University of Strathclyde

Department of Naval Architecture, Ocean and Marine Engineering

"Design for safety and energy efficiency of electrical power systems in ships"

PhD Thesis

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Signed: *Date:*

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ABSTRACT

The ever-growing intercontinental maritime trade and transport have identified the need for the ship and passengers safety, energy efficiency and environmental pollution to be considered as dominant issues within shipping industry and academia. Recently introduced safety regulations, known as Safe-Return-to-Port, and 'green' regulations, by the IMO, came into force to address and, indirectly, couple the above objectives through the enforcement of specific safety performance requirements of ship systems after a casualty and mandatory environmental measures for GHG emissions limitation, for the former and the latter regulations respectively.

This thesis focus is on improving the safety and the energy efficiency of ships during design and operation by adopting approaches assessing the safety-critical systems availability at emergencies and estimating performance requirements of electrical energy onboard ships over their life cycle. Through the adoption of methodologies successfully applied in damage stability, the probabilistic assessment of systems safety is employed with the logical modelling of the system into the ship environment and the application of statistical flooding damages to be initiated. Critical zones for the systems location are investigated with topological and geometrical optimisation to be performed identifying 'enhanced-availability areas' onboard targeting, also, the components redundancies reduction.

First principles were introduced for the numerical modelling of the electrical energy systems onboard aiming to evaluate the energy performance of the ship. However, the great number of input parameters and computational problems shown up during the systems development, especially for larger

vessels such as passenger, triggered necessary simplification considerations for the design. Investigation was considered for the identification of the key design parameters, with a verification process based on energy simulations to have been used for constructing guidelines and indicating acceptable assumptions. Investigation results were used for the systems optimisation in energy efficiency and cost perspectives during the design through the development of the Power Management System, with the latter's functionality to be extended also during operation aiming fuel consumption minimisation. The amount of consumed fuel were quantified for both case, and results were used to create design and operation guidelines for power generation sets sizing and loading respectively.

All findings were used to form methodology for the design of the electrical energy systems aiming to increase the energy efficiency through the appropriate sizing of the power generation sets and also, for the case of passenger vessels, to increase systems safety through the optimisation of their onboard location. Implementation of the methodology was exhibited with two case studies, one for a cargo and one for a passenger ship.

The work undertaken and the derived results clearly demonstrate the applicability of probabilistic assessment for the quantification of systems availability post-casualty not only for rules compliance but also for the increased results accuracy and the integration to ship survivability concept. In addition, the introduction of Dynamic Energy Modelling concept as a platform in shipping to support life-cycle energy management were concluded through the electrical energy systems simulations during operation and design considering simplification during the latter's process. Those concepts could be applied under the multi-objective optimisation platform in order to explore the whole design space concerning systems common parameters. All these constitute significant developments in shipping.

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NOMENCLATURE

Abbreviations

A/R	Auxiliary Room
AC	Alternative Current
AD&A	Alternative Design and Arrangements
AVR	Automatic Voltage Regulator
BDD	Binary Decision Diagram
CO_2	Carbon Dioxide
CPP	Controllable Pitch Propeller
D/G	Diesel-generator
DC	Direct Current
DE	Diesel Engine
DEM	Dynamic Energy Modelling
DO	Diesel Oil
E/R	Engine Room
EEDI	Energy Efficiency Design Index

EEOI	Energy Efficiency Operation Index
EMSWBD	Emergency Switchboard
EU	European Union
FMEA	Failure Mode and Effect Analysis
FO	Fuel Oil
FTA	Fault Tree Analysis
FW	Fresh Water
GA	General Arrangements
GHG	Greenhouse Gases
H_2	Dihydrogen
HiP-HOPS	Hierarchically Performed Hazard Origin and Propagation Studies
HT	High Temperature
HVAC	Heating, Ventilation and Air Conditioning
IMO	International Maritime Organisation
LNG	Liquefied Natural Gas
LO	Lubricating Oil
LT	Low Temperature

MARPOL	Marine Pollution (International convention for the prevention of pollution from ships)
ME	Main Engine
MEPC	Marine Environmental Pollution Committee
MSWBD	Main Switchboard
NOx	Oxides of nitrogen
PID	Proportional Integral Derivative
PMS	Power Management System
p.u.	Per Unit
Ro-Pax	Roll-on/Roll-off Passenger
SEEMP	Ship Energy Efficiency Management Plan
SFOC	Specific Fuel Oil Consumption
SOx	Oxides of sulphur
SRtP	Safe Return to Port
SSWBD	Secondary Switchboard
SW	Sea Water
SWBD	Switchboard
WT	Watertight

List of symbols

$a_{i,j}$	Approximated constant
b_i	Specific fuel oil consumption for each unit
C_0	Maintenance cost when generator's operation at minimum power
C_1	Maintenance cost for generator's operation over 50% of rated power
C_2	Maintenance cost for generator's operation above upper loading limit
C_h	High load cost
C_l	Low load cost
$C_{stand\text{-}by}$	Stand-by cost
E	Approximated polynomial
FC	Polynomial relation of fuel consumption-power production
F_j	Aggregated probability of j-th system being unavailable
Fuel	Fuel consumption
i	Current
J	Inertia
k	Selected online generators
L_{const}	Electrical inductance per meter constant value
Length	Distribution line length

L_{Line} Electrical inductance of the line

L_{LOAD} Electrical inductance of the load

n Number of time steps

N_p Poles

p_i Probability of occurrence of the i-th damage scenario

$P_{i,d}$ Dispatched power of the i-th generator (in p.u.).

$P_{i,high}$ High loading limits of the i-th generator (in p.u.)

$P_{i,load}$ Active power load of the i-th generator

$P_{i,low}$ Low loading limits of the i-th generator (in p.u.)

$P_{i,max}$ Technically maximum power of the i-th generator (in p.u.)

$P_{i,min}$ Technically minimum power of the i-th generator (in p.u.)

$P_{i,rated}$ Rated active power of the i-th generator

P_L System load demand

$P_{L,max}$ Maximum system's load demand (simplified system's model)

P_{LOAD} Active power demand of the load

P_{MCR} Maximum continuous rated power

Q_{LOAD} Reactive power demand of the load

r Resistance

R_{const} Electrical resistance per meter constant value

R_{Line}, Electrical resistance of the line

R_{LOAD} Electrical resistance of the load

S Vector quantity for system components and functions

slip Slip

T Torque

$T_{constant}$ Diesel engine time constant

u Voltage

w Rotating speed

x_i Active power consumption of the simplified model for the i^{th} case

$x_{reference}$ Active power consumption of the detailed (benchmark) model

Z_{LOAD} Electrical impedance of the load

Greek symbols

ψ Flux linkage

θ Angle between the q-axis and the a-axis

List of drawing's symbols

 Circuit breaker

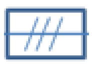
Uninterruptible power supply

 Battery storage

Outlet box

 Electrical resistance

 Electrical inductance

 Distribution lines

 Electrical transformer

Subscripts

d	d-axis
em	Electromagnetic
err	Error
f	Field winding
md	Mutual winding
mech	Mechanical
q	q-axis
r	Machine’s rotor
ref	Reference
s	Machine’s stator
syn	Synchronous rotating field
t	Terminal

1 INTRODUCTION

1.1 Preamble

Shipping has a 5,000 years documented history, playing always a significant role in the development of human civilisation as a key means of transportation. Up to the early 19th century, all merchant vessels were built by wood using wind as the primary source of power. However, fuelled by the increased global need for trades, a side effect of the capitalism, the shipping industry was forced to adopt new technologies and design practices disregarding the structural and power generation limitations, aligning with the social demand for larger, more complex and specialised ships. Ship design evolution is always fuelled by energy considerations, rendering energy systems vital for ship functionality and performance.

The continuous growth of the maritime transport, addressed the ship, passengers and crew safety as one of the most dominant issues in shipping industry with systems safety to be considered as driving force during the design, especially considering the case of passenger ships. However, the inadequacy of the existing maritime safety regulations, which are driven mainly by individual catastrophic accidents, and also the deterministic design approaches, did not allow the shipping industry to deal effectively with the concept of systems. Contrary to safety, the systems energy performance was never addressed as key objective within the shipping industry. The absence of strict environmental regulations and the continuous fluctuations of the price of fossil fuels, had underestimated the need for energy efficient ship systems during the design, retrofit and operating stages, with the exception perhaps of prime movers.

Fortunately, this situation is gradually changing. The recently introduced safety regulations, known as SRtP [1], and environmental [2] regulations, by the IMO, came into force to address and, indirectly, couple the above issues. SRtP defines a number of systems as critical for the safety of passenger ships and imposes specific performance requirements on them after a casualty. Approaches successfully applied in damage stability for ship safety evaluation, could be adopted addressing ship systems safety as a design objective and not as constraint.

In addition, the required technical and operational measures for GHG emissions limitation, introduced by the environmental regulations, have forced the designers and the operators to come up with new practices for reducing the fuel consumption. The empirical formulae and conventional methodologies are being evolved by taking advantage of well-established numerical techniques and also of the advanced computational power nowadays.

To this end, the research undertaken in this thesis is focusing on improving the safety and the energy efficiency of ships through logical and numerical modelling of the electrical onboard energy flows, allowing for systems multi-objective optimisation during the design.

1.2 Need for energy efficiency in the shipping

Shipping is considered as the most efficient means of transport taking into account the weight and the distance that ships transport, with approximately 85% of the global demand for transport to be covered by ships [3]. Nevertheless, poor quality fossil fuel is used, known as bunker fuel oil, which is cheaper compared to the domestic land utilised and mostly produces sulphur oxide, nitrogen oxide and particulates, in addition to carbon monoxide and dioxide and hydrocarbons [4]. Considering the above in conjunction with the increasing ratio of transport needs, have driven the shipping emissions to be globally substantial.

According to the third greenhouse gas study published by the IMO in 2014 [5], shipping was responsible for 6.100 million tonnes of CO_2 emissions in 2007-2012 and on average global man-made emissions over a period of 5 years at 3.1%. Also, the conventional pollutants are estimated to have emitted of the same period 15% of NO_x and 13% of the SO_x total anthropogenic emissions [6].

The above side effects from the use of the bunker fuel in shipping, affect not only the environment but the humanity as well. In harbour cities, the causes of urban pollution through ship emissions are translated to poor air quality and to acidification and eutrophication of the natural ecosystem. Cardiopulmonary disease, lung cancer, and respiratory illnesses like bronchitis, asthma and pneumonia are some of the consequences of the marine fossil fuels consumption [7].

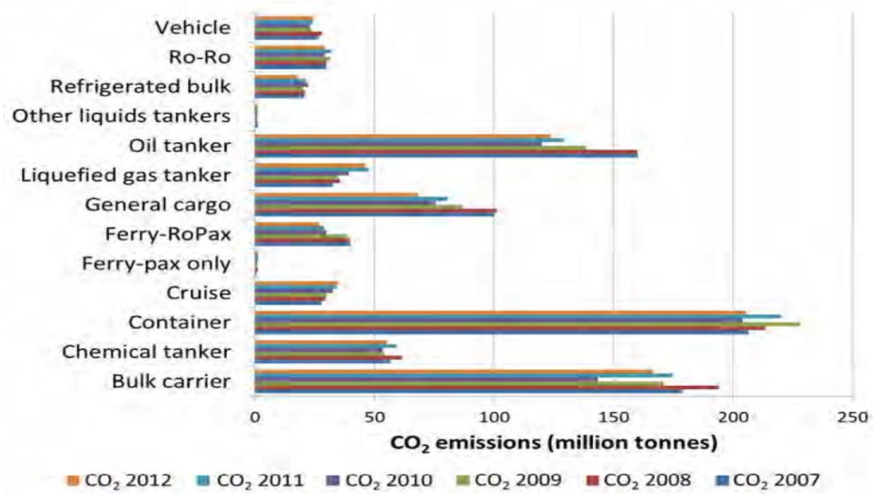


Fig 1-1. "International shipping CO_2 emissions by ship type, 2007-2012", [5]

Considering the growth of human population, close to 8 billion by 2030, and also the growth rates of the developing Eastern countries[8], the need for trades and by extension the capacity of world fleet is expected to be higher during the next ten years. Estimations about the total fleet, measured in million dwt, are forecasting an increase by approximately 50% between now and 2020, based on annual economic growth of 3.3% [3]. This suggests that an average of 1,700 to 2,000 new vessels will be contracted for in each year. To sum up, the above facts prove the high potential increase in the level of the GHG emissions produced by shipping in the next years, forcing shipping industry to deal with the energy efficiency performance as a key objective during ship design, retrofit and operating stages.

