



**TÜRKİYE CUMHURİYETİ
ADANA ALPARSLAN TÜRKER SCIENCE AND TECHNOLOGY
UNIVERSITY**

**GRADUATE SCHOOL
ELECTRICAL AND ELECTRONIC ENGINEERING DEPARTMENT**

**DESIGN, OPTIMIZATION AND ENERGY EFFICIENCY ANALYSIS
OF A SHAFT GENERATOR FOR MILITARY SHIPS**

KAMER GÖKBULUT BELLİ

Ph.D.



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ADANA, 2025

DECLARATION OF CONFORMITY

In this thesis study, which was prepared following the thesis writing rules of Adana Alparslan Türkeş Science and Technology University Institute of Graduate School, I declare that I provide all the information, documents, evaluations and results in accordance with scientific ethics and moral codes without resorting to any means or assistance that would be contrary to scientific ethics and traditions. I also declare that I refer to all of the articles I used in this study with appropriate references and accept all moral and legal consequences if a situation is found contrary to my statement regarding my work.

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ÖZET

DESIGN, OPTIMIZATION AND ENERGY EFFICIENCY ANALYSIS OF A SHAFT GENERATOR FOR MILITARY SHIPS

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Doktora, Elektrik-Elektronik Mühendisliği Anabilim Dalı

Danışman: Doç. Dr. Tuğçe DEMİRDELEN

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Denizcilik sektörü, küresel ticarete kritik bir rol oynayan ve önemi giderek artan bir alan haline gelmiştir. Deniz ticaretinin artan hacminden kaynaklanan emisyonları azaltmak amacıyla Uluslararası Denizcilik Örgütü (IMO) bir dizi yönetmelik yayınlamıştır. Bu düzenlemelere uymak ve enerji verimliliğini artırmak için sektördeki şirketler mevcut sistemlerin iyileştirilmesine ve operasyonel süreçlerin geliştirilmesine odaklanmıştır. Askeri gemilerdeki enerji sistemlerinin konfigürasyonu operasyonel gerekliliklere, gemi yapısına ve geminin faaliyet göstereceği coğrafi bölgelere bağlı olarak değişkenlik göstermektedir. Bu bağlamda, gemilerde kullanılan 50 Hz ve 60 Hz frekanslı sistemlerin teknik, performans ve enerji verimliliği üzerindeki etkilerinin karşılaştırmalı bir analizine ihtiyaç duyulmaktadır.

Bu tez, şaft jeneratörlerinin askeri gemilerdeki rolüne ilişkin kapsamlı bir inceleme sunmakta ve frekans, gerilim özellikleri ve kutup sayısına odaklanarak güç sistemleri üzerindeki etkilerinin ayrıntılı bir analizini sağlamaktadır. Çalışma, şaft jeneratörlerinin mekanik ve elektrik enerjisi gereksinimlerini karşılamadaki katkısını sistem optimizasyonu ve enerji verimliliği perspektifinden analiz etmeye devam etmektedir. ANSYS/Maxwell ve Matlab/Simulink'te gerçekleştirilen analizler, askeri gemiler için optimum değerlerin seçiminin söz konusu sistemin gereksinimlerine ve taleplerine bağlı olduğunu göstermektedir.

Anahtar Kelimeler: ANSYS/Maxwell; Matlab/Simulink, askeri gemiler; enerji verimliliği, şaft jeneratör.

ABSTRACT

DESIGN, OPTIMIZATION AND ENERGY EFFICIENCY ANALYSIS OF A SHAFT GENERATOR FOR MILITARY SHIPS

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Supervisor: Assoc. Prof. Dr. Tuğçe DEMİRDELEN

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The maritime sector has become an increasingly significant domain, playing a critical role in global trade. In an effort to mitigate the emissions resulting from the burgeoning volume of maritime trade, the International Maritime Organisation (IMO) has promulgated a series of regulations. In order to comply with these regulations and improve energy efficiency, companies in the sector have concentrated on upgrading existing systems and improving operational processes. The configuration of energy systems on board naval ships is subject to variation depending on operational requirements, ship structure and the geographical regions where the ship will operate. In this context, a comparison of the technical, performance and energy efficiency impacts of 50 Hz and 60 Hz frequency systems used on ships is required.

This thesis presents a comprehensive discussion of the role of shaft generators on naval ships and provides a detailed analysis of their impact on power systems, focusing on frequency, voltage characteristics and number of poles. The study goes on to analyse the contribution of shaft generators in meeting mechanical and electrical energy requirements from the perspective of system optimisation and energy efficiency. The analyses performed in ANSYS/Maxwell and Matlab/Simulink demonstrate that the selection of optimal values for naval ships is contingent on the requirements and demands of the specific system in question.

Keywords: ANSYS/Maxwell; energy efficiency; MATLAB/Simulink, military ships; shaft generator

Dedication

I would like to express my sincere thanks to my valuable advisor Assoc. Prof. Dr. Tuğçe DEMİRDELEN for her knowledge, experience and support in the preparation of this thesis.

I wish to express my deepest gratitude to my mother Fatma GÖKBULUT, my father Murat GÖKBULUT and my sister Betül GÖKBULUT for their endless support, encouragement and patience. I would like to thank my dear husband Onur BELLİ, who has encouraged me in every project and job in my professional life, and who has not spared her endless belief and support, especially during this thesis process.

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LIST OF ABBREVIATIONS

IMO	: International Maritime Organization
Hz	: Hertz
AC	: Alternatig Current
DC	: Direct Current
PTO	: Power Take Off
PTI	: Power Take In
WHRS	: Waste Heat Recovery System
BDFIG	: Double Fed Induction Generator
RW	: Rotor Winding
CW	: Control Winding
DFIM	: Doubly Fed Induction Machine
PTH	: Power Take Home
IM	: Induction Machine
CO ₂	: Carbon Dioxide
SVPWM	: Space Vector Pulse Width Modulation
VSCF	: Variable Speed Constant Frequency
kW	: KiloWatt
QOS	: Quality of Service
SG	: Shaft Generator
DFIM	: Doubly
PMSG	: Permanent Magnet Synchronous Generator
SPSG	: Salient-Pole Synchronous Generator
PID	: Proportional Integral Derivative
BDFM	: Brushless Doubly-Fed Machine
DSW	: Double-Sine Wound
SCR	: Silicon-Controlled Rectifiers
VSCF	: Variable
PSV	: Platform Supply Vessel
LVAC	: Low-Voltage Alternatig Current

AFE	: Active Front End
MVAC	: Medium-Voltage Alternating Current
LVDC	: Low-Voltage Direct Current
MVDC	: Medium-Voltage Direct Current
IM	: Induction Machine
SPG	: Ship-Borne Power Grid
IGBT	: Insulated Gate Bipolar Transistor
PWM	: Pulse Width Modulation
EPS	: Electric Power System
SGI	: Shaft Generating Installation
LNG	: Liquefied Natural Gas
APS	: Auxiliary Power System
DM	: Diesel Mechanical
DE	: Diesel Electrical
HP	: Hybrid Propulsion
EEOI	: Energy Efficiency Operational Indicator
ESS	: Energy Storage System
DG	: Diesel Generators
TG	: Turbine Generators
MSB	: Main Switchboard
SC	: Synchronized Generator
HF	: Harmonic Filter
BMSB	: Bow Main Switchboard
SMSB	: Aft Main Switchboard
GTG	: Gas Turbine Generator
BTIB	: Busbar Tie Breaker
POD	: Drive Type Propulsion Unit
CPP	: Controllable Pitch Propeller
GHG	: Greenhouse Gas
EEDI	: Energy Efficiency Design Index
SEEMP	: Ship Energy Efficiency Management Plan
IEE	: International Energy Efficiency
IAPP	: International Air Pollution Prevention

MCR : Maximum Continuous Power
SFC : Specific Fuel Consumption



LIST OF SYMBOLS

P_{ME}	: Main Engine Power
C_f	: Emission Rate
SFC	: Amount of Fuel Burned
Capacity	: Ship's Capacity
V_{ref}	: Speed of the Ship
P_{AE}	: Auxiliary Engine Power
C	: Fuel to CO ₂ Factor
f_j	: Correction Factor For Capacity
f_w	: Correction Factor For Performance
f_i	: Correction Factor For Efficiency
P	: Power
SFC_{AE}	: Amount of Fuel Burned For Auxiliary Engine
SFC_{ME}	: Amount of Fuel Burned For Main Engine
P_{PTO}	: Power of Power Take Of
Nm	: Newton Meter
A	: Amper
T	: Torque
Hz	: Hertz
V	: Volt
d axis	: Magnetic field axis
q axis	: Torque axis
L_d	: D Axis Inductance
L_q	: Q Axis Inductance
L_m	: Magnetic conjugate inductance
V_d	: D Axis Voltage
V_q	: Q Axis Voltage
I_d	: D Axis Current
I_q	: Q Axis Current
I_f	: Current through the field winding

W	: Watt
<i>f</i>	: Frequency
T	: Time Period
t	: Time
<i>p</i>	: Pole
<i>i_r</i>	: Rotor Current
<i>i_s</i>	: Stator Current
<i>n_s</i>	: Number of Slots for Stator
<i>n_r</i>	: Number of Slots for Rotor
<i>R_s</i>	: Resistance of Stator Windings
<i>ω</i>	: Rotor Angular Speed
<i>λ</i>	: Magnetic Flux
rpm	: Speed
<i>P_{PTO,NP}</i>	: Nameplate Power of the PTO
<i>B</i>	: Magnetic flux density
<i>H</i>	: Magnetic field strength
<i>μ</i>	: Magnetic permeability
N	: Number of winding turns
<i>e_d</i>	: D Axis Induced Voltage
<i>e_q</i>	: Q Axis Induced Voltage
<i>τ_e</i>	: Electromagnetic Moment

1. INTRODUCTION

The maritime industry plays a pivotal role in global trade, with its importance growing exponentially. In particular, over the past decade, the level of maritime trade has increased significantly in order to meet the demands of the sector. In order to reduce the emissions caused by this intensity, the International Maritime Organization (IMO) has introduced a series of regulations. In order to comply with the aforementioned regulations and achieve greater energy efficiency, maritime companies in the sector have engaged in a variety of research and development initiatives. While the initial approach to these efforts is the renewal of existing systems, the renewal process also presents a considerable financial challenge. Consequently, maritime companies are striving to comply with the IMO's emission regulations by assessing the efficiency of existing systems and implementing more efficient operational procedures. In order to enhance the energy efficiency of ships, it is first necessary to ascertain the current efficiency level, obtain data that can be subjected to analysis, and then build system improvements upon this data. The increase in technological applications in the maritime sector in recent years, coupled with the ease of obtaining data from ships, has led to the collection of voyage data from these vessels. This data encompasses a range of information types, including meteorological data encountered during the voyage route, external factors, data obtained from machine sensors, and details related to the ship's internal dynamics.

The primary role of shaft generators in military ships is to address high load factors aboard. This is related to the amount of area of use required, both in terms of energy. Shaft generators facilitate the full range of mechanical and electrical energy demands.

It is imperative to note that the ship's propulsion is only required during manoeuvring to avoid damage or in the event of evasive action in the face of damage. The mechanical energy is of paramount importance during emergency events, such as moving with great speed to escape or changing position in case of collision. In this manner, shaft generators fulfil the primary needs of the propulsion system, thereby supporting the ship's intended operation.

The electrical demand is more associated with the ship's internal systems. This occurs when the ship is not engaged in movement, but rather utilising its internal systems. Electric power can be particularly important in operating multiple systems concurrently, including ventilation, transfer systems, onboard generators, weapon systems, and other critical infrastructures. The utilisation of electrical energy is of paramount importance in ensuring the effective functioning of these systems, thereby enhancing the ship's overall energy capacity. In conclusion, shaft generators offer a versatile solution that improves the operational effectiveness and energy efficiency of naval vessels by meeting both mechanical and electrical energy requirements. The necessity of shaft generators on naval vessels is further compounded by the imperative to ensure uninterrupted operation of systems and optimised energy resources on these platforms, which are subject to high load variability.



Figure 1.1. Naval Ship (Bilgen, M. E., 2024)

It is evident that the shaft generator, when in operation, fulfils all the requirements of a ship's mains without limitations. It is imperative to ensure the reliable initiation and cessation of large consumers in the absence of voltage and frequency fluctuations, thereby facilitating the generation of the requisite active and reactive power. In the design phase, specific considerations are given due consideration in order to meet the unique requirements of military

vessels. This encompasses the selection of robust and rugged components that are capable of withstanding harsh environments, including generators, prime movers, and power conversion equipment. The design also incorporates redundancy and fault-tolerant features to ensure continuous power availability in critical situations. This is especially important for military ships. It allows the ship to safely maintain its position, keep its systems operating and arrive in port in any emergency (Xu et al., 2009, Sarigiannidis et al., 2015). Unlike other vessels, military ships are fully redundant in vital systems. Factors such as cylinder temperatures, main engine cooling water, fuel inlet temperature in the shaft generator cause an increase in the shaft generator temperature. If these temperature values and the temperature ranges at the hottest point can be determined, it can lessen the aging of shaft generators. The determination of these values can be achieved through the utilisation of ANSYS/Maxwell and Matlab/Simulink programmes, thereby ensuring the longevity of the shaft generator.

The energy systems employed in military ships are contingent on the operational requirements of the vessel and the geographical area in which it is to be deployed. In this context, the frequency values utilised in ships generally vary between 50 Hz and 60 Hz. The majority of newly constructed military ships in the Turkish inventory utilise 50 Hz, though there are also vessels operating at 60 Hz.

A detailed analysis of the operational advantages and technical requirements of these varying frequencies is therefore essential. The present study aims to provide a meticulous analysis of the technical, performance and energy utilisation implications of utilising 50 Hz and 60 Hz frequency systems. The results obtained from this study are intended to provide a comprehensive evaluation of the effectiveness of engineering approaches and operational choices for the utilisation of different frequency ratings.

The voltage scales of shipboard systems are subject to variation, contingent on the frequency employed. The utilisation of high voltage systems is typically favoured in order to minimise voltage losses and enhance energy transmission efficiency. As the voltage increases, current values decrease, thus enabling the cable cross-sections of fuses, equipment and connected

systems to be selected smaller. This reduction in weight consequently results in a corresponding increase in the ship's overall cost.

However, the implementation of high voltage necessitates the incorporation of transformers within the energy system, which can introduce additional costs. Transformer necessity must, therefore, be considered as a pivotal factor in system design, and a total cost-benefit analysis should be performed.



Figure 1.2. Naval Ship (Kaya, G., & Kaya, G. 2024)

The present study undertakes a detailed analysis of the effects of frequency and voltage characteristics on system design in ship power systems. By comparing different frequency and voltage levels, the effects on the efficiency, cost and operational performance of ship energy systems are evaluated. The findings yielded from this study offer valuable insights that will inform the optimal design of ship energy systems.



(a)



(b)

Figure 1.3 (a) Alternator of shaft generator and (b) Clutch of shaft generator

The application of optimization techniques is intended to ensure maximum performance and efficiency of the shaft generator system. This involves the precise calibration of control algorithms, the optimisation of power distribution, and the minimisation of losses within the system. Optimisation of shaft generator operation has been demonstrated to reduce fuel consumption, thereby extending the ship's operational range and enhancing mission capabilities. In addition, the optimisation of power distribution ensures that power is allocated efficiently to various onboard systems. This process minimises waste and maximises energy utilisation. As illustrated in Figure 1.3, the shaft generator and its connection details are depicted in a general view.

Energy efficiency analysis is crucial for military ships to optimize fuel consumption and increase overall operational efficiency. The analysis of power consumption patterns and the identification of areas of high energy usage are fundamental to the implementation of energy-saving measures. This may encompass load management, power demand forecasting, and the integration of energy storage systems. Energy efficiency analysis facilitates the identification of opportunities for the incorporation of renewable energy sources, such as solar or wind power, with a view to reducing reliance on traditional fuel sources and enhancing sustainability.

The design, optimization, and energy efficiency analysis of a shaft generator for military ships ensure that a reliable and efficient power supply is in place for vital operations. It is evident that these endeavours serve to enhance operational capabilities, extend mission endurance, and reduce environmental impact by minimising fuel consumption and maximising energy utilisation.

2. LITERATURE REVIEW

The primary focus of studies in the domain of ship electrification and energy management is on enhancing the effectiveness and sustainability of power generation systems. In this regard, shaft generator systems are of particular significance in meeting the energy requirements of the vessel's electrical grid. Shaft generator systems facilitate the conversion of mechanical energy obtained from the vessel's main engine into electrical energy, thereby ensuring the effective fulfilment of energy demands on board. A review of the extant literature reveals that studies on the relative merits and drawbacks of these systems present them as a hybrid alternative to the completely electric propulsion design. (Prousalidis et al., 2005).

Research in the field examines how shaft generator systems affect the operational performance of the ship's electrical network under different operating modes. In these investigations, energy efficiency, system stability and electrical characteristics are evaluated using a typical shaft generator system. Simulation-based investigations offer more in-depth insights into the performance of the system, providing an important reference point for future development work.

Nishikata et al. (1997) focus on the stable performance of the shaft generator system driven by the propulsion engine of the vessel. The system's capacity to deliver adequate electrical power to the vessel's electrical apparatus is the subject of this discussion. The research derives a set of system equations to determine parameters concerning the output voltage's total harmonic distortion. A detailed analysis of the steady-state performance reveals that a wide operating range can be achieved with a small AC reactor's reactance in the inverter's outputs. Additionally, effects of the inverter's leading angle of commutation on the system performance are clarified.

Mitcham and Grum (1998) research the advancements and initiatives by Rolls Royce in developing electric propulsion systems for vehicles in the automotive, marine, and aerospace sectors. The company is focusing on motor generator design, efficient power electronic devices, and high-performance permanent magnets to drive progress in energy management. Their goal

is to capitalize on the potential of more electric aircraft and simplify existing systems while reducing ownership costs. Engine architectures with electrically driven accessories and embedded motor generators are being explored, along with the concept of oil-free engines operating on Active Magnetic Bearings. Establishing an all-electric interface between the engine and the airframe is considered crucial. Overall, the article provides insights into ongoing efforts and the future outlook for electric propulsion systems in transportation, highlighting Rolls Royce's involvement.

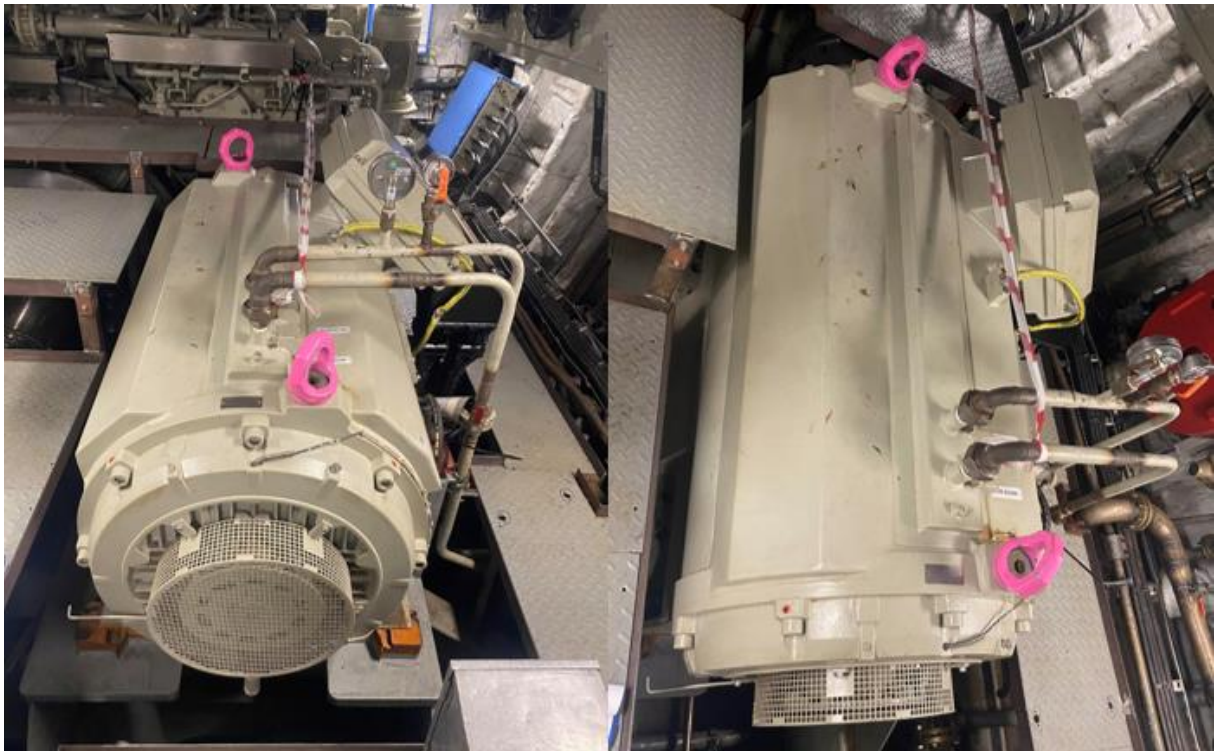


Figure 2.1. Model of shaft generator

Clegg et al. (1999) offer the design of the electrical power systems for a fleet of container ships constructed in 1996. The ships were specifically designed for low manning levels and cost-effective operations. The power systems featured a 6.6 kV, 60 Hz main distribution system, a shaft generator that utilized power from the main engine, and diesel-engine driven generators for backup power. Detailed explanations of the power system components, such as the shaft generator, variable frequency converter, and control system, are provided in the paper.

Nishikata et al. (2000) conducted a study on the implementation of a shaft generator system on board ships. This system utilises a proportion of the propulsion engine's power to generate electrical energy. To generate alternating current power with a constant voltage and a constant frequency, an externally commutated thyristor inverter is generally employed in view of the variable speed range of the main engine. The authors develop a set of system equations to estimate the total harmonic distortion of the output voltage and analyze the impact of the inverter's leading angle and the AC reactor's reactance on system performance and operation limits. The study further proposes a methodology for the consideration of system losses, with the objective of achieving more precise calculation outcomes. In conclusion, the authors tackle the apparent requirement for power that the synchronous condenser must supply in order to facilitate the provision of reactive power within the system.

McCoy (2002) examines the significant growth and diversity in the construction of electric propulsion ships since the 1980s. From cruise liners to amphibious assault ships, various vessels have adopted electric propulsion, leading to a revolution in the marine industry. Despite its transformative impact, this technology has received limited attention outside the industry. The paper provides a concise overview of the developments in electric propulsion ships, explores the driving factors behind this resurgence, and discusses the potential future advancements in the field. By highlighting the progress and potential of electrically propelled ships, this research sheds light on an important and evolving aspect of maritime transportation.

Mindykowski (2003) discuss the evaluation of electrical energy quality in power systems operating under non-sinusoidal conditions, such as real-world scenarios. The author presents a three-part framework that covers the fundamental definitions of power quality and its assessment, methodologies for calculating electrical power quality indices using suitable mathematical tools, and the necessary instrumentation for conducting power quality assessments. Each component is described and analyzed, with real data from ship electrical power systems serving as examples. The central objective of this study is to furnish a detailed comprehension of the evaluation of electrical power quality in practical applications, leveraging authentic real-world data to substantiate the analysis.

Doerry et al. (2005) examined the U.S. Navy's electrical power system design, which emphasised continuity as well as survivability of the supplied electrical power. However, there is an absence of specific measures or metrics that have been formulated to assess the continuity of service. The authors propose a Quality of Service (QOS) measuring tool to address this gap and aid in the design of shipboard power systems. The QOS metric is derived from the likelihood of the power system maintaining uninterrupted power supply to support the ship's operations for each load. The QOS is influenced by various factors including the ratings, reliability, and failure modes of prime movers, power conversion equipment, load equipment, and system configuration. These factors collectively impact the ability of the power system to meet the required continuity of power and support the ship's missions. Although incorporating design features that prioritize QOS may enhance the resilience of the system, the designer must consider both survivability and QOS for different failure modes.

Haznadar et al. (2005) present a numerical calculation method that is employed to analyse the characteristics of a low-speed ship's generator that has been installed in the shafting between the main propulsion engine and the propeller. The method is utilised to assess the performance of the generator under both no-load and full-load conditions. The specific design of this generator requires a numerical analysis of its electromagnetic state. The authors used the MagNet 6.16 programming package, based on the finite element method, to perform analysis. Based on the numerical analysis, all relevant characteristics of the generator are determined, providing valuable insights into its performance under different load conditions.

Tatsuta et al. (2005) conducted a study into a novel wind energy conversion system that employs a shaft generator system, a configuration that is commonly utilised in maritime vessels. The researchers elucidate the arrangement of the proposed system and derive the equations that describe its operation. The study delves into the steady-state characteristics of the generator system. To facilitate the research, an experimental setup is employed to simulate wind turbine properties within a laboratory environment. Additionally, the paper explores the system's transient responses when there are variations in wind velocity. These experimental results closely align with the simulated results, confirming the effectiveness of the proposed theory.

Yijian et al. (2007) presents a new-type marine shaft-driven generator system that utilizes an IGBT technology-based PWM converter to convert varying mechanical energy into fixed-frequency and voltage AC energy. The system utilizes space vector control to ensure a consistent voltage and frequency output from the generator. This enables the efficient supply of both active power and reactive power to the vessel's load. The system aims to achieve energy-saving benefits through its design and operation.

McCoy and Amy Jr (2009) explore the resurgence of electric ships in the end of the 1980s and beginning of the 1990s, focusing on the re-powering of the Queen Elizabeth 2 as a notable example. It highlights advancements in propulsion motor and drive systems, leading to improved efficiency and compactness. The article investigates the current systems and technologies used in naval warships and commercial ships while speculating on future advancements. The goal is to understand the present state of electric ship technology and anticipate its future development in propulsion systems.

Xu et al. (2009) investigate the shaft generator that utilizes silicon-controlled rectifiers (SCR) and is driven by the primary propulsion shaft of the ship. The research paper commences with a presentation of an outline of the configuration of the SCR shaft generator, subsequently analysing its power supply characteristics during normal operation in addition to instances of decreased output. Subsequently, mathematical models were developed to describe the field current control process and inverted angle control mechanism of the SCR shaft generator. The simulation results demonstrate that the behaviour of the SCR shaft generator, as modelled, aligns to that of practical systems. This finding serves to substantiate the rationality of the mathematical model employed for the control processes of the marine SCR shaft generator.

Michtti et al. (2010) discuss the integration of ship control systems and the application of dynamic simulation techniques in the Fremm project. It focuses on the wide integration of control systems across the ship and the use of dynamic simulations for testing and analysis. The objective of this project is to enhance the ship's overall performance, efficiency, and safety. The paper highlights the benefits of integrating control systems and using dynamic simulations, such as enhanced system understanding, better fault detection and isolation, and improved system

response. The Fremm project is utilized as a practical example to showcase the efficacy of these approaches in ship design and operation.

Tarnapowicz's (2010) study explores the stability of frequency in shipping systems utilising high-power shaft generators. The prevailing electronic systems, which are predicated on thyristor inverters, are not without their drawbacks. In order to surmount the aforementioned issues, the article proposes the utilisation of multi-level inverters constructed with fully controllable valves, specifically Insulated Gate Bipolar Transistors (IGBTs). The objective of this solution is twofold: firstly, to eliminate the disadvantages associated with thyristor inverters, and secondly, to improve the stability of frequency in the operation of high-power shaft generators.



Figure 2.2. Naval Ships (Elkon)

Gully et al. (2011) conducted a study on the fuel consumption of a container vessel and explored methodologies for reducing fuel demand. The study models fuel usage from the primary propulsion engines and auxiliary engines that utilise a Power Take Off (PTO) system. The outcome of the study highlighted opportunities for the retrofitting of the PTO system with a modernised shaft motor-generator system, known as an Auxiliary Power System (APS). The implementation of this system would enable electrification and potential fuel savings. The research project under consideration here evaluates the potential fuel savings at different levels of the APS, taking into account a variety of scenarios of operation. The implementation of the APS facilitates the exploration of innovative approaches by operators and manufacturers to

reduce fuel costs, which often account for a substantial proportion of total voyage expenses in the domain of commercial marine transportation.

Kruszewski's (2011) study investigates the integration of monitoring and control systems for the main engine, shaft generator, and pitch propeller in a ship's propulsion plant. The proposal calls for the implementation of a Supervisory Optimal Fuzzy Logic Controller, a sophisticated and adaptable system, to oversee the components in question. This controller is part of a larger "Sail by Wire" Supervisory System aimed at ensuring the ship's safety performance. The abstract emphasizes the integrated, optimal, adaptive, and intelligent nature of the control and monitoring system and its significance in maintaining ship safety.

Prosalidis et al. (2011) examine the current trends in ship technology, which aim to enhance energy efficiency by extensively electrifying ship systems, including propulsion. The electrification of ships offers a compelling solution for greener and more efficient operations. The paper provides an overview of emerging trends in electric energy generator schemes, highlighting the challenges they present and the need to revise traditional design and operation standards. The analysis is grounded in the findings of a model that incorporates a vessel's generic power grid, comprising multiple supply units. By analyzing these developments, the paper emphasizes the importance of electrification in improving environmental sustainability and efficiency in ships. It also underscores the evolving considerations and requirements associated with this transition.

In their seminal study, Xiong and Wang (2011) examined a novel brushless doubly-fed machine (BDFM) outfitted with a meticulously engineered double-sine wound rotor (DSW rotor), expressly designed for independent vessel shaft generator applications. The investigators performed performance analyses on a prototype DSW-rotor BDFM with 2 and 4 pole pairs, using a combined finite element analysis modelling and experimental strategy. The investigation chiefly concentrated on the examination of magnetic fields, air-gap flux density distribution, and on-load characteristics of the prototype machine. The empirical evidence corroborated the theoretical analysis, thereby validating the hypothesis that the prototype DSW-rotor BDFM demonstrated optimal performance.

Wang et al. (2011) investigate the nonlinear torsional vibration of a diesel generator shaft system with a flexible rubber coupling. A multi-degree-of-freedom lumped-parameter mechanical model is established, taking into account the nonlinear restoring force in the coupling. The vibration differential equations are derived using the Lagrange equation, and numerical computation methods are employed to obtain the results. The obtained computational outcomes are juxtaposed with the linear system equations and real-world testing data in order to examine and investigate the nonlinear vibration properties of the diesel generator shaft system.

Prousalidis et al. (2012) conducted an investigative study with the objective of delivering a comprehensive analysis of the role of a shaft generator in enhancing the efficiency of a vessel's power system, with a particular focus on optimising vessel operations. The main focus of this study is to examine the interaction between the shaft generator and the power management system, to consider their impact on the operating point of the electrical generators and propulsion engine, and to explore how these factors influence the achievement of optimum operating conditions.

Sarasquete et al. (2012) conducted an analysis of the vessel's technical specifications, machinery, and fuel-saving possibilities. For ships equipped with controllable pitch propellers and shaft generators, the implementation of a variable speed generation system can be a particularly salient solution. The system under discussion enables the synchronous generator to operate at variable speeds, thereby enhancing both energy efficiency and hydrodynamics. Running at partial load enhances performance, while optimizing the propeller's pitch and advance ratio reduces cavitation and noise issues. The implementation of this system necessitates a consideration of the diesel engine's novel operational envelope, with the potential for a redesign of the propeller blades to achieve further enhancements. Evaluating electrical loads and space requirements is essential for retrofitting projects, which are increasingly common in response to rising fuel prices.

In the 2012 paper by Solla et al., a novel method for enhancing energy efficiency and reducing expenditure in a shaft generator is introduced. This innovative apparatus is capable of

functioning at multiple speeds across a substantial range of engine revolutions per minute (rpm). The configuration under consideration comprises a rectifier that receives the variable voltage and frequency three-phase AC current from the shaft generator and transforms it into DC current. Subsequently, an inverter is utilised to reverse the process, thereby converting the three-phase AC current back into a direct current, while ensuring the maintenance of a constant voltage and frequency.

