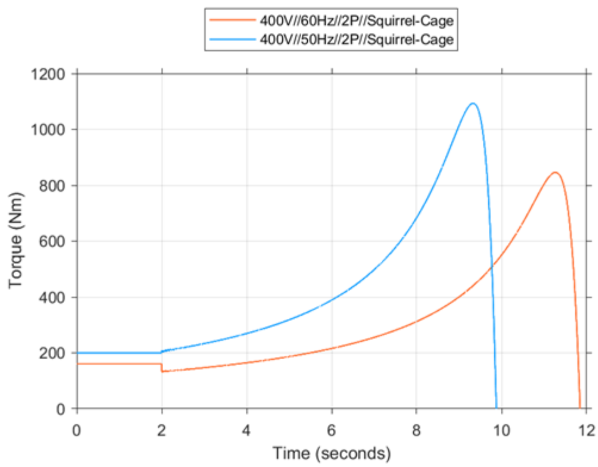

Figure 24. Torque/time graph at 400 V 50 Hz and 60 Hz frequency.

As demonstrated in Figure 25, an analysis of the torque/time plot was conducted to investigate the response of the SG to frequency variation at low voltage (50 Hz and 60 Hz) at 380 V. The initial torque values at both 50 Hz and 60 Hz frequencies were found to be approximately equal (200 Nm), indicating that the initial torque is not significantly influenced by frequency variations. The initial torque remains constant at both frequencies. The maximum torque for the 50 Hz frequency is approximately 900 Nm, while for the 60 Hz frequency the maximum torque is lower, at approximately 700 Nm. However, the 50 Hz frequency exhibits a higher maximum torque, which is an advantageous feature in applications requiring high starting or peak torque, while the 60 Hz frequency, although giving a lower maximum torque, exhibits superior stability.

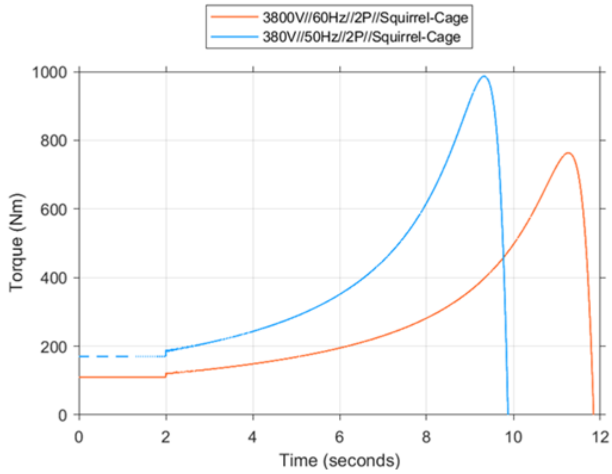

Figure 25. Torque/time graph at 380 V 50 Hz and 60 Hz frequency.

This analysis demonstrates the variability in SG performance under various low voltage and different frequency scenarios. It provides guidance on the selection of optimal frequency and voltage values, tailored for specific applications.

The parameters of the simulation model and datasheet parameters for optimum values are listed in detail in Table 1.

Table 1. Design parameters of shaft generator model for datasheet and analysis.

Parameters	Datasheet Values	Analysis Values
Generator Type	Squirrel Cage	Squirrel Cage
Connection Type	Star	Delta
Rated Power	1500kW	800kW
Rated Voltage	690V	690V
Frequency	50Hz	60Hz
Speed	1036rpm	3560rpm
Current	1572	780A
Torque	14292Nm	2500Nn
Poles	6p	2p

5. Conclusions

This paper presents a thorough analysis of rotor shapes, frequencies and voltages affecting the performance of shaft generators on naval ships. It proposes a method for selecting the most suitable generator, taking into account the specific requirements of the application. The findings of this study will facilitate the optimization of responsiveness and reliability of industrial applications over time, with simultaneous improvements in energy efficiency.

In this study, the MATLAB/Simulink environment is utilized for the analysis of shaft generators employed on naval ships. This analysis was conducted to furnish a comprehensive evaluation of the electromagnetic performance, operational dynamics and effectiveness of the generators within the

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overall system integration. The findings of this study have facilitated the identification of pivotal parameters for enhancing designs and ensuring operational reliability.

A comparative analysis of the speed, torque and frequency-dependent dynamics of squirrel cage and double squirrel cage rotor types for naval ships was conducted, and their performance in different operational scenarios was compared. The results obtained demonstrate that double squirrel cage structures offer advantages in applications requiring high starting torque, while single squirrel cage structures offer higher efficiency at nominal speed. In addition, the impact of varying voltage and frequency levels on the performance of the shaft generator has been the subject of rigorous investigation. The findings will be useful in selecting suitable shaft generators for engineering applications and system design.

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Data Availability Statement: The data presented in this study are available at the request of the corresponding author. The data are not publicly available due to the content of confidential information/trade secrets in them.

Conflicts of Interest: The authors declare no conflicts of interest.

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