Fig 1-2. "Growth in world fleet and total seaborne trade (with forecast)", [3]

1.3 Need for safety in shipping

The maritime industry is characterised as a high risk business considering on one hand the global merchandised trade volumes, nearly 9.6 billion tons in 2013 [9], and the number of passengers internationally and domestically, with the international popularity only in Europe to be almost 400 million people in 2013 [10], and on the other hand the unpredictability of the sea environment. Even though the safety of the ship and its passengers is highly prioritised during ship design, the existence of a large number of accidents being followed by grievous disaster, especially considering the passenger ships, has been recorded in maritime accidents documentation, such as the loss of Titanic in 1912 [11], the loss of Herald of Free Enterprise in 1987 [12], Estonia in 1994 [13], Concordia in 2012 [14], etc.

Depending on the nature and seriousness of the accidents, the ability of sailing to the nearest port for repair post-accident should be set as minimum requirement. This is what logic dictates. However, there are accidents that even though damages are, apparently, not so large, they affect systems crucial for the ship operation and eventually result to capsize. Costa Concordia and MS Al-Salam Boccaccio 98 [15] are good references with the first suffering from power blackout after grounding in 2012 and the second suffering from machinery loss after a fire in 2006 resulting to the loss of 32 and 1.018 lives, respectively.

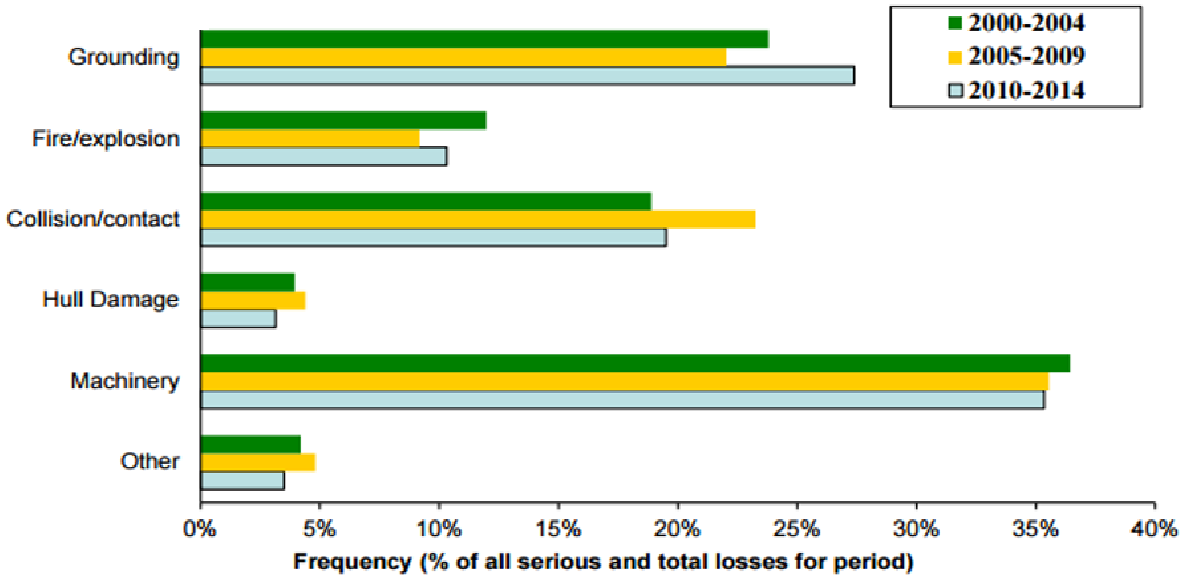


Fig 1-3. "Frequency of ship losses by nature of the accident, 2000-2014", [16]

Apart from the loss of lives, marine accidents are responsible for the environmental pollution of the sea and the air as well. According to the statistics, in 126 cases of pollution as a consequence of a marine accident have been reported in Europe, with 86% of them to be marine pollution, due to the release of the ship's bunkers and cargo, of other pollutants as residues, lubricating and hydraulic oils and 14% were air pollution mostly from fuel explosion [17].

Table 1-1. Number of lives lost per types of ship for the period of 2006-2009, [18]

	2006	2007	2008	2009	Total
Bulk Carrier	46	17	20	30	113
Tanker	11	30	8	3	52
Container ship	19	4	5	14	42
Cargo ship	74	10	18	0	102
Passenger ship	1.079	4	774	68	1.925
Towing Pushing Tug	5	8	0	5	18
Fishing vessel	26	3	2	35	66
Others	117	92	6	24	239

1.4 Regulations

In an attempt to improve safety and energy efficiency of onboard energy systems, the IMO introduced new international regulations. The scope of these is to evolve the systems design by forcing the shipping industry not only to include energy efficiency and safety as design objectives but also to broaden the aspects of systems reliability considering the nature of the accident occurrence.

Through the introduction of the new environmental regulations, which entered into force January 1st 2013, technical and operational measures to address GHG emissions were introduced. Mandatory quantitative performance assessment is imposed to the shipping industry for addressing the CO_2 efficiency of the new ships, through the EEDI, and also the energy efficiency of the existing ships through the SEEMP, (to be elaborated in Chapter 2).

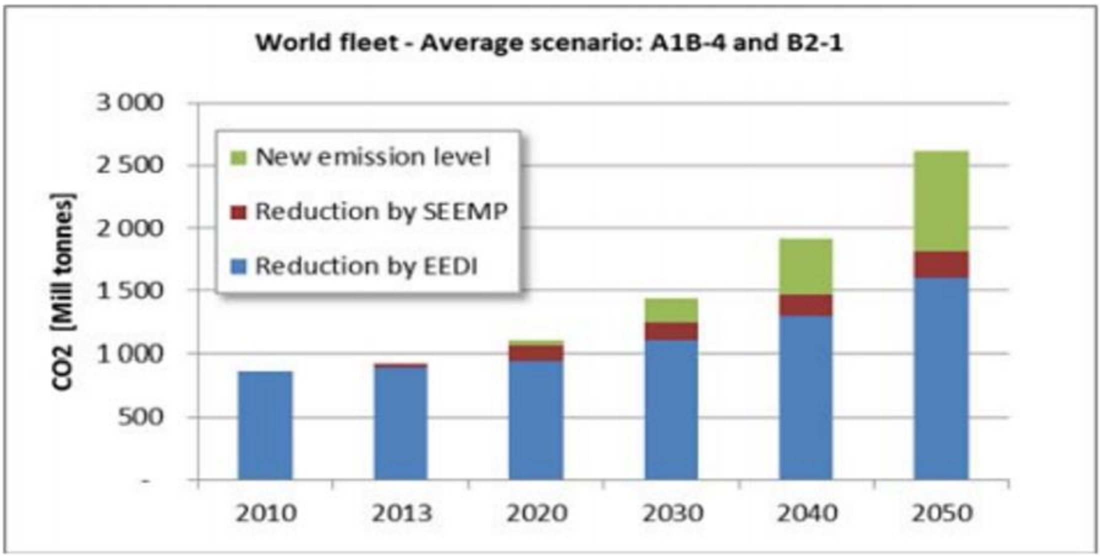


Fig 1-4. "Projection of CO_2 emissions reduction for an average growth scenario with average uptake of EEDI and SEEMP", [19]

Following the 'green' framework, international regulations concerning the passenger ships systems safety, known as SRtP, were introduced following the marine tragedy of the Al Salam Boccaccio '98 at 2006. SRtP is imposing quantitative performance assessment of pre-defined systems, vital for the safety of the passenger ships, after a casualty. In addition, new, innovative concepts for passenger ships design were established, related to 'casualty threshold', 'safe areas' and 'safe return to port' and being connected with ship systems. Furthermore, contrary to the previous strict regulations about systems reliability and redundancies, the AD&A framework provides the necessary flexibility to the designers for innovations, (to be elaborated in Chapter 2).

1.5 Design practices of the energy systems onboard

The design of the marine energy systems is a process, which has, regardless of the vessel's mission and size, to assure the compliance with the rules and regulations either directly or indirectly through the equivalent designs with incorporation of innovations, considering potentially maximum safety and minimum power consumption at the lowest cost. However, because of the strict nature of the regulations and the time restrictions, the designers used to have lack of freedom during the design process, especially considering systems safety. Therefore, the design nature was rules-based with the absence of quantitative performance assessment of systems energy efficiency and reliability, resulting in non-cost-ineffective designs.

The design of the electrical energy systems onboard is a good reference of an inefficient design in terms of energy efficiency, safety and cost. Electrical energy systems onboard are of vital importance in generating, converting, controlling and distributing the necessary power for the requisite ship functionality. The consideration of the ship mission and size and by extension its load requirements, early in the design allow for the appropriate sizing and topological onboard location of the electric power plant.

However, they are currently designed based on past experience and empirical formulae, i.e. static balances, lacking of interactions with other energy systems and eventually resulting in having oversized auxiliary systems as operating away from their optimum efficiency point. Moreover, even though systems reliability was addressed as a key design factor in the shipping industry, the design approaches are deterministic with the operational experience to be one of them [20]. In addition, commonly used qualitative and quantitative reliability analysis tools (will be explained in Chapter 3), are based on components failure description with their topology to be considered completely independent from the ship environment. Consequently, the energy systems end up installing potentially unnecessary amount of redundant units, increasing the cost and ship weights with simultaneous reduction of available spaces for beneficial purposes.

To this end, aiming for optimum design of the electrical energy systems in energy efficiency and safety perspectives, well-established design methodologies have to be adopted. In this respect, following the trodden path of energy simulation, the energy performance of the ship systems can be addressed in a holistic manner capturing also the interactions between the energy systems. Moreover, approaches successfully applied to the damage stability could account for electrical systems reliability by taking into consideration all possible ship casualties during the design.

1.6 Structure of the thesis

Chapter 1 (*Introduction*) defines the problem of energy efficiency and systems safety in shipping sector as well as sets the aims and specific objectives of this research. Recently introduced international regulations are mentioned attempting to address these two issues. The disadvantages of current design methodologies are briefly presented, giving rise to the need to evolve towards energy simulation and probabilistic assessment, on the basis of which the aim and objectives of this work are laid out.

Chapter 2 (*Critical review*) presents the state-of-the-art of shipboard electrical energy systems and reviews their current ship design and optimisation approaches. Recent developments and regulations concerning energy efficiency and safety in conjunction with the applied methodologies in this thesis are detailed reviewed.

Chapter 3 (*Approach adopted*) explains the approach adopted.

Chapter 4 (*Modelling electrical energy systems onboard ships*) describes the numerical and logical modelling principles of the electrical energy systems onboard.

Chapter 5 (*Design electrical systems for energy efficiency*) examines the possibility to reduce the electrical modelling effort during design by neglecting electrical, geometrical and topological input parameters of the system and defining the loss of accuracy at each step.

Chapter 6 (*Power management systems onboard ships*) defines optimisation process for electrical power systems during design and operation.

Chapter 7 (*Safety-critical systems availability during emergencies*) proposes the probabilistic-based approach for the optimal onboard location of the safety-critical systems. Systematic investigation as well as topological and geometrical systems optimisation in terms of safety and cost are performed.

Chapter 8 (*Conceptual design*) proposes a design methodology for the electrical power systems of commercial vessels based on the findings of this thesis, and demonstrates its application in two case studies.

Chapter 9 (*Discussion and recommendations*) outlines the contributions of this work and discusses recommendations for future work in the field of ship design with the use of energy modelling and probabilistic assessment.

Chapter 10 (*Conclusions*) which concludes this work, provides an overview of the need for energy efficiency and safety in the shipping sector and summarises the main conclusions of the research presented in this thesis.

1.7 Aim and Objectives

The overall aim of this thesis is to improve the energy efficiency and safety of ships through the dynamic modelling of the electrical processes onboard and their interactions, as well as through the probabilistic assessment of the safety-critical systems at emergencies.

To achieve this aim the following specific objectives are targeted:

- To review the state of the art of 'electrical energy systems onboard ships' and of current design methodologies
- To develop onboard marine electrical power systems model of a cargo and a passenger ship considering the geometrical, topological and electrical parameters.
- To undertake parametric studies for identification of Key Design Parameters of shipboard electrical energy systems from energy efficiency (fuel consumption) perspectives.
- To develop PMS strategies considering the fuel optimisation during operation and design.
- To identify critical zones of the electrical energy systems topologies onboard and optimise the latter in terms of safety and cost.

- To make suitable recommendations for the preliminary design of electrical energy systems in terms of energy, safety and cost as derived from the results of the proposed methodologies and also for future research in this area.

1.8 Closure

In this introductory chapter the need for energy efficiency and safety in the shipping sector has been discussed and the corresponding improvements to the international regulatory frameworks stated. The current design practices of onboard energy systems and also of electrical energy systems have been briefly described and the need for adoption of new methods taking advantage of computational power and targeting a multi-objective design optimisation has been established. Finally, the structure of the thesis has been laid out.