Herdzik (2013) discusses the challenges associated with selecting the power system and propulsion system configuration for offshore ships, especially when incorporating a dynamic positioning system. The design process becomes complex due to the need for long-term engine operation at low loads during station keeping or dynamic positioning, as well as the potential for quick and significant changes in power demand for industrial operations. The choice between Diesel Mechanical (DM), Diesel Electrical (DE), and hybrid (HP) propulsion systems affects parameters such as fuel consumption, overall efficiency, and operational costs. This presentation provides an overview of these challenges and their impact on vessel design, highlighting the importance of selecting the appropriate power system components.

Tafanidis et al. (2013) examine the economic analysis of a warship power system that incorporates an energy storage system (ESS). The study utilizes previously developed analytic formulas to estimate the system's marginal cost, employing a nonlinear mathematical equation. The proposed methodology offers a valuable tool for the technical and economic evaluation of such systems. The paper applies this methodology to a Hellenic Navy MEKO type frigate, presenting the analysis and results of the electric power system. The study emphasizes the potential advantages of ESS in warship power systems, including reduced fuel consumption, improved efficiency, and enhanced reliability.

Chen and Wang (2014) put forward the proposal of utilising a brushless doubly fed induction generator (BDFIG) in the context of a shaft generator that necessitates both variable speed and constant frequency operation. The researchers also examined the characteristics of a shaft generator. In a meticulously devised BDFIG, magnetic fields of two and four pole pairs are induced in the rotor windings (RW) without any direct coupling between the primary winding

(PW) and the control winding (CW). Consequently, the steady-state equivalent circuit of the BDFIG is derived by separating the space vector representations of the BDFIG.

Dermentzoglou's (2014) research focuses on the modelling and control strategy of the doubly fed induction machine, which is employed as a shaft generator within the ship's electrical system. The machine has been engineered to reduce CO₂ emissions and fuel consumption, with a control system that utilises a vector control technique to maintain a constant electrical torque. The research demonstrates effective speed regulation in both motor and generator modes.

Diao et al. (2014) present a position sensorless control strategy for a doubly fed induction machine (DFIM) applied in vessel shaft generation systems. The approach under consideration employs direct voltage control and Space Vector Pulse Width Modulation (SVPWM) to guarantee a consistent frequency and voltage, even in the face of variations in load and main engine speed. This innovative method obviates the necessity for a speed signal or position encoder by calibrating the reference stator vector angle to expeditiously and precisely attain the desired stator voltage. The efficacy of the proposed approach is demonstrated by simulation results, which also confirm its capacity to achieve the desired results.

Gao et al. (2014) conducted research into the utilisation of the brushless doubly fed machine, driven by the ship's main engine, for the purpose of generating electricity and reducing operating costs by decreasing reliance on diesel generator sets. The present study conducts an analysis of the mathematical model and control principles of the independent generator system using scalar control, proposing a control strategy that does not require a speed sensor. A simulation model of the marine shaft generator system was established and tested, thereby demonstrating the effectiveness of the proposed system.

Kanellos et al. (2014) proposed the introduction of an integrative control system with the objective of optimising vessel operations in relation to both economic efficiency and environmental impact. Furthermore, the proposal encompasses the implementation of a revised energy efficiency operation indicator. This would facilitate real-time assessment of gas emissions. The present research work comprises simulations of a vessel power system equipped

with full electric propulsion, thereby demonstrating the efficacy of the proposed system. The outcomes of this study contribute to the advancement of economically optimized and environmentally friendly ship operations. This research project has expanded the existing knowledge base by considering full electric propulsion systems and introducing an integrated control system. The findings of the study offer valuable insights for ship operators and designers, ensuring compliance with emissions regulations and fuel economy standards.

Kruszewski (2014) concentrates on the implementation of monitoring and control systems for the primary components of a vessel's propulsion system, specifically the main engine, shaft generator, and pitch propeller. While each component has its own controllers, there is a need for a higher-level supervisory controller to gather and monitor the entire system. In order to fulfil this requirement, the study recommends the implementation of a supervisory controller based on neural network principles. The study is structured into three parts. The first part discusses the problems and goals connected to controller usage. The second part presents a dynamic model that includes the basic parts of the ship and its propulsion system. Finally, the third part gives a full description of the dynamic system that includes the supervisory neural controller. Computer simulations of the system are carried out using Matlab/Simulink with a neural network database.

Liu et al. (2014) conducted a study on vessel operational modes and proposed a control strategy for brushless doubly-fed generators (BDFG). The utilisation of BDFGs offers several advantages, including reduced inverter capacity requirements, diminished capital and operating expenditures, and enhanced reliability. The implementation of the control strategy occurs within a hardware environment, with physical verification being conducted as a concomitant process. The results demonstrate that the control method exhibits excellent dynamic performance in response to changes in speed and power.



Figure 2.3. Naval Ships (Elkon)

Mindykowski (2014) explores the problem of electrical power quality on vessels, examining its current state and anticipating future challenges. The assessment and improvement of power quality are central to the discussion, with an analysis of existing ambiguities and proposed measures to address them. The paper delves into two key layers of power quality improvement: technological solutions and the competences required by the ship's staff. Future expectations and challenges are outlined, considering both legal and professional aspects, with a focus on mitigating the risk of vessel accidents. Theoretical considerations are complemented by experimental results, providing valuable insights for enhancing power quality in practical ship operations.

Liu et al. (2015) present a stand-alone shaft generator system based on a brushless doubly fed machine (BDFM). The system is designed to maintain a constant output voltage magnitude and frequency of the BDFM, even in conditions of variable rotor speed and load, by regulating the excitation current of the control winding (CW). The study puts forward a control scheme and offers a hardware design for the control system. The present study investigates the dynamic performance and energy-saving capabilities of a proposed shaft generator system, as tested on a container vessel. The results demonstrate that the system functions effectively and is capable of significant energy savings.

Mindykowski and Tarasiuk (2015) investigate the issue of power quality in vessel systems and its impact on ship safety. The growing significance of power quality in light of advancements in energy generation and utilization methods is emphasized. The challenges faced by vessel

designers, crew members, and ship classification societies are examined in the context of legal requirements and engineering best practices. The paper presents the author's perspective on the ongoing discussion following a specific ship incident. Key aspects such as power quality characterization, setting limits, measurement approaches, and enhancing ship classification society regulations and procedures are discussed. The aim is to prevent potential catastrophic consequences arising from deteriorating power quality in ships.

Sarigiannidis et al. (2015) propose an improved Shaft Generator (SG) for a Ro-Ro ship, with a particular focus on a low-speed direct-driven Permanent Magnet Synchronous Generator (PMSG) that has been optimised. The present study compares the PMSG with a high-speed Salient-Pole Synchronous Generator (SPSG) and demonstrates that the low-speed PMSG is a suitable option for SG applications. The study further delves into the design of a drive system for assimilating the PMSG into the vessel's electrical grid, accentuating the generator control methodology and converter topology. Additionally, the study explores the economic benefits of the proposed SG system, highlighting its potential for reducing fuel consumption and achieving cost savings.

Schoyen and Sow's (2015) study examined the potential for fuel savings through the retrofitting of a shaft generator frequency converter during ship operation. The retrofit allows for the vessel to reduce steam while maintaining voltage and frequency. The research proffers a decision-making framework predicated upon a cost-benefit analysis and risk identification. The findings indicate that fuel prices exert the most substantial influence on profitability, and the cost of retrofitting is considerable in the short term. The primary customers for the conversion are liner operators. The study also identifies eight risk areas that affect retrofit profitability and maps them on a risk matrix from acceptable to intolerable.

Wang et al. (2015) propose a ship energy efficiency monitoring and control system that takes into account environmental factors. It aims to optimize the energy efficiency of vessels by calculating the Vessel Energy Efficiency Operational Indicator (EEOI) and providing real-time monitoring. The system adjusts the propulsion system to operate at the optimum energy

efficiency level and reduces emissions. Overall, the system enhances vessel energy efficiency by considering environmental factors and optimizing energy usage.

Zhang et al. (2015) tackle the issue of achieving variable speed constant frequency and constant voltage in shaft power generation systems. The suggested methodology integrates a vector control strategy that relies on stator power winding flux orientation with fuzzy adaptive Proportional Integral Derivative (PID) controllers, enabling independent control of a brushless doubly-fed shaft generator (BDFG) system's operations. The study employs simulation studies utilising Matlab/Simulink software to evaluate the anti-interference performance of the BDFG shaft generator system on the vessel. The results of this study suggest that the system demonstrates optimal dynamic and static stability when utilising this particular control strategy.

Barros and Diego (2016) offer a thorough literature review focusing on the energy quality in marine energy systems. It highlights the significance of power quality in terms of efficient energy usage, navigation safety, and overall well-being at sea. This study critically investigates and discusses essential factors, including voltage and frequency variations, voltage fluctuations, transient events, voltage irregularities, fault identification and classification, harmonic distortion, voltage imbalances, power quality measurement instruments, and regulations governing electrical installations on ships. The objective is to provide a comprehensive overview of power quality issues in the maritime industry, serving as a valuable resource for professionals and researchers in the field.

Gkotzia et al. (2016) set out a cogent argument for the utilisation of shaft electric machines as a viable intermediate step on the road to fully electrifying vessels. The authors identify two problems that must be addressed: the necessity for power dispatch according to the Lagrange method or dynamic models, and the economic viability of installing shaft generators. While the authors have already addressed the first issue in previous work, this paper focuses on the second. The authors introduce a mathematical model based on the Lagrange method and the technical constraints of the engines, and apply it to a general-purpose ship. Subsequently, the authors conducted a sensitivity analysis on various factors, including fuel price, operational life period, interest rate, and the vessel's propulsion power duration curve. By examining these

factors, the study gains valuable insights into the crucial elements that strongly influence the economic viability of shaft generator installations. These results contribute to the advancement of knowledge regarding the financial aspects and considerations involved in the implementation of shaft generator systems.

Liu and Wang (2016) research a 700-kW brushless doubly fed induction generator (BDFIG) designed specifically for use as a stand-alone ship shaft generator. The authors employ a multi-pitch unequal-turn-coil wound rotor, which incorporates the principles of tooth harmonics and a sinusoidal winding structure. The objective of this design is twofold: firstly, to reduce harmonic content, and secondly, to enhance the coupling between the two stator windings. The research team analysed 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. Utilising simulation analysis and empirical experimentation, the researchers substantiated that the prototype apparatus is capable of generating the requisite output power and attaining the stipulated efficiency. Moreover, the findings of the present study indicate that the wound rotor structure is well-suited for high-power brushless doubly fed machines.

Michalopoulos et al. (2016) explored the electrification of vessel propulsion systems, with a particular focus on the utilisation of shaft electric machines for partial electrification. The text is concerned with the discrepancy between power distribution methodologies employed on board seafaring vessels and those utilised in continental power systems. It puts forward a novel algorithm for the management of power, which is intended to be optimal. The algorithm under consideration takes into account the integration of shaft electric machines, the operational limitations of the vessel, and the environmental regulations that have been enforced by the International Maritime Organization (IMO). The purpose of the present analysis is to undertake a comparative study of various ship propulsion and power generation configurations, utilising real-world data from engines, generators, shaft generators, and other constituent components. The findings demonstrate the cost-saving benefits of implementing the proposed algorithm in ship power system operations. The research under scrutiny herein demonstrates the potential advantages of incorporating shaft electric machines into vessel propulsion

systems, and moreover presents an optimised approach to the management of power, with the resultant enhancement of efficiency and reduction of costs.



Figure 2.4. Naval Ships (Elkon)

Sarigiannidis et al. (2016) investigate the development and implementation of an improvement to the Shaft Generator (SG) for a practical Ro-Ro ship. This system integrates the Permanent Magnet Synchronous Generator (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 research 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. It delves into the design of the machine and power converter control subsystems, optimizing them based on specific operational characteristics. Additionally, the controller design undergoes refinement, and the system's performance is assessed under various conditions. The findings highlight that the proposed SHG system delivers vital grid services, acts as an emergency propulsion mechanism, and achieves a little bit decrease in fuel consumption compared to conventional SG systems during typical voyages.

Skjong et al. (2016) offer a historical overview of the utilization of electricity in marine vessels, highlighting its evolution over time. It explores the transition from early applications of electric

light bulbs for illumination to the emergence of fully electric marine vessels powered by batteries. The article discusses the advantages and challenges associated with electricity usage in marine power systems, taking into account conversion technologies like power electronics and battery energy storage. It emphasizes the importance of reevaluating standards concerning power quality, safety, integrity, and stability in ship power systems. Additionally, the article underscores the need for future research in this field.

Xia et al. (2016) carried out research on the use of a variable-speed constant-frequency (VSCF) control system for vessel shaft generators, analysing its characteristics during the process of grid-connection. A mathematical model of the vector control technique is established, with the stator flux of the doubly-fed induction generator (DFIG) forming the basis of this model. The control strategy for grid-connection under no-load conditions and power decoupling is then investigated. In order to simulate the entire system process, ranging from grid-connection to power generation, a simulation model is developed using time-sharing modelling in Matlab/Simulink. The results demonstrate that the DFIG system exhibits favorable performance in terms of tracking reference voltage and stabilizing frequency. It shows satisfactory dynamic and steady-state characteristics even when subjected to varying generator speed or load. The present study corroborates the efficacy of the VSCF control system for vessel shaft generators.

Xia et al. (2016) conducted an investigation into the operational principles of a control system known as variable-speed constant-frequency (VSCF) for ship shaft generators. The investigation meticulously appraised the control tasks and operational characteristics of the system prior to and following grid-connection. Utilising the mathematical model of the doubly-fed induction generator (DFIG), the researchers have developed a mathematical model for a vector control technique based on the stator flux of the generator. Furthermore, the study investigates control strategies for no-load grid-connection and power decoupling using stator flux-oriented vector control technology. In order 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 findings of the simulation indicate that the DFIG system exhibits optimal functionality in terms of its ability to track reference voltage, stabilise frequency, and sustain both satisfactory dynamic and steady-state characteristics, even in

conditions involving variable generator speeds and loads. The present simulation investigation validates the system's accuracy and effectiveness, confirming that the variable-speed constant-frequency control system for shaft generators functions as intended.

Avdeyev and Vyngra (2017) set out the key findings on the significance of energy efficiency in the shipping and vessel construction industry. In the context of elevated energy expenditures, shipowners are undertaking investments in new vessels and implementing upgrades to existing ones with the objective of decreasing fuel consumption. The researchers emphasise the significance of conducting a thorough analysis of system performance prior to the implementation of any technological solution, with the objective of ensuring a successful application and the assurance of economic efficiency. One such solution that has been proposed is the utilisation of a shaft generator, powered by a propeller shaft, to ensure a uninterrupted power supply for shipboard consumers. Depending on the type of vessel and power plant, various configurations of ship power plants are utilised. The utilisation of a generator to facilitate the provision of power to receivers during vessel movement has the potential to curtail the number of operational generating sets and operating hours. This, in turn, can engender substantial cost savings on fuel and lubricants for individual actuating mechanisms.

Kruszewski and Seghir (2017) present the Supervisory 'Sail by Wire' Control System, which integrates ship systems for complete ship control. It introduces an ideal controller for the vessel's propulsion system that detects critical situations, provides warnings, and reports them to the ship's operator. The controller uses data from subsystems to manage ship dynamics and operations, including identifying and compensating for failures. The 'Sail by Wire' Supervisory Controller offers a major study and proposes an innovative approach to addressing critical situations in shipping, aligned with common European strategies and decisions.

Kamala et al. (2018) examined different propulsion system architectures for platform supply ships (PSVs) and compares their performance in terms of fuel consumption, emissions, weight, volume, efficiency, and reliability. The conventional low-voltage AC (LVAC) system is compared with alternative architectures, including LVAC with active front end (AFE) converter, medium-voltage AC (MVAC), low-voltage DC (LVDC), and medium-voltage DC

(MVDC). The performance evaluation considers factors such as fuel consumption, emissions, weight, volume, efficiency, and reliability. Based on the assessment, the most suitable architecture for the PSV application is found to be LVDC, followed by MVDC, LVAC with AFE, MVAC, and the conventional LVAC system.



Figure 2.5. Naval Ships (Elkon)

Leclerc et al. (2018) present the performance of high torque density induction machine driven by a transformerless variable speed drive. The authors highlight the advantages of using variable speed drives for large power take-off (PTO) applications, where fixed pitch propellers are utilized. By employing a power take-in (PTI) mode, operational flexibility is achieved, allowing for optimization of energy consumption by regulating the available power from a waste heat recovery system (WHRS).

Sokolov et al. (2018) research to improve the stability of ship equipment operations by examining the factors that impact reliability. The main goal is to enhance the reliability of ship power plants by evaluating various influencing factors. The findings from this evaluation are used to develop systems and devices that can make decisions and compensate for the effects of operational parameters on the performance of diesel engines. The study includes analyzing the engine's operation with different loads and utilizes an algorithm to optimize parameters. The

calculations and analysis are based on real parameters, providing valuable insights for enhancing the reliability of ship power plants.

Wegrzyn (2018) examine the reliability criteria for designing power supply systems in commercial ships, with a particular focus on Main Switchboard arrangements and receiver installations. The importance of safety and quality in these systems is emphasized. Through analysis and practical examples, the paper explores the essence of this matter and presents practical conclusions to improve the reliability of power supply systems. The objective is to ensure reliable and efficient power distribution in merchant ships, considering the unique challenges and requirements of the maritime environment.

In the study by Zhao et al. (2018), the application of a doubly-fed induction machine (DFIM) with a partial rated converter as a shaft generator system is discussed. While the DFIM does indeed have the capability to be used for adjustable speed operations, it is noteworthy that it lacks the ability to self-start under the power take me home mode when the main engine is not operational. In light of this limitation, the study puts forward a solution that entails the initiation of the equipment in the induction machine (IM) mode, thereby drawing power from the ship-borne power grid (SPG). Consequently, the system undergoes a seamless transition to the doubly-fed induction machine (DFIM) mode once the rotational speed attains its optimal range. The article presents the hardware scheme, the start procedure, and the control algorithm for this approach. The validity and efficacy of the proposed approach are confirmed through the validation of simulation results.

Kowalak (2019) directs their focus towards the construction of a power plant on a large container vessel, specifically examining the waste heat recovery system and shaft generator-motor. Utilising experimental methodologies, the authors meticulously monitor fuel consumption and electric load during the vessel's acceleration and deceleration at slow steaming speeds. The utilisation of collected data facilitates the establishment of approximate functions that describe the relationship between fuel consumption and the main engine speed in the proximity of the minimum permissible speed of the shaft generator-motor. The authors of the study have based their research on the experimental findings. They have simulated a

hypothetical 4,000-nautical-mile voyage and analysed the ship's total fuel consumption per voyage at different engine speeds. These speeds were both below and above the minimum cut-in speed of the shaft generator-motor. The findings of the study demonstrate the considerable impact of the auxiliary boiler's fuel consumption on the aggregate fuel expenditure per voyage, particularly in instances where the minimum permissible speed of the shaft generator-motor is not attained during slow steaming. Additionally, the study identifies a range of engine speeds just below the minimum permissible speed that are considered non-economical.

Zhao et al. (2019) propose a solution for a shaft generator system by utilizing a Doubly Fed Induction Machine (DFIM) with a partially rated converter. However, the DFIM lacks self-start capability under the Partial Torque Hysteresis mode, which limits its practical application in real systems. In order to address this limitation, the paper proposes a methodology 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 paper provides a comprehensive overview of the hardware configuration, the initiation process, and the control algorithm employed by this approach. A series of simulation and experimental studies were conducted in order to validate the effectiveness of the proposed method.

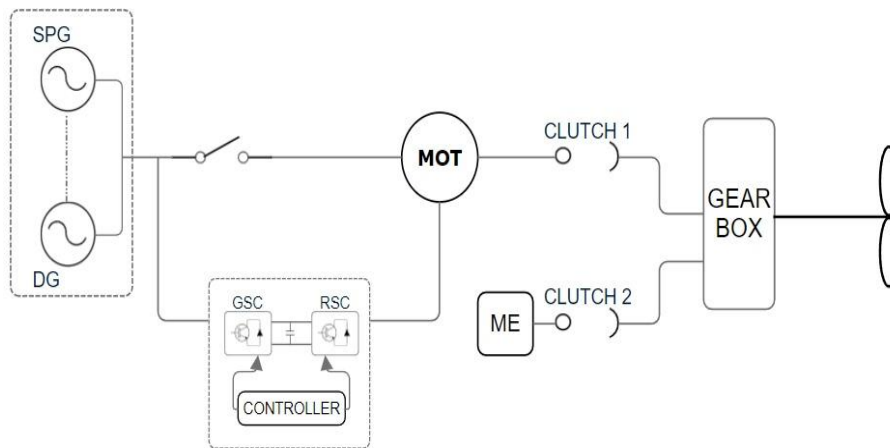


Figure 2.6. Doubly-feed shaft generator model

Ammar and Seddiek (2020) concentrate on enhancing energy management on large container vessels. The study evaluates the impact of diverse methods on environmental and economic aspects using class A13, A15, and A19 container vessels as references. The energy efficiency

values for these maritime vessels have been calculated, and the A19 class has been found to be the most effective in terms of emissions reduction. The reduction potential for this class of ship is specified in relation to SO_x, NO_x, CO, CO₂, and PM emissions. In order to enhance energy management for the A13 class, it is recommended that a 45 per cent decrease in speed is implemented, in accordance with legislation that will be in force in 2023. The estimated cost of the proposed concept is \$5860 per tonne of CO₂ prevented from being emitted. As an alternative proposition, the implementation of the strategy of utilising Liquefied Natural Gas (LNG)-powered engines for the A19 class has the potential to engender an augmentation of energy measures by 9.34%, accompanied by an annual operating cost reduction amounting to \$24.7 million.

Churkin et al. (2020) analyse the application of shaft-generating installations (SGI) in vessel electric power systems (EPS) and proposes methods to address related challenges. The energy efficiency of a EPS of ship is a significant concern in ship design and operation. In view of the fact that ship EPS is ordinarily limited in terms of power supply, it is imperative to identify methodologies that will facilitate an augmentation in the quantity of electrical energy generated, in conjunction with an enhancement in its quality. The following method may be employed to achieve this: firstly, SGI should be introduced into the EPS of the ship. The implementation of SGI has been demonstrated to engender a number of advantages, including enhanced energy generation and diminished fuel consumption. Nevertheless, the process is not without its complexities, which manifest in the form of more intricate control requirements and the necessity for system synchronisation. That paper aims to study and address these issues.

Gnacinski et al. (2020) investigate the effects of power quality disturbances on induction motors within ship power systems. It examines the adverse consequences of voltage fluctuations, frequency variations, waveform distortions, and voltage imbalances on energy receivers. By conducting empirical studies in real ship microgrids, the research demonstrates the impact of these disturbances on induction motors under different operational scenarios. The findings highlight the importance of revising power quality standards and regulations to optimize energy efficiency in ship operations.

Nuchturee et al. (2020) discuss the growing concerns about energy consumption and environmental impact in the shipping industry. The International Maritime Organization (IMO) has enacted rules to restrict the release of greenhouse gas emissions from maritime ship, focusing on energy efficiency. Electrification of vessel propulsion and power systems has been proposed as a solution to improve efficiency. The study investigates a range of technologies and methodologies that are designed to address the increasingly stringent restrictions, including the integration of energy storage and intelligent power management systems, the utilisation of direct current (DC) power distribution networks, the adoption of non-traditional propulsion systems, the combustion of low-carbon fuels such as liquefied natural gas, the installation of onboard renewable energy systems, and the incorporation of fuel cells with diesel generators. The study identifies promising technologies and practices for all-electric ships and highlights the sensitivity of energy efficiency to various applications. For the most efficient energy operation, it is recommended to combine the proposed strategies with other measures.

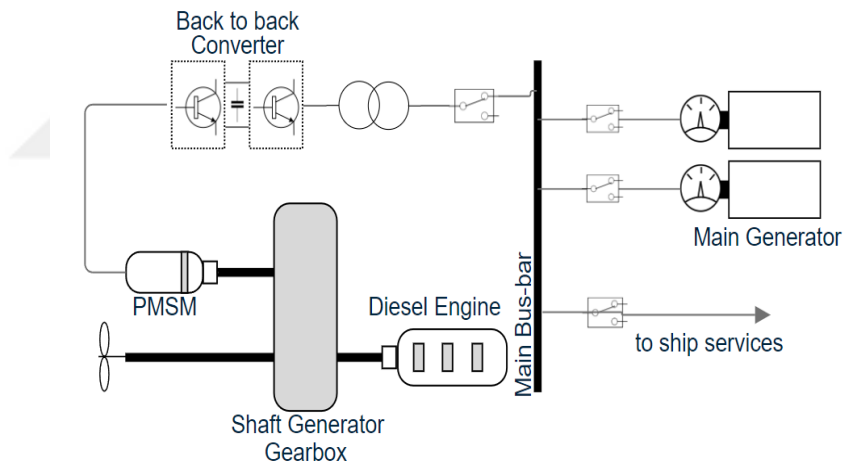


Figure 2.7. Hybrid propulsion system configuration

Perez and Reusser (2020) concentrate on maritime propulsion systems founded on diesel engines, which offer benefits like reduced fuel consumption and elevated thermal efficiency. Nevertheless, the emissions resulting from their operation, including CO₂, SO_x, and NO_x, have led to the establishment of regulations by the International Maritime Organization (IMO) with the aim of reducing the environmental impact of the sector. In order to address this challenge,

the study proposes the incorporation of a shaft generator (SG) into the propulsion system. This integration is posited as a solution to reduce CO₂ emissions and enhance energy efficiency.

Tadros et al. (2020) conducted a research investigation into the development of an optimisation device for the maritime propulsion system of a fishing trawler during the vessel's preliminary design phase. The tool, consisting of two Matlab modules, is designed to simulate and optimize the system's performance. The primary module is oriented towards the minimisation of fuel consumption and emissions, with this objective being pursued by means of the simulation of the performance of the marine diesel engine. The subsequent module facilitates the selection of an appropriate propeller, with the objective of enhancing fuel efficiency and addressing performance issues. The implementation of this instrument led to a substantial decrease in fuel consumption, amounting to approximately 30% in comparison with alternative scenarios. In summary, the tool contributes to improving fuel efficiency and aids in the design of an efficient propulsion system for fishing trawlers.

Nguyen et al. (2021) put forward a control system for a ship's power station that utilizes a doubly-fed induction generator (DFIG). The study examines the properties of the Doubly Fed Induction Generator (DFIG)-based power generation system and puts forth a control system that enables adjustment of the active and reactive power supplied to the grid. The benefits of employing the rotor sync technique are emphasized, as it facilitates independent control of active and reactive power. The author recommends the utilization of a Fuzzy-PID controller for each control channel, leading to rapid response times and precise tracking of desired power values. The proposed system is implemented for automatic load allocation in a parallel power grid aboard the ship, ensuring efficient distribution between the shaft-generator and the grid, even in the presence of changes in rotor speed and load consumption of the generator.

In the study undertaken by Nguyen et al. (2021), both conventional and advanced electrical propulsion systems utilised in commercial ships and smart vessels are provided with a thorough and detailed examination, offering a comprehensive review and analysis. The selection and optimization of propulsion systems in modern commercial ships are challenging due to factors such as greenhouse gas emissions, environmental regulations, and energy efficiency standards.

The integration of electrical systems has introduced electric propulsion, which brings benefits like compliance with regulations, flexibility, cost reduction, and advanced automation. However, ship owners and designers face pressure to optimize propulsion and power systems. This article offers a comprehensive and in-depth analysis of both traditional and cutting-edge electrical propulsion systems implemented in commercial ships and smart vessels. The study methodically compares and analyses various system configurations, power sources and propulsors, with a view to assisting in the selection of the most suitable electric or hybrid powertrain systems for commercial fleets.

Uyanık (2021) presents a machine learning approach to the operational electrical power requirements of shaft generators. The present study utilised a data set from a container ship. Despite the fact that the algorithms were trained using the training data, the test data was not utilised in the teaching process. Instead, the objective was to evaluate the effectiveness of the algorithms utilised in the prediction process. The findings of the subsequent evaluations indicated that the Multiple Linear Regression algorithm exhibited superior performance in comparison to the other algorithms evaluated in the study, particularly with regard to the estimation of the electrical power of the shaft generator.

Souflis-Rigas et al. (2021) present a discussion of the results of a cost benefit analysis conducted on the feasibility of installing a shaft generator system in an LNG carrier. The analysis examines the economic and environmental benefits of implementing such a system. The study demonstrates that the installation of a shaft generator system in an actual ship leads to improvements in key performance indicators, including fuel consumption and emissions. Overall, the findings suggest that the adoption of a shaft generator system could be advantageous in terms of both economic and environmental performance.

Table 2.1. A literature review on energy, design and efficiency based on shaft generators

Analysis Type	References	Focus Subject
Efficiency	Prousalidis et al., 2011	Analysing the conversion of ships into more energy efficient vessels.

Design Modeling	Solla et al., 2012	The impact of a dynamic generation system on energy performance
	Prousalidis et al., 2012	Analyse the system productivity of the vessel's power generation apparatus, specifically the shaft generator
	Sarasquete et al., 2012	Increase energy efficiency by operating the generator at variable speeds over a wide range of engine speeds using a variable speed generation system
	Tafanidis et al., 2013	Economic analysis of the warship power system.
	Liu et al, 2014	BDFM mathematical model analysis based on SG characteristics
	Schoyen and Sow, 2015	Saving fuel during the operational phase of the vessel
	Gkotzia et al., 2016	Mathematical basis for techno-economic analysis of SGs
	Avdeyev and Vyngra, 2017	By reducing the number of generator sets and operating hours, it enables operating costs to be reduced.
	Churkin et al., 2020	The integration of the shaft generator into the ship's electrical power system is a pivotal development that has the potential to enhance the efficiency of energy generation through the ship's electrical installation
	Ammar and Seddiek, 2020	It focuses on improving energy management on large container vessels.
	Nishikata et al., 1997	It combines the vector control strategy of the BDFG system with PID controllers.
	Doerry et al., 2005	To determine a criterion for the Quality of Service in the design of ship power systems.
	Yijian et al., 2007	Principle of operation of the VSCF control system of the SG
	Tarnapowicz, 2010	Inclusion of aDFIM as a SG in a Maritime System
	Wang et al., 2011	Nonlinear Torsional Vibration of the SG

Xiong and Wang, 2011	To start the system in induction machine mode and switch to DFIM mode when the speed reaches the normal operating range..
Diao et al., 2014	Vessel Design with Permanent Magnet Synchronous Generator and SG
Chen and Wang, 2014	Analysis of an excitation control mechanism for stand-alone BDFG based on the characteristics of the vessel SG
Dermentzoglou, 2014	Operating a generator using DFIM in PTH mode
Gao et al., 2014	It deals with frequency stabilization of transportation systems employing high power SGs.
Sarigiannidis et al., 2015	The analysis of the SG was conducted utilising a finite element analysis model in conjunction with experimental methods
Zhang et al., 2015	A control strategy for DFIM without position sensors
Liu et al., 2015	The steady-state performance is contingent upon an examination of total harmonic distortion
Xia et al., 2016	Comparison of high speed Salient-Pole Synchronous Generator and low speed direct drive PMSG with the same rated power as SG.
Sarigiannidis et al., 2016	To create a new RW design model to develop rotor structure with ease of manufacturing and low cost.
Xia et al., 2016	Analysis of output voltage amplitude and frequency of BDFM under variable rotor speed and load
Liu and Wang, 2016	Mathematical model and control principle of independent generator system of brushless dual-feed machine
Zhao et al., 2018	Principle of operation of the VSCF control system
Zhao et al., 2019	Mathematical model and control principle analysis of SG system based on BDFM.
Uyanik, 2020	Analysis of Machine Learning for SG
Emission	
Kanellos et al., 2014	Emission profile of SG system

Michalopoulos et al., 2016	Optimal power management algorithm
Kowalak, 2019	The waste heat recovery system and the SG focus on energy efficiency.
Tadros et al., 2020	Propeller efficiency with SG dependent parameters
Nguyen et al., 2021	It focuses on a comprehensive and detailed examination of electric drive systems.