2 CRITICAL REVIEW

2.1 Preamble

This chapter focuses on the shipboard electrical energy systems configurations, critically reviewing the current design and optimisation methods and practices that shipping industry applies. The up-to-date developments and regulations concerning energy efficiency and safety are described. New, well-established and successfully applied design methodologies are proposed that are used in this work.

2.2 Shipboard electrical energy systems

2.2.1 Power plant configurations and planning

Shipboard electrical power plants are similar, in terms of functionality and architecture, to land-based power networks with the major differences to be considered to the complexity and the variety of consumers that they supply as well as the level of the components protection requirements [21]. For instance, considering the case of a passenger ship, where the passenger safety and comfort are the main objectives, the propulsion, which in some cases is electric, and auxiliary systems are responsible for more than 1/3 of the total power consumption, with HVAC systems being the other major power consumer, for roughly less than 1/3 of the total. The rest 1/3 is distributed to ship machinery, to accommodation facilities (lighting, fresh water, electrical appliances, etc.), to communication and navigation systems and other type of comfort systems (swimming pools, cinemas, etc.).

Mainly in power systems, the key design objective is the safety, however, not only of the power system but also of the crew, passengers and the ship itself. Therefore, the systems should be design in a way of not only 'rejecting' any possible disturbance, as a consequence of a fault or accident regardless of its duration and nature, but additionally be located into ship environment in areas where are less vulnerable to be damaged, from fire and flooding, and potentially resulting to fault. In other words, the shipboard electrical power plants have to deal with additional constraints during their design and comply with stricter rules, due to its autonomy, employed by the independent classification societies.

Furthermore, energy efficiency is considered another objective that has to be addressed during the design and the corresponding emission reduction for the required compliance with the green environmental regulations. The appropriate sizing of the power generation has a major contribution on it in conjunction with the choice of the power system's control strategy. Apart from the fuel savings during the operation, the initial and the maintenance costs that can be potentially decreased without, concurrently, sacrificing the level of systems safety. The electrical power plants onboard can be broadly divided into four major systems [22]:

- *the power generation,*
- *the power distribution and conversion,*
- *the power utilisation,*
- *the control and automation.*

Each of the systems configuration has to be evaluated during the design process not only as a part of the electric power plant but additionally into the ship environment. In other words, the geometrical, topological and electrical design characteristics of the systems have to be addressed and coupled within the ship constraint environment. As a consequence, the size and the type of the ship affect the whole design of the electric power plant, revealing the importance to specify them initially.

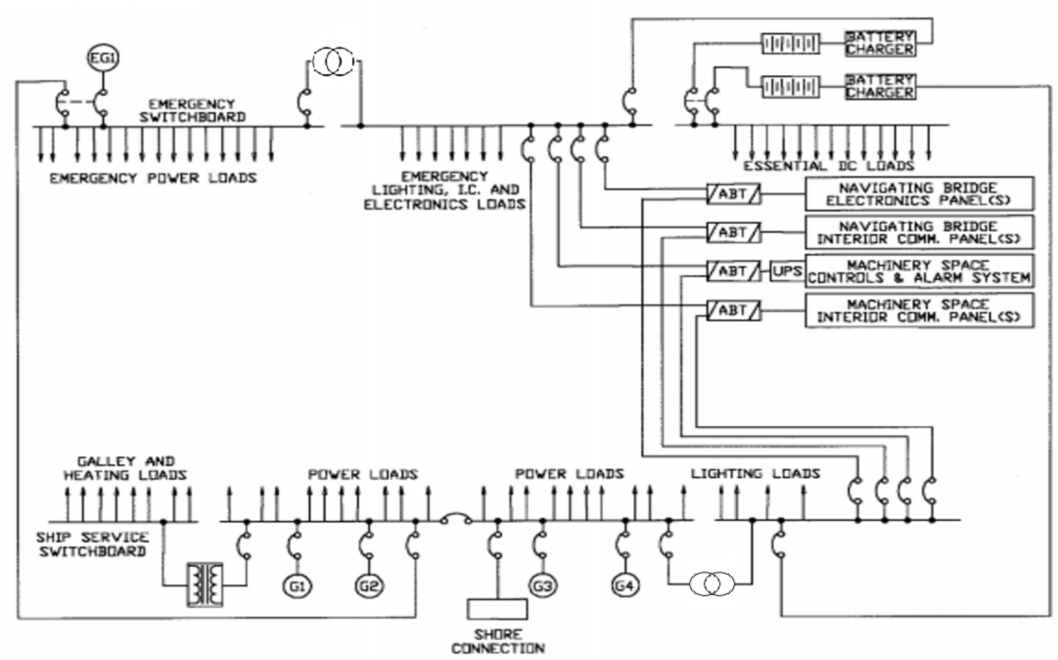


Fig 2-1. "Diagram of a typical electric power plant", [23]

2.2.1.1 Power generation systems

The power generation, usually located to the auxiliary room at the bottom decks of the ship, comprises the equipment appropriate for the generation of the electricity to supply almost all energy systems on board ships. Commonly, the generation's capacity is ranging from a few hundred kilowatts at the lower end of scale up to a few hundred megawatts in cruise industry (depending on the propulsion's configuration). Apart from the main power generation, the emergency generation is considered at all ships, in case of any malfunction to the main and its location is on the middle or the top of the ship for increased safety.

The equipment that is commonly used in ships are the prime mover-generator set with the former to be the diesel engines, gas and steam turbines and the latter AC or DC generators being connected via a shaft. Other concepts of power generation are the:

- shaft generators, which are applied on the shaft of the diesel-mechanical propulsion train with the created power supplying the main switchboard with the use of power converter equipment for synchronisation to the network.
- fuel cells as source of power coupled with the appropriate power converter equipment for power plant connection
- energy storage devices (batteries) couple with the appropriate power converter equipment for power plant connection
- renewables couple with the appropriate power converter equipment for power plant connection

The sizing of the generation sets are of major importance for the functionality of the power plant in terms of safety and energy efficiency. The type (AC or DC, frequency, voltage) and the number of generators of the main power supply are closely connected with the ship size and type, the power demand and the control strategy that will be applied. In addition, the classification requirements for the existence of an extra generator of smallest capacitance for redundancy apart from the emergency have to be considered. Corresponding rules compliance for application of any other concept of power generation has to be taken under consideration.

However, apart from the geometry and the electrical characteristics of the power generation, its topology into the ship environment is crucial to the ship safety, located to less vulnerable areas, and energy efficiency, being as close as possible to the higher power consumers. The size and topology of the emergency generation sets, are based on the size and number of the redundant units that has to supply and their topology on board, being usually at the upper decks for protection from the flooding casualties.

2.2.1.2 Power distribution and conversion systems

The objectives of the distribution and power conversion scheme are to transform and supply the required amount and form of power to the loads throughout the ship. The complexity and the geometrical coverage of the systems are closely connected to the ship size and type with the passenger and cruise ships to require advanced concepts. The main components concerning the distribution are the main and load-centre switchboards, distribution boards and power cables and for the power conversion the transformers. Commonly the location of the main switchboard is inside the engine control room, next to the power generation sets, at the bottom decks. The location of the rest boards, power cables and power transformers varies throughout the ship depending on the systems loads topology.

The main switchboard(s) receive(s) and monitor(s) the received electric power from generators and through the cabling systems it is distributed either directly or indirectly through the load-centre switchboards and the distributions boards to the loads [24]. The regulations concerning the main switchboards locations are very strict with no room for innovations contrary to the rest switchboards and cables of the system. In addition, the level of protection so the switchboards as the power cables are imposed by classification societies to be high. The emergency switchboard, located next to the emergency power generation sets, is usually considered as redundant to main being connected via a bus-tie and supplying apart from the redundant units, during the emergencies, consumers located close to it as well. Concepts of reducing the redundant units vital for ship safety with power flow paths have to be considered during the design for the cost minimisation and potential reliability maximisation have to be assessed. Concerning the secondary electric energy supplies (such as navigation system, lighting system etc.) where the use of transformer is necessary, the rules enforce the existence of an emergency transformer, of smaller capacitance, as a redundant.

2.2.1.3 Power utilisation systems

The electrical power utilisation systems are comprising all the units, ranging from some watts to hundred kilowatts (ballast motors), being supplied by the power distribution and conversion systems. In the highest rate are the motors linked to engines auxiliary system (pumps, fans), bilge and ballast system (motors), HVAC system (fans), steering system (thrusters motors) etc. and at lower rate are the lighting system, navigation system, controls, communication etc. Power consumers are considered boundaries of the electrical energy systems integrated with other systems and with the environment. Also, they are located in a huge variety of spaces around the ship depending on the ship mission and size (in passenger ships the power demand is high at the cabin spaces and in the machinery as well). Because of the safety requirements, a number of consumers are parts of the safety-critical systems and the need for potential redundancies is under investigation during the design.

The consideration of the load requirements during the design are connected with the sizing of the power generation units, the geometrical coverage and topology of the power distribution systems and also the control of the power systems for getting a robust power plant.

2.2.1.4 Control and automation systems

The control of the shipboard power system can be divided to local and global. The local control comprises the frequency and voltage control of the power generation units to the levels that the rules imposes, through the governor and the AVR, correspondingly. However, the overall monitor of the power system's energy and safety performance is employed by PMS that can be considered as global systems controller located in the control engine room of the ship. The data collection from the control points of the power system located on the main, load-centre and emergency switchboards enables integrated actions to the whole power network. The PMS is commonly used in the land-based projects, but because of the presence of independent power source(s) in marine applications, its necessity is even higher for the efficient operation of the network [25]. The classification societies rules are very strict about its integrated functionalities as some are considered crucial for the safety of the ship during operation and at the emergencies (such as thrusters and electric propulsion control).

The PMS is very important during all the ship stages: design, retrofitting and operation. At the design stage PMS as an optimiser can be useful for the sizing and the number of the power generation units that has to be online at each operating stage based on the fuel consumption. Also, during operation the PMS can be helpful for fuel optimisation, disturbance rejection and in the maintenance of the equipment of generation, conversion, distribution and consumption through the actions of: load sharing and unit commitment, load shedding and the quality of power that it supplies. In addition, at the retrofitting the re-configuration of the existing control system in conjunction with the appropriate location of monitoring and data collection points, can be obtained through the PMS improving so the energy efficiency as the marine power systems reliability. A sophisticated ship power management system usually provides the following main functions [26]:

- Diesel generator (D/G) start, stop control
- Auto-synchronizing of generators and breaker control
- Load depend start, stop
- Unit commitment - Load sharing
- Load increase control
- Blackout monitoring
- Load shedding
- Shaft generator load transfer

2.2.2 Current design methodologies

2.2.2.1 Design of power generation

The sizing of the power generations is crucial for the energy and safety performance of the power plant. The approaches that shipping industry applies for the generating sets sizing are addressed by steady-state calculations, leaded by the lack of integration with other energy systems allowing for accurate identification of ship real power needs and not considering only the worst case scenarios. Thus, the determination of the electric power generation capacity and configuration is gained through the insight into the electric power demand of the ship under various operational conditions based on static practices and the classification societies rules. The operational conditions depend on the ship mission and size. For many ship types, the following static operational conditions are examined:

- at sea
- manoeuvring
- in port, loading and discharge
- in port, no loading or discharging
- at anchor.

For certain ships, for example cruise vessels, it is necessary to make a distinction between summer and winter conditions [27]. Traditionally, there are two ways to determine the electric power demand: through the empirical formulae and through the electrical load analysis. During the design process, the first estimate of the electric load is often made with empirical formulae and as the process progresses, a more detailed calculation is made with a load analysis [28].

Empirical Formulae

The empirical formulae can be used successfully to obtain a first estimate of the electric power demand in the pre-design stage, if the formulae are based on a sufficient number of ships with the same mission and comparable size. They are used to determine the electric power demand or installed electric power by using the main dimensions of the ship such as deadweight or installed propulsion power. A common formula is shown below that uses the installed propulsion power to determine the electric power demand at sea going for a cargo vessel without special equipment such as cargo refrigeration system or bow thruster. As a rule of thumb, the electric load when manoeuvring is 130% of the electric load at sea, and the load in power is 30 % to 40% [28].

$$P_L = 100 + 0.55(P_{MCR})^{0.7} \tag{2.1}$$

Electric Load Analysis

The most widely used method for determining the electric power demand is the so-called electric load analysis or electric load balance. Through the estimation of a load factor, indicates the relative (%) load of the machinery and thus specifies how much electric power is absorbed in an actual situation, and a simultaneity factor, indicates the relative (%) mean operational time of the machinery, for all power consumers at each operating state, the capacity of the generated power, in turn, the size of the power generation units, can be approximated. However, the estimation of both factors is very difficult and often result in being overestimated, in order to minimise the risk of designing a plant with a generator capacity that is too small. Consequences of an overestimated electric power demand, are the extremely large generators capacitance, the high initial investment, the operation of the generator sets away from their optimum point increasing the fuel consumption, the pollutants and eventually the maintenance costs.

consumer name	number installed	power at full load	installed power E-motor	absorbed electric power	in port				at sea		
		[kW]	[kW]	[kW]	number in service	load factor	sim. factor	average absorbed power	number in operation	etc.	
Propulsion system - - - Auxiliary systems - - - etc. 115 V, 60Hz, 1phase 24V, DC											
Total											

Fig 2-2. "Electric load balance/analysis of a ship", [28]

Following one of the above approaches and also complying with the corresponding classification rules, the sizing of the power generation units is achieved. The same approach and the compliance with the corresponding rules is applied for the emergency generation units which have to serve the safety-critical systems consumers during the emergencies.

Apart from the sizing, the location of the power sources is of major importance in shipping. The compliance with regulations and classification rules concerning power generation safety provide no room for innovations. The adjunct connection of the power generation with the switchboard (main and emergency) imposing the choice of auxiliary room and engine control room for the main and the middle or top decks for the emergency as the safest and most efficient locations.

2.2.2.2 Design of power distribution

Due to the nature of the electrical power distribution as it is the connecting link between the power generation and the power consumers, the design concept should guarantee high levels of reliability and quality of service for achieving the ship's functions and mission [29], [30]. However, the traditional concepts in power distribution design are far from their 'applied' environment, in other words the ship. In most of the ships, the cable routing and the switchboards location is selected by previous experience of the same ship type designs. In addition, there are designs where risk assessment and analysis is applied for addressing system reliability focused on evaluation of the system failure probability on the basis of the components failure description and the system topologies, such as FTA, FMEA and HiP-HOPS [31].

FTA is a tool applicable for quantitative and qualitative risk analysis. Fault trees themselves are graphical representations of logical combinations of failures, and show the relationship between a failure or fault and the events that cause them. A fault tree normally consists of a top event, which is typically a system failure, connected to one or more basic events via the logical AND and OR. Basic events are usually either failures or events expected to happen as part the normal operation of the system. The analysis of the fault tree consists the qualitative (logical) and the quantitative (probabilistic) analysis. Qualitative analysis is done by reducing the logical expression represented by the fault tree into a set of minimal cut sets, which are the smallest possible combinations of failures required to cause the top event. Quantitative analysis is done by calculating the probability of the top event given the probability of each of the basic events occurring [32].

In a FMEA, the basic process consists of compiling lists of possible component failure modes (description of how an entity fails), gathered from descriptions of each part of the system, and then trying to infer the effects of those failures on the rest of the system. Usually, these effects are evaluated according to a number of criteria, such as severity, probability and detectability. These criteria are then combined into an overall priority figure for the effect of the failure mode generally by multiplying the criteria together. All of this data is then presented in the form of a table, which allows the analyst to quickly see what the effects are of each failure mode [33].

In addition, HiP-HOPS technique was developed for the semi-automatic construction of fault trees and FMEAs. In this technique fault trees and FMEA are automatically constructed from topological models of the system that have been manually augmented with appropriate component failure data. Both qualitative (logical) and quantitative (numerical-probabilistic) analysis provide both the minimal cut sets of each fault tree and the unavailability (i.e. failure probability) of top events [34].

2.2.2.3 Design optimisation

Systems optimisation is an incorporated part of ship design following the methodologies being utilised. However, not only the ship design approaches but also the objectives that are used nowadays, indicating the deterministic nature of them targeting the rule compliance without exploring the whole range of design space. Sequential optimisation techniques are applied from the industry with the most popular to be called 'Design Spiral' [35], see Figure 2-3. 'Design Spiral' is a step-wise approach where the design decisions are based on pre-defined steps targeting the sequential optimisation of the designing ship.

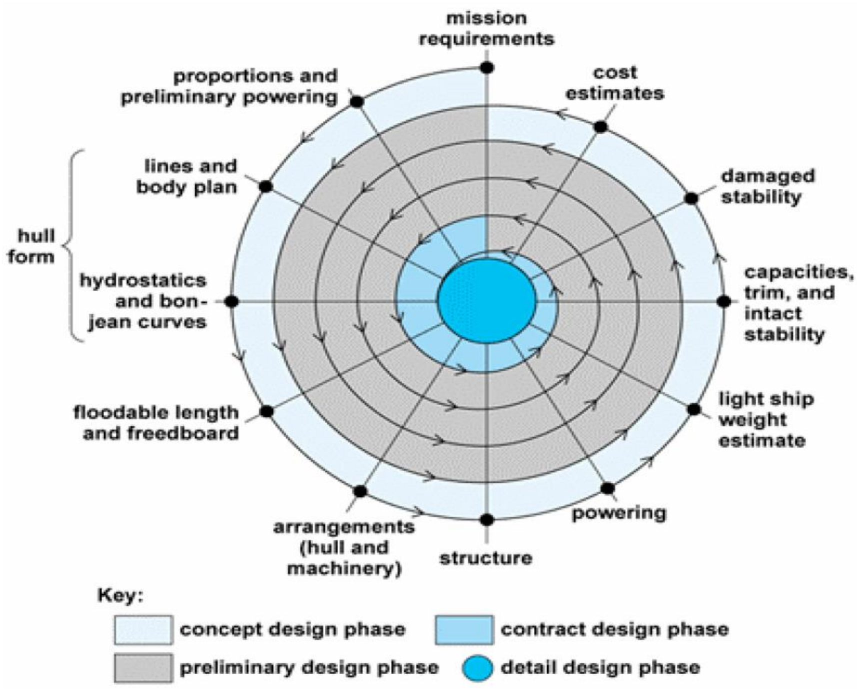


Fig 2-3. "Design Spiral approach for ship design", [35]

2.3 Energy efficiency of energy systems onboard ships

2.3.1 Regulations

Initial thoughts for the need to introduce international regulations for air pollution and GHG emissions reduction in shipping industry came up due to the evidence in the 1960s and '70s that concentrations of CO_2 in the atmosphere were increasing. Following that, in 1997, it was the Kyoto Protocol containing the provisions for reducing GHG emissions from international shipping that pursuing the IMO for introduction of international strict green regulations that was in place but it took years before the international community responded. That happened in 2008, when MEPC at its 58th session made noteworthy progress in developing technical and operational measures to address GHG emissions, which entered into force on January 1st 2013.

The EEDI and SEEMP concepts were introduced with both being mandatory for all cargo ships over 400 gross tonnes (excluding ships with gas turbine, diesel-electric and hybrid propulsion). The EEDI is a performance-based mechanism that identifies certain minimum energy efficiency in new ships and it is expressed by a simplified formula evaluating the efficiency of the highly power consumers onboard along with the transportation effort. The SEEMP as an operational measure, establishes a mechanism for improving the energy efficiency of ships considering also the cost-effectiveness of the actions. An additional voluntary monitoring tool, the EEOI was introduced, which measures the fuel efficiency of a ship during operation. Furthermore, thoughts for extension to other ship types and sizes of the EEDI and SEEMP applicability are being reviewed by the IMO.

2.3.2 Energy efficiency considerations

After the introduction of the strict environmental regulations for reduction of the GHG emissions, scientific and technological developments that fuel innovations in the shipping sector were considered by the ship designers and builders to meet the required energy efficiency level. The concept that were considered are mainly the:

- use of alternative, environmental friendly, energy sources
- energy efficiency increase with CO_2 reduction technologies

Considerations for up-to-date technologies substitution of the bunker oil with other fuel types or even other source of energy have been introduced in marine industry. Technologies for alternative solutions to the fuel oil include the LNG, H_2, Bio-fuels, methanol, nuclear and fuel cells [9]. Regarding the alternative energy sources, the renewables have been considered as additional power sources to the main configurations with various sorts of wind power systems such as kites, Flettner rotors, Dynarigs or foldable wings to have been tested [36]. In addition, solar panels have been fitted on ship deck as well as wave energy concepts on board ships have been tested [37]. The installation of alternative fuel and renewable technologies is still in an experimental stage and has only been applied in a short amount of cases. Furthermore, it is certain that new technologies will require rules and standards to assure their normal installation and operation, whereas their economic feasibility is yet to be verified. Consequently, fuel oil is likely to remain the dominant energy source for commercial ships with the industry to, currently, focus on energy efficiency considerations for fuel oil powered vessels.

The increase of the ship energy efficiency in conjunction with the reduction of the CO_2 emissions can be achieved with the use of technical and operational measures. The former option can be categorised into three groups with a number of measure available for implementation in each of them:

- Increase in propulsion train efficiency
- Increase in power production efficiency
- Reduction in power consumption

The optimisation of the propeller design and the electric propulsion are considered at the efficiency increase of the ship propulsion. Technologies as the waste heat recovery, the shaft generation, the hybrid power systems and the energy storage are measures that even though increase the complexity of the systems on board, are configurations that could potentially provide energy production benefits. As for the reduction of the power demand concepts as ship hull optimisation, power management systems, improved transmission systems, ballast treatment systems optimisation and propeller optimisation can be employed. In addition, operational measure that have already been addressed are the voyage optimisation, the speed management, trim/draft optimisation, propeller and hull cleaning are some of them. Extensive guides of operational and technical measures have been published by FATHOM [38] and DNV-GL [39].

2.3.3 Energy simulations

The effectiveness of the above described operational and technical measures has been assessed in small scale experiments and on board monitoring. Although, they are well applied and well established, the cost not only for their installation but also of the lab experiments has fuelled the industry to come up with practices taking advantage of numerical simulations through the advanced computational power.

Literature exists in onboard energy systems simulation for marine application in a way of addressing the systems performance [40], [41], with adequate research to have been done about the optimisation of the electrical power systems in terms of fuel consumption [42], [43], [44] and quality of supplied power [45, [46]. Although, simulations of individual energy systems has been introduced by [47], [48], there have not been any noticeable coordinated endeavour to simulate the energy performance of on board systems in a holistic manner until very recently [49], [50], [51]. The need for addressing the total power demand of the vessel is leading the research and industrial concerns to perform global energy simulations capturing the interactions between different energy systems. In an attempt to apply and advance the available knowledge in computer simulation and systems modelling, EU has funded a number of projects (TARGETS, REFRESH [52] and JOULES), focusing on improving the global energy efficiency of ships under the concept of DEM [53]. DEM method uses first principles for the modelling of all on board energy systems and by simulating them under the same platform, considering also their interactions, the holistic energy performance of the ship can be evaluated.

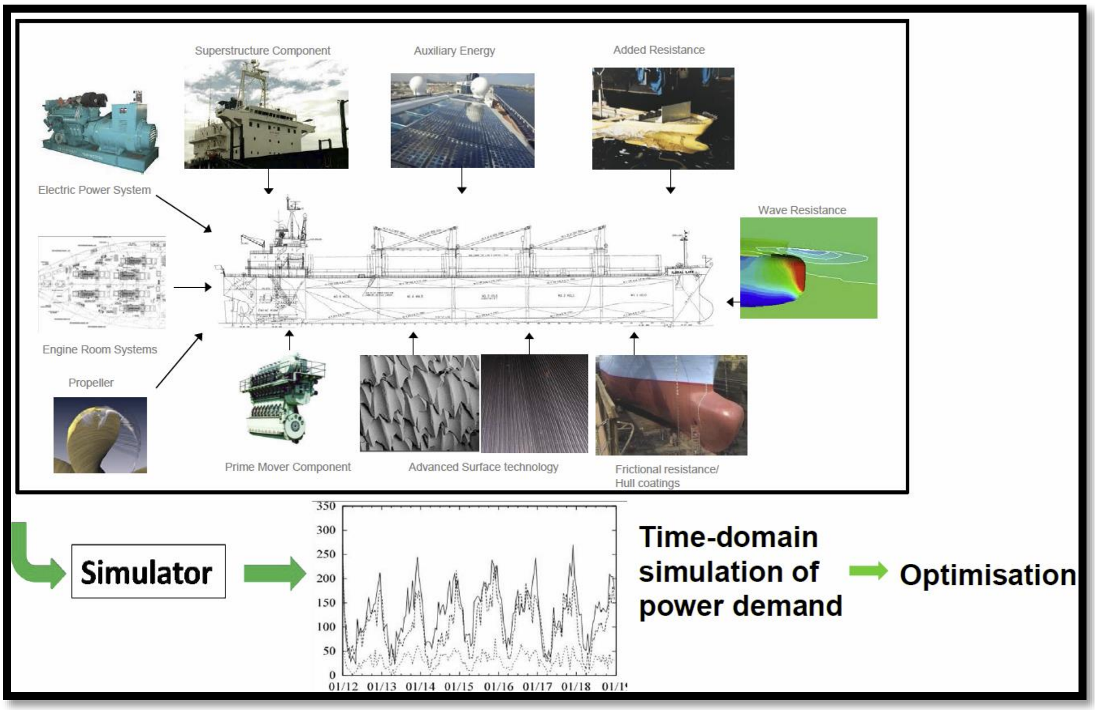


Fig 2-4. "Holistic approach to ship energy systems simulation", [36]

Energy simulations could be an efficient tool also for design of the electrical energy systems onboard ships and the appropriate diesel-generator sets sizing. The estimation of the real power needs by quasi-dynamic simulations of all possible operating states and the coupling with the other disciplines, could result to equipment designs close to their operating points and consequently more energy efficient. As a consequence, the first principles modelling of the whole electrical power systems on board ships is examined in this study targeting the estimation of the electrical power consumption of the system through quasi-static simulations as a function of time. In addition to this, the applicability of a proposed exhaustive search optimisation algorithm is investigated for the optimal sizing of the diesel-generation sets. They above described concepts are considered as original contribution to the field of electrical power systems design for energy efficiency.