3. MATERIALS AND METHODS

3.1. Ship Electrical Power System Structure and Technological Development

Due to the continual advancements in ship electrical and electronic engineering, notable alterations have been observed in the setup of vessel electrical power systems. Figure 3.1 presents an overview of a three-phase vessel electrical power system. The ship's power system comprises generator sets, such as diesel generators (DG), shaft generators (SG), turbine generators (TG), emergency generators, transformers, switchboards with protection units, power cables and consumers. Within electric propulsion systems, propulsion motors ordinarily connect to the main busbars. The use of power converters on these vessels increases the importance of power quality concerns compared to traditional vessels (Barros and Diego, 2016).

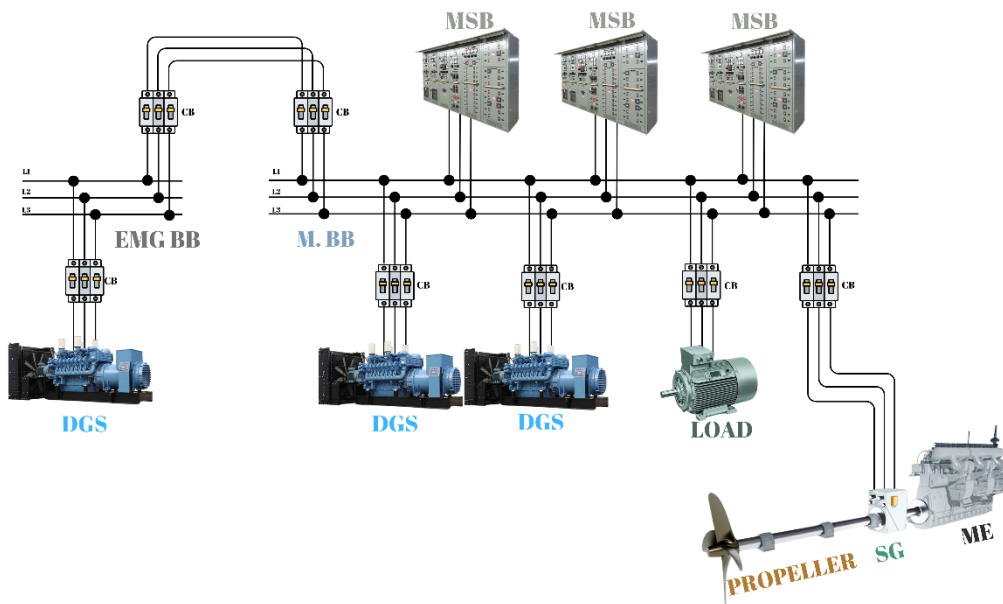
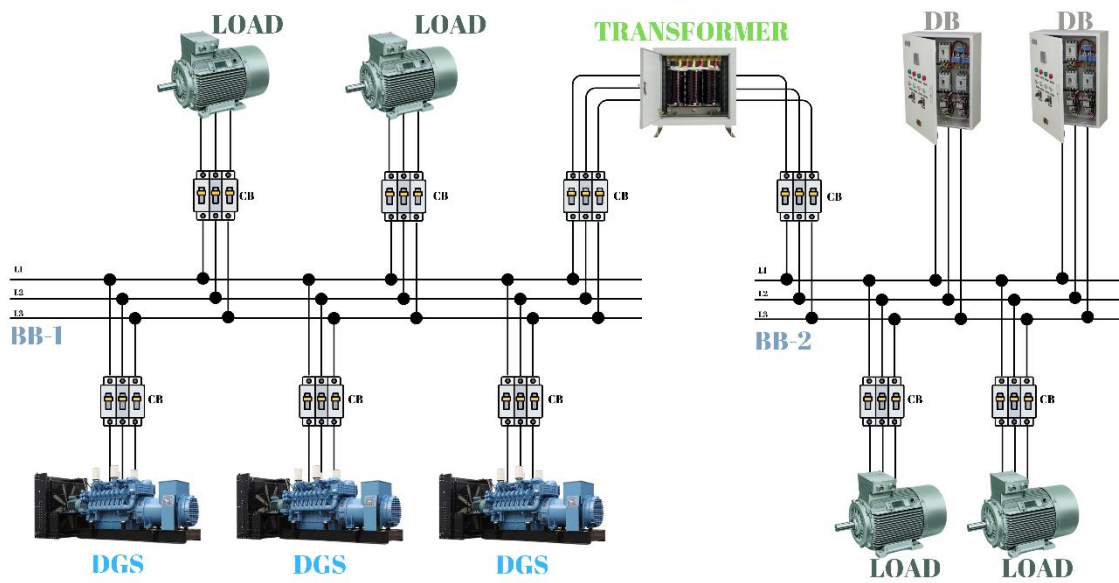


Figure 3.1. General diagram of the electrical power system of a three-phase vessel

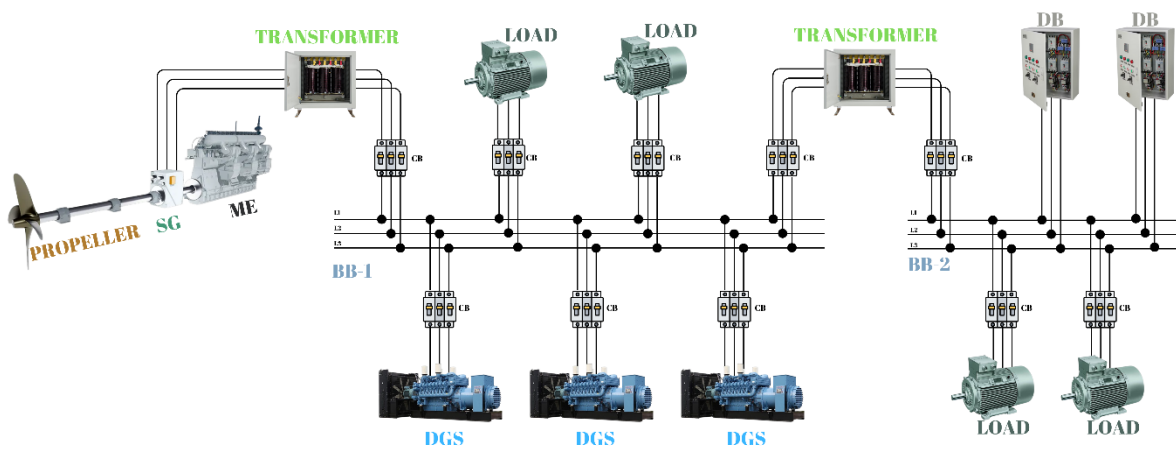
The differentiation between shipboard power systems and onshore distribution circuits heightens the impact of inadequate power management on shipboard systems (Spagkouros, and Prousalidis, 2004). A number of the most important specific characteristics of shipboard power systems are listed.

- Limited space for generators on board restricts expansion due to the limited area the vessel operates in,
- The system comprises devices like power converters and transformers that convert varying levels of voltage and frequency. A restricted number of generators, each with different capacities, along with primary starter and control systems are also included. It is designed for optimal performance and efficiency,
- The substantial size of some power loads in relation to the total capacity of installed generators is noteworthy,
- On-board generators have a relatively high short-circuit impedance,
- Non-linear load usage,
- Operation of the generators in parallel,
- Installed loads exhibit greater sensitivity to power quality compared to onshore power systems.

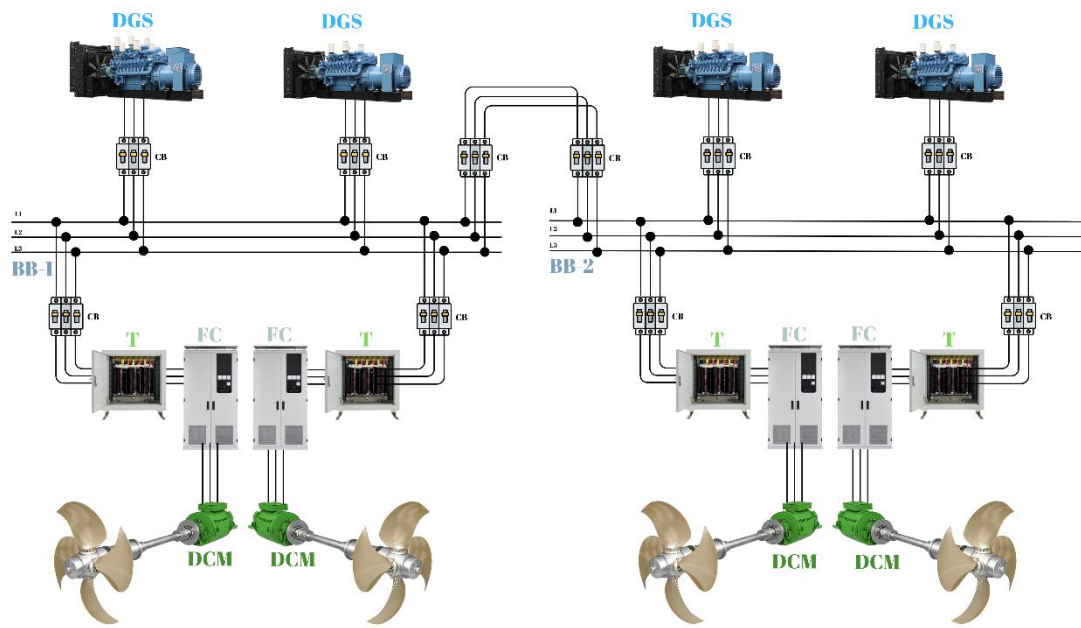
The structure of the electrical system for certain ship types is depicted in Figure 3.2. The alterations encompass not solely untried energy source implementations, but also auxiliary gas turbines, including those with the potential to function alongside a shaft generator, turbo generator, or separate generator systems (Mindykowski, 2014).



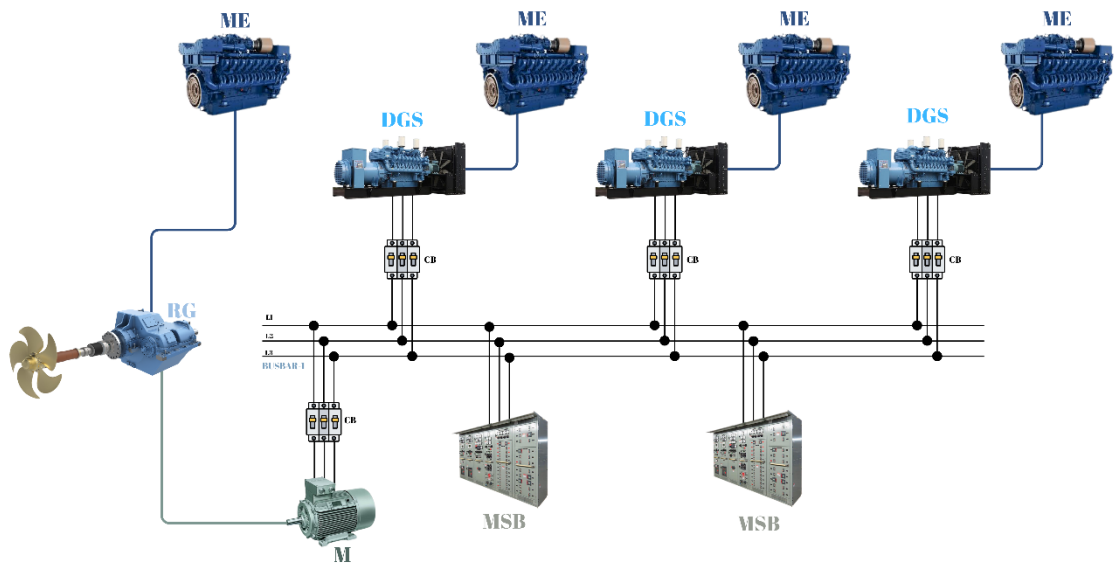
(a)



(b)



(c)



(d)

Figure 3.2. Examples of ship electrical energy system structures as a result of the development of ship technology, a) Traditional structure, b) Shaft generator structure, c) Full electric structure d) Hybrid electric system structure

The ship's electrical energy system structures, as presented in Figure 3.2, are described as follows:

3.1.1. Traditional Structure

The basic, standard configuration of an electrical system for a ship utilizing three-phase synchronous gensets driven by diesel engines is described. These generators provide energy for two busbar sections exhibiting distinct voltage ratings. The power is generated by three diesel generators. MSB 1 (Main Switchboard 1, 3-phase AC 380V/50Hz) and MSB 2 (Main Switchboard 2, 3-phase AC 220V/50Hz) distribute the power to the consumers.

3.1.2. Shaft Generator Structure

Main propulsion shaft-driven generators provide additional energy in conjunction with generator sets for ship power systems. With a fixed propeller, the generators operate exclusively at a consistent speed whenever the main engine is in operation, particularly in cruise mode. During maneuvers with pitch-controlled propellers, the generators could be utilized provided that the machine speed remains constant. SG systems are implemented in certain applications due to their ability to provide electrical power to vessels while lowering fuel consumption and operating costs in comparison to traditional vessel construction with fueled gensets (Mindykowski, 2014). Figure 3.2.(b) depicts a system in which electricity is generated by a genset containing one SG and three DGs. The power panels consist of MSB 1 (Main Switchboard 3-phase AC 440V/60Hz) and MSB 2 (Main Switchboard 3-phase AC 220V/60Hz). Additionally, SC serves as the synchronized generator and HF operates as the harmonic filter.

3.1.3. Full Electric Structure

Figure 3.2.(c) depicts the power diagram of a passenger vessel utilizing all-electric propulsion, commonly known as a fully electric ship. The bow/front MSB (3-phase AC 11kV/60Hz) is referred to as BMSB, while the aft main switchboard (Main switchboard in the stern and 3-phase AC 11kV/60Hz) is known as SMSB. The main busbar tie breaker is abbreviated as BTIB, while the diesel engine generators and gas turbine generators are referred to as DG and GTG, respectively. The harmonic filters, which are installed in the aft and front switchboards, are

referred to as HF. Meanwhile, the power converters are referred to as PC and the mermaid azimuth drive type propulsion units are abbreviated as POD.

3.1.4. Hybrid Electric System Structure

In the hybrid propulsion system revealed in Figure 3.2.(d), equipment number 1 provides an effective direct mechanical drive for attaining high speeds. An electric motor (equipment number 2) is connected to the same shaft either through a gearbox (equipment number 3) or directly to the propeller-driving shaft to deliver propulsion at low speeds. This ensures the main motor operates effectively at full load, avoiding inefficiency at partial load. Additionally, this motor can be employed as an electrical load generator for the ship's electrical grid (equipment number 4) (Geertsma, Negenborn, Visser, and Hopman, 2017).

3.2. Shaft Generator System

Power generation on board ships is a critical issue in terms of operational efficiency and fuel conservation. In this context, shaft generators and conventional generators represent the two main systems employed to meet the ship's electrical demands. However, they exhibit substantial disparities in terms of their operating principles and utilisation domains.

A shaft generator constitutes a type of generator driven by the vessel's main engine. During operation of the main engine, it generates electricity through the utilisation of the main shaft, which facilitates the rotation of the propeller. This system is frequently employed to supply energy during voyages, thereby enhancing energy efficiency by reducing the fuel consumption of auxiliary generators. The shaft generator operates on the principle of using the vessel's main engine to generate electricity, eliminating the need for auxiliary generators to consume additional fuel. This feature enables the shaft generator to provide uninterrupted electricity during cruising, thereby reducing the necessity for maintenance due to the minimised reliance on auxiliary generators. However, it is important to note that it cannot operate independently; that is, it cannot generate energy when the main engine is off or running at low speeds. Furthermore, as the engine speed changes, the frequency of the electricity generated may also change.

Conventional generators are driven by an independent internal combustion engine or turbine and are utilised for diverse purposes, including port operations, manoeuvring and emergency situations on board. They serve as the primary energy source in instances where the shaft generator is non-operational. They function as an autonomous energy source, capable of generating electricity even in the absence of the main engine. This characteristic ensures the provision of constant voltage and frequency without any speed restrictions. Consequently, when the shaft generator is not operational, it fulfils the ship's electricity requirements. However, it should be noted that fuel consumption is notably high, and it requires a substantial amount of fuel when operating continuously. This also results in a greater requirement for maintenance.



Figure 3.3. General layout of the ship propulsion system

Shaft generators and conventional generators represent two pivotal components in the ship's energy system. Shaft generators offer an efficient source of energy during voyages, while conventional generators possess the advantage of functioning independently and providing emergency backup. Consequently, it is a common practice on modern ships to utilise both systems in conjunction to optimise fuel consumption and costs.

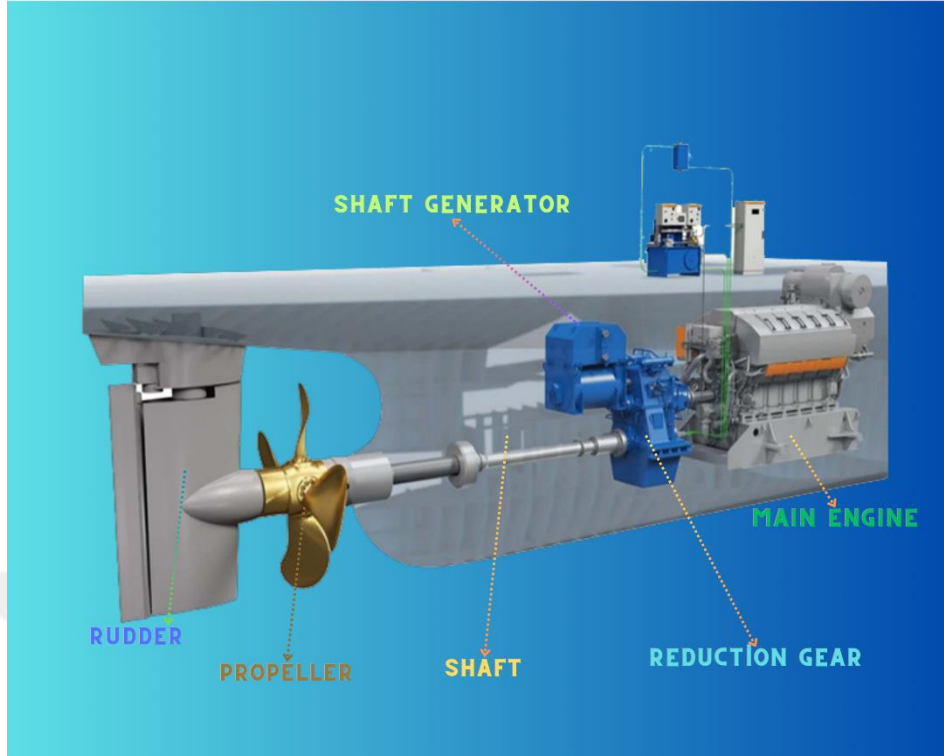


Figure 3.4. Ship consisting of shaft generator structure

As illustrated in Figure 3.3 and Figure 3.4, the location of the shaft generator and the systems that energise and propel the ship are delineated, along with the integration of these systems.

D-Q analysis allows three-phase AC quantities to be analysed by converting them to a rotating reference frame. This allows AC systems to be viewed and controlled in the same way as DC systems. In shaft generators, magnetic flux (λ) and voltage (V) are defined with respect to the D-Q axis as follows Equation 3.1, Equation 3.2, Equation 3.3 and Equation 3.4.

$$\lambda_d = L_d I_d + L_m I_f \quad (3.1)$$

$$\lambda_q = L_q I_q \quad (3.2)$$

$$V_d = R_s I_d + L_d \frac{dI_d}{dt} - \omega L_q I_q \quad (3.3)$$

$$V_q = R_s I_q + L_q \frac{dI_q}{dt} + \omega L_d I_d + \omega \lambda \quad (3.4)$$

d axis	: Magnetic field axis
q axis	: Torque axis of the generator
V_d, V_q	: D and Q axis voltages
L_d, L_q	: D and Q axis inductances
I_d, I_q	: D and Q axis currents
R_s	: Resistance of stator windings
L_m	: Magnetic conjugate inductance
I_f	: Current through the field winding
ω	: Rotor angular speed
λ	: Magnetic flux

These equations form the foundation for the analysis of magnetic field variations as well as the voltage generation within the shaft generator.

D-Q controlled shaft generator systems are highly effective in generating power at a constant frequency despite the variation in main engine speed on ships. These systems improve vessel energy management, save fuel and increase operational efficiency.

In the maritime industry, "shaft generator" refers to an AC generator, also known as an alternator, that is powered by the main engine of the ship. The propulsion system of the ship comprises a drive shaft connected to the propeller, which drives through a large gearbox. The gearbox may contain additional auxiliary shafts to drive various equipment such as compressors, hydraulic pumps or an alternator. Technical abbreviations will be explained when first used. In this specific context, the alternator is commonly referred to from here on as the shaft generator.

For the proper operation and power delivery of this shaft generator, it is essential that the propeller shaft, and consequently, the ship's main engine, maintains a consistent speed that

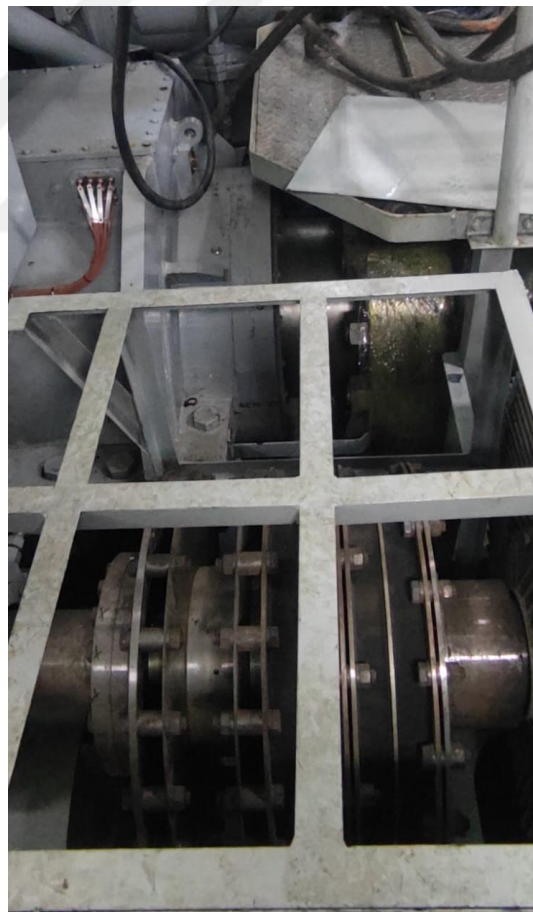
aligns with the requirements for generating a reliable voltage and frequency output. A considerable number of vessels currently operate at 450V and 60Hz. Thus, the shaft generator can only be utilised for power supply when the ship is sailing at a consistent speed.

During cruising, the ship's main engine typically possesses ample excess power, making it economically profitable to switch off the diesel generators. These generators are only necessary when the main engine is either overworking or underperforming. This situation arises frequently when a ship is entering or exiting a port, navigating through areas of high traffic, or encountering difficulties in rough areas of navigation.

As illustrated in Figure 3.5, the shaft generator and control panel are depicted from multiple angles, illustrating their configuration on a naval ship.



(a)



(b)



(c)



(d)

Figure 3.5.(a) and (b) Shaft generator system different views and (c) and (d) Shaft generator system control panel

The vessel's main propeller shaft, which extends from the engine to the propeller, traverses a substantial transmission box. This box may include numerous secondary shafts intended to power devices such as compressors, hydraulic pumps, or conceivably another generator. Marine shaft generators exhibit great versatility in their usage, serving as generators via a power take-off (PTO) to supply the vessel's primary electrical power as standard. The shaft generator can also act as an electric motor to provide extra power for the drive engine, known as power take-in.

As part of a waste heat recovery system, it utilizes excess heat from the engine to generate additional propeller work. In its current function, the shaft generator functions as a motor by

drawing power from the vessel's electrical system to propel the propeller at a lower speed. The shaft generator functions by means of a power take-off (PTO) which is driven by a reduction gear. This reduction gear is located between the medium-speed main diesel engine and the propeller.

A marine shaft generator is a mechanism deployed on ships to produce electrical power by harnessing the rotational force of the ship's propulsion shaft. Vessels with a standard shaft drive propulsion system use a main engine to drive the propeller via a shaft. By exploiting the rotary motion of this propulsion shaft, the marine shaft generator generates electrical power. The marine shaft generator has the primary objective of generating electrical power for the ship's on-board systems, minimising the necessity for an auxiliary generator set.

The following is a comprehensive explanation of the marine shaft generator's essential components and functions;

3.2.1. Connection to the main engine shaft

The marine shaft generator is commonly linked directly to the main engine or propulsion system of a ship. In many instances, it is mounted on the same shaft that drives the vessel's propeller. Consequently, a marine shaft generator rotates as the engine drives the vessel's propeller.

3.2.2. Generator Mode

The primary constituent within a ship's electrical system is the shaft generator, which encompasses an electrical generator unit that incorporates coils and magnets arranged in a configuration that facilitates the flow of electrons, thereby generating electrical power as the shaft undergoes rotation. Depending on the requirements of the vessel's electrical system, not only Alternative Current (AC) but also Direct Current (DC) electricity can be produced by the generator.

3.2.3. Power Generation

As a rotor revolves, it generates AC electricity through the stator. This electrical energy is then available for powering several onboard systems, including navigation equipment, lighting, communication systems, and other electrical devices.

3.2.4. Voltage Regulation and Control Systems

To secure a consistent and trustworthy source of power, marine shaft generators frequently integrate voltage regulation systems. These systems supervise the created electrical voltage and rectify it to match the vessel's electrical needs. Control systems may also be employed to direct the generator's operation according to the power required by the vessel.

3.2.5. Integration with Electrical System of Vessel

Electrical distribution system of vessel incorporates the power generated by the marine shaft generator. This can provide power for various onboard systems, including lighting, navigation equipment, communication systems, refrigeration units and other equipment. In addition, certain ships may use the generated power to charge batteries for backup or to provide power when the main engine is not operating.

3.2.6. Efficiency and Fuel Savings

The utilisation of a marine shaft generator has the potential to enhance fuel efficiency and increase effectiveness. By employing the rotational energy of the principal engine's shaft for both movement and electricity production, the vessel can optimise its energy consumption and moderate the necessity for supplementary fuel usage for powering discrete generators.

The utilisation of a marine shaft generator bestows multiple benefits, among them being the capability to generate electricity sans the need for auxiliary generators. Using the main engine's rotational energy for both propulsion and power generation can lead to fuel savings. Moreover, it can enhance power distribution efficiency throughout the ship.

Marine shaft generators are frequently deployed in different types of vessels like cargo and container ships along with cruise ships, providing a practical way of producing electricity onboard by utilizing the existing propulsion system. The design and capacity of a marine shaft generator are determined by the ship's size, power needs, and characteristics of the propulsion system.

3.3. Principle Of Operation

3.3.1. Power Take Off (PTO) Operation

As consider the variable main engine speeds, frequency converters are embedded into shaft generator system to produce three-phase, constant voltage and frequency current to the grid. SG's speed range can be chosen according to operational claims of the ship. For instance, the half speed range and full speed range of main engine can be selected with stable system output. Figure 3.6 shows schematic view of shaft generator in PTO mode.

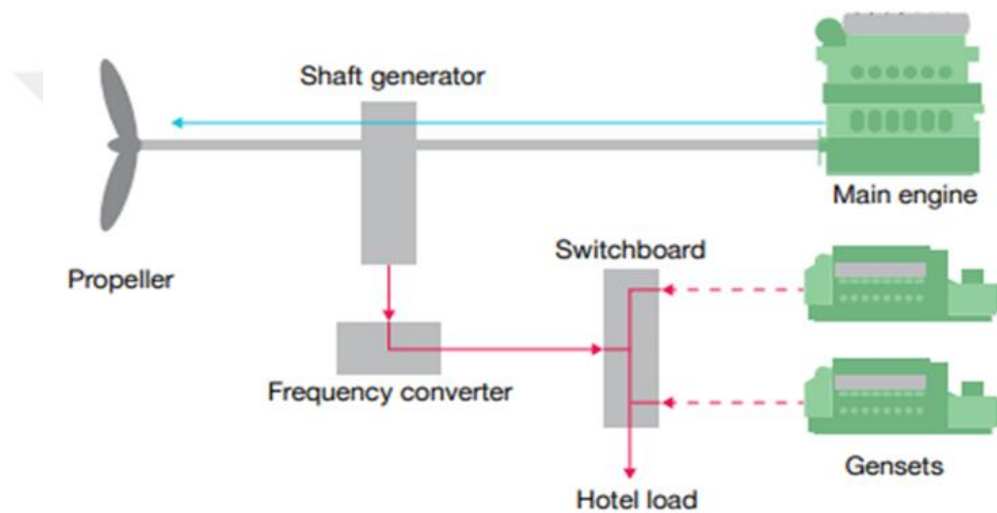


Figure 3.6. The schematic representation herein illustrates the configuration of the propulsion system, with the shaft generator operating in Power Take Off (PTO) mode (Shaft Generators for Low Speed Main Engines, 2021).

All shaft generator system has intersection area which active power can be supplied with main engine. In addition to this, Main engine can run and drive the shaft generator with various settings.

- The SG is positioned along the shaft line that links the low-speed primary diesel engine to the propeller. This configuration features a notable distance between the stator and rotor, establishing itself as the most commonly adopted installation without the need for additional bearings. It is exceptionally uncomplicated and durable and necessitates

minimal upkeep. This configuration is not anticipated to cause any torsional vibration difficulties linked to design and operation, in contrast to other arrangements.

- The power take-off system propels the generator, connecting to a reduction gear situated between the medium-speed primary diesel engine and the propeller. This setup is extensively utilized and well-suited for medium-speed main diesel engines.
- A tunnel gear unit fixed along the shaft line between the low-speed main diesel engine and the propeller drives the shaft generator.

3.3.2. Power Take In (PTI) Operation

In this operational modality, the shaft generator functions as a synchronous motor driven by auxiliary diesel generators on board the vessel. Its functionality encompasses the capacity to augment speed by amplifying power in conjunction with the primary engine, or to diminish power, thereby reducing fuel consumption and minimising wear on the primary engine. In this operating state, known as PTI (Power Take-In), the shaft generator does not require self-starting, as it typically rotates as an alternator prior to transitioning to engine mode. As illustrated in Figure 3.7, the schematic representation of the shaft generator in PTI mode is displayed.

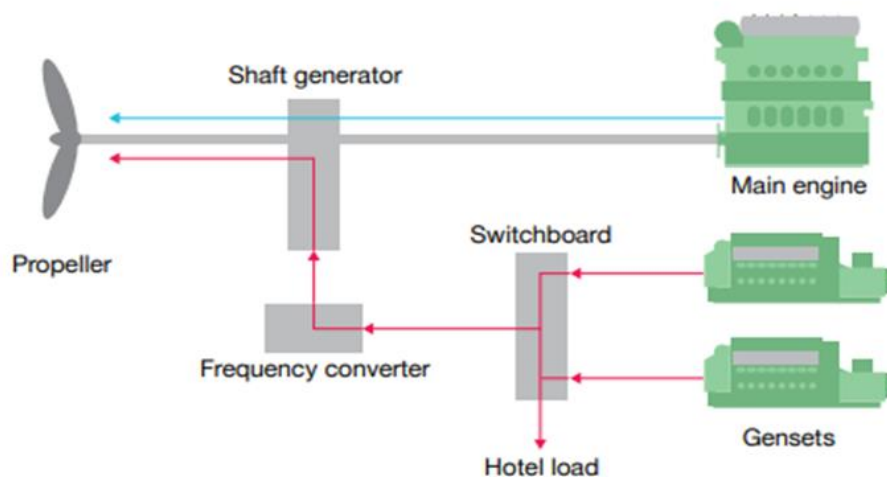


Figure 3.7. Displays a schematic overview of the propulsion system including the SG operating in Power Take In (PTI) mode, as presented in reference (Shaft Generators for Low Speed Main Engines, 2021).