2.4 Safety of energy systems onboard ships

2.4.1 Regulations

In the knowledge that a significant number of accidents do not necessitate immediate evacuation from the ship, and in the event of such accidents, subject to meeting the basic needs of the occupants, the damaged ship may be taken to a nearby port or safe refuge. Similarly, many accidents can be mitigated and the ship can continue with her planned voyage.

However, the quality allowing a ship to keep sailing following an accident cannot be ensured incidentally. It has to be deliberately designed for. More specifically, in the knowledge that accidents lead to damage or destruction of onboard systems, and in order to withstand such consequences the overall design must have in-built redundancy from the point of view of a casualty, not only from the point of view of component reliability, which is the norm in designing for systems redundancy.

Following the above, new safety regulations introduced by the IMO, SRtP, in shipping industry attempt to address and couple the systems with the ship safety in the emergencies at the design stage. Safety-critical systems that have to remain operational post-casualty are formally initiated proving the need for redundancies to them. In addition, SRtP considering not only the nature of the accidents but also the damage and the destructions of the onboard systems by them, the systems design is driven by a need for in-built redundancy from the point of view of a casualty, not limited to component reliability. In addition, its considers that evacuation of the ship during emergencies is the last line of defence and highlights the need for post-casualty ship floatability and stability for a minimum duration of 3 hours ('casualty threshold') as well as capability to proceed to the nearest port under its own power ('safe return to port').

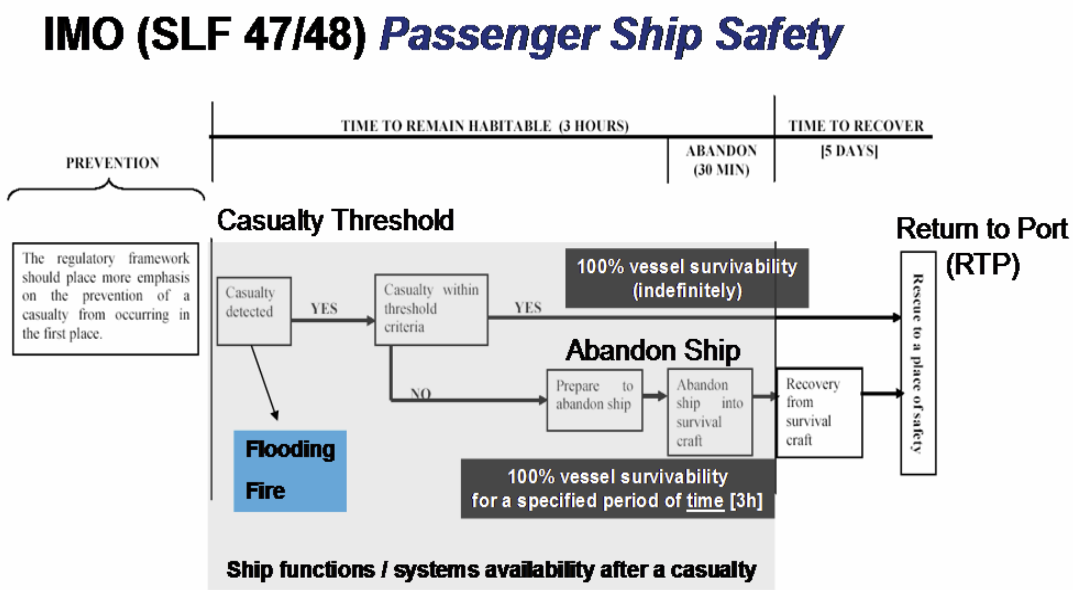


Fig 2-5. "The framework of IMO for passenger ship safety", [1]

2.4.2 Post-damage systems availability

Although design flexibility is provided through the AD&A, "designing damage tolerant ship systems" is a far more complex problem than one would initially imagine. Even though standard reliability engineering methods, such as the capacity outage probability table (COPT) [54], have been used in the evaluation of electrical power system redundancy provisions [55], [56], [57] and electrical distribution systems designs [58], [59], [60], such methods rarely take into account the spatial "locality and historical frequency" of shipboard damage scenarios. Locality here implies the property that a damage scenario is more likely to simultaneously affect systems that are located close together. Hence, if two systems that can stand in for each other are located far away from one another they provide a greater degree of robustness than they would if they were located side by side. This consideration is implicitly used in design and positioning of ship systems, but an explicit and quantitative treatment incorporating this property and damage incidence frequency will substantially enhance system availability in emergencies.

In an attempt for alternative systems safety design methods, EU has funded the SAFEDOR project [61] with one of the major tasks to focusing on the probabilistic analysis of systems availability by following the same probabilistic framework as in damage stability [62]. In this approach, the modelling process involves the mapping of the functionality of each safety-critical system to logical structures, which are preserving the physical, functional and spatial relations of the systems and across the other systems. Having built these dependency diagrams, the post-casualty systems availability assessment can be performed with the initiation of the systems and components failures at emergencies [63]. In particular, through the application of all possible flooding damage scenarios to the systems models, be combined with each damage probability of occurrence p_i, the derivation of a weighted averaged can be calculated.

There are standard approaches for evaluating probabilities of flooding ship spaces. Generally they are based on statistical data of damage location (along the ship), damage length, vertical extent and penetration. Such a multivariable probability distribution is integrated over domains formed by WT partitions. The integrals (probabilities) obtained for each compartment and all possible combinations (groups) of compartments are called p-factors and are denoted as p_i. Dedicated tools for the generation of all possible damage scenarios and the corresponding p-factors are commercially available with software NAPA to be the most popular in shipping industry.

The adoption of this method is considered in this work for the identification of the onboard location of the electrical distribution systems with potential reduction of the redundant units and in turn the cost. The consideration of electrical systems modelling into the ship environment and the application of damages of specific natures, is examined in this study for the safe design of the electrical power distribution systems through the adoption of probabilistic assessment. This concept is considered as original contribution to the field of electrical power systems design for safety.

2.5 Optimisation of energy systems onboard ships

Nowadays, innovative and efficient system designs can be, potentially, accomplished without targeting only the rule compliance, disregarding deterministic optimisation approaches which do not allow for exploration of the whole design space. By taking advantage of the computational capability, advanced optimisation methodologies can be applied to simultaneously search the design space given a list of requirements and constraints ending up to the optimal designs. In addition, new regulations have changed the scope and the targets during design of the ship systems, but not limited only to them. The safety and the energy efficiency have to be considered as key design objectives and not as constraints for the choice of the 'optimum' design aligning also with the rules and regulations even directly or through the equivalents design option.

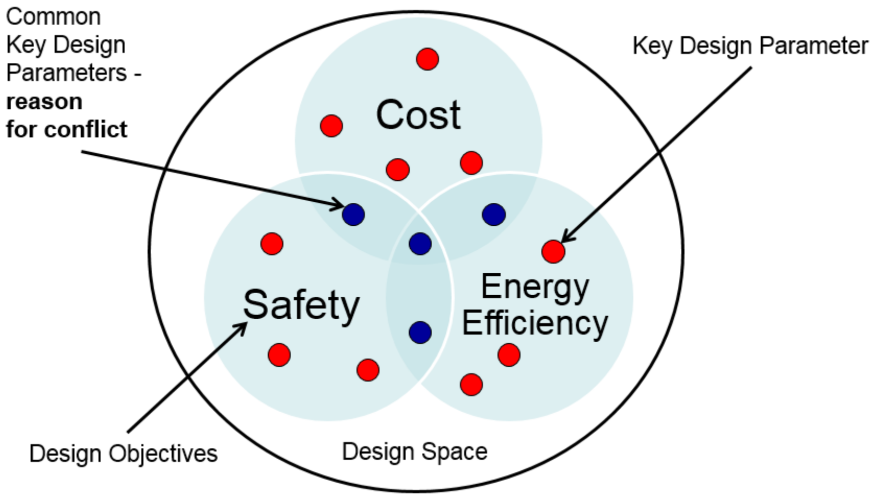


Fig 2-6. "Multi-Objective optimisation approach for ship systems design"

Having the above in mind, the concept of multi-objective optimisation methodologies can be adopted for the ship design and by extension to the systems design and for this work to the electrical energy systems design. The identification of parameters that affect each of the design objective will lead to the identification of the common between them that will conclude to simultaneous optimisation and the reduction of feasible designs to the level that the designers determine.

2.6 Closure

In this chapter the current state and developments of electrical energy systems in the shipping industry have been reviewed, as well as their design practices. The recently safety and environmental regulations were presented and additionally the methodologies that are adopted for the purposes of this study.

3 APPROACH ADOPTED

3.1 Preamble

The objective of this chapter is to explain the methodology that will be followed throughout this thesis. Following the thesis chapters outline, the detailed description is elaborated next

3.2 Preparation and implementation process

The stages describing the approach that has been adopted in this thesis are presented in figure 3-1 and summarised in the following lines. Along with that, the flow chart of the proposed methodology is shown in figure 3-2.

Stage 1: Systems Modelling

At this stage, the detailed model of the marine electrical power plant is developed having at first initiated the principles that are applied. The interactions with other energy systems as well as with the environment are included and considered as boundary conditions. Through the detailed numerical modelling the systems energy performance can be assessed something that is necessary for next stages.

For the passenger vessels, apart from the systems energy efficiency considerations, safety also are considered due to the SRtP regulatory framework. Consequently, at this stage the topological modelling of the pre-defined from the regulations safety-critical systems is also applied through the latter's safety assessment. The use of logical modelling is initiated for building the physical, functional and spatial systems dependencies into the ship environment.

Stage 2: Systematic Parametric Investigation

In an attempt to reduce the modelling effort during the design, the need for modelling simplifications are necessary. Parametric studies are performed, evaluating the systems energy performance, in an attempt to identify the key design parameters of the electrical systems for the cases of cargo and passenger vessels. Through that process, the derivation of a simplified electrical power network model is derived for each examined ship case within acceptable level of results accuracy.

In addition, systematic investigation aiming to identify the most vulnerable zones for passenger ship systems location onboard is performed. Having placed the systems into ship environment from the previous stage, the application of statistical damages, derived from probabilistic framework used in damage stability, is applied for the identification of ship zones with high rates of systems unavailability post-casualty.

Stage 3: Systems Optimisation

Having performed the parametric studies, the systems optimisation through exhaustive research targeting the energy efficiency and cost is considered through the functionality of the PMS during the design. Design tables comprising sizing of power generation sets with corresponding fuel consumption are derived considering simulation results from the simplified electrical energy system model. For the choice of the appropriate sizing of the power generation sets, according design decisions are necessary regarding the area of vessels operation and the power generation sets loading strategy that will be applied during operation.

Systems energy efficiency optimisation during operation is, also, investigated, with the unit commitment and the economic load sharing functionalities of PMS to be considered for the installed power generation units attempting the fuel consumption minimisation. For that case, stage 2 is omitted.

For the passenger vessel safety and cost optimisation, the derived results from stage 2 are considered. Having identified the critical zones, corrective actions for the safety-critical systems topological and geometrical optimisation are evaluated aiming the maximum systems safety with the concurrent components redundancies reduction.