3.3.3. Power Take Home (PTH) Operation

In this operational state, the SG functions as a synchronous motor, supplying all of the vessel's propulsion power. As a synchronous motor, the shaft generator operates comparably to PTI. In this operational mode, the SG functions like a synchronous motor, supplying one hundred per cent of the vessel's propulsion power. This situation may arise during emergencies, caused by the failure of the main engine or its crucial unexpected maintenance. On the other hand, this can also be a customary mode of operation in situations, like a scheduled main engine maintenance or when the engine is shut down on entering port. Unlike in the Power Take-In (PTI) operation, the shaft generator needs to possess the capability of self-starting and functioning as a motor from standstill in this mode. Figure 3.8 shows schematic view of shaft generator in PTH mode.

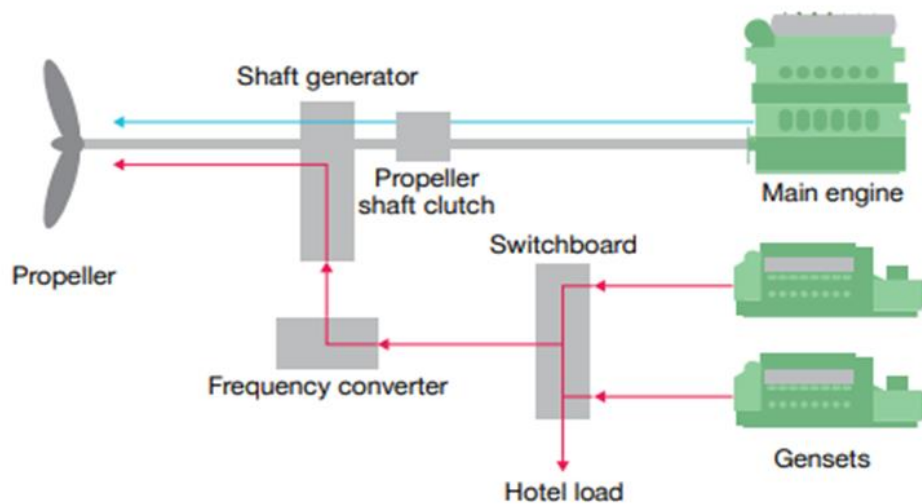


Figure 3.8. Showcases a schematic of the propulsion system featuring the SG in Power Take Home (PTH) mode (Shaft Generators for Low Speed Main Engines, 2021).

3.3.4. PTH / PTO / PTI Operation

To enable further operation of the shaft motor, the diode rectifier is replaced by a Pulse Width Modulation rectifier that resembles a PWM converter, and so the management of the system is modified appropriately. The following operation of the motor is achieved with this configuration:

- The booster drive functions in conjunction with the primary engine to facilitate the vessel's ascent, propulsion power, and velocity.
- In the event of a main engine failure, the booster drive can be used as an emergency drive without the primary motor. In this operation the primary motor must be disconnected from the propeller shaft.
- Additionally, the Power Take In operation can be supplied from the main switchboard, being powered by the auxiliary generator(s) and independent of a Waste Heat Recovery System (WHRS).

In summary, this grant optimal flexibility in distributing power among various units using a single converter for the shaft generator.

3.3.5. PTH / PTO / PTI + Hybrid Operation

To facilitate shore connection at either 60 Hz or 50 Hz, adjust the vessel's mains frequency through the frequency converter located within the SG set. This could be achieved by making the connection between the SG and the converter and supplying the converter from shore with a cable coil, transformer and circuit breaker. With this configuration, the vessel will possess full flexibility for worldwide shore connection.

3.4. Benefits of Implementing the Shaft Generator System

- a) An independent-driven generator on a ship offers a significant advantage due to its ability to produce power without releasing harmful pollutants into the air, as opposed to more traditional methods of power production. Another major benefit is the decreased noise level.
- b) A further advantage is its cost-effectiveness, due to the fact that it does not require high-priced fuel for power generation, as the main engine acts as the prime mover.
- c) Using an independent driven generator also reduces wear and tear and lowers maintenance costs compared to other methods of power generation.
- d) The installation space required for the shaft generator is reduced when installed in close proximity to or in line with the main engine's shaft.

- e) The investment cost of the shaft generator varies depending on its type and system. However, a basic design typically requires a low investment cost.
- f) The setup expense for a shaft generator is typically economical, as it doesn't require a distinct foundation, prime mover, or exhaust system. Additionally, the installation time is also minimal.
- g) The shaft generator's scheduled maintenance schedule is longer than that of a diesel generator due to lower spare parts and labour costs. (The Green Source of Power On Ship - Shaft Generator, 2019).

3.5. Drawbacks of the Shaft Generator System

- a) The efficiency of the propeller and engine in a basic shaft generator system decreases when the propulsion power is low. Due to the constant frequency requirement, a primary engine equipped with Controllable Pitch Propellers (CPP) needs to maintain a constant speed, including during low load.
- b) Power generation is not possible while the prime mover is in a stop condition during port.
- c) Incorporating an additional attachment onto the engine's shaft leads to an augmented load, which consequently leads to increased consumption of the specified fuel and cylinder oil when using a shaft generator.
- d) The generators are unable to handle high load demands on its own and may negatively impact main engine performance and maintenance.
- e) The installation of the shaft generator requires complicated arrangements, including gears and couplings, in some systems. (The Green Source of Power On Ship - Shaft Generator, 2019).

3.6. Efficiency of Shaft Generator

The aim of the International Maritime Organization (IMO) is to set up and keep up an extensive regulatory structure for worldwide shipping these factors in both the environment and shipping performance. In 1973, the IMO formed the Marine Environmental Protection Committee (MEPC) to tackle contamination issues resulting from shipping activities. Furthermore, the organization introduced MARPOL for the same goal. MARPOL Annex VI was first

implemented in 1997 to curtail ship exhausts, primarily focusing on sulfur oxides (SO_x), nitrogen oxides (NO_x), and substances that deplete the ozone layer. In 2011, a revised edition of MARPOL Annex VI was enforced, augmenting the drive to minimise oceanic pollution, mainly through limiting greenhouse gas (GHG) discharges. These rigorous regulations are mandatory for all shipping companies to reduce ship emissions by adopting technological innovations and operational measures.

As per the International Maritime Organization's definition, vessel energy efficiency is directly proportional to the fuel energy required for the transport work performed. As carbon dioxide causes significant anthropogenic greenhouse gas emissions and has a direct correlation with fuel consumption, it is possible to express standard indicators for evaluating the performance of shipboard energy systems in terms of CO₂ emission indices. Energy efficiency indexes have been established, specifically the energy efficiency design index (EEDI) and energy efficiency operational indicator (EEOI). As per regulations, newly built vessels with the gross tonnage of 400 or more are required to comply with the EEDI, while all existing and future vessels should adopt the EEOI as part of their vessel energy efficiency management plan (SEEMP) (IMO Resolution MEPC 203, 2011).

The effectiveness of a marine shaft generator can be affected by several factors, and it is essential to appraise various aspects when assessing its overall efficiency. Presented here are some critical elements that can have an impact on the functioning of a marine shaft generator.

3.6.1. Generator Type

The choice of generator for a marine shaft generator can significantly impact its efficiency. Various generator designs, including synchronous and asynchronous types, may exhibit differing efficiency features.

3.6.2. Load Characteristics

The efficiency of a generator is typically reliant on the load it supplies. In the marine sector, shaft generators are likely to operate with greater efficiency when exposed to higher loads, leading to a power output that is more consistent and stable.

3.6.3. Voltage Regulation

The efficiency of the shaft generator heavily relies on the voltage regulation system's effectiveness. A consistently regulated voltage output guarantees that the ship's electrical systems acquire the necessary voltage, thus boosting overall efficiency.

3.6.4. Operational Conditions

The effectiveness of a marine shaft generator can fluctuate with differing operational conditions. The velocity of the ship, the engine's usage, and the environmental variables are all crucial factors in the genesis of electrical energy by the generator, which is achieved by the conversion of mechanical energy.

3.6.5. Power Management System

Integration of a complex power management system increases overall efficiency. These systems optimize the usage of power sources, such as the marine shaft generator, to satisfy the diverse requirements of the ship's electrical systems.

3.6.6. Generator Control and Monitoring

The efficient operation of the marine shaft generator is dependent on reliable control and monitoring, which involves monitoring the speed of the primary engine shaft and modifying the output of the generator accordingly to ensure optimum performance within pre-determined parameters.

3.6.7. System Integration

The level of integration with the ship's electrical system and other power sources like auxiliary generators or energy storage systems, can affect the overall efficiency. A properly integrated system allows for the effortless co-ordination of the power sources according to the requirements.

3.6.8. Maintenance and Condition Monitoring

To maintain efficiency over time, regular maintenance and condition monitoring of the marine shaft generator is essential. Properly maintained equipment is less susceptible to mechanical and electrical faults that could potentially have a negative impact on overall efficiency.

It is important to note that the efficacy of marine propeller-driven electrical generators can differ across ships and systems. The effectiveness of the generator is related to a number of factors, including the design, technology and engineering considerations of the generator, in other respects the overall power management strategy adopted by the vessel. Efficiency specifications are often provided by manufacturers and ship operators can assess the effectiveness of their systems using actual operating data and performance measurements.

3.7. Energy Efficiency Design Index

Purpose of The Energy Efficiency Design Index (EEDI) is measuring CO₂ emissions which is transport work in per unit. To promote more efficient ships, it is recommended that baselines be established for newly constructed vessels. In the design phase, EEDI values for newly built ships and those undergoing significant modifications should be assessed, with final verification taking place after official sea trials (IMO Resolution MEPC 254, 2013). An EEDI reference curve represents the average EEDI value that results from calculating individual index values (IMO Resolution MEPC 231, 2013) and is already established for various types of ships. Thus, the attained EEDI cannot exceed the reference curve. Following the implementation phases, the index will be strict every five years as per the IMO requirement. The first stage of reducing CO₂ emissions, starting in 2015, requires a 10% reduction, while the final stage demands a 30% reduction beginning in 2025 (Smith et al., 2014). It is expected that be encouraged the more productive ships which has several technologies.

The EEDI regulations apply to vessels weighing 400 gross tonnage and above that are involved in international routes, excluding non-mechanically propelled vessels such as barges, platforms and drilling rigs. An International Energy Efficiency (IEE) certificate will be granted to a vessel that satisfies the arrangement. For new ships that fall into categories 1-3, the first survey for the IEE certificate must be conducted before being put into service. In the context of an existing ship, the International Air Pollution Prevention (IAPP) certificate's initial intermediate or renewal survey is required to be conducted on or after 1 January 2013, as stipulated by the International Tanker Owners Pollution Federation (ITOPF) (IMO 2014 Guidelines on the method of calculation of the Attained Energy Efficiency Design Index (EEDI) for new ships,

2014; IMO Preventions of Air Pollution from Ships, Marine Environment Protection Committee, 2010).

The EEDI regulation solely concerns new ships that fall within the ship types specified by the Convention. The main types of these ships are as follows;

- Bulk cargo ship,
- Gas carrier, Tanker,
- Container ship,
- General cargo ship,
- Refrigerated cargo ship,
- Combined carrier, Passenger ship, Ro-ro cargo ship
- Ro-ro cargo ship,
- Ro-ro passenger ship
- Passenger ship with LNG carrier having unconventional propulsion systems such as diesel-electric, turbine, or hybrid systems (ICCT The Energy Efficiency Design Index for New Ships, 2011).

The EEDI formula is as follows: $EEDI = CO_2 \text{ emission} / \text{transport energy}$. Carbon Dioxide (CO_2) emission means the total CO_2 emitted when burning fuel. Transport energy is the design capacity of the vessel multiplied by the design speed of the vessel.

The EEDI value is obtained through the straightforward method presented in Equation 3.5.

$$EEDI = \frac{P_{ME} \times C_F \times SFC}{capacity \times V_{ref}} \quad (3.5)$$

- P : 70% of the power of the engine (main and auxiliary) in kW
C_f : Emission rates of the ship's fuel usage
SFC : Amount of fuel burned by the engines in kW
Capacity : Ship's capacity (in tons)

V_{ref} : The speed of the ship in knots.

- The power of the ME at 75% Maximum Continuous Power (MCR) is P_{ME} .
- C_f is the dimensionless factor that takes into account the amount of CO_2 (in mass) that is emitted per unit mass of fuel burned.
- SFC is a measure of specific fuel consumption in grams per kilowatt hour at 75% maximum combustion rate.
- The term 'capacity' is used to denote the deadweight tonnage of an object or vessel.
- The engine is the focus of this study, and V_{ref} is used to denote the vessel speed at 75% MCR.

The calculation of the index is furthermore subject to the consideration of the emission contribution originating from genenerator sets/auxiliary engines, PAE (genenerator set), shaft generator/motor and efficiency technologies. The second equation presents the numerical value of the EEDI equation.

$$\left(\prod_{j=1}^n f_j \right) \left(\sum_{i=1}^{n_{ME}} P_{ME_i} C_{FME_i} S_{ME_i} \right) \rightarrow \text{Mainengineemissions} \quad (3.6)$$

$$(P_{AE} C_{FAE} S_{AE}) \rightarrow \text{Auxengineemissions} \quad (3.7)$$

$$\left(\prod_{j=1}^n f_j \right) \left(\sum_{i=1}^{n_{PTI}} P_{PTI_i} C_{FAE} S_{AE} \right) - \left(\sum_{i=1}^{n_{eff}} f_{eff_i} P_{AE_{eff_i}} C_{FAE} S_{AE} \right) \quad (3.8)$$

↳ *Shaftengineemissions – Auxenginepowerreduction*

$$\left(\sum_{i=1}^{n_{eff}} f_{eff_i} P_{eff_i} C_{FME} S_{ME} \right) \rightarrow \text{Mainenginepowerreduction} \quad (3.9)$$

And according to them equation 3.10;

$$\begin{aligned}
EEDI = & \left(\prod_{j=1}^n f_j \right) \left(\sum_{i=1}^{n_{ME}} P_{ME_i} C_{FME_i} S_{ME_i} \right) + (P_{AE} C_{FAE} S_{AE}) \\
& + \left(\prod_{j=1}^n f_j \right) \left(\sum_{i=1}^{n_{PTI}} P_{PTI_i} C_{FAE} S_{AE} \right) - \left(\sum_{i=1}^{n_{eff}} f_{eff_i} P_{AE_{eff_i}} C_{FAE} S_{AE} \right) \\
& - \left(\sum_{i=1}^{n_{eff}} f_{eff_i} P_{eff_i} C_{FME} S_{ME} \right)
\end{aligned} \quad (3.10)$$

$$\begin{aligned}
EEDI = & (CO_2 \text{ from Propulsion system} + CO_2 \text{ from Auxiliary} \\
& - CO_2 \text{ emission reduction}) / DWT \times Speed
\end{aligned} \quad (3.11)$$

$$f_j \text{Capacity} \times V_{ref} \times f_w : \text{Efficiency technologies} \quad (3.12)$$

$$f_i \text{Capacity} \times V_{ref} \times f_w : \text{Transport Work} \quad (3.13)$$

P_{ME}	:Main Engine Power (kW);
P_{AE}	:Auxiliary Engine Power (kW);
SFC	:Specific fuel consumption (g/kW);
C	:Fuel to CO ₂ factor (g CO ₂ / g Fuel) (nearly 3);
Capacity	:for Cargo ships DWT, for Passenger ships GT;
V_{ref}	:Reference speed (nm/hour);
f_j	:Correction factor for capacity;
f_w	:Correction factor for performance in real weather;
f_i	:Correction factor for efficiency.

In the EEDI equation, the variable $f_{j..i}$ denotes the presence of alternative energy systems on board, such as cranes and ramps. This aspect, however, is not considered in this analysis.

The installation of a shaft generator allows the substitution of SFC_{AE} by SFC_{ME} , resulting in a reduction of the EEDI index. Furthermore, it is possible to decrease P_{ME} by utilizing the nameplate power of the PTO, $P_{PTO,NP}$ provided that $P_{PTO, NP}/0.75$ is adequate to account for P_{AE} . However, subtracting more than P_{AE} from P_{ME} is not possible due to the P_{PTO} .

$$\left(\left(P_{ME} - \frac{P_{PTO,NP}}{0.75} \right) \times 0.75 + P_{PTO,NP} \right) \quad (3.14)$$

The reference speed V_{ref} must be aligned with P_{ME} , so the PTO installation also reduces the reference speed. Nevertheless, the power consumption of a standard merchant ship is proportional to the speed raised to an exponent of 3 to 4, $P \propto V^{3 \text{ to } 4}$. Thus, the reduction of P_{ME} in the numeral by the PTO improves EEDI more than reducing the speed to V_{ref} in the denominator.

Using the power take-in function (PTI) to increase the service speed of the ship has the contrary effect on the EEDI as the gensets undergo increased fuel consumption, thus causing an increase in emissions.

3.8. Technical Specifications of Shaft Generators

In this section, an analysis and comparison of the models of the shaft generators of the 800kW 60Hz shaft generator according to 690V and 440V power values, which are most preferred in naval ships, is presented. It is acknowledged that the operating characteristics of weapon systems, communication systems, ventilation, ammunition, and other systems in naval ships encompass a range of voltage values, including 115V, 230V, 380V, and 440V. Accordingly, 690V or 440V is typically favoured, contingent on the designated utilisation of the vessel. The process of obtaining low voltage values from high voltage values and deriving voltage ranges suitable for other systems is also outlined.

Table 3.1 show the characteristic specifications of the model for 690V.

Table 3.1. Design parameters of shaft generator model for 690V

Characteristic	Unit	Values
Generator Type		Squirrel Cage
Standards		IEC
International Efficiency Classification		60034-30
Ambient Temperature (max)	°C	50
Connection of Stator Winding		Delta
Rated Output	kW	800
Voltage	V	690
Frequency	Hz	60
Speed	rpm	3586
Related Max Torque	p.μ	2,4
Poles	p	2
Number of Slots for Stator	n _s	60
Number of Slots for Rotor	n _r	60
Partial Power Factor Data	%	0,93
Protected by Enclosure	IP	IP54
Weight	kg	3200
Rotor Weight	kg	739
Cost	€	89.500€
Colour		RAL7032

And Table 3.2 show the characteristic specifications of the model for 440V.

Table 3.2. Design parameters of shaft generator model for 440V

Characteristic	Unit	Values
Generator Type		Squirrel Cage
Standards		IEC
International Efficiency Classification		60034-30
Ambient Temperature (max)	°C	50
Connection of Stator Winding		Delta
Rated Output	kW	800
Voltage	V	440
Frequency	Hz	60
Speed	rpm	3586
Related Max Torque	p.μ	2,6
Poles	p	2
Number of Slots for Stator	n _s	60
Number of Slots for Rotor	n _r	60
Partial Power Factor Data	%	0,93

Protected by Enclosure	IP	IP55
Weight	kg	6600
Rotor Weight	kg	1524
Cost	€	118.500€
Colour		RAL7045

According to the parameters given above, the shaft generator 3D model is designed as shown in Figure 3.9 and Figure 3.10. Figure 3.11 shows the top view and front 3D view of the shaft generator while Figure 3.10 shows the side view and bottom 3D view of the shaft generator. In addition, Figure 3.11 shows the dimension of shaft generator and Figure 3.12 shows the 3D view as AutoCAD design.

The design process incorporated three-dimensional ANSYS/Maxwell simulations, incorporating electromagnetic behaviour and efficiency analysis. The simulation results allow the analysis and comparison of current, efficiency and torque data of shaft generators at different power and frequency values. A comprehensive analysis was conducted, encompassing a range of parameters including current, efficiency, speed, power factor and torque. The design parameters are then optimised according to the established methodology.

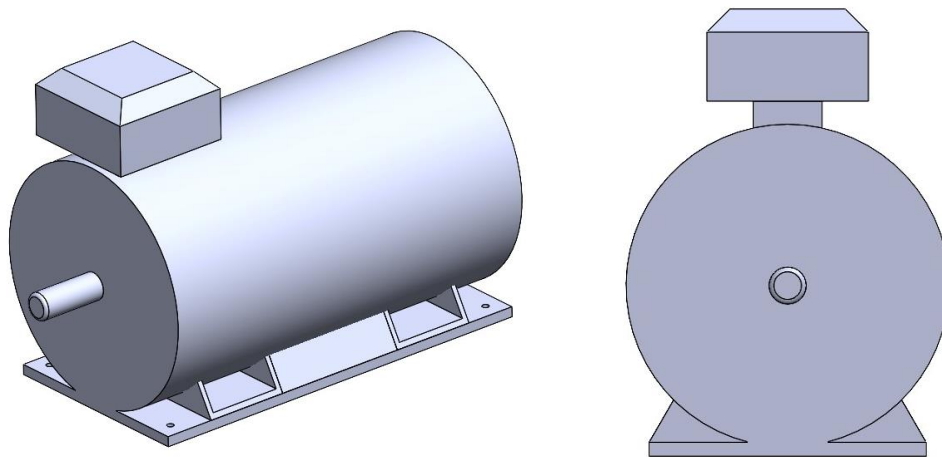


Figure 3.9. Top view and front view of shaft generator 3D model.

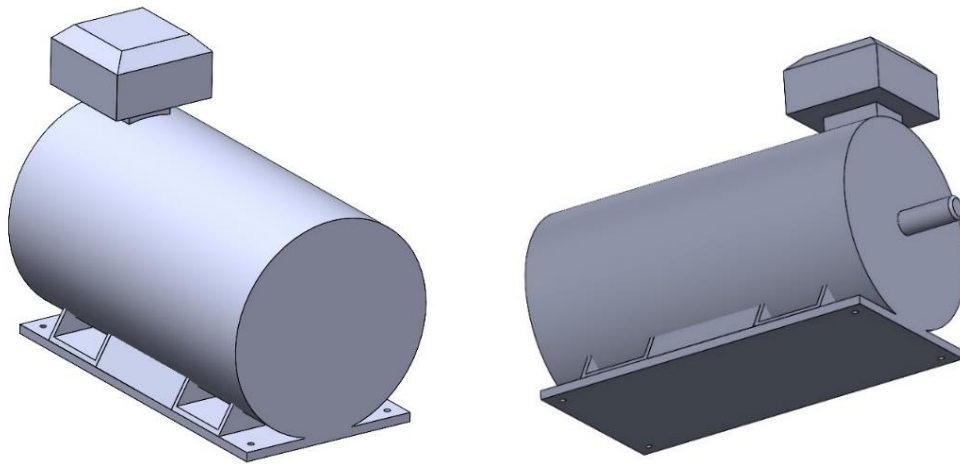


Figure 3.10. Side view and bottom view of shaft generator 3D model.

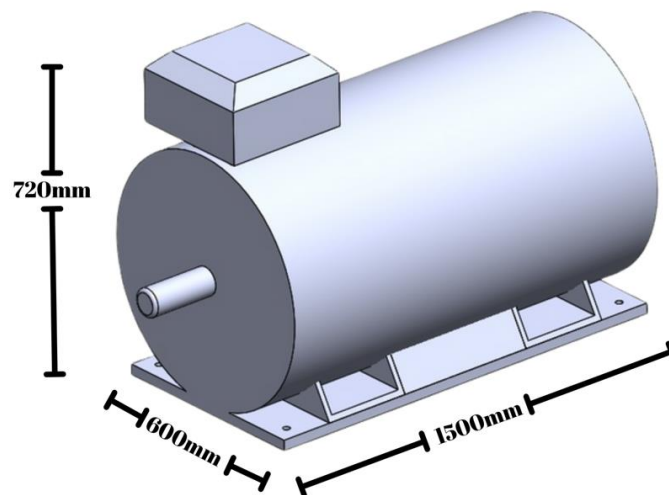


Figure 3.11. Dimension of shaft generator 3D model.

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 sum of the poles of the stator being $2P$, the quantity of double poles is P as well as the frequency that the applied voltage f generates is f , the rate of synchronisation of an asynchronous motor is n_s .

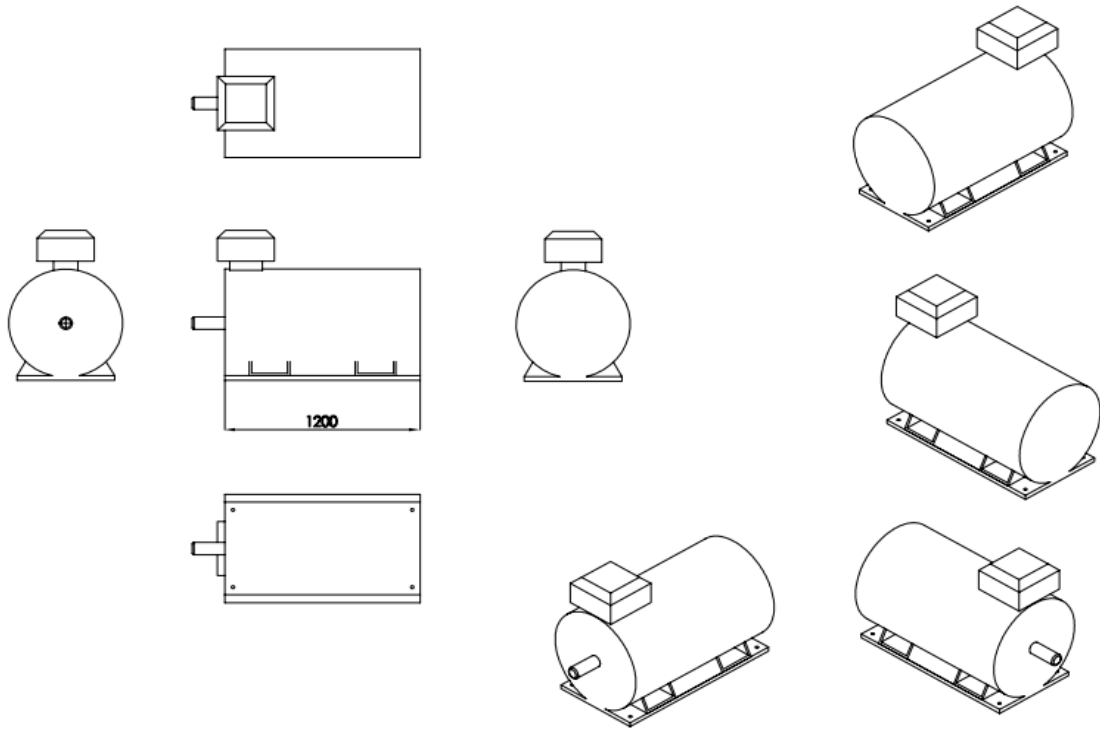


Figure 3.12. AutoCAD design of shaft generator 3D model.

$$n_s = \frac{120f}{2p} \text{ d/d} \quad (3.15)$$

Angular speed:

$$\omega_s = \frac{120f}{2p} \cdot \frac{2\pi}{60} \text{ rad/s} \quad (3.16)$$

Depending on these values, the sliding speed :

$$s = n_s - n_r \text{ (d/d)} = \omega_s - \omega_r \text{ (rad/s)} \quad (3.17)$$

The slip expression as a percentage based on these values is shown in Equation 3.18.

$$s = \frac{n_s - n_r}{n_s} = \frac{\omega_s - \omega_r}{\omega_s} \quad (3.18)$$

And rotor frequency given equation 3.19.

$$f_r = s.f = \frac{n_s - n_r}{n_s} . f \quad (3.19)$$

The relationship between magnetic flux density (B) and magnetic field strength (H) is contingent on the magnetic permeability of the material and shows equation 3.20.

$$B = \mu H \quad (3.20)$$

B : Magnetic flux density (Tesla)

H : Magnetic field strength (A/m)

μ : Magnetic permeability (μ)

The rotating magnetic field is understood by a hollow stator structure containing three coils placed at an angle of 120 degrees to each other. The applied currents are calculated according to equation 3.21.

$$i_{aa'}(t) = I_m . \sin \omega t \quad (3.21)$$

$$i_{ab'}(t) = I_m . \sin(\omega t - 120^\circ) \angle 120^\circ \quad (3.22)$$

$$i_{ac'}(t) = I_m . \sin(\omega t - 240^\circ) \angle 240^\circ \quad (3.23)$$

The equations giving the resulting magnetic fields are;

$$B_{aa'}(t) = B_m . \sin \omega t - \angle 0^\circ \quad (3.24)$$

$$B_{bb'}(t) = B_m . \sin(\omega t - 120^\circ) \angle 120^\circ \quad (3.25)$$

$$B_{cc'}(t) = B_m \cdot \sin(\omega t - 240^\circ) \angle 240^\circ \quad (3.26)$$

Depending on these equations;

$$B_{net} = \frac{3}{2} B_m \quad (3.27)$$

It is evident that the result of the vectorial sum is the establishment of a net magnetic field that is 1.5 times the maximum magnetic field.

The distribution of the magnetic field between the stator windings and the rotor is pivotal in determining the electromagnetic moment and voltage induction of the generator. In the case of shaft generators, the voltage induced in the stator windings (electromotive force (EMF)) is calculated by Faraday's Law:

$$e = -N \frac{d\lambda}{dt} \quad (3.28)$$

and EMF components in the D-Q axis:

$$e_d = -\frac{d\lambda_d}{dt} + \omega \lambda_d \quad (3.29)$$

$$e_q = -\frac{d\lambda_q}{dt} - \omega \lambda_d \quad (3.30)$$

e_d, e_q : D-Q axis induced voltages

N : Number of winding turns

λ : Magnetic flux

ω : Rotor angular speed

Equation 3.29 and equation 3.30 show how the shaft generator realises the voltage generation depending on the magnetic field variations. The electromagnetic moment (Torque $-\tau_e$) produced by the generator is related to the magnetic field and currents:

$$\tau_e = \frac{3}{2}P(\lambda_q I_q - \lambda_d I_d) \quad (3.31)$$

τ_e : Electromagnetic moment (N·m)

P : Number of poles

According to this equation, the torque produced by the shaft generator depends on the magnetic flux and currents in the D and Q axis.

The magnetic field of shaft generators can be modelled by the magnetic flux, voltage, current and torque equations. By using the D-Q axis, the magnetic flux and magnetic field strength of the generator are better analysed.

Control of the magnetic field is a critical factor to reduce power fluctuations in the ship power grid, provide voltage regulation and improve energy efficiency.

The methodology employed in this study entails the utilization of the ANSYS Maxwell simulation program and the electromagnetic analysis of shaft generators. This involves a series of steps, including the creation of a model, the definition of geometry, the specification of power and efficiency, the determination of analysis types and the evaluation of results.

In the ANSYS/Maxwell simulation program, a series of detailed design steps are performed in order to determine the most appropriate values for the induction motor of the shaft generator and the rotor and stator windings. This process involves the consideration of a number of factors, including the desired performance, the operating conditions and any constraints that may apply. By leveraging the capabilities of ANSYS/Maxwell, the design process can be

accurately simulated and analyzed in order to ensure that the shaft generator meets the required specifications.

The electromagnetic analysis of a SG necessitates the completion of a number of steps. Initially, a mathematical model is employed to ascertain the various parameters of the shaft generator. These parameters include values such as poles, speed, power, current, torque, and the connection of the stator winding. Consequently, the efficiency of the shaft generator is contingent upon the power factor, stator winding connection model and frequency values.

The ANSYS/Maxwell simulation program was utilised to evaluate the performance and efficiency of an 800kW 60Hz delta-connected shaft generator. The process was initiated with the selection of an appropriate simulation type, which in this instance was magnetic-transient. The selection of this option was determined to be the most suitable due to the fact that SGs are electromagnetic devices, and the results of the analyses are time dependent.

The analysis employed herein utilises a modelling approach, whereby the rotor and stator windings are conceptualised as solid objects. This method enables the capture of the physical dimensions and configurations of the shaft generator. The conceptualised model of the shaft generator is demonstrated in Figures 3.13, 3.14 and 3.15. The generation of a three-dimensional representation of the geometry of the shaft generator is then initiated within the ANSYS/Maxwell simulation program. The subsequent step in the process entails the modelling of the rotor and stator as solid objects. This involves the creation of their physical dimensions and the generation of the configurations of the SG.

In defining the boundaries of a simulation, it is essential to specify the specific regions and conditions within which the simulation is to be conducted. The programme has been developed to simulate the behaviour of the transformer under specific operating conditions. In order to do so, it takes into account factors such as the surrounding environment and external influences.

Subsequently, the slot numbers of the rotor and stator are assigned to the transformer model, which in turn assigns the motor pole number and terminals representing the stator and rotor

windings. These characteristics pertain to the rotor and stator windings, which are essential for the operation of the SG. In the design parameters of the shaft generator, low operating temperature ensures low temperature losses; low temperature losses ensure high efficiency.

Subsequently, the simulation is executed, during which the program calculates the time-dependent behavior of the shaft generator. This analysis entails solving the electromagnetic equations that govern the operation of the shaft generator, taking into account the specified boundary conditions and excitations.

Upon completion of the simulation, the results and diagrams provide valuable information regarding the performance of the shaft generator. The results include a variety of electromagnetic quantities, such as magnetic fields, flux densities, and currents, which can be visualized and analyzed to evaluate the shaft generator's behavior and efficiency.

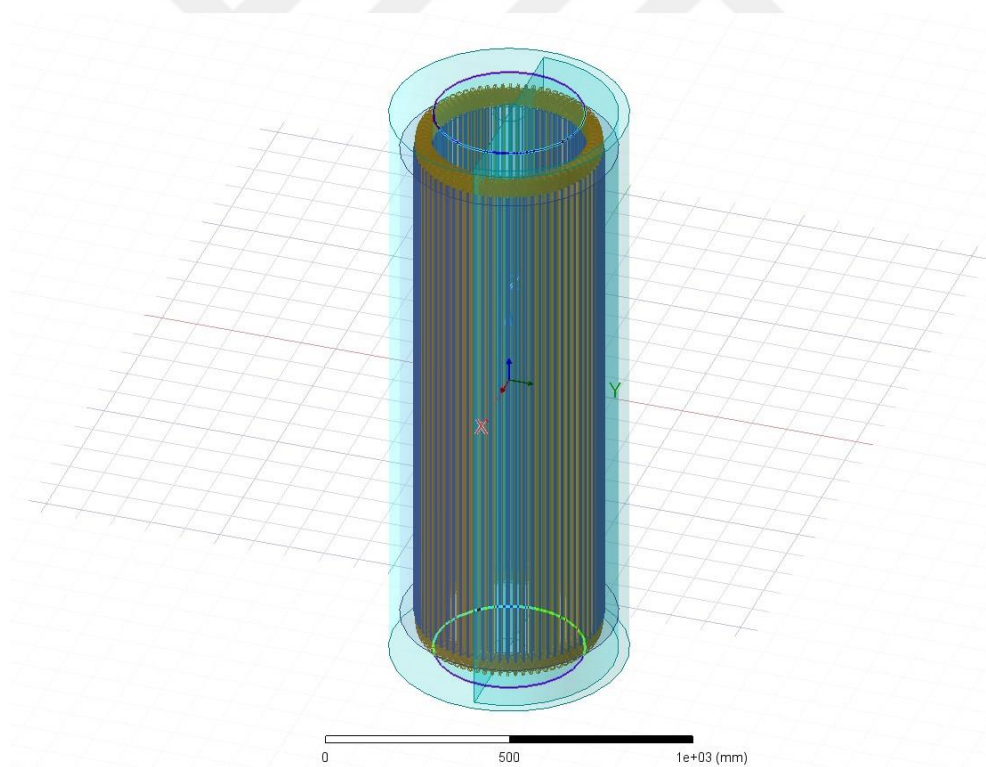


Figure 3.13. ANSYS Maxwell design of shaft generator.

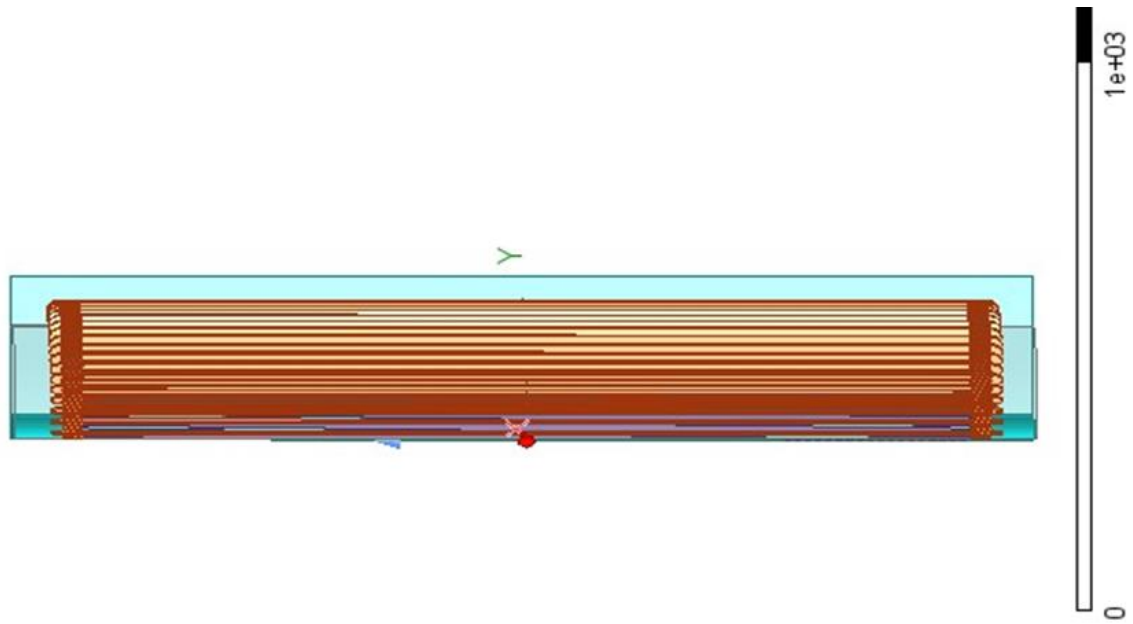


Figure 3.14. ANSYS Maxwell design of shaft generator.

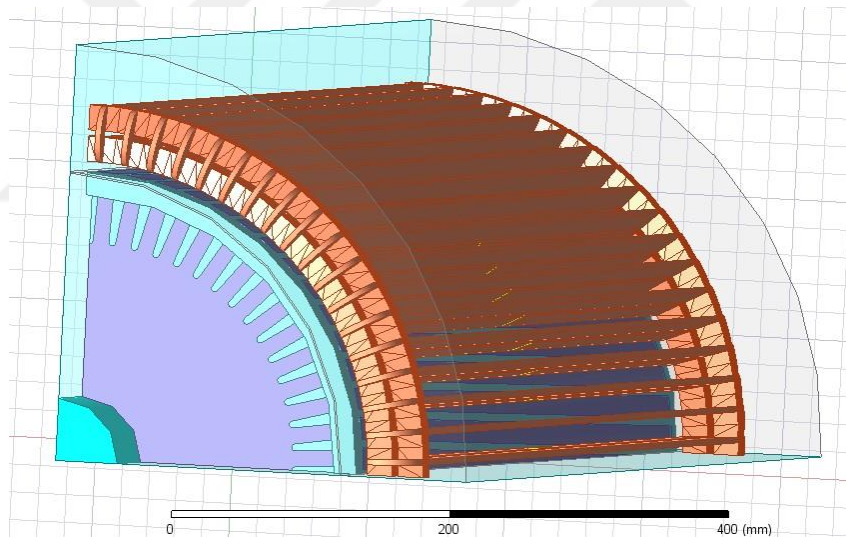


Figure 3.15. ANSYS Maxwell design of shaft generator cross section.

The shaft generator design procedure is initiated by creating a three-dimensional (3D) model using Maxwell-3D within the ANSYS/Maxwell simulation program. The modelling stage involves the accurate representation of the shaft generator and the motor pole numbers, rotor and stator windings.

The capabilities of Maxwell-3D are employed to meticulously design the physical dimensions and configurations of the shaft generator's induction motor and windings. This approach ensures the generation of a highly detailed and precise representation of the geometry of the shaft generator.

The resulting three-dimensional model of the shaft generator, as demonstrated in Figure 3.16, provides a visual representation of the configuration of the rotor and stator windings within the design. This representation is pivotal in facilitating a comprehension of the physical layout and configuration of the design components.

The simulation program facilitates the analysis of electromagnetic fields and the operation of the shaft generator's interior, employing Maxwell-3D for the design of shaft generators. This facilitates a detailed evaluation of factors such as magnetic fields, flux densities and currents, ultimately offering insights into the performance and efficiency of the shaft generator design.

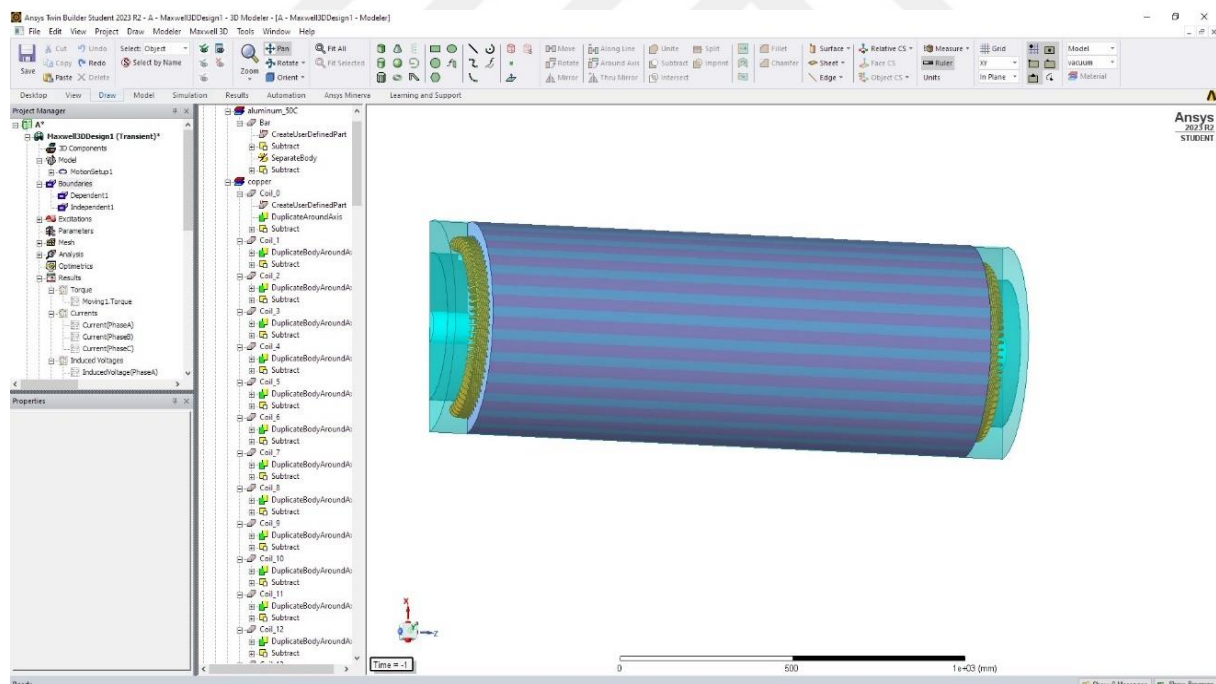


Figure 3.16. ANSYS/Maxwell 3D design operation panel.

The simulation program facilitates the analysis of electromagnetic fields and behaviour within the shaft generator, with the design of the shaft generator system being accomplished through

the utilisation of Maxwell-3D. The present method enables a comprehensive evaluation of various factors, including but not limited to magnetic fields, torque value and current value, thereby facilitating insights into the performance and efficiency of transformer design.

In the subsequent step of the modelling process, the most appropriate material types for the components of the induction motor and its windings must be selected. The selection of the most suitable material types for these components is achieved through the utilisation of the material property panel within the ANSYS/Maxwell simulation program, as demonstrated in Figures 3.17, 3.18 and 3.19.

The material property panel in ANSYS/Maxwell offers a user-friendly interface designed to accurately define the electromagnetic properties and characteristics of the induction motor and its windings. By carefully assigning the appropriate material types, the simulation program is capable of precisely replicating the behavior of these components under various operating conditions. This accurate simulation is crucial for predicting the performance of the induction motor, thereby informing design decisions that enhance the overall efficiency and functionality of the shaft generator system. By utilizing the material specification panel, you can make informed decisions on material selection, which improves the performance, efficiency and reliability of the overall system. In summary, the integration of Maxwell-3D within the ANSYS/Maxwell simulation environment provides a robust platform for the detailed analysis and optimization of electromagnetic systems in shaft generators.

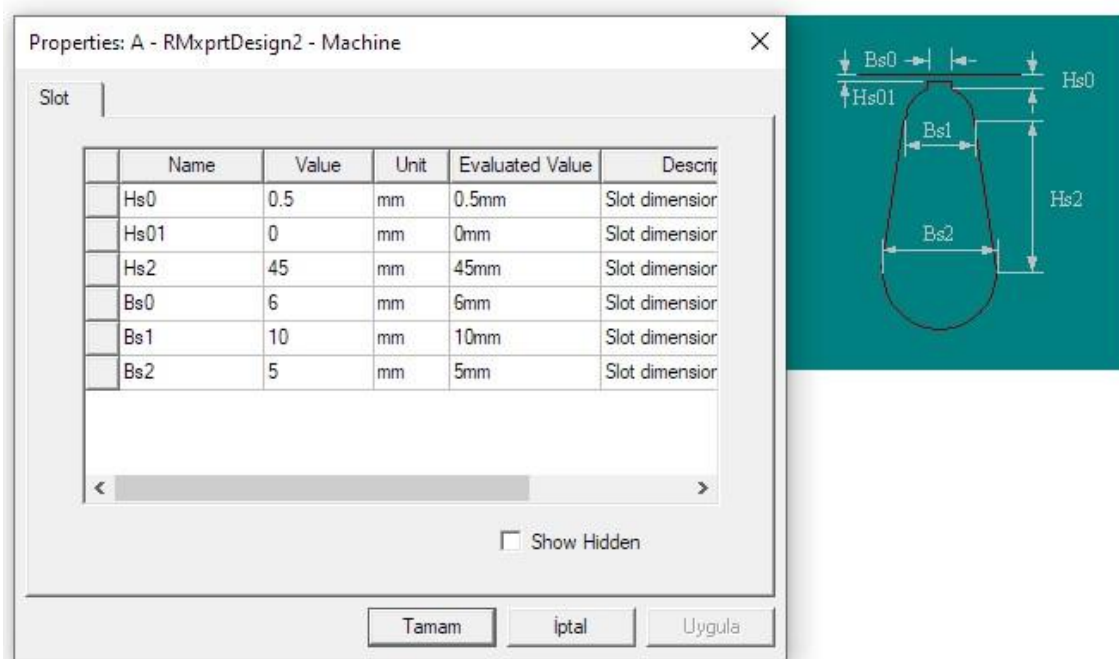


Figure 3.17. Creating specific dimension value for rotor slot.

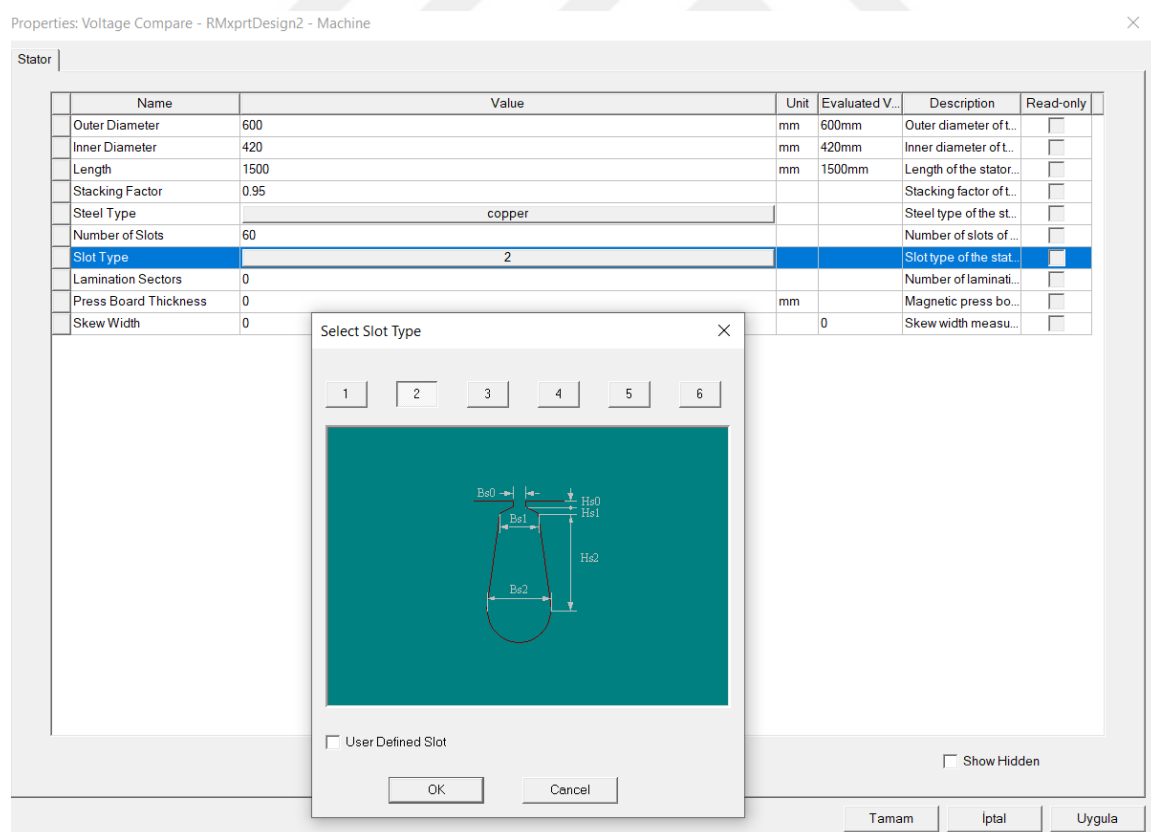


Figure 3.18. Creating specific properties for stator.

In the selection of materials, factors such as magnetic permeability, electrical conductivity and other relevant material properties are given careful consideration. These properties exert a considerable influence on the electromagnetic performance and efficiency of the shaft generator. Electrical conductivity is a crucial factor, particularly in the context of windings and other conductive components. Materials with high electrical conductivity facilitate the efficient flow of current by reducing resistance losses and minimizing the generation of heat. This is of the essence for the generator to maintain its performance and reliability under different operating conditions. Other crucial material properties include thermal conductivity, mechanical strength and resistance to corrosion and temperature changes. Thermal conductivity is of significant importance for the efficient dissipation of heat and the prevention of overheating, thus ensuring the stability of generator operation. The mechanical strength of a material guarantees the durability and longevity of components, while resistance to environmental factors ensures consistent performance over an extended period.

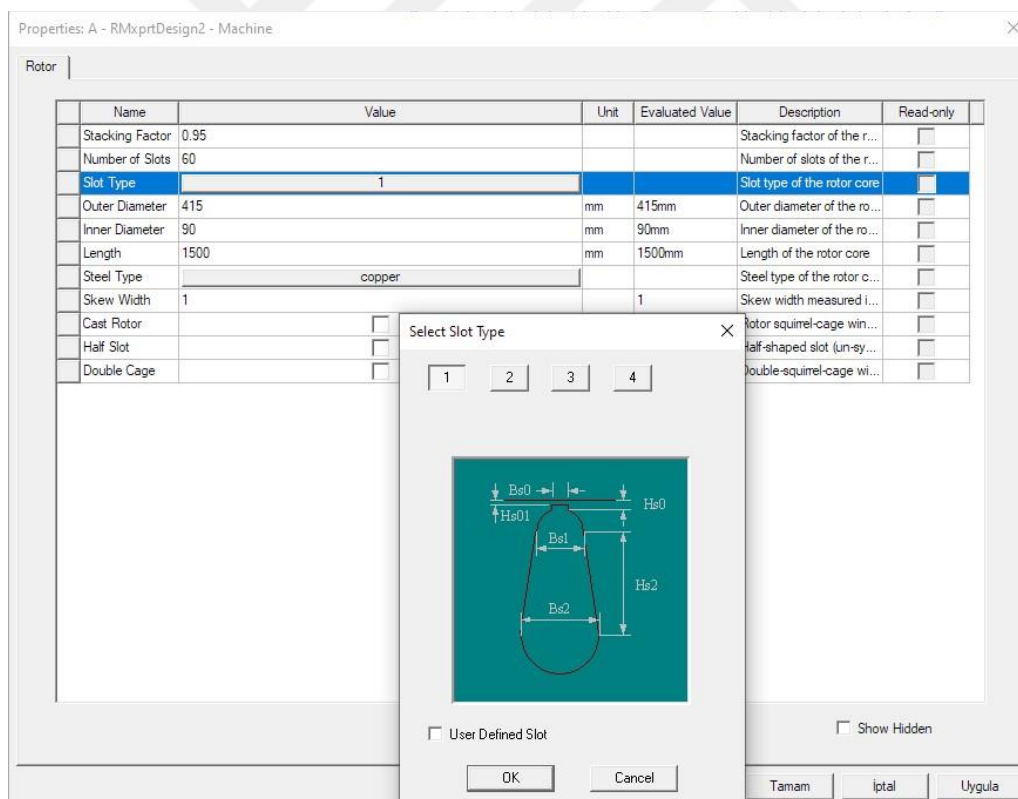


Figure 3.19. Creating specific properties for rotor.

By meticulously evaluating and selecting materials with these specific properties in mind, the ANSYS/Maxwell simulation program is capable of accurately modelling the behavior of shaft generator components. This rigorous material selection process not only enhances electromagnetic performance but also contributes to the overall efficiency and reliability of the shaft generator system. Such comprehensive material analysis can enhance the functionality of the shaft generator by optimizing its design and operational parameters. Furthermore, the shaft generator model must accurately reflect the real-world behavior of the selected materials in order to enable the electromagnetic response of the transformer to be accurately analyzed and predicted.

In the course of the design process, the decision was taken that copper would be the optimal material for the rotor of the shaft generator. The selection of materials was informed by the superior characteristics of copper. It is evident that copper is particularly well-suited to the fabrication of transformer cores and analogous applications, a consequence of its distinct electromagnetic properties. Copper's high electrical conductivity and low electrical resistivity facilitate its extensive utilization in electromechanical systems. Furthermore, copper's high mechanical strength and thermal conductivity ensure stable performance of the rotor even under overheating and mechanical stress.

The stator windings of the shaft generator were also selected to be manufactured from copper. Copper is a material that is widely used for transformer windings, offering excellent electrical conductivity. This property ensures that the flow of electricity in the windings is efficient and lossless. Concurrently, the thermal conductivity of copper facilitates the effective dissipation of heat generated during operation, thereby enhancing the reliability and longevity of the system.

The subsequent stage in the process entails the excitation and energisation of the rotor and stator windings, in accordance with the specified shaft generator parameters. This is preceded by the assignment of the requisite materials to the rotor and stator windings. The movement of electric charge within the stator windings gives rise to the generation of a current load. Furthermore, the closed circuit current generates a magnetic field in the opposite direction to that of the

magnetic field that generated it. In consideration of the aforementioned factors, the windings have been engineered to achieve the desired electrical characteristics of the shaft generator.

The allocation of excitations to the windings is demonstrated in Figure 3.20, which offers a visual depiction of the connections and energisation of the windings within the shaft generator configuration.

Additionally, in order to account for certain characteristics of the shaft generator, the air material is designated as a zone or boundary. This is done in order to accurately represent the presence of air voids or regions within the structure of the shaft generator.

The ANSYS/Maxwell program enables a comprehensive analysis of the electromagnetic behavior of the shaft generator by assigning appropriate materials and excitations. This analysis is concerned with factors such as magnetic fields, electric currents and voltage distributions.

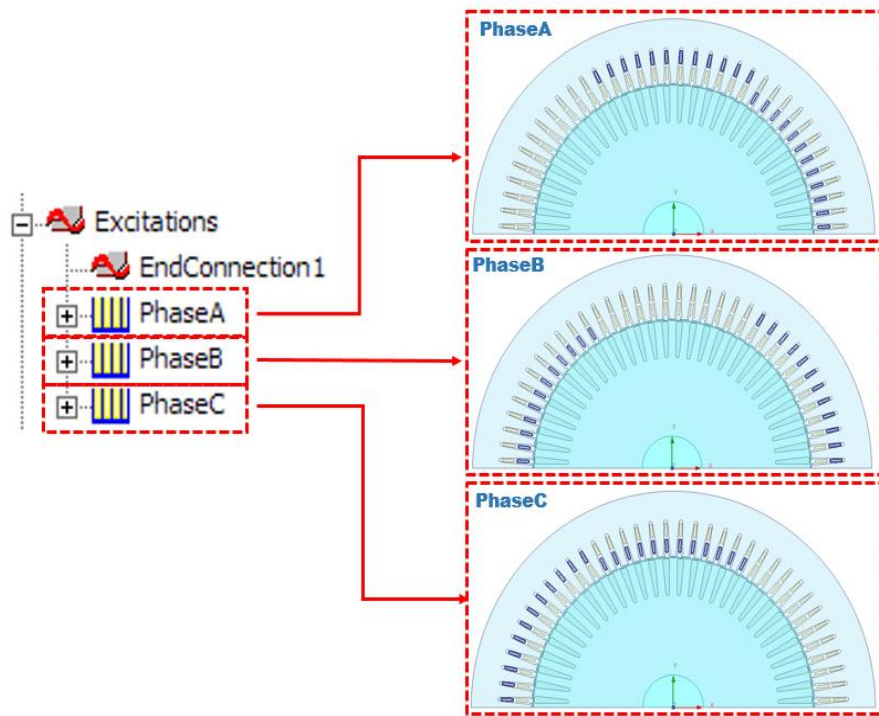


Figure.3.20. Assignment of excitation to windings of shaft generator.

In order to guarantee the dependability of the ensuing analysis outcomes, meticulous attention was paid to the selection of optimal values for these parameters. The settings for the shaft generator, as illustrated in Figure 3.21, provide a visual representation of the selected parameters and settings. This provides a clear indication of the manner in which the analysis time is defined and the configuration of the analysis solution step.

The ANSYS/Maxwell program is a computer program designed to facilitate the accurate simulation and evaluation of the electromagnetic transient behaviour of the shaft generator. This is achieved by setting appropriate analysis parameters. This facilitates the analysis of fundamental electrical quantities, including current, voltage, and efficiency values, over the specified analysis time interval.

Subsequently, the analysis results are obtained based on the defined analysis time.

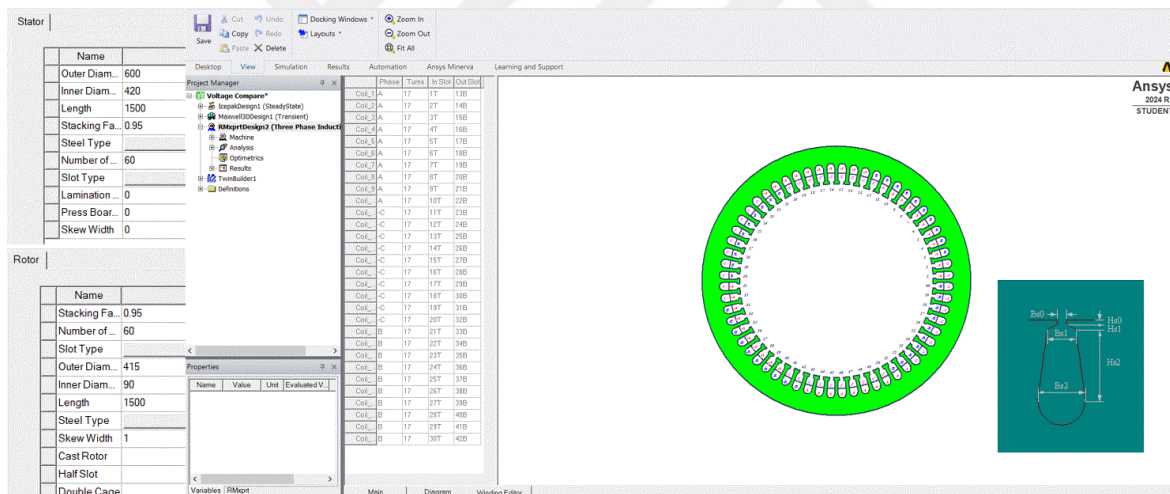


Figure 3.21. Analysis value of shaft generator in ANSYS/Maxwell.

3.9. MATLAB/Simulink Dynamic Model

As illustrated in Figure 3.22, the shaft generator model developed on the MATLAB/Simulink platform facilitates the analysis of stator and rotor currents, voltage characteristics, speed and torque values, contingent on diverse power, frequency and operating conditions. This model furnishes users with a comprehensive perspective on design and optimization processes by

enabling the comparative evaluation of system performance against parameter variations. The primary objective of this model is to facilitate a more profound comprehension of the dynamic behavior exhibited by shaft generator systems, particularly within the domains of marine engineering and energy production, with a view to enhancing operational efficiency.



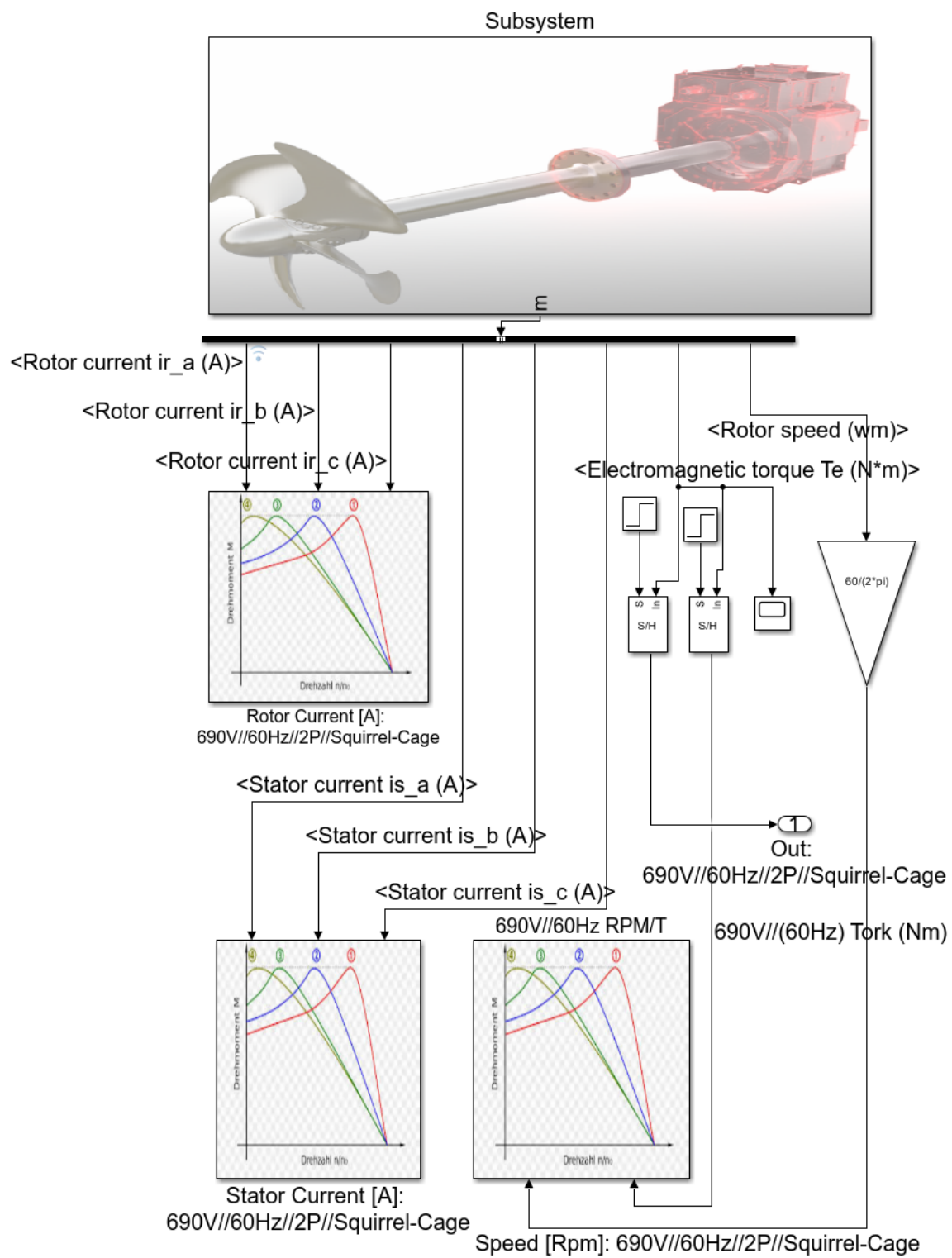


Figure 3.22. The shaft generator was subjected to an analysis by altering the power and frequency parameters.