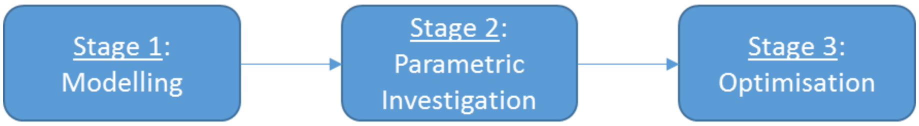


Fig 3-1. "Stages of the adopted approach"

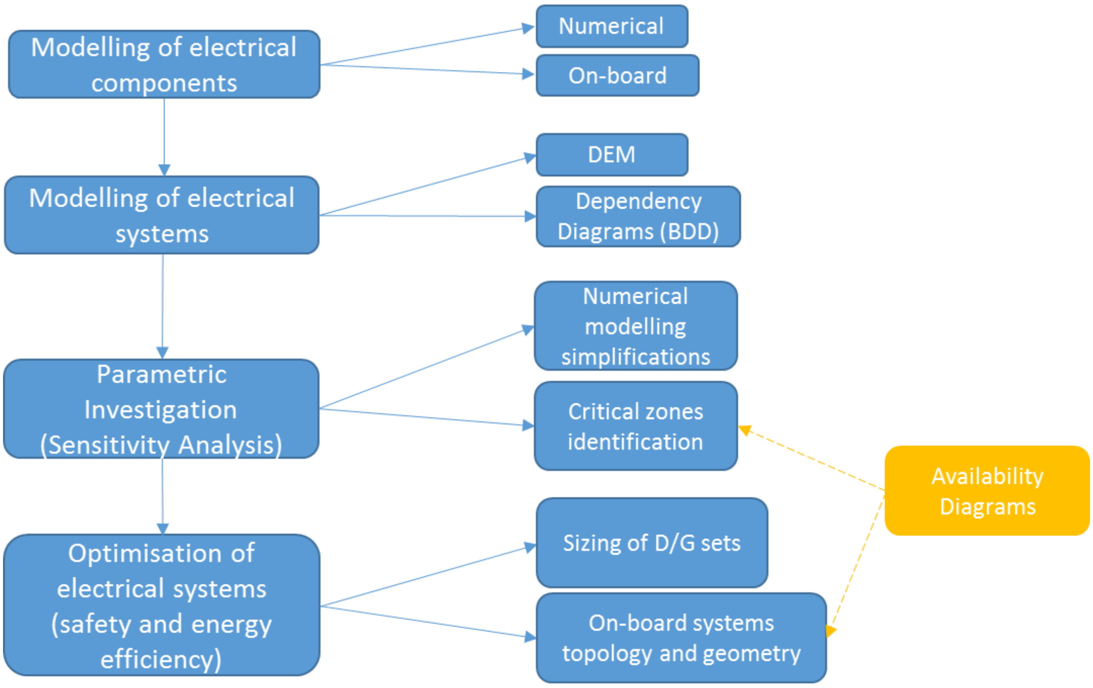


Fig 3-2. "Flow chart of the adopted approach"

The above stages and flow chart are assembling the proposed design methodology of this work with its applicability to be demonstrated with two case studies, one for each ship type.

3.3 Closure

The approach adopted in this thesis has been presented above. The detailed modelling principles, configurations, methodologies, design decisions and application cases will be presented in latter chapters.

4 MODELLING ELECTRICAL ENERGY SYSTEMS ONBOARD SHIPS

4.1 Preamble

This chapter focuses on the development of the electrical power network model, i.e. the power generation, distribution and conversion, utilisation and control systems, for estimating its energy and safety performance. Based on first principles and manufacturers data, the assessment of the dynamic performance of the electrical systems as a function of time is applicable. In addition, through the topological and geometrical coupling of the passenger vessels safety-critical systems with the ship environment using Boolean functions to build dependencies between the components and systems topologies, the systems safety performance is feasible to be evaluated in emergencies.

4.2 Numerical energy modelling

As discussed in Chapter 2, the marine electrical power plant can be subdivided to a number of systems with each of the systems comprising a number of components. The development of mathematical models that represent the physical meaning of each of the components and by extension systems are presented below in an attempt to address the energy performance of a ship during the design, retrofit and operation stages. The application and integration platform was selected the Matlab/Simulink software as in literature were used for systems modelling purposes [64], [65].

4.2.1 Power generation

The power generation system in marine applications usually includes the components of prime mover, three-phase synchronous generator and their connecting shaft. The shaft can be considered as the electrical power systems boundary with the mechanical and chemical systems. Manufacturers data were used for the modelling of the diesel engines effects on fuel consumption.

Prime Mover

The type of prime mover that was used in this study is the most widely applied in the marine industry, i.e. the diesel engine. A variety of mathematical models have been used in the past for the representation of the diesel engine characteristics depending on the application and the manufacturers data availability [66], [67]. The use of a first order model was applied for the diesel engine dynamics [68]:

$$T_{constant}\frac{d}{dt}T_{mech} = -T_{mech} + E \tag{4.1}$$

where, T_{mech} is mechanical output torque, $T_{constant}$ is the diesel engine time constant and C is the approximated polynomial derived from the SFOC of diesel engine, i.e. the fuel consumption as a function of mechanical load applied to the shaft.

Three-phase synchronous generator

The most common main and emergency source of power for on board ship applications is the well-known three-phase synchronous generator. The way it is represented by mathematical equations varies depending on the purpose of the study. Usually for power systems studies it is modelled according to *dq0*-frame through which the magnetic conductivity of the windings is not the periodic function of time, but a constant for an ideal generator. Therefore, every parameter of an ideal generator could be considered as constant and independent of time. Following this approach, the three-phase *abc*-frame voltages and currents were transformed to *dq0*-frame, using Park's transformation, see APPENDIX I, and through that the speed of the simulation was increased.

In order to facilitate our solver convergence and real time simulation, the stator transients, $d\psi_d /dt$ and $d\psi_q /dt$, and the damper windings effect were neglected from the below equations [69]. The concluded stator voltage mathematical model was as below:

$$u_q = r_s i_q + w_r \psi_d \tag{4.2}$$

$$u_d = r_s i_q - w_r \psi_q \tag{4.3}$$

The equation representing the field winding voltage was:

$$u_f = r_f i_f + \frac{d}{dt}\psi_f \tag{4.4}$$

with the flux linkages set of equations to be:

$$\psi_d = \left(L_{md} i_f + L_d i_d \right) \tag{4.5}$$

$$\psi_q = L_q i_q \tag{4.6}$$

$$\psi_f = L_f i_f \tag{4.7}$$

The electromagnetic torque was given by:

$$T_{em} = \frac{3}{2}\frac{P}{2}(\psi_d i_q - \psi_q i_d) \tag{4.8}$$

The rotor dynamics were calculated as:

$$J\frac{d}{dt}w_r = T_{mech} - T_{em} \tag{4.9}$$

where, w_r is the rotating speed of the rotor and *L, r, u, i, J* and *T* denote the inductance, resistance, voltage, current, inertia and torque, respectively. Subscripts {*q, d, s, r, md, f*}, denote the *qd*-axis, stator, rotor, mutual and field winding, respectively, and *{mech, em}* denote the mechanical and electromagnetic respectively. The component parameterisation was based on the parameterisation method [70] and industrial data used for TARGETS and REFRESH projects purposes as well as in-build data of the applied software.

Marine power systems are weak networks meaning that the voltage and frequency are not constant as the corresponding land-based. Consequently, the choice of one generator to behave as primary, setting frequency and voltage on the network has been applied to this work, while other generators connected to the main switchboard were secondary generators giving current as output. Therefore, for the mathematical expression of the rest of the system (secondary) power generation sets, the equations (4.2) and (4.3) were converted so as to be solved regarding to i_q and i_d state variables. The primary generator's rotor *q-axis* was chosen as reference axis of the plant. The effects of stator and rotor iron saturation were ignored.

4.2.2 Local control of power generation

For the appropriate functionality of the electrical power systems, the monitor and control of the generated frequency and voltage have to be guaranteed within specific limits. In the land-based power systems this can be achieved due to their direct connection to the grid, which is considered as an ideal source of power concerning the above issues. However, in a marine power plant the plant per se has to guarantee safety, efficiency and maintenance, translated in turn to cost as the key responsibility. The use of governor with speed-droop, *R*, characteristics, see Figure 4-1, was applied to this study for the frequency control of the power network regarding the rules and regulations performance limitations [71].

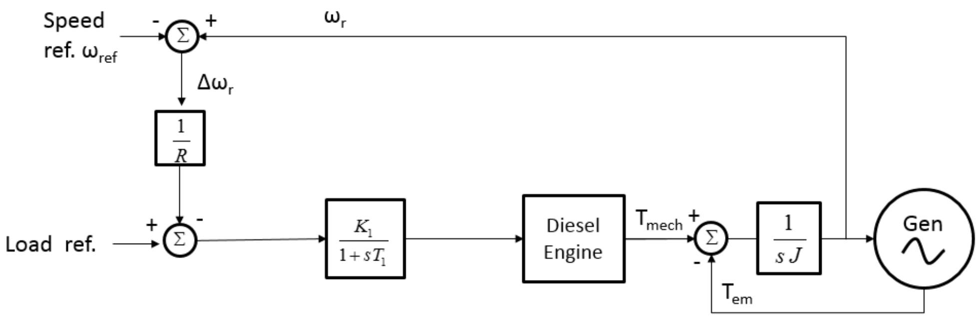


Fig 4-1. "Generating unit control with speed-droop governor characteristics"

The network voltage is controlled by the AVR which has to comply with the rules and regulations performance limitations [71]. The AVR is receiving the measurement of the terminal voltage and responds very fast to any changes. A conventional AVR system as the one shown in Figure 5-2 were used [72], where V_F is the field voltage reference, V_{ref} is the voltage reference, V_{err} is the error voltage and V_t is the system voltage in *abc*-frame. The tuning of the PID-controllers parameters were based on the trial and error method so as appropriate performance to be achieved.

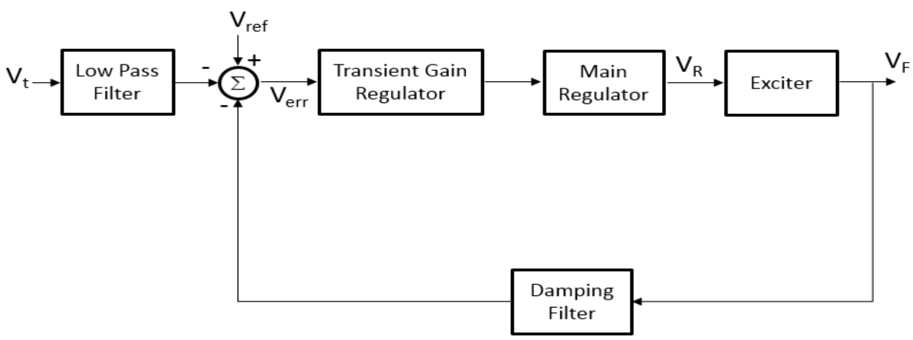


Fig 4-2. "AVR block diagram"

4.2.3 Power distribution and conversion

Power cables

The power cabling system was expressed as electrical impedances, i.e. electrical resistances and inductances, with capacitors effects to have been neglected. Taking into account the distribution line lengths, with the latter to have been approximated by the vessels GA, the resistance and inductance per meter, ohm/m and Henry/m respectively, were applied:

$$R_{Line} = Length R_{const} \tag{4.10}$$

$$L_{Line} = Length L_{const} \tag{4.11}$$

where R_{const}, L_{const} are the electrical resistance and inductance per meter constant values, *Length* is the distribution line length and R_{Line}, L_{Line} are the electrical resistance and inductance of the line. The voltage drop of the cabling system in the *dq0*-frame was expressed as:

$$u_q = R_{Line} i_q - w L_{Line} i_d \tag{4.12}$$

$$u_d = w L_{Line} i_q + R_{Line} i_d \tag{4.13}$$

The systems switchboards, panel boards and circuit breakers were assumed to be ideal without considering any power losses.

Power Transformer

For the mathematical modelling of the power transformer behaviour in power system studies considering the input and output voltages and currents on its both sides, the equivalent single phase circuit were used, see Figure 4-3, with secondary elements and quantities referred to the primary side. For the case of a three-phase transformer, the assumption that each of the three phases contains a single-phase transformer were made and also that the voltage supply is symmetrical. The input parameters estimation were initiated by the method [73] used for TARGETS and REFRESH projects purposes and the data provided by industrial partners of it. The incorporation to the electrical power system was applicable through the Park's transformation described in APPENDIX I.