The shaft generator models developed using MATLAB/Simulink provide the following analysis possibilities:

- **Stator and Rotor Current Analyses:**

An in-depth analysis is conducted of the instantaneous magnitude changes, frequency spectrum and harmonic contents of the stator and rotor currents when operating under various conditions, including load variation, speed fluctuations, sudden loads and lightning strikes. This analysis is of paramount importance in determining the deviation rates of the currents from their nominal values and in particular in elucidating the impact of harmonics on system performance.

- **An Investigation into Varying Voltage Characteristics:**

At the voltage levels that are commonly utilized within shipboard electrical systems, such as 690V, 440V, 400V and 380V, a detailed analysis of system performance is conducted in relation to various parameters. These parameters include the harmonic content of stator and rotor currents, current fluctuations, torque stability and speed constancy. This comprehensive analysis provides a detailed overview of the system's performance under various load profiles and operating conditions, as well as identifying potential areas for enhancement.

- **Speed and Torque Variations:**

A comparative analysis of speed and torque characteristics at various power and frequency values provides a significant foundation for comprehending the dynamic behavior of shaft generator systems. These analyses comprehensively examine the effect of speed variations on torque and the consequences of these variations on energy losses, mechanical stability and performance of the system. In particular, critical performance parameters such as the system's response to dynamic load fluctuations during ship operations and the stability of speed and torque are evaluated. Furthermore, these evaluations provide insights into the impact of sudden operating changes, such as loading and lightening, on system efficiency, and facilitate the determination of optimal operating points. The outcomes of these evaluations provide guidance on energy conservation and the prolongation of equipment life.

- **Frequency and Power Variables:**

The analysis of the impact of operating at 50Hz and 60Hz frequencies on the system involves the evaluation of performance variations under different scenarios. These analyses consider in detail the effects of frequency changes on harmonic distortions in stator and rotor currents, torque fluctuations and speed stability. The disparity between 50Hz and 60Hz has substantial ramifications for the configuration of generator windings, energy efficiency, and the durability of mechanical components over an extended timeframe. Furthermore, the study of energy efficiency at different power levels includes detailed calculations and recommendations for optimum power transfer and minimization of energy losses.

These analyses provide a comparative evaluation of stator and rotor currents, different voltage characteristics, speed and torque values of shaft generator systems depending on different power, frequency and operating mode values. The analysis provides critical information for the more efficient design and optimization of shaft generator systems in the marine industry. The selection of appropriate components during the design phase is facilitated by comparative analyses of different parameters, thereby ensuring optimal efficiency. Furthermore, these analyses form a foundation for advanced studies, including harmonic analysis and system stability. These studies provide critical information for more efficient design and optimization of shaft generator systems in the marine industry. The studies provides a strategic basis for improving energy efficiency and reducing operational costs, while guiding the identification of the right components in the design phase.

4. RESULTS AND DISCUSSIONS

4.1. Analysis According to Shaft Generator Type in ANSYS Maxwell

4.1.1. Analysis of Voltage Characteristic

An analysis and comparison of 690V and 440V shaft generators is conducted. Firstly, the transformer models are subjected to analysis using the ANSYS/Maxwell simulation program. The results obtained from the ANSYS/Maxwell program are then compared with the actual value.

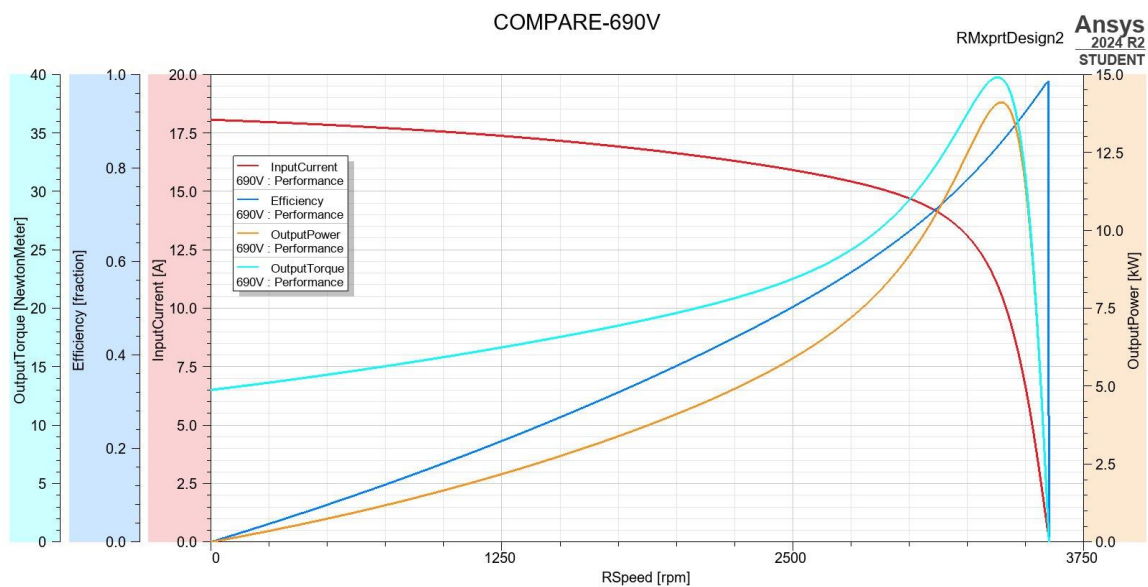


Figure 4.1. Results of efficiency, torque, current and output power analysis of 690V.

The results of the analysis of 690V are presented in detail in the results graphs in Figure 4.1. These graphs illustrate the performance of 690V in terms of critical performance parameters such as torque, efficiency, input current and output power. The graphs provide a comprehensive understanding of the performance of Model A and visually illustrate its behavior under different operating conditions.

Likewise, the evaluation of the data obtained from analyzing 440V is shown in detail in the results graphs in Figure 4.2 for critical performance parameters such as torque, efficiency, input current, power factor and output power. These graphs provide a comprehensive understanding

of the performance of 440V and visually demonstrate its behavior under different operating conditions.

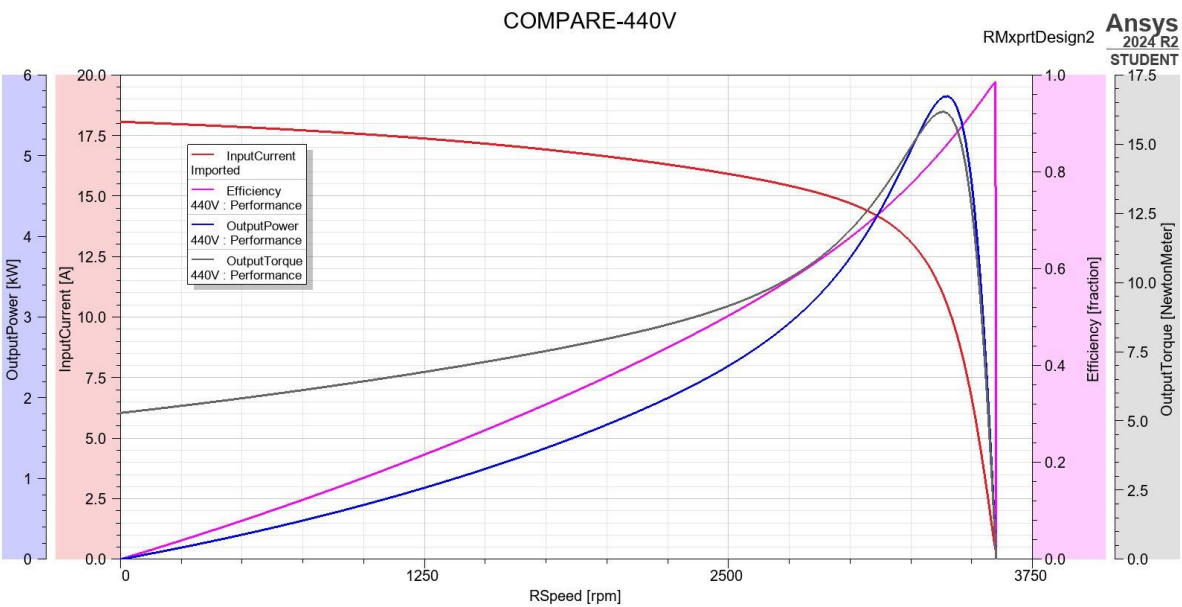


Figure 4.2. Results of efficiency, torque, current and output power analysis of 440V.

This performance graph is a valuable tool for determining the most efficient operating range of the generator. This is particularly pertinent in systems that demand high reliability and efficiency, such as military ship applications. Operating the generator within its rated speed range ensures optimal energy efficiency and minimises losses. The high energy consumption at low speeds indicates that starting strategies should be optimised accordingly.

The preliminary analysis focuses on the input current values obtained for the shaft generator in relation to the speed values. The graphical and comparative analysis results for 690V and 440V are presented in Table 4.1 and Figure 4.3.

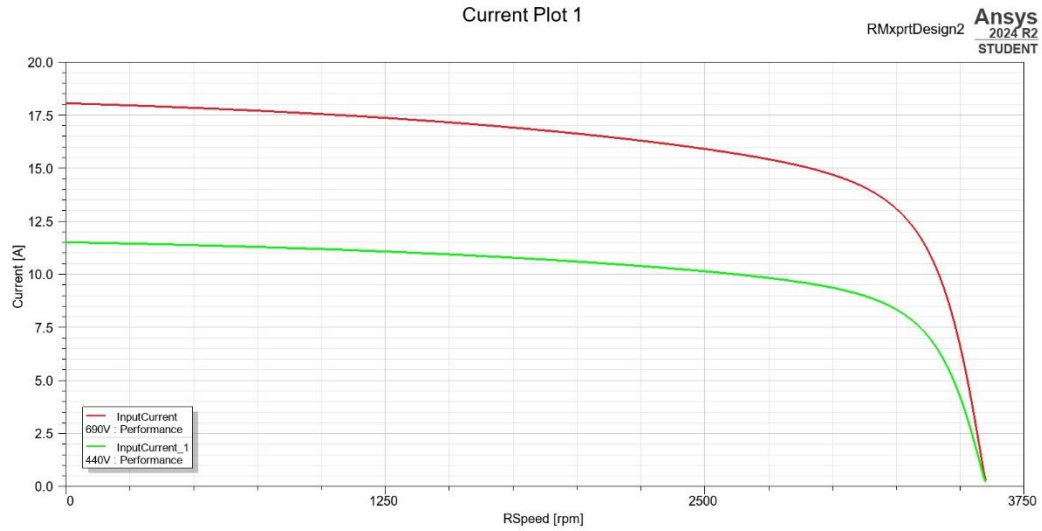


Figure 4.3. Comparative input current graph of 690V and 440V.

As illustrated in Figure 4.3, the variation of input current with speed (RSpeed [rpm]) in a generator system is analysed for two distinct cases.

690V Status: This configuration necessitates a higher input current, which results in increased energy consumption at low speeds. The 440V condition is as follows: It is more efficient in terms of energy consumption as it operates with lower input current. After 2500 rpm, a precipitous decline in current is observed in both cases, indicating that the generator demands less energy at higher speeds.

It can be concluded that 440V operating conditions are more favourable in terms of energy consumption because the starting current is lower. Conversely, the 690V system may be more appropriate for applications with higher power requirements; however, it generates more losses at low speeds in terms of energy efficiency. In the design and utilisation of generators, it is imperative to consider the impact of voltage level on energy consumption.

Table 4.1. Input Current Analysis Result for 690V and 440V.

	RSpeed [rpm]	Input Current [mA]: 690V	Input Current [mA]: 440V
1	0	18.056.835	11.512.863
2	72	18.029.184	11.495.239
3	648	17.762.161	11.325.042
4	1368	17.271.477	11.012.279
5	1836	16.817.54	10.722.93
6	2196	16.371.021	10.438.304
7	2556	15.806.695	10.078.577
8	2916	14.982.865	9.553.421
9	3276	12.788.285	8.154.379
10	3474	7.851.588	5.006.742
11	3556.8	3.157.946	2.013.761
12	3600	312.553	199.309

The red line signifies an operating scenario that necessitates a greater energy consumption, attributable to a higher initial current. Conversely, the green line signifies a more efficient scenario, characterised by reduced energy consumption. The analysis presented in this figure indicates that optimisation of generator design and control systems is imperative to minimise energy loss at low speeds and ensure optimal efficiency at high speeds.

The second analysis is concerned with the resulting output power values for the shaft generator, as a function of the speed values. The graphical and comparative analysis results for 690V and 440V are shown in Table 4.2 and Figure 4.4.

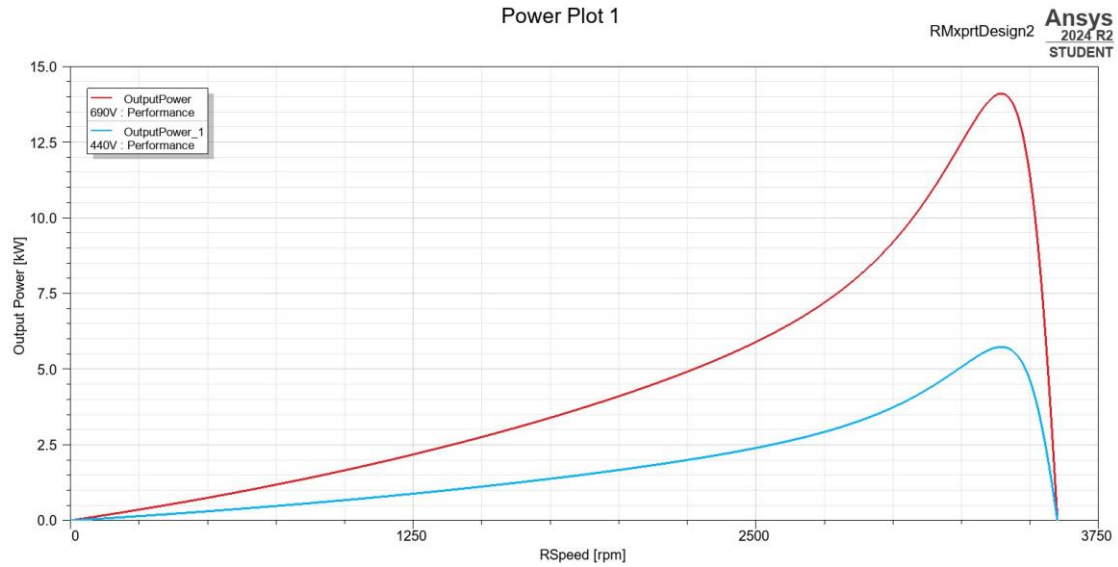


Figure 4.4. Comparative output power graph of 690V and 440V.

At a voltage of 690V, the output power demonstrates a more rapid increase. For 690V, the output power increases linearly, reaching approximately 8.4 kW. Conversely, at 440V, the output power is more constrained within the same speed range, reaching approximately 3.4 kW. The findings indicate that the utilisation of 690V voltage enables the motor to attain higher levels of efficiency and power output.

Table 4.2. Output Power Analysis Result for 690V and 440V.

	RSpeed [rpm]	Output Power [kW]: 690V	Output Power [kW]: 440V
1	0	0	0
2	72	0.099.380.104	0.040.400.093
3	648	0.999.798.591	0.406.442.983
4	1368	2.443.996.441	0.993.562.295
5	1836	362.715.898	147.457.795
6	2196	4.728.006.144	1.922.142.232
7	2556	6.148.112.248	2.499.523.552
8	2916	8.403.923.455	3.416.719.655
9	3276	12.875.220.065	5.234.932.664
10	3474	12.740.685.463	5.180.692.952
11	3556.8	6.067.808.172	246.739.141
12	3600	0	0

However, it is important to note that in both systems, the output power experiences a rapid decline to zero after 3600 rpm. This observation indicates that the motor's efficiency and mechanical stability reach their limits at these speeds.

This analysis demonstrates that the 690V voltage level facilitates enhanced power generation and more efficient performance. However, it is important to note that significant power losses were observed in both systems when the speed limits were exceeded. Consequently, when selecting a motor, it is imperative to choose the appropriate voltage level by taking into account the power and speed requirements of the specific application.

The third analysis is concerned with the resulting output torque values for the shaft generator, as a function of the speed values. The graphical and comparative analysis results for models A and D are presented in Table 4.3 and Figure 4.5.

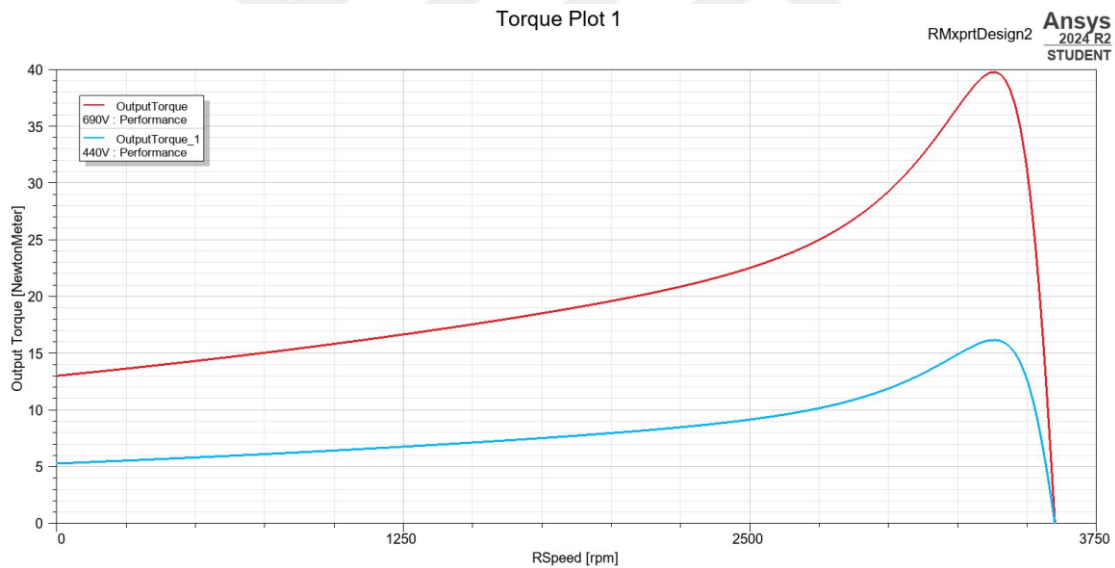


Figure 4.5. Comparative output torque graph of 690V and 440V.

For 690V, the torque value increases linearly with increasing speed. A subsequent decline in torque is evident as the velocity rises. Conversely, for 440V, the torque value increases with a lower slope as the speed increases.

Table 4.3. Output torque Analysis Result for 690V and 440V.

	RSpeed [rpm]	Output Torque [Nm]: 690V	Output Torque [Nm]: 440V
1	0	13.004.015	5.286.399
2	72	13.180.696	5.358.229
3	648	14.733.601	5.989.575
4	1368	17.060.268	6.935.542
5	1836	18.865.369	7.669.489
6	2196	20.559.714	8.358.427
7	2556	22.969.541	9.338.299
8	2916	2.752.111	1.118.905
9	3276	3.753.031	1.525.944
10	3474	35.021.469	14.240.637
11	3556.8	16.290.851	6.624.452
12	3600	0	0

It is evident that the 690V operating voltage facilitates enhanced torque production and more efficient operation. Conversely, the 440V system offers reduced torque values and exhibits constrained performance. In both systems, the torque value exhibits a rapid decline at high speeds. This phenomenon signifies that the motor has attained its mechanical and electrical limits.

It is therefore concluded that the 690V voltage level provides higher torque performance and is a more suitable choice, especially in applications requiring high torque. Conversely, the 440V level offers reduced torque ratings and is better suited to light load applications. It is evident that both systems demonstrate substantial performance deterioration under conditions of over-speed operation.

4.1.2. Analysis of Connection Characteristic

690V 800kW 60Hz shaft generator is analysed and compared according to wye and delta connection structure.

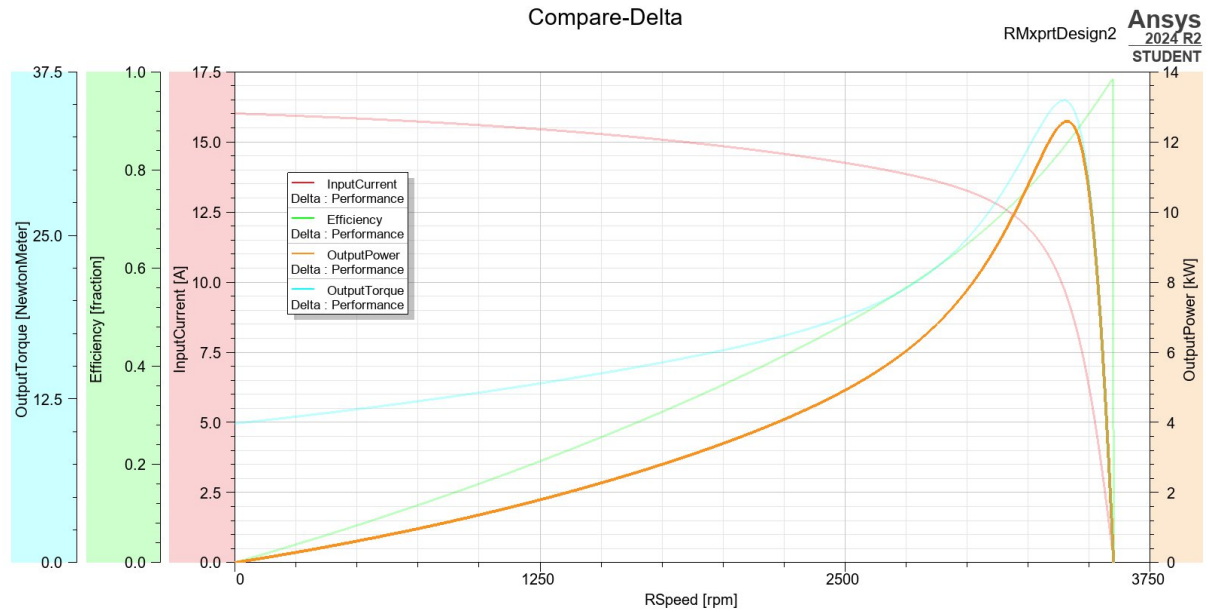


Figure 4.6. Results of efficiency, torque, current and output power analysis of Delta Connection.

The figure 4.6 illustrates the variation in performance parameters (torque, efficiency, input current and output power) of an electric motor with rotational speed (RSpeed [rpm]).

The optimum operating point is identified as follows: The medium speed range is delineated as 1000-3000 rpm. Within this range, the values of efficiency, power and torque are at their optimal levels. It is imperative to note that a high current draw at low speeds necessitates meticulous monitoring of the motor during the start-up phase. The torque and power reach their maximum values at specific speed ranges and then decrease rapidly. It is therefore critical to select the appropriate speed range and feed parameters according to the operating conditions of the motor in order to ensure optimal system performance and efficiency.

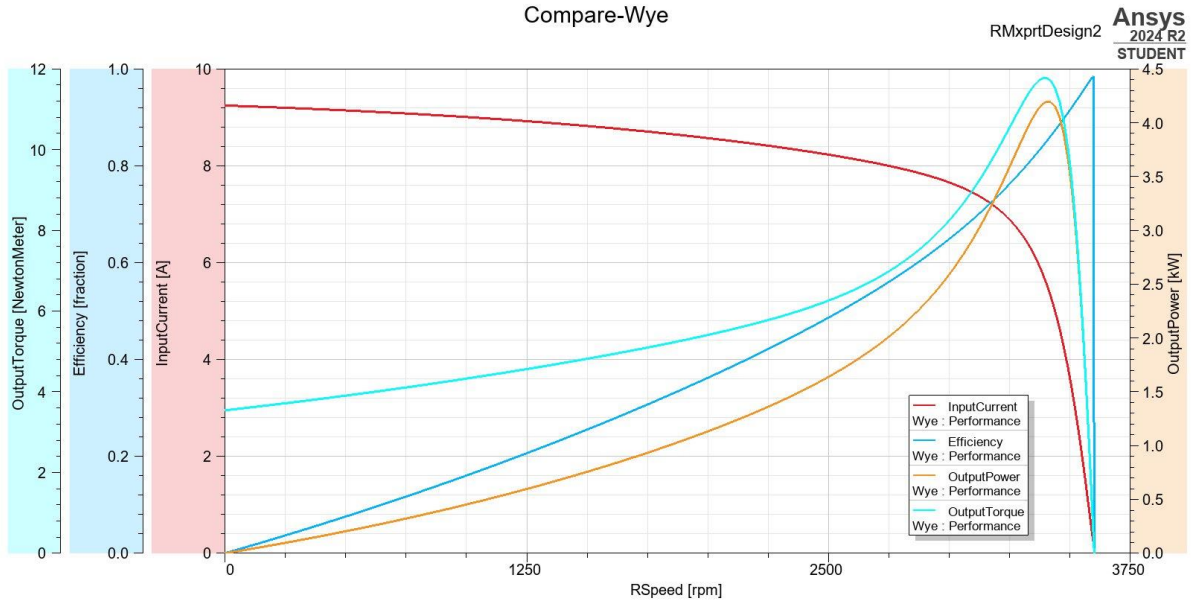


Figure 4.7. Results of efficiency, torque, current and output power analysis of Wye Connection.

The figure 4.7 under consideration herein analyses the Wye connection performance of a 690V 800kW 60 Hz shaft generator in terms of speed.

At low speeds, the inlet current is high and decreases slightly with increasing speed. Conversely, at elevated speeds, the input current undergoes a precipitous decline. Torque, conversely, exhibits a peak at low speeds, gradually declining as the speed increases. It is observed that maximum efficiency is attained at medium speed ranges. Conversely, efficiency is observed to decrease at both low and high speeds. Power increases at low speeds and reaches maximum power at a certain speed. Subsequent to attaining maximum power, a decline in power is observed with an increase in speed. The efficiency and power of the motor reach maximum levels at medium speeds.

Conversely, at elevated speeds, both efficiency and torque undergo a decline, accompanied by a rapid decrease in input current. The operating point that optimises efficiency and power is located within the medium speed range. The analysis presented in this graph is of paramount importance in understanding the operating characteristics of the motor and determining the ideal operating range.

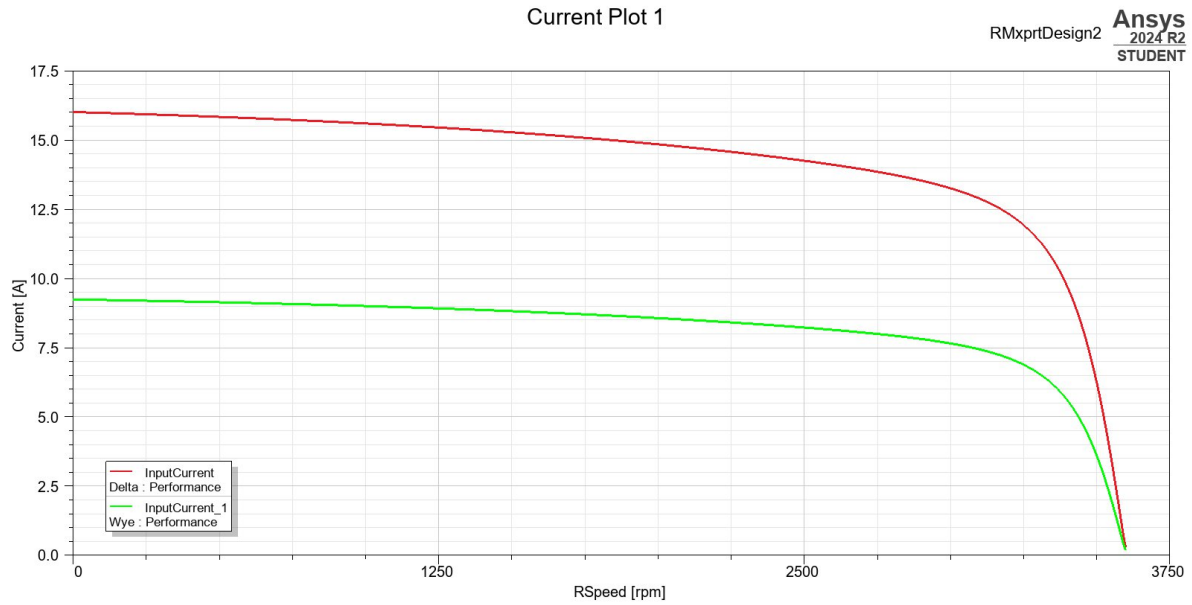


Figure 4.8. Comparative input current graph of Delta and Wye Connection.

Table 4.4. Input Current Analysis Result for Delta and Wye Connection.

	RSpeed [rpm]	Input Current [mA]: Delta	Input Current [mA]: Wye
1	0	16.009.169	9.241.749
2	72	15.986.76	9.228.816
3	648	15.770.086	9.103.77
4	1368	15.370.569	8.873.197
5	1836	14.999.45	8.659.009
6	2196	14.633232	8.447.646
7	2556	14.169569	8.180.038
8	2916	13.493353	7.789.748
9	3276	11.678292	6.742.099
10	3474	73.74912	4.257.849
11	3556.8	30.18359	1.742.649
12	3600	304.958	176.068

The Figure 4.8 and Table 4.4; at low speeds, the delta connection exhibits a higher input current, while the wye connection draws a lower current. At moderate speeds, both connection types exhibit a reduction in current, yet the Delta connection continues to demand a higher current. At higher speeds, a rapid decline in current is observed in both connection types; however, the Wye connection exhibits superior efficiency.

The Delta connection, while drawing a higher current and providing more power, exhibits lower efficiency. Conversely, the Wye connection draws a lower current, indicating its superior efficiency, although it may be constrained in applications necessitating high power. In applications where low power and high efficiency are paramount, the Wye connection should be favoured. Conversely, when high power is the primary concern, the Delta connection should be prioritised. The graph provides crucial data for comprehending the current performance of the motor with different connection types and to determine the appropriate connection strategy.

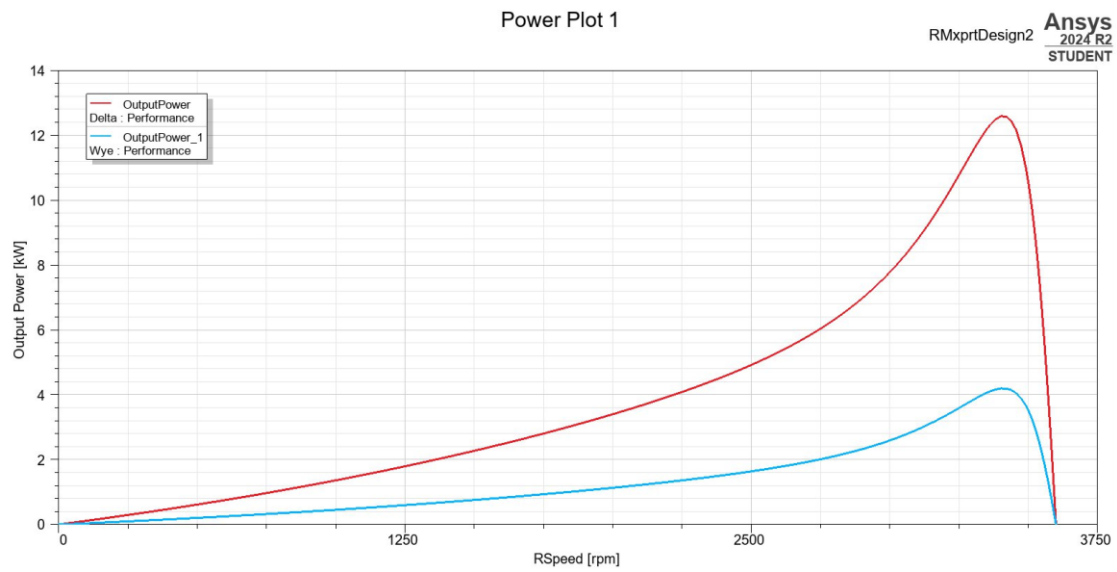


Figure 4.9. Comparative output power graph of Delta and Wye Connection.