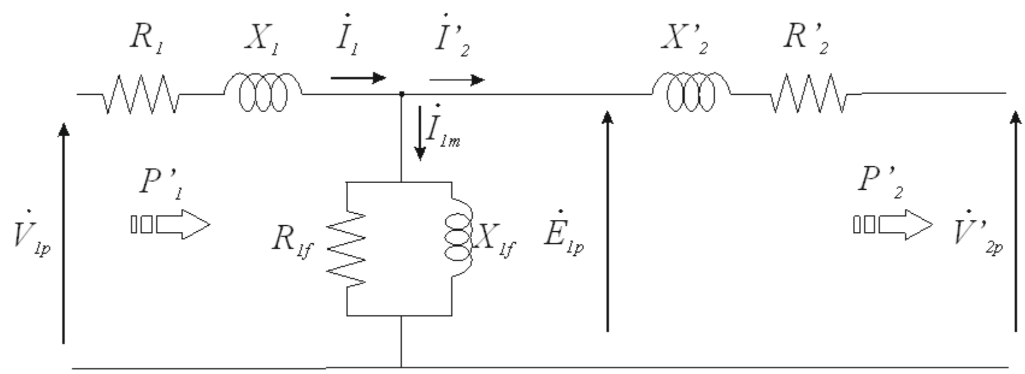


Fig 4-3. "Power transformer's equivalent circuit"

4.2.4 Power utilisation

Three-phase asynchronous motor

Three-phase asynchronous motors are the most widely used motors utilising the highest amount of power on board ships. Steady state model was used to represent motor's behaviour considering the stator's voltage and current and the shaft's velocity and torque as boundaries on both sides. The input torque was applied by the mechanical systems side, the shaft, which is considered boundary of the marine electrical power plant. The equations represent the component were:

$$u_{qs} = R_s i_{qs} + w_{syn} \psi_{ds} \tag{4.14}$$

$$u_{ds} = R_s i_{ds} - w_{syn} \psi_{qs} \tag{4.15}$$

$$u_{qr} = 0 = R_r i_{qr} + slip\, w_{syn} \psi_{dr} \tag{4.16}$$

$$u_{dr} = 0 = R_r i_{dr} - slip\, w_{syn} \psi_{qr} \tag{4.17}$$

$$\psi_{ds} = L_s i_{ds} + L_m i_{dr} \tag{4.18}$$

$$\psi_{qs} = L_s i_{qs} + L_m i_{qr} \tag{4.19}$$

$$\psi_{dr} = (L_r i_{dr} + L_m i_{ds}) \tag{4.20}$$

$$\psi_{qr} = (L_r i_{qr} + L_m i_{qs}) \tag{4.21}$$

$$T_{em} = \frac{3}{2}\frac{N_p}{2}(\psi_{qr} i_{dr} - \psi_{dr} i_{qr}) \tag{4.22}$$

$$T_{em} = T_{mech} \tag{4.23}$$

where, w_s is the synchronous rotating speed and L, r, u, i, ψ, s, N_p and T denote the inductance, resistance, voltage, current, flux linkages, slip, poles and torque, respectively. Subscripts {*q, d, s, r, m, f*}, denote the q*d* axis, stator, rotor, mutual and field winding, respectively, and *{mech, em}* denote the mechanical and electromagnetic respectively. Through the method [74] developed for TARGETS and REFRESH projects purposes, the evaluation of the induction motors parameters were achieved.

Load model

Apart from the induction motors that consume the most of the generated on board power, a variety of loads especially in the case of passenger vessels are required to be supplied for the vessels functionality and for the passengers and crew needs. Communication and navigation systems, lighting systems, galley, sanitary, entertainment equipment etc. were represented as power consumers in the systems through constant impedances. So, they were independent from the frequency and voltage deviations, being considered equal to their reference values. Getting as input the active and reactive power demand, knowing also the value of the reference voltage, corresponding impedances were calculated:

$$Z_{LOAD} = R_{LOAD} + jX_{LOAD} = \frac{|V_{ref}|^2}{P_{LOAD} + jQ_{LOAD}} \tag{4.24}$$

where P_{LOAD}, Q_{LOAD} are the active and reactive power demand of the load respectively, V_{ref} is the reference systems voltage, and Z_{LOAD}, R_{LOAD} and L_{LOAD} are the electric impedance, resistance and inductance of the load respectively. All the above represented loads are following a power transformer. Therefore, for sake of simplicity, all the loads that were supplied by the same transformer, were aggregated and integrated with them. In other case, the use of the equations (4.12) and (4.13) should have been applied substituting the distribution lines with the constant load impedances.

4.3 Electrical system configurations

Current design methodology of onboard electrical energy systems requires power load calculations, i.e. the electric load analysis, which gives the amount of electrical energy that needs to be generated approximating the loading of each of systems equipment at all possible operating conditions and excluding distribution losses. Then based on this value and according to the designers experience, the number and the sizing of the power generation sets is performed. Although straightforward and easy to implement, this technique is based on steady state calculations, it is over simplified and neglects the dynamic interactions between the electrical systems equipment, the environment and other disciplines energy systems onboard. For detailed calculations concerning the sizing of power generation sets, starting from component-level and ending to system-level modelling is required.

Having discussed the electrical components numerical models previously at this chapter, the system-level even though is comprised by similar components, the configurations can differ depending on the application. A generic single line electric diagram for marine applications is presented in Figure 4-4.

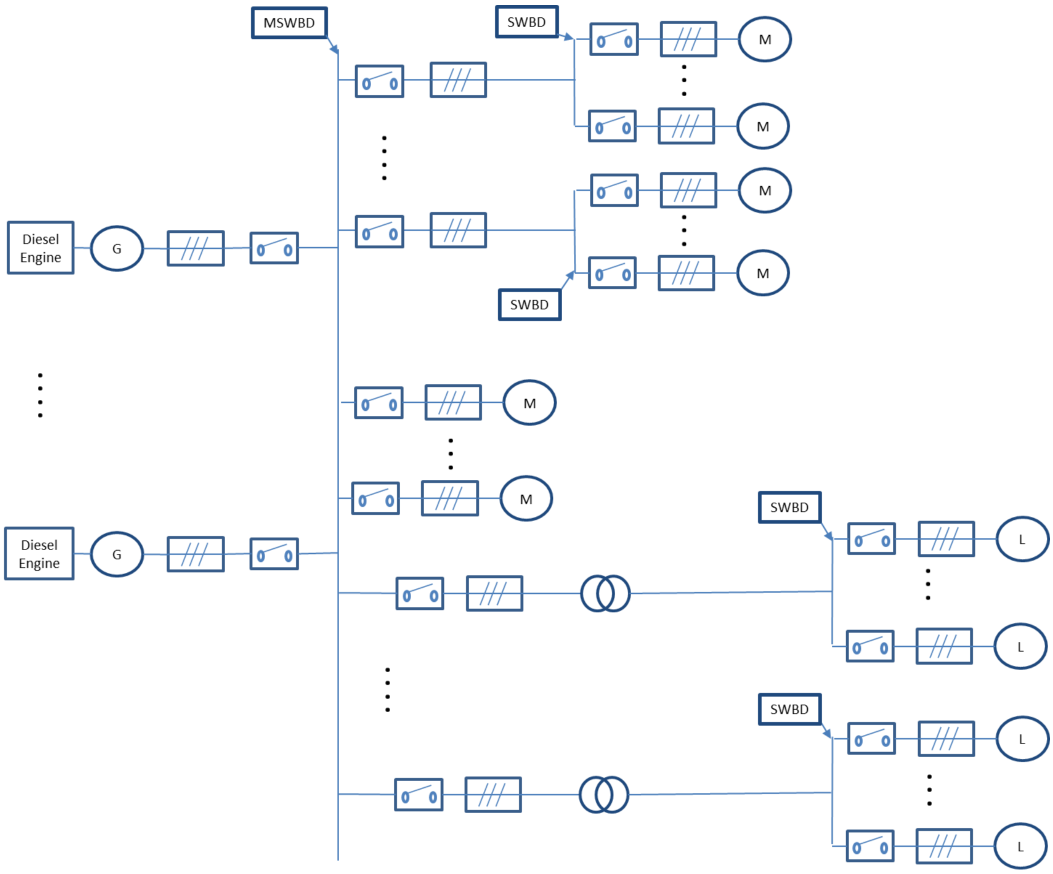


Fig 4-4. "Generic line diagram of an electrical marine power system"

Cargo ship

Conventional cargo ships are designed based on past data of similar ship type. Their limited length, number and complexity of the energy systems on board, simplifies the designers duties without any space for innovation. Traditionally, electrical power generation sets are equally rated and driven by diesel engines, with the redundant set to be of the same capacity as well. In addition, they are located close to the main switchboard in order to directly supply it, with the loads to be either directly connected to the latter or indirectly through the distribution systems switchboards. Furthermore, the power management system has a restricted functionality with the equal load sharing method to be pursued and the power demand to be within the expected limits, without peak variations, during any operating condition. The detailed configuration of a cargo ship's electrical power plant, which was used for the purposes of this work, are described on latter chapter.

In the framework of holistic ship energy modelling, all systems components would ideally be coupled to an integrated ship energy model where the power generation is affected by the performance of the boundary conditions, such as the HVAC system, the propulsion system etc. Although, developing a holistic ship energy model is not in the scope of this work, the first principles modelling of the electrical power network, as described previously, and the simplification of the design of it, which is attempted later in the thesis, are crucial steps towards the integration of different energy types in a single model.

Passenger ship

Passenger ships comprises higher number and bigger size of energy systems and consequently their design is much more complex taking into account the interactions of each other systems. Usually, the power generation sets are of unequal capacitance so as to perform effectively under different operating conditions. Mostly, they are equally sized by pairs, with the biggest capacity to be also adopted by a redundant unit. There are also alternative source of power such as the shaft generation, fuel cell, etc. but they are out of the scope of this work. Traditionally, all power generation units, apart from the emergency, are located into the auxiliary room and close to the main switchboard which they directly supply. The distribution and conversion system is of excessive length because of the variety in locations and forms of power loads throughout the whole range of ship. In addition, the presence of power management system is inevitable for the energy efficient power generation performance under a huge variety of operating conditions and the systems safety and protection. The detailed configuration of a passenger ship's electrical power plant, which was used for the purposes of this work, are described latter in this thesis.

By modelling the electrical power plant based on this chapter's approach, the power demand can be estimated in an attempt to size efficiently the power generation units. Models simplifications will be applied targeting the conceptual design facilitation.

4.4 Logical Boolean modelling

The modelling process of the electrical distribution energy network involves mapping the functionality of each safety-critical system to logical structures, which have to preserve firstly physical and functional relations of the system as well as across the systems and secondly spatial distribution of the system. The latter corresponds to the components placement into appropriate rooms or spaces. The spatial arrangement of the vessel corresponds to NAPA standards (for marine applications) and therefore a room constitutes the smallest, undividable volume enclosed within the ship. Therefore, "room-wise" physical components placement were considered at the first level of modelling procedure. At this level, components and energy flow paths that are sharing the same room cannot be assumed as redundant. At the next level, the accurate position of the systems components inside a specific room is applied, targeting the topological optimisation of the systems.

The dependency structures are built by blocks representing physical components of the electrical energy systems, like three-phase synchronous and asynchronous machines, switchboards, power cables, etc. In general, they are grouped into larger abstract structures, such as propulsion system, steering system, etc., representing their functions and performance. The physical components are directly linked to the corresponding spaces and therefore state of the space (intact or damaged) is automatically passed on to the components within. As for the abstract components, they cannot be directly damaged – their state is logical consequence of system dependencies on the physical components. The above expressions are implemented in terms of basic Boolean functions with the use of three basic logical operations: AND (&), OR (|) and NOT (~) performed on all relevant physical components.