The figure 4.9 and Table 4.5 illustrates the variation in output power of a 690V 800kW 60Hz shaft generator, as a function of motor speed (RSpeed [rpm]), for both Delta and Wye connection types.

At low speeds, both connection types produce low power; however, the Delta connection provides higher power. At medium speeds, the Delta connection exhibits a distinct advantage in power generation. At higher speeds, the Delta connection exhibits a substantial increase in power generation, while the Wye connection achieves a more limited power level.

Table 4.5. Output power Analysis Result for Delta and Wye Connection.

	RSpeed [rpm]	Output Power [kW]: Delta	Output Power [kW]: Wye
1	0	0	0
2	72	0.081.212.798	0.027.064.154
3	648	0.819.111.044	0.27.297.076
4	1368	2.011.732.928	0.670.424.157
5	1836	2.998.723.145	0.999.357.941
6	2196	3.925.963.197	1.308.386.639
7	2556	5.134.598.168	1.711.208.253
8	2916	7.083.689.333	2.360.835.056
9	3276	11.158.603.546	3.719.123.826
10	3474	11.681.502.303	3.893.723.078
11	3556.8	5.759.183.811	1.919.723.517
12	3600	0	0

The Delta connection is thus the more advantageous option in applications requiring high power. However, it should be noted that it can draw more current in terms of efficiency. Conversely, the Wye connection generates lower power but facilitates more efficient and stable operation.

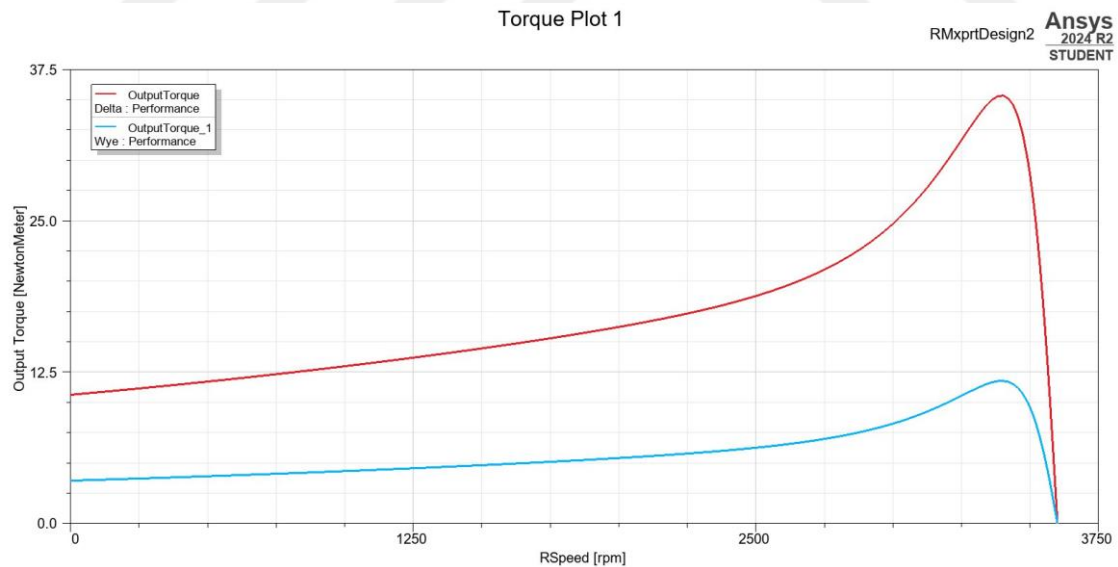


Figure 4.10. Comparative output torque graph of Delta and Wye Connection.

The figure 4.10 and Table 4.6 illustrates the variation in output torque of a 690V 800kW 60Hz shaft generator, as a function of motor speed (RSpeed [rpm]), for both Delta and Wye connection types.

Table 4.6. Output torque Analysis Result for Delta and Wye Connection.

	RSpeed [rpm]	Output Torque [Nm]: Delta	Output Torque [Nm]: Wye
1	0	10.624.006	3.540.446
2	72	10.771.182	3.589.495
3	648	12.070.886	4.022.652
4	1368	14.042.861	4.679.882
5	1836	15.596.785	5.197.802
6	2196	17.072.034	5.689.514
7	2556	19.183.021	6.393.128
8	2916	23.197.617	7.731.246
9	3276	325.265	1.084.097
10	3474	32.109.997	10.703.027
11	3556.8	15.462.257	5.154.074
12	3600	0	0

The Delta connection configuration generates a comparatively elevated torque at low speeds, reaching a maximum at approximately 3750 RPM before decreasing. The Delta connection configuration appears to offer enhanced torque generation capacity at higher speeds. In contrast, the Wye connection configuration generates a lower torque at lower speeds, reaching its maximum at a lower speed than the Delta connection configuration before decreasing. The Wye connection configuration provides a more stable torque at low and medium speeds.

Conversely, the Delta connection offers superior torque generation at elevated speeds, making it a favourable option for high-speed applications. In contrast, the Wye connection is advantageous in low- and medium-speed applications due to its ability to provide enhanced stability at lower speeds. The selection of the optimal connection for a given system is determined by the specific speed and torque requirements of the application.

4.2. Analysis According to Shaft Generator Type in Matlab/Simulink

In this study, a detailed and comparative analysis has been performed on two distinct shaft generator systems, namely the 2-pole Squirrel Cage and Double Squirrel Cage types, utilizing an operating voltage and frequency of 690V and 60Hz, respectively, within a MATLAB/Simulink model. The objective of this study was twofold: firstly, to evaluate the performance parameters of both types of shaft generator, and secondly, to understand their behavior under different operating conditions.

The analysis commences with an examination of rotor currents and stator currents, with subsequent comparison of their magnitudes, fluctuation rates, and harmonic contents. An analysis of the current profiles of both systems has been conducted, with specific attention devoted to the response times of the rotor currents and the stability of the stator currents. The evaluations thus provide critical data with which to understand the effects of the systems on energy efficiency and operational stability.

The dynamics of speed and torque represent a further significant facet of the study. The response of both systems under different load profiles has been analyzed based on the speed-torque graphs obtained during the simulations. The evaluations, particularly in terms of speed fluctuations and torque stability, reveal the operational advantages and disadvantages of Squirrel Cage and Double Squirrel Cage structures. These analyses comprehensively reveal the response of the systems to dynamic load variations and their performance under stable operating conditions.

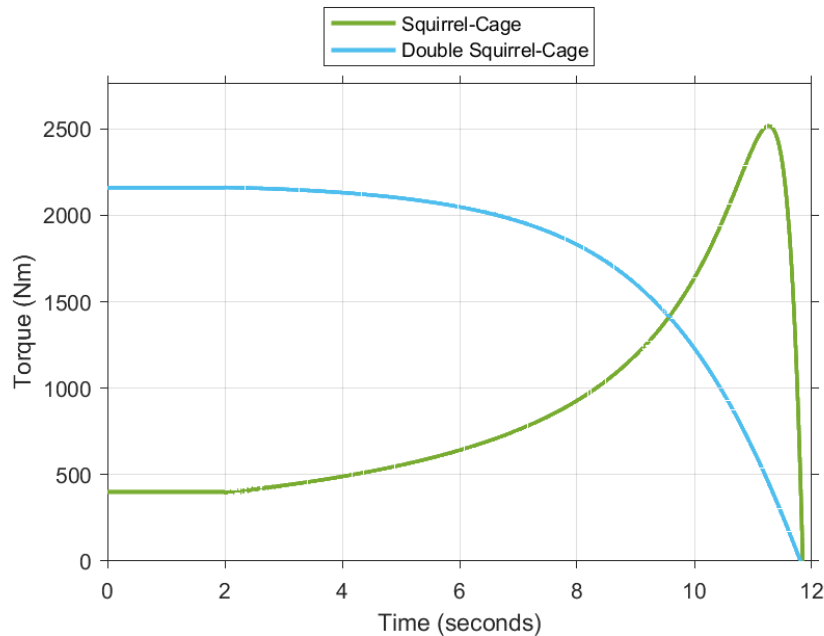


Figure 4.11. Squirrel Cage and Double Squirrel Cage torque graph

In Figure 4.11, it is observed that the torque value decreases with time in the Double Squirrel-Cage model. The high torque advantage initially experienced by the shaft generator results in a decrease in torque as the shaft generator accelerates. The efficacy of the shaft generator is maximized in applications requiring high initial torque, such as the initial movement of heavy loads and crane systems. Conversely, torque performance is found to decline in applications necessitating prolonged operation and consistent speed.

In the Squirrel-Cage model, torque values increase over time and reach a maximum, which is exceeded by the torque of the double squirrel cage shaft generator at approximately 10 seconds. The maximum torque value of approximately 2600 Nm is reached at 12 seconds. Despite an initial low starting torque, torque production increases over time and reaches the maximum level. This characteristic renders the model well-suited for applications necessitating constant speed and prolonged operation.

The low speed range with constant torque suggests that the generator is suitable for starting and low load conditions, while torque loss at high speeds indicates that the design limits and efficiency of the generator should be considered. Such analyses are of paramount importance

for the optimization of systems and the determination of appropriate operating points in ship operations.

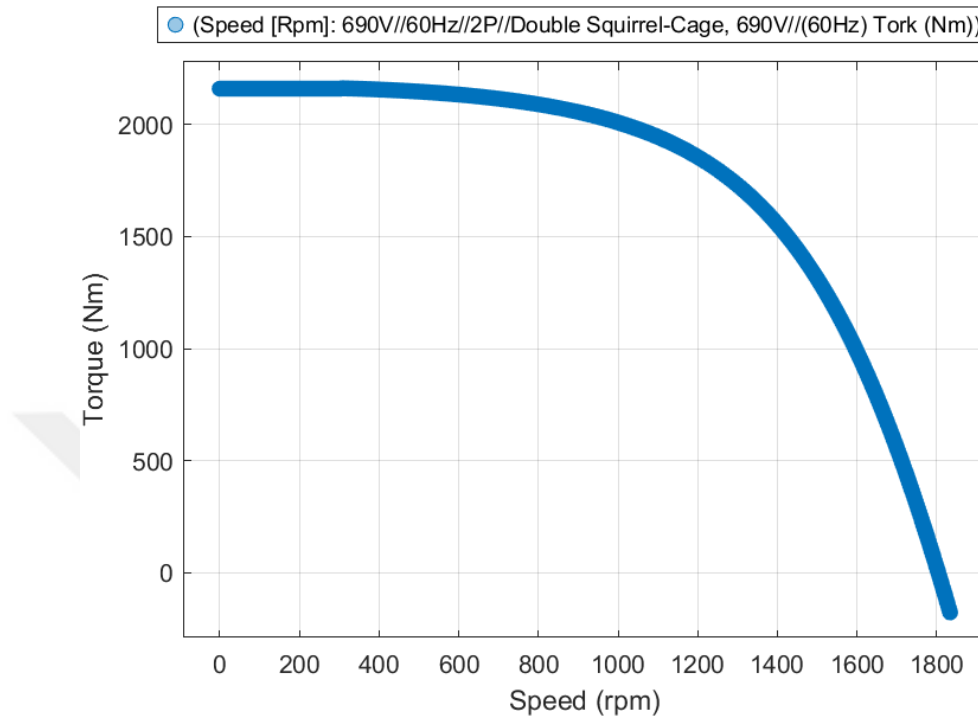


Figure 4.12. Speed dependent torque graph of Double Squirrel Cage model

As demonstrated in Figure 4.12, the torque remains constant at low speeds, indicating that the generator operates with high efficiency at these speeds. In the medium speed range, the decrease in torque is controlled, indicating operational stability. Conversely, a rapid decrease in torque at high speeds indicates that it may be inefficient to operate the generator at these speeds and that the ideal operating speeds should be maintained within the lower range.

It has been demonstrated that double squirrel cage shaft generators demonstrate effective performance, particularly in applications requiring high starting load. This effectiveness is attributed to their high starting torque and balanced speed increase. However, the decline in torque with increasing speed underscores the necessity for more efficient utilization in applications necessitating constant speed and low torque. This analysis underscores the necessity for a precise determination and selection of the application domains of double squirrel cage shaft generator, with consideration for the specific operating conditions.

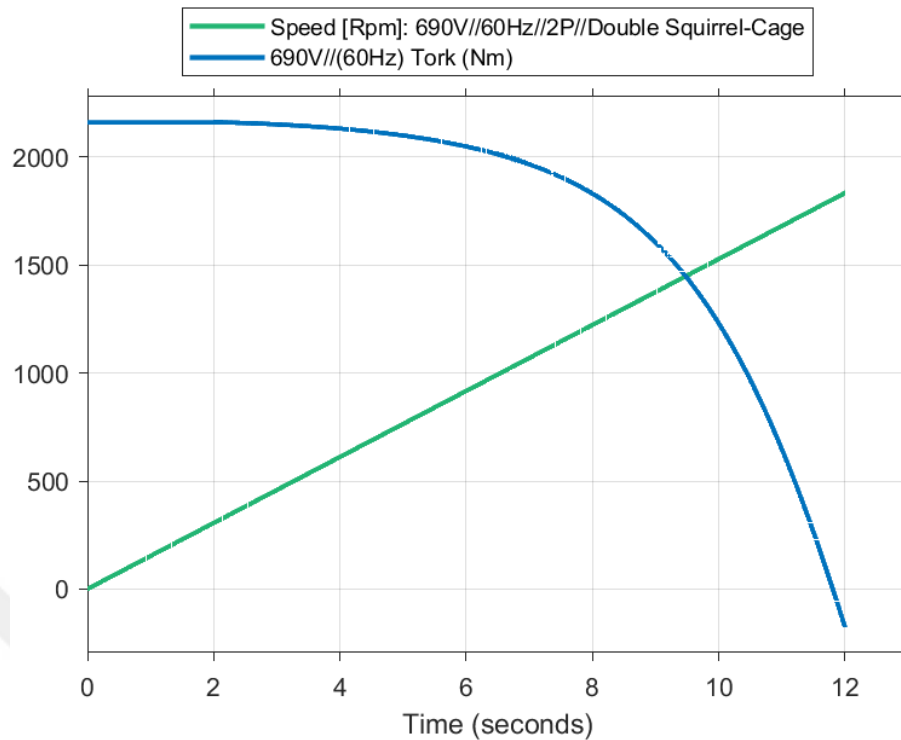


Figure 4.13. Double Squirrel Cage time-dependent speed and torque comparative graph

As demonstrated in Figure 4.13, at the initial start-up of the shaft generator (0 seconds), the torque value is considerably elevated, reaching approximately 2200 Nm. This observation underscores the efficacy of Double Squirrel-Cage shaft generator in delivering high torque at the point of ignition. Concurrently, the speed value commences from zero and increases linearly as time progresses.

The intersection of the torque and speed curves occurs at approximately the 9th second. This intersection marks a critical juncture where the shaft generator attains maximum efficiency and optimal operating conditions.

The high torque at the initial stage enables the shaft generator to effectively overcome substantial loads. The linear increase in speed with time indicates that the shaft generator exhibits a stable acceleration process. Conversely, the decline in torque with an increase in speed indicates that the shaft generator functions most efficiently within a specific speed range. Double Squirrel-Cage shaft generators are particularly advantageous in applications requiring high starting loads due to their high starting torque and stability in speed increase. The inverse

relationship between torque and speed indicates that these shaft generators can be employed more efficiently in applications where speed remains consistent. Figure 4.13 underscores the significance of selecting the most appropriate shaft generator for specific application areas.

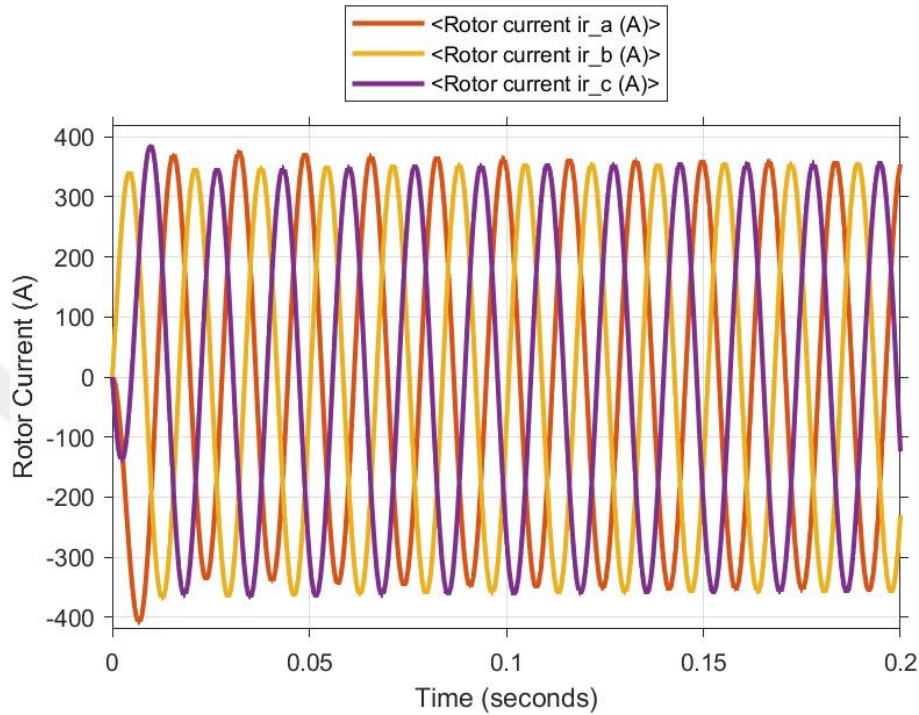


Figure 4.14. Double Squirrel Cage time dependent rotor current graph

As demonstrated in Figure 4.14, the shaft generator exhibits stability and balance, while the rotor currents align with the theoretical predictions of the three-phase system. The operation of the shaft generator at a voltage level of 690V gives rise to high amplitude rotor currents, which in turn generate a strong magnetic field. This, in turn, supports the shaft generator in its production of high torque. The initial transient is rapidly dampened, and the shaft generator enters a steady state. This outcome demonstrates the efficacy and reliability of the shaft generator design.

The presence of high rotor currents indicates that the shaft generator is well-suited for applications that demand high performance. The low transient effect enables the shaft generator to swiftly transition to a stable operating mode under load. This feature is advantageous in areas with continuous load variations, such as ship applications.

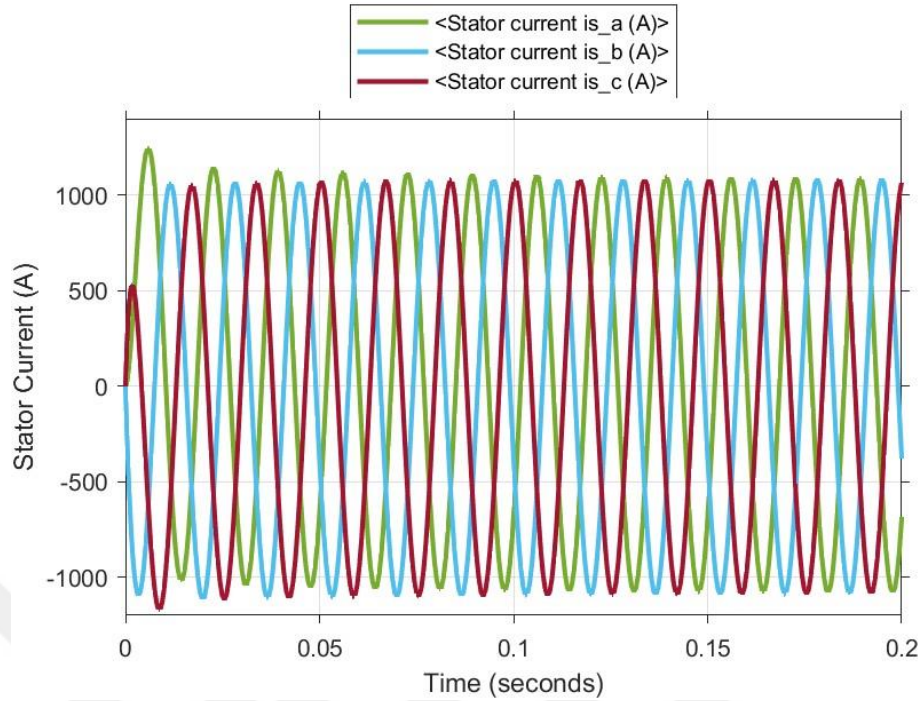


Figure 4.15. Stator current graph according to Double Squirrel Cage time

As illustrated in Figure 4.15, the currents exhibit a constant frequency of 60 Hz and a smooth, sinusoidal form. This observation indicates that the shaft generator is operating at its nominal frequency and that the power generation is stable. The amplitude of the stator currents is approximately ± 1000 Amperes. These values are indicative of the shaft generator's loading level and its operation under a voltage of 690V. The observation of equal current amplitudes thus indicates that the loads are balanced and the shaft generator is operating correctly.

The interval under consideration by Figure 4.15 is from 0 to 0.2 seconds. During this brief interval, the frequency and amplitude of the currents remain constant, thereby indicating that the shaft generator is operating in a stable state. The three-phase currents are balanced and symmetrical, with no indication of unbalance or harmonic distortion.

The figure 4.15 indicates that the shaft generator is operating within its rated conditions and that the loads are connected to the shaft generator in a balanced manner. In the event of a system being connected to a grid, synchronization between the shaft generator and the grid is successful. Consequently, the shaft generator is operating in a stable mechanical and electrical

state. This outcome suggests that the current operating state of the system is reliable and that efficient energy production is achieved.

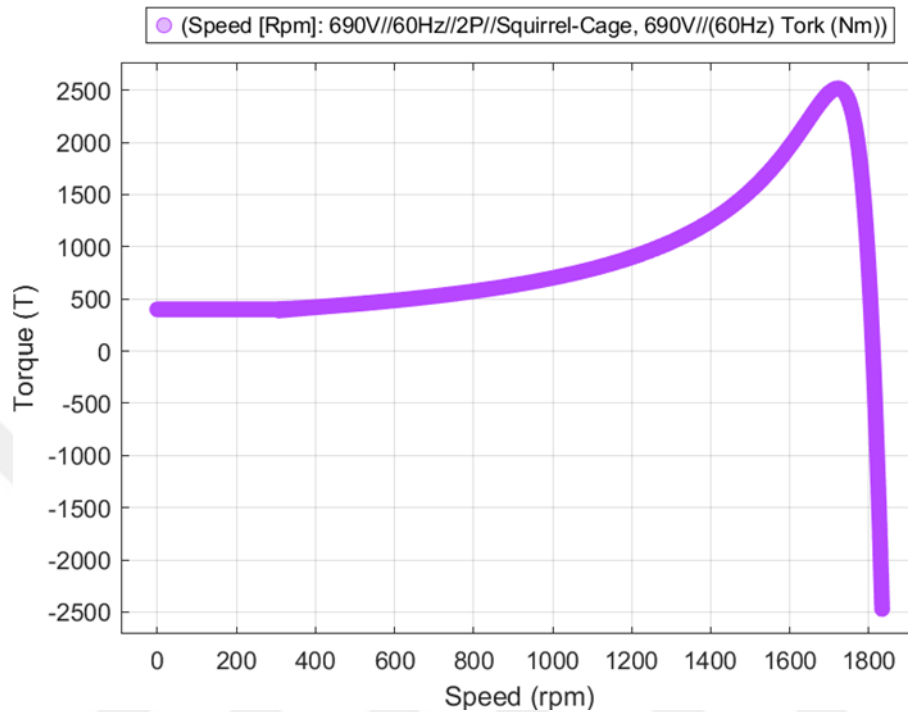


Figure 4.16. Squirrel Cage speed-dependent torque graph

As demonstrated in Figure 4.16, the torque-speed characteristics of a 690V, 60Hz, 2-pole shaft generator with a squirrel cage structure are illustrated. The interpretation of such graphs is pivotal in comprehending the mechanical behavior and operational range of the shaft generator. When the speed is close to zero (0 rpm), the torque is positive and notably high. This observation indicates that the shaft generator possesses the capacity to generate a sufficient torque to rotate the load during the take-off phase. The high torque at low speeds is a defining feature of the squirrel cage rotor structure. As the speed increases, the torque also increases, albeit gradually. This phenomenon signifies that the effectiveness of the magnetic field increases in proportion to the rate of rotation of the rotor.

As demonstrated in Figure 4.16, the maximum torque is attained at a speed close to 1800 rpm. This indicates that the shaft generator has attained its maximum mechanical load capacity, and that an increase in load may result in system instability. Beyond this point, the torque undergoes a rapid decline as the speed increases. This phenomenon can be understood by considering the

shaft generator's mechanical stability. When the synchronous speed of 1800 rpm is exceeded, the generator loses mechanical stability, leading to a decline in torque production. The shaft generator's stable operating point is found at speeds slightly below the maximum torque (approximately 1500-1800 rpm). This range is characterized by the operation of the shaft generator under conditions of rated load.

The torque-speed curve provides confirmation that the shaft generator has been designed to accommodate both starting loads and dynamic load variations. In the event of the shaft generator being operated in conditions of overload or subject to rapid dynamic changes, Figure 4.17 provides a useful framework for understanding the design limits. It is imperative to note that the maximum torque point must not be exceeded, as this may result in mechanical overload or electrical failure.

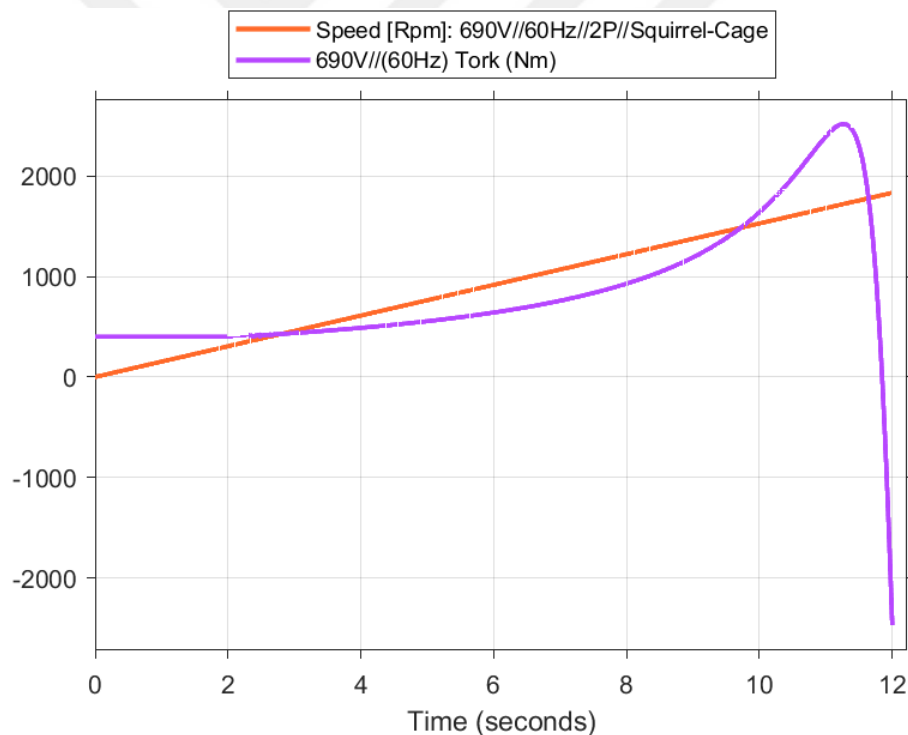


Figure 4.17. Squirrel Cage time-dependent speed and torque comparison graph

As demonstrated in Figure 4.17, the variation of speed (rpm) and torque (Nm) of a squirrel cage induction shaft generator (690V, 60Hz, 2 poles) with respect to time is illustrated. After

approximately 10 seconds, the speed approaches a constant value. This finding suggests that the shaft generator has attained synchronous speed and is balanced according to the load torque. The theoretical synchronous speed of a bipolar shaft generator with 690V/60Hz is as in equation 4.1:

$$N_s = \frac{120 \cdot f}{P} = \frac{120 \cdot 60}{2} = 3600rpm \quad (4.1)$$

However, it is evident that this speed indicates that the shaft generator has not yet attained synchronous speed, but rather remains slightly lower due to slippage. The torque of the shaft generator has an elevated initial value, which is necessary for the shaft generator to move the load at the initial start-up. The torque then decreases after its maximum value and stabilizes at approximately 8-10 seconds. However, a sudden decrease in torque is observed at approximately 12 seconds. This may be indicative of overloading of the shaft generator, a modification in the torque requirements, or a sudden disturbance in the system (e.g. a sudden loss of load or a failure of the shaft).

Initial dynamics: The shaft generator commences with an initial high torque, which subsequently decreases as the shaft generator accelerates.

Steady state: The shaft generator reaches a stable operating point around 10 seconds, as illustrated by the graph of speed and torque.

Sudden drop: At 12 seconds, a sudden drop in torque indicates a fault in the system or a sudden change in load. This may be attributed to either the overload of the shaft generator or a malfunction in the speed control circuit.

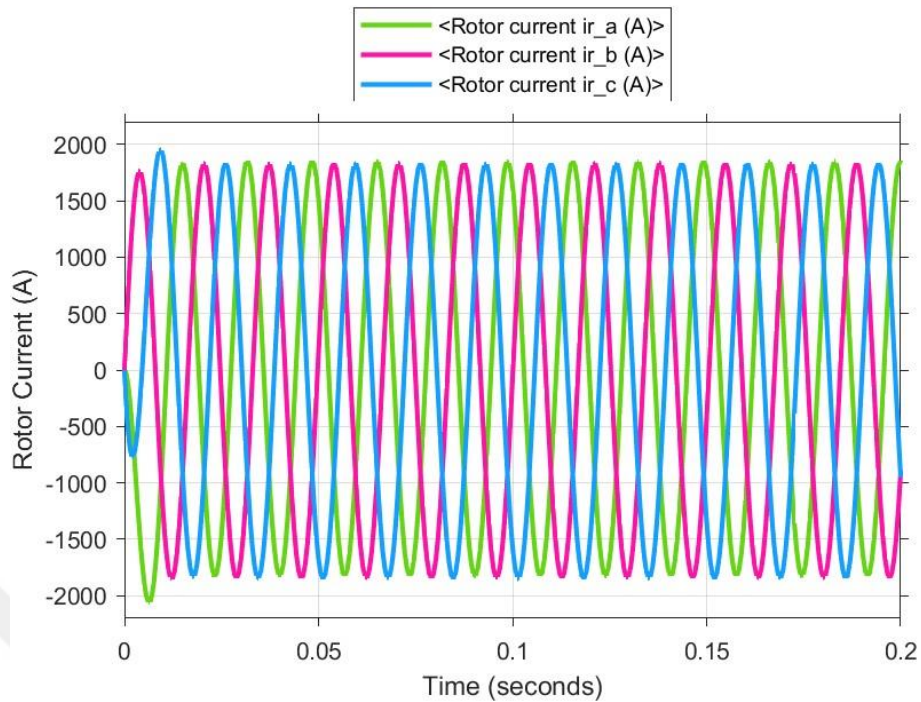


Figure 4.18. Squirrel Cage time dependent rotor current graph

As demonstrated in Figure 4.18, the time-dependent variation of the currents in the rotor windings (ir_a , ir_b , ir_c) of a 690V, 60Hz, 2-pole squirrel-cage asynchronous shaft generator is illustrated. Initially, the amplitude of the currents increases rapidly and reaches a constant value. This phenomenon is known as the starting current effect of the shaft generator. As the rotor has not yet begun to rotate during the start-up phase, the currents within the rotor circuit increase to high values. Within a brief interval, the currents attain a constant amplitude and a stable sinusoidal form.

As demonstrated in Figure 4.18, these currents stabilize after an interval of 0.05 seconds. The amplitude and phase difference of the currents remain constant. This indicates that the speed of the shaft generator is stabilized and it operates stably under load. The generation of rotor currents is contingent on the sliding speed and torque requirements of the shaft generator. The maintenance of constant amplitude in the rotor currents signifies that the shaft generator is operating under a constant load or has attained a fixed operating point. It is evident that the current amplitudes are notably high. This observation indicates that the shaft generator is being utilized within a high-power application or is being operated with a high load during the initial

start-up phase. The initial high rotor currents are attributable to the slipping effect of the shaft generator during the start-up phase. However, after 0.05 s, the system has attained a stable current level, signifying that the shaft generator is functioning in a regular and stable manner. The maintenance of the three-phase sinusoidal structure signifies the symmetry between the phases and the absence of imbalance.

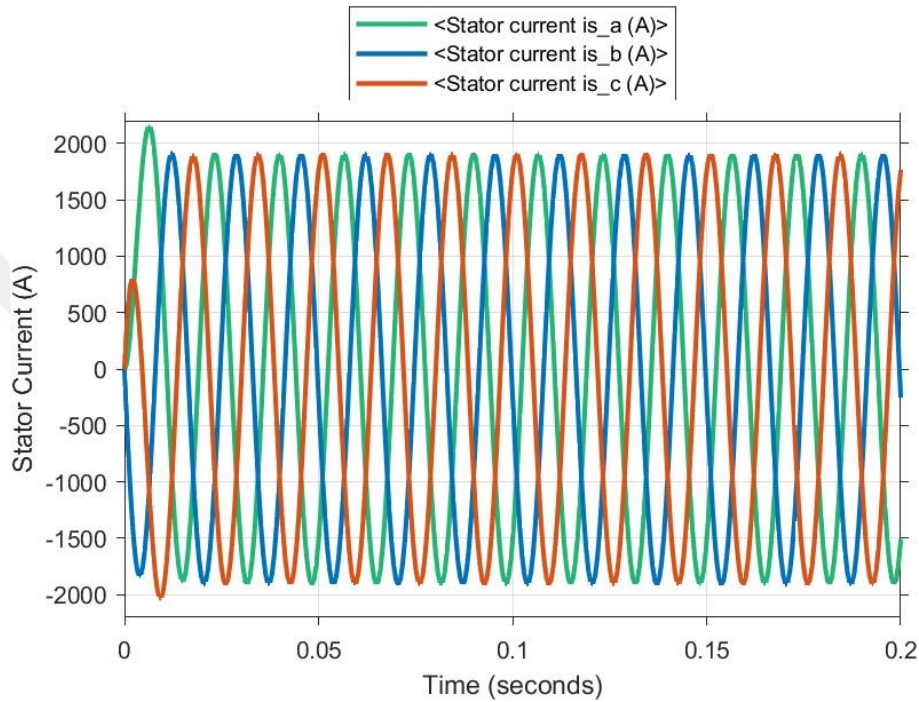


Figure 4.19. Squirrel Cage time dependent stator current graph

As illustrated in Figure 4.19, the time-dependent variation of the currents in the stator phases (*is_a*, *is_b*, *is_c*) of a 690V, 60Hz, 2-pole squirrel cage asynchronous shaft generator is demonstrated. The amplitude of the currents is approximately ± 2000 A, and a phase difference of 120 degrees is observed between the phases. This phase difference is a fundamental characteristic of a balanced three-phase system. The currents are characterized by sinusoidal behavior, exhibiting uniformity in both amplitude and phase angle.

As illustrated in Figure 4.19, the stator currents exhibit a significant increase during the start-up phase of the shaft generator, reaching high values. This is indicative of the high current demand and the creation of the magnetic field during the initial start-up of the shaft generator.

After approximately 0.05 seconds, the currents attain a steady state. After 0.05 seconds, the amplitude of the currents stabilizes and remains in a regular sinusoidal waveform. This indicates that the shaft generator has attained its nominal operating conditions and is operating at a constant speed under a balanced load.

The symmetrical and uniform nature of the three-phase currents indicates that the phase balance and system health of the shaft generator are satisfactory. It is evident that the current waves are well-suited to this frequency and do not exhibit any phase shift or distortion. The amplitude of the stator currents is observed to be comparable to that of the rotor currents. This finding indicates that the shaft generator is operating at a balanced point.

The rotor currents oscillate at a slip frequency relative to the stator currents. However, it is important to note that the stator currents are found to be entirely dependent on the grid frequency of 60 Hz. The stator currents are balanced, sinusoidal, and demonstrate the anticipated behavior for a three-phase system. It is imperative to note that a phase difference of 120 degrees is maintained between the phases, and the system is devoid of any imbalance or harmonic distortion. This observation indicates that the shaft generator is operating within its designed parameters and is not experiencing excessive loading.

As demonstrated in Figure 4.19, the stator currents of the shaft generator are generated correctly, and the shaft generator is operating synchronously with the grid. The absence of distortion further validates the efficacy of the shaft generator's operation. However, it is imperative to exercise caution in the evaluation of the high magnitude of the inrush currents, as this may necessitate the implementation of appropriate adjustments to the overcurrent protection systems.

4.3. Analysis by Number of Poles

The present study investigates the characteristic behavior of the Squirrel Cage shaft generator operating at 690V voltage and 60Hz frequency at different numbers of poles. Within the scope of this study, torque values were measured and compared for five different configurations of the generator, namely 2, 4, 6, 8 and 12 poles. The study has evaluated the impact of each pole

number on the performance of the generator, with a particular focus on torque generation. The analysis has also examined the differences in operating efficiency and torque values of the generator across different pole numbers.

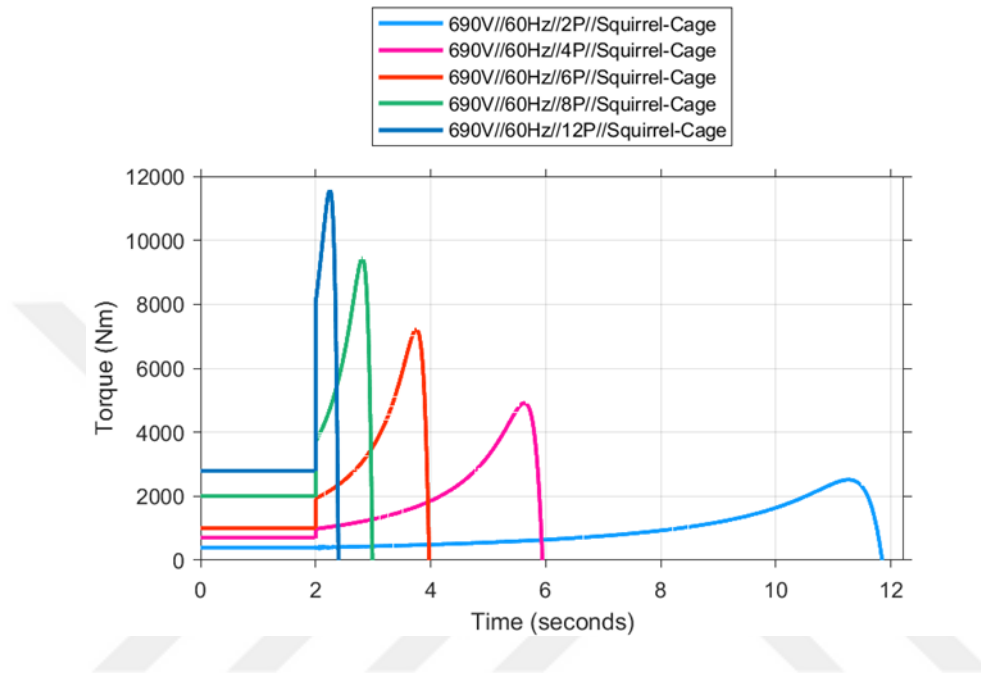


Figure 4.20. Torque - time graph for different number of poles

It is important to note that as the quantity of poles rises, the power generated by the generator may fluctuate. Generators with particularly high pole numbers generally necessitate a greater mechanical force, given their operation at low speed, which can result in power losses. Conversely, generators with higher pole numbers tend to exhibit higher torque at lower mechanical speeds. Additionally, generators operating at lower speeds frequently exhibit reduced efficiency, owing to increased electricity loss and heat generation at these speeds.

Conversely, generators with higher pole numbers exhibit a reduced sensitivity to variations in speed, thereby maintaining grid frequency with greater stability. A 12-pole generator, for instance, can exhibit enhanced stability in maintaining frequency consistency due to its lower operational speed and reduced mechanical power dissipation. Conversely, generators with a

high pole count can operate more efficiently at low speed. This is particularly salient in the context of torque and speed stabilization under heavy loads.

The high torque capability of 12-pole generators is attributable to their ability to operate at a low speed. This is a particularly advantageous feature when dealing with heavy loads. In contrast, 2-pole generators are employed in compact and efficient systems, operating at higher speeds.

4.4. Analysis by Voltage Characteristics

A comprehensive analytical investigation has been conducted into the impact on the rotor and stator, the time-torque relationships, and the overall performance characteristics of 2-pole squirrel cage shaft generator systems operating at 60Hz frequency. The analysis considered various voltage levels, including 690V, 440V, 400V, and 380V, which are widely utilized in shipboard applications. The objective of this analysis is to comprehensively examine the impact of each voltage level on the rotor dynamics and stator voltages. This enables a more profound comprehension of the torque, speed, and efficiency trends that emerge under varying shaft generator operating conditions.

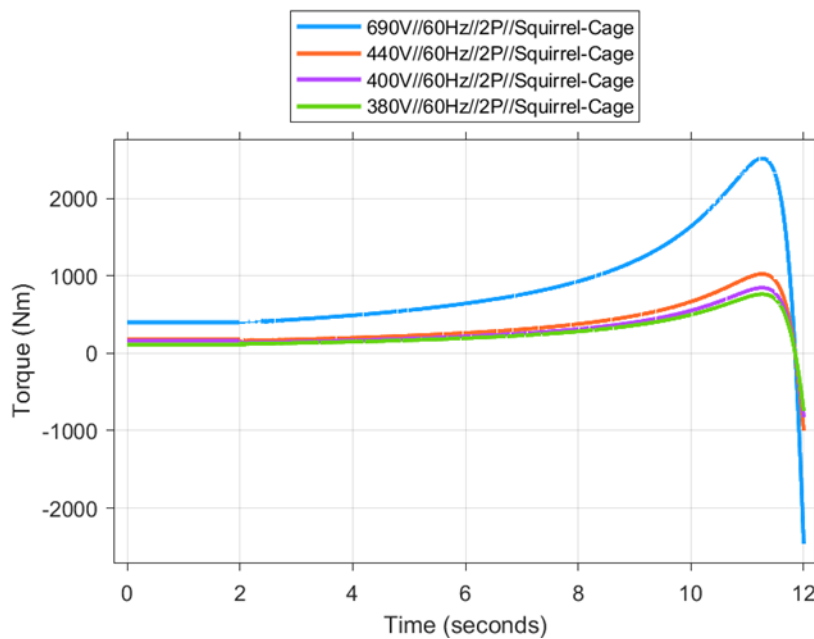


Figure 4.21. Torque - time graph for different voltage characteristics

As demonstrated in Figure 4.21, the initial low values for all voltage levels are almost identical around the torque. Consequently, this period marks the commencement of the shaft generator, and the rotor is unable to be synchronized to zero time. As a result, the load torque increases gradually, and the shaft generator torque slope is more precipitous than in other voltages, commencing from 690V. The torque increases more gradually at lower voltages (440V, 400V, 380V), and the shaft generator's torque production capacity is limited, impacting the applied voltage and magnetic field. The shaft generator operating at 690V has the greatest torque capacity and the fastest rise curve, and it is at this point that the shaft generator achieves maximum torque. It is evident that the torque of a generator operating at lower voltage levels is constrained and exhibits a more gradual rise. Conversely, an increase in voltage results in a corresponding rise in the generator's torque capacity. This observation underscores the fact that the torque curve of the shaft generator is a performance feature that is directly proportional to the applied voltage. The shaft generator operating at the 690V level demonstrates optimal torque output and efficiency. However, as the voltage is reduced to lower levels (380V-400V), the generator's efficiency undergoes a decline, leading to torque limitations. This finding indicates that lower voltage levels have a detrimental effect on the efficiency of the generator.

The observation that maximum torque is followed by an abrupt decrease indicates the necessity for a re-evaluation of either the load dynamics or the system speed control mechanism. As illustrated in Figure 4.21, the performance of the Generator is optimized at a voltage level of 690V.

4.5. Analysis of Poles Characteristic

The effects on the rotor and stator, torque-time relationships and general performance characteristics of 2-pole squirrel cage shaft generator systems operating at 50Hz frequency, considering various voltage levels such as 690V, 440V, 400V and 380V, which are widely used in ship applications, have been extensively investigated.

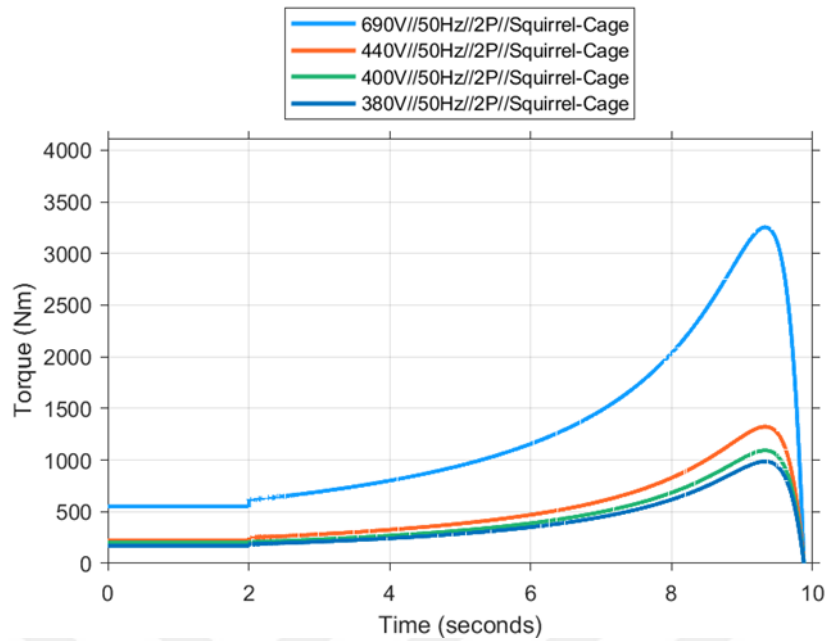


Figure 4.22. Torque - time graph for different pole values

The shaft generator functions at elevated voltage levels, thereby yielding higher torque. This finding indicates that squirrel cage shaft generators exhibit substantial performance characteristics that are contingent on the voltage level. The findings reveal that the maximum torque and acceleration are attained at the 690V level, with a decline in performance at lower voltage levels. It is evident that, for a constant initial torque value, high voltage levels yield a substantially higher and more rapid torque development. Consequently, when ships demand higher torque and acceleration performance, higher voltage levels such as 690V should be considered. It is also acknowledged that voltage levels can be reduced to a level that optimizes energy consumption.

4.6. Analysis of Frequency Characteristic

As demonstrated in Figure 4.23, the time-dependent variations of torque in a squirrel cage generator operating at voltages of 690V and 60Hz are depicted. The figure source can be found below. It is evident from the figure that the initial torques for both frequencies are negligible and almost equal (approximately 500 Nm). This observation pertains to the transient phase following the initiation of operation, wherein the rotor has not yet attained synchronous

velocity. Consequently, the torque change at the beginning is not significantly influenced by the inherent frequency difference. As the data illustrate, a shaft generator operating at 50 Hz generates a much faster torque curve rise than a shaft generator operating at 60 Hz. This is due to the fact that, at 50 Hz, the rotor operates at a lower synchronous speed, resulting in a higher slip ratio. The shaft generator is capable of producing greater torque because the magnetic force acting on the shaft is reduced due to the higher slip ratio.

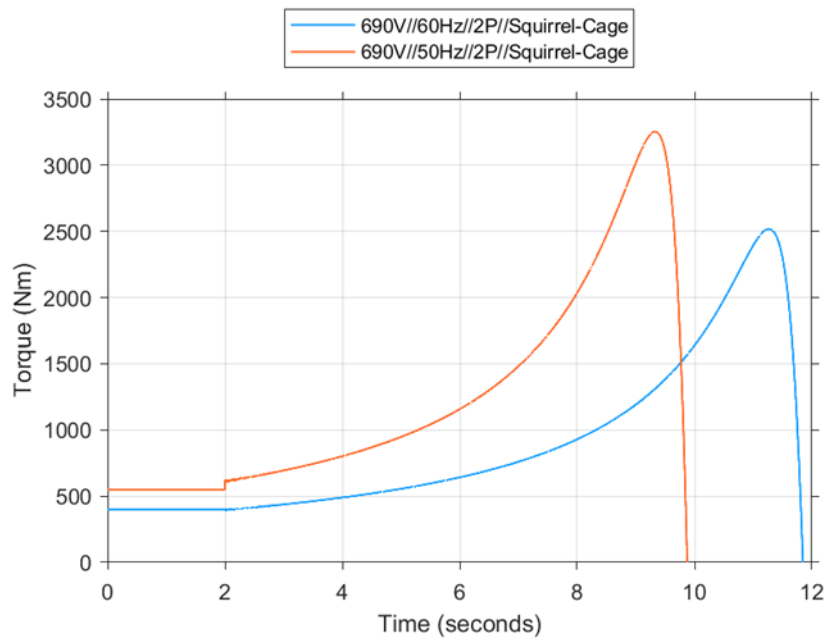


Figure 4.23. Torque - time graph according to 50Hz and 60Hz frequency values at 690V voltage value

The shaft generator operating at 50Hz is capable of producing a maximum torque of 3500 Nm within 8 seconds. Conversely, at a frequency of 60Hz, the maximum torque level is attained approximately 12 seconds after the initiation of the process. The Figure 4.23 also illustrates that the torque at 50 Hz is significantly higher than that at 60 Hz. It is important to note that a decrease in frequency results in an increase in the slip ratio.

It is evident that decreasing the frequency (50Hz) leads to a reduction in the slip rate of the shaft generator, thereby enabling an enhancement in torque. The output torque at 50Hz is more than 75% of that at 60Hz. The effect of low frequency on the shaft generator performance is therefore

positive. Conversely, low frequency has the potential to adversely affect the shaft generators efficiency, resulting in increased losses. The observed decline in instantaneous torque may be attributed to limitations inherent in the mechanical or electrical systems. It is evident that at a frequency of 50Hz, the torque capacity of the shaft generator is amplified. This capacity is instrumental in meeting the demands of high loads. The shaft generator functions for a greater duration and is under the control to reach its maximum torque at 60Hz.

In order to align with the requirements of the specific application, 50Hz may be utilized when a greater torque is desired, while 60Hz may be favored for ensuring the efficient maintenance and operation of the system in a stable manner. It is imperative to analyze alterations in frequency with respect to speed, losses, and ultimately, applied torque.

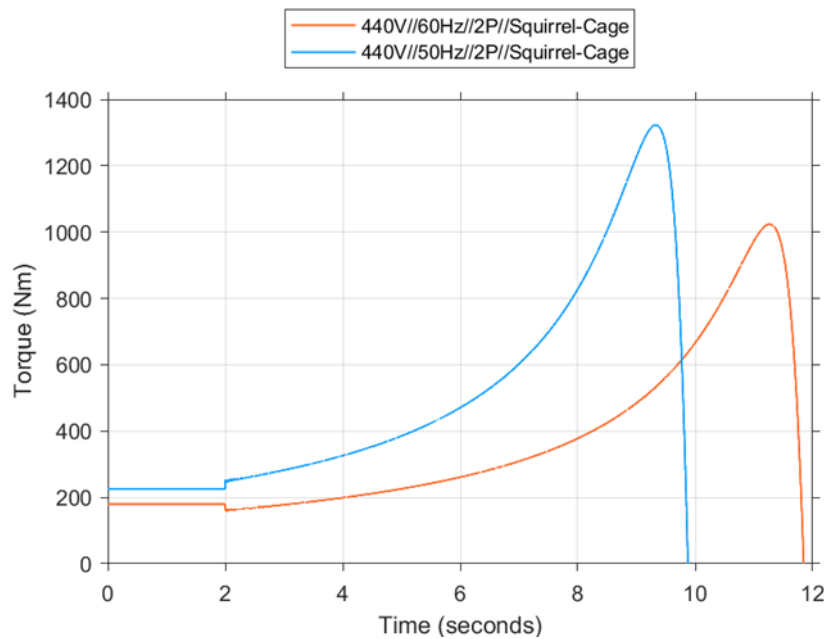


Figure 4.24. Torque - time graph according to 50Hz and 60Hz frequency values at 440V voltage value

As demonstrated in Figure 4.24, the torque-time variations of a squirrel cage generator operating at 440V voltage at 50Hz and 60Hz frequencies are illustrated. The initial torque values at these frequencies are found to be almost identical, with a discrepancy of approximately 200 Nm. This observation indicates that the frequency difference has minimal

impact on the initial torque of the shaft generators during start-up. The torque curve of the shaft generator operating at 50Hz rises more rapidly than at 60Hz. The rotor operates at a reduced synchronous speed and a higher slip ratio at 50Hz. This results in increased magnetic flux, consequently leading to higher torque production.

The shaft generator at 50Hz achieves maximum torque in approximately 8 seconds, with a value of approximately 1300 Nm. Conversely, at 60Hz, the maximum torque is achieved at a later point (after approximately 12 seconds) and at a lower level (approximately 800 Nm). The maximum torque value at 50Hz is significantly higher than that at 60Hz. This outcome demonstrates that decreasing the frequency of operation results in an enhancement of the torque capacity of the SG.

The SG operating at 50Hz is well-suited to applications characterized by high torque requirements. However, it should be noted that at this frequency, the shaft generator may be susceptible to increased losses and sudden torque variations. Conversely, the shaft generator operating at 60Hz is more appropriate for applications with lower torque requirements, where the importance of stable and efficient operation is paramount. The selection of the optimal frequency should be informed by considerations such as the load requirements of the specific application, the objectives of speed control, and the necessity for energy efficiency.

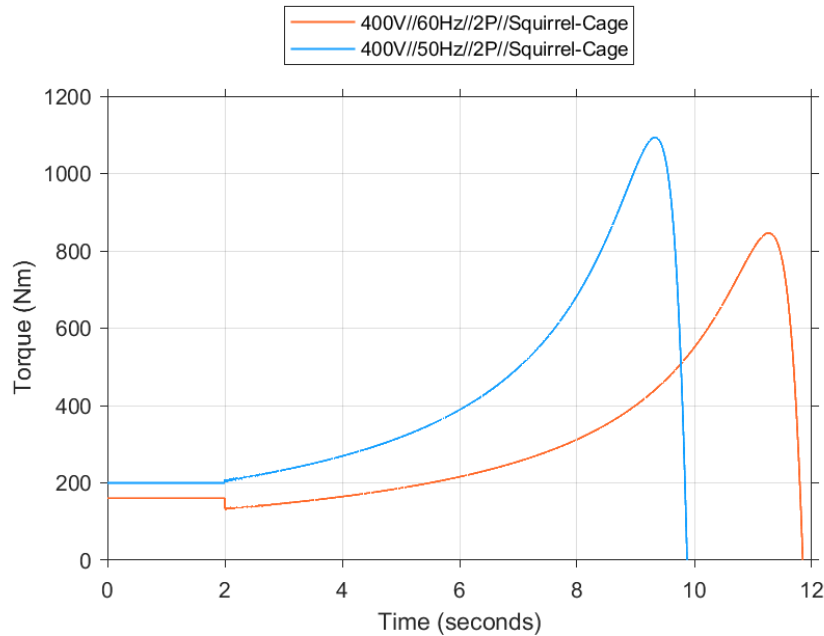


Figure 4.25. Torque - time graph for 50Hz and 60Hz frequency values at 400V voltage value

As demonstrated in Figure 4.25, the torque-time plot for 50Hz and 60Hz frequencies at a voltage of 400V provides significant data for understanding the response of the shaft generator to changes in frequency.

The initial torque values at 50Hz and 60Hz frequencies are approximately 200 Nm. It is evident that at 50Hz, the rate of torque increase is more rapid. The curve rises more steeply, reaching maximum torque in approximately 8 seconds. In contrast, at a frequency of 60Hz, the torque increase is more gradual. The maximum torque is achieved at approximately the 12th second. The maximum torque at 50Hz is approximately 1100 Nm. Conversely, at a frequency of 60Hz, the maximum torque occurs at a lower value, approximately 800 Nm.

It is also notable that at a frequency of 50Hz, the torque undergoes a rapid decline following the attainment of maximum torque. This phenomenon may be indicative of a loss of shaft generator stability under load at a certain point. In contrast, at a frequency of 60Hz, the decline after the maximum torque is more gradual and extends over a longer duration.

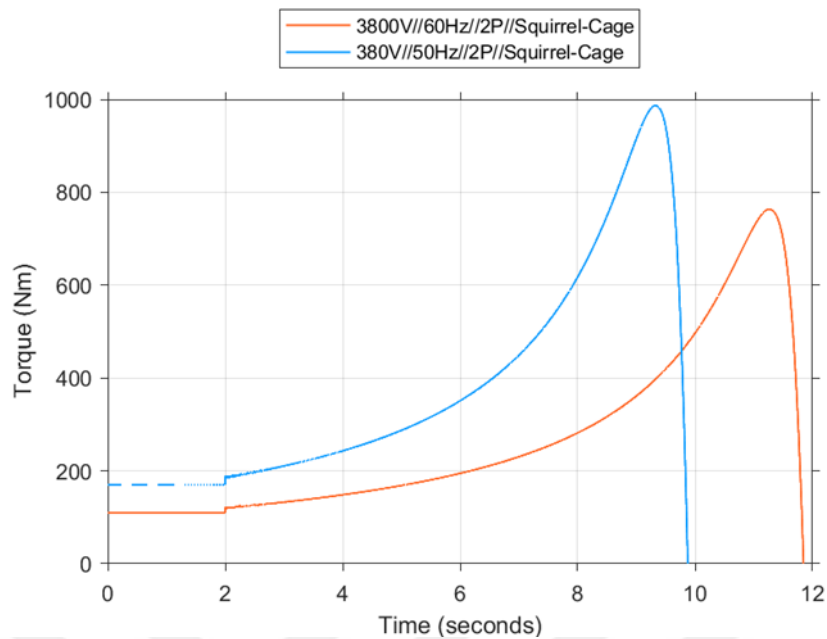


Figure 4.26. Torque - time graph for 50Hz and 60Hz frequency values at 380V voltage value

As demonstrated in Figure 4.26, the torque-time plot for 50Hz and 60Hz frequencies at 380V voltage is a valuable analytical tool for examining the response of the shaft generator to frequency variation at low voltage.

The initial torque values at both 50Hz and 60Hz frequencies are approximately 200 Nm. The analysis demonstrates that the initial torque remains largely unaffected by variations in frequency. In both instances, the initial torque remains at a constant level. The maximum torque for the 50Hz frequency is approximately 900 Nm. Conversely, the maximum torque for a 60Hz frequency is lower, approximately 700 Nm.

The 50Hz frequency, however, exhibits a higher maximum torque, a property that is advantageous in applications necessitating high starting or peak torque. Conversely, the 60Hz frequency, despite yielding a lower maximum torque, exhibits superior stability.

This analysis demonstrates the variation in shaft generator performance under low voltage and different frequency values, providing guidance for selection of frequency and voltage based on specific applications.

5. CONCLUSION

In this study, the speed, torque and current dynamics of Squirrel Cage and Double Squirrel Cage rotor types for naval ships are analyzed and their performance in different operational scenarios is compared. In addition, the effects of frequency and voltage levels on shaft generator performance are analyzed in detail. The findings have important implications for engineering applications and system design.

- Squirrel Cage and Double Squirrel Cage Rotor Comparison:

The Squirrel Cage Rotor has been shown to provide higher efficiency at rated speed and to minimize current losses due to the low resistance of the rotor bars. It is thus considered an economical and efficient option in applications requiring constant load and nominal speed. The Double Squirrel Cage Rotor, by contrast, has been shown to offer an advantage by providing high torque at take-off and low speeds. However, slight losses may occur at rated speed due to the resistance of the outer rotor bars, which may lead to slightly lower efficiency at rated speed compared to the Squirrel Cage rotor.

- The Effect of Frequency on Torque Performance

It has been demonstrated that as the frequency is reduced (to 50 Hz, for example), there is an increase in both the high starting supplied torque and the peak torque values. This is advantageous in scenarios where the initial movement of heavy loads is the primary objective. Conversely, this configuration exhibits a pronounced propensity for elevated energy consumption and current draw, which are salient disadvantages.

Conversely, power generated at 60 Hz (although the initial torque is lower) is more conducive to even and consistent torque curves, as well as power efficiency. Consequently, such systems are well-suited to applications requiring sustained operation at a consistent speed.

- The Effect of Voltage Level on Torque Performance:

400V Voltage Level; It produces higher torque values and allows more torque production by reducing the magnetic saturation effect. While it exhibits reduced torque production at lower

voltage levels, it offers the advantage of reduced energy losses, making it a preferable option in certain applications.

- A comparison of Squirrel Cage and Double Squirrel Cage Shaft Generators:

Double Squirrel Cage Shaft Generators are well-suited for applications requiring high starting torque and offer distinct advantages in systems where heavy loads need to be moved. In contrast, Single Squirrel Cage Shaft Generators exhibit a low initial torque, which increases over time, resulting in a more stable torque curve. Consequently, Single Squirrel Cage Shaft Generators are particularly well-suited for applications necessitating constant speed and minimal slip.

- The following recommendations are made with regard to the selection of application-based shaft generators:

In instances where high starting torque is a prerequisite, and a 50Hz frequency is required, the utilization of a Double Squirrel Cage Shaft Generator is strongly advised. This combination is particularly suitable for heavy industrial machinery or cranes that are required to carry high loads.

Conversely, in scenarios where energy efficiency and constant speed are paramount, the 60Hz frequency and Single Squirrel Cage Shaft Generator emerge as the optimal choice. This configuration is particularly advantageous in long-term operational applications, such as military ships.

This research study undertakes a thorough investigation of the rotor shapes, frequencies, and voltage values that affect the performance of shaft generators on naval ships. It recommends a method for selecting the optimal generator, taking into account the specific requirements of the application. The findings of this study will facilitate the optimization of responsiveness and the reliability over time of industrial applications, with concomitant enhancements in energy efficiency.

The results of an electromagnetic analysis employing the ANSYS Maxwell software are utilised for the assessment of the magnetic field distribution, current, power dissipation, efficiency, and other crucial parameters. The results provide guidance for the optimization of the shaft generator design, with the objective of improving its performance and efficiency.

The field of power systems engineering is currently engaged in a significant research endeavor pertaining to the electromagnetic analysis of shaft generators. This study represents a preliminary step towards optimizing the performance of shaft generators through the utilization of ANSYS Maxwell software and electromagnetic analysis techniques. The findings obtained may be of use in the marine sector and could inform future research.

This study utilised the ANSYS Maxwell and MATLAB/Simulink environment to conduct analyses of shaft generators employed in naval ships. The objective of this analysis was to provide a comprehensive evaluation of the electromagnetic performance, dynamic behaviour and effectiveness in system integration of the generators. The findings of this study enabled the determination of critical parameters for design optimisation and operational reliability.

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