A generic dependency diagram is shown in Figure 4-5. At the top, the abstract function is defined (systems) and the direct dependencies starts through the sub-systems definition. Each sub-system comprises a number of components and each of them is supplied by a switchboard with the latter to supply a number of components. The redundant components are not placed separately in the dependency trees, but as an alternative dependency flow path through their power supplying source representation, i.e. emergency switchboard or another network's switchboard. At the bottom, the direct dependency of the systems switchboards with the main is identified and consequently depicted the latter's importance to the distribution of power. The below safety-critical systems were considered in this study:

- the propulsion system
- the steering system
- the bilge and ballast system
- the emergency system

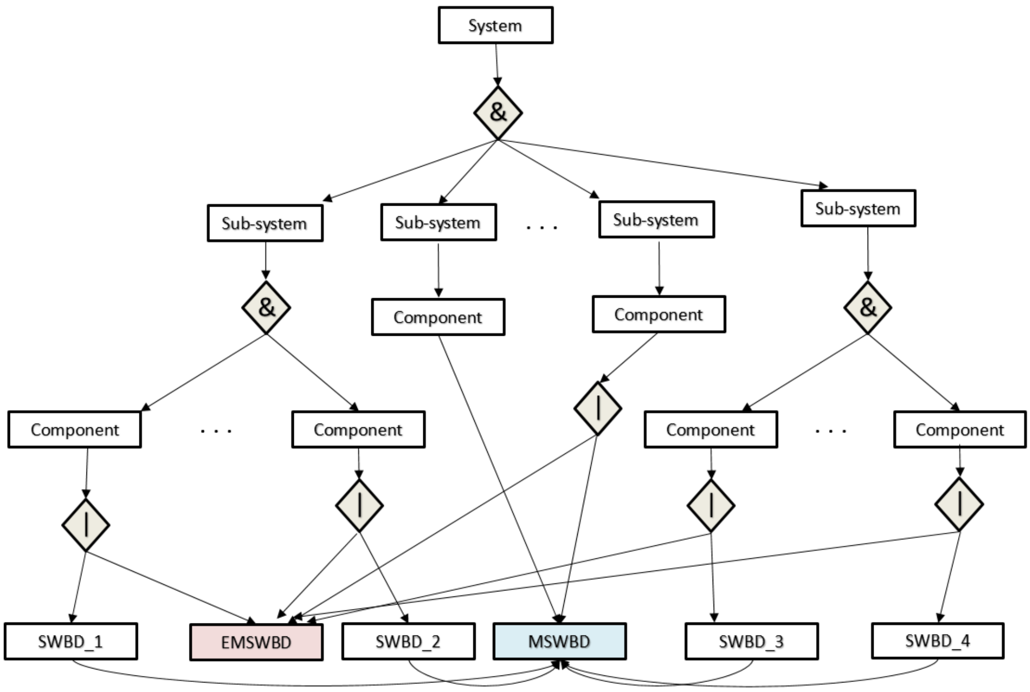


Fig 4-5. "Generic dependency tree of passenger ship systems"

Through the systems logical structures screening, the components dependencies and the systems as well can be apparently understood. Having this in mind, an example of the topological and geometrical placement of the systems switchboards into the ship environment, in specific rooms, is shown in Figure 4-6, for the passenger being investigated in this work. The figure shows the decks from the tower and profile view. The blue coloured switchboards are the main distribution systems located in the second deck whereas the red colour indicated the emergency distribution system on the fifth deck of the vessel.

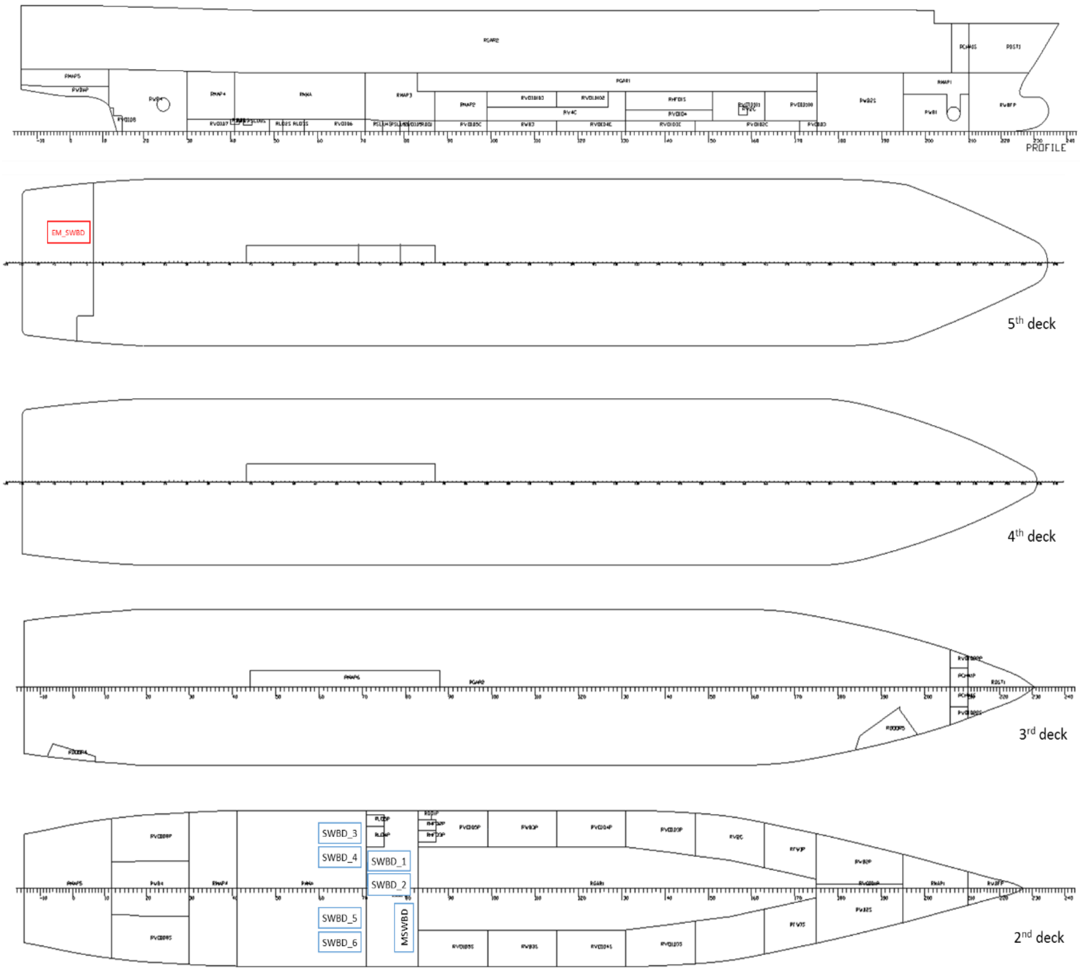


Fig 4-6. "Distribution systems switchboards location on board passenger ship"

The tool used for the modelling part was the commercial software iSys developed by the Safety-at-Sea Ltd based in Glasgow. All safety-critical passenger vessel systems dependency diagrams and location into the ship environment are shown at latter chapter.

4.5 Closure

In this chapter the numerical modelling of the electrical energy systems in component and system level has been described for the cargo and passenger vessels. Furthermore, the architecture of marine electrical systems for both ships has been discussed. Also, the topological and geometrical modelling of the safety-critical systems into the ship environment based on Boolean algebra for passenger ships has been presented.

5 DESIGN ELECTRICAL SYSTEMS FOR ENERGY EFFICIENCY

5.1 Preamble

With the detailed modelling of the electrical energy systems as presented in the previous chapter, the estimation of the power consumption at each life-cycle stage but especially during design of both cargo and passenger vessels is now feasible. However, the development and modification of such detailed models for the holistic power system, under the consideration of components accurate initialisation is time consuming, even computationally demanding and susceptible to modelling errors, especially for a large number of systems and components as in passenger vessels. Targeting to reduce modelling effort for design studies, this chapter focuses on the investigation of electrical and topological parameters that will drop the requirements for exact systems and components modelling and will keep the consistency and accuracy in acceptable levels.

5.2 Need for parametric investigation

In order to accurately model the interactions between the electrical power systems with the other systems and the environment, all electrical components need to be included and be coupled in the same holistic model. Although electrical systems modelling approach is developed and presented in the previous chapter, large models are susceptible to modelling and convergence errors that can be time consuming to correct. Misplacement of independent variables and systems convergence issues, can be very time consuming to be fixed to the extent that it might be easier to build the systems from the beginning.

Apart from the above modelling issues, exact electrical modelling raises computational problems when only a few systems are being investigated. For example, sizing the power generation units in a ship with more than one sets, would ideally require building and running a whole electrical systems model interacting with other energy systems and the environment. This means that the systems model will include all the components in a detailed way, involving all input parameters of each component, and would result in large quasi-dynamic simulation times, lots of simulation results and inconvenience in model error checking.

In an attempt to reduce modelling effort and computational requirements, electrical parameters of on board electrical systems were investigated. Taking into account that the level of accuracy has to be compensated with the time and effort spending, the need for detailed electrical modelling during the design is sought to be dropped.

5.3 Methodology

As mentioned in previous chapters, the marine electrical power network comprises the power generation (with its local control systems), power distribution and conversion and the power utilisation systems each of which can be modelled based on first principles and manufacturers data as described in chapter 4. Having this in mind, the load of independent parameters needed for detailed modelling of such a holistic system, could make it rather demanding in terms of effort and time to collect the data and run the appropriate number of simulations for the designers. Therefore, the main idea of this chapters' investigation is the reduction of the above mentioned systems parameters that hardly influence the global design parameters and keeping those affecting the process.

At first, the fully detailed model of the electrical energy systems is developed, based on the modelling process described in chapter 4, creating the benchmark model for comparison. Afterwards, targeting the systems design simplification, the neglect of each of the electrical power network's system local parameters was investigated. Apart from separate systems parameters, whole systems where omitted such as in the case of power distribution and conversion in an attempt to merge the power generation with the utilisation system. Further, the consideration of systems connection to an ideal power source, in other words grid connection, that supplies the utilisation system with the absence of the distribution and conversion system has be assessed. At the end, the fully simplified model as derived from the investigated cases was compared with the fully detailed model in order to evaluate the consistence of the systems parametric reduction.

Each simplified systems performance was quantitatively compared with the benchmarks model and corresponding guidelines for systems model design were presented. Cargo and passenger vessels were investigated for the application of the above described methodology to a conventional and a complex systems vessel type. The duration of five days trip for the cargo vessel and one day trip for the passenger vessel were quasi-dynamically simulated with each ship's operational profile to be found in APPENDIX II.2 and APPENDIX III.2 respectively and electrical systems configurations and line diagrams in APPENDIX II.1 and APPENDIX III.1 respectively. For comparison purposes, the control strategy was kept the same for all investigating cases, apart from the power generation systems investigation where the reference values of systems voltage (440 V) and frequency (60 Hz) actions were kept constant.

To examine the feasibility of the above assumptions, the inaccuracy during the reduction process had to be investigated first.

5.4 Verification methodology setup

The main idea of the electrical energy systems design simplifications is to model and compare the performance between the detailed and the reduced parameters cases systems models. Simulations were carried out considering the active power consumed from the power generation units or from the ideal source of power, as the comparison measure between the different cases. In addition to the active power, the power factor variation is presented during the whole simulation time in a matter of verifying the validity of the model simplifications.

Results were compared using the mean value of the relative difference method. The latter is given by:

$$Relative\ Difference(x_i, x_{reference}) = \frac{|x_i - x_{reference}|}{x_{reference}} \tag{6.1}$$

where $x_{reference}$ is the active power consumption of the detailed (benchmark) model and x_i is the active power consumption of the simplified model for the i^{th} case. For the mean value of each of the design cases, which is expressed in percentage form (%), the sum of all the above relative difference at each simulation's time step over the number of time steps, *n*, is applied.

$$Mean_i = \frac{\sum Relative\ Difference(x_i, x_{reference})}{n} 100\,\% \tag{6.2}$$

Therefore, mean values of the relative difference closer to 0 (or 0 %), show better agreement between the two sets of data which in this case means validation of the assumed models simplifications.

5.5 Parametric investigation

To examine the feasibility of local and global parameters reduction, each of the electrical power network systems was studied separately and the power consumption results were compared with the benchmark case for each ship type identifying the level of accuracy. At the end, all the investigated cases were gathered to a fully simplified model. The below cases were considered:

- power utilisation system
    - neglect separately each of the input parameters of the generic induction motor model for the whole range of ship applications
    - neglect separately each of the input parameters of the constant loads model
- power distribution and conversion systems:
    - neglect the whole system including the power transformers, switchboards and cabling losses
- power generation and local control systems:
    - neglect the whole systems and let the power network behaving as connected to the grid, i.e. with constant frequency and voltage.
- fully simplified systems model

For the benchmark model, the detailed modelling of the electrical power systems was initiated based on chapter's 4 principles. Parameterisation methodologies and manufacturers data were applied for the three-phase synchronous machines, the power transformers and the three-phase induction motors. For the diesel-engine model, the equations described in section 4.2.1 were applied with the parameters being derived by the SFOC of sets shown in APPENDIX IV.1 and APPENDIX IV.2, employed for the cargo and passenger vessel case respectively. Since the curves describe the behaviour of the electrical generated power, the exclusion of the generators efficiency was necessary and the conversion to (produced) torque by dividing the mechanical power over the constant mechanical speed. Equal load sharing was applied for the power generation units with each of them to be loaded considering their rated power as upper limit. In addition to this, equal sharing of the reactive power needs was considered between the online diesel generator units, which in turn means equal power factors of the latter. Also, the cables lengths where estimated by the vessels GA and for the lines electrical resistance, R_{const}, and inductance, L_{const}, per meter constants manufacturers data where applied. Constant system loads active and reactive demand at each time interval are presented in the corresponding operational profiles.

5.5.1 Power utilisation systems

The power utilisation units that are commonly located at all ship types are the three-phase induction motors coupled either with pumps, fans or propellers. Considering that their modelling is based on first-principles, the reduction of the input parameters is of much importance. In addition, the existence of consumers like the lighting system, the navigation and communication system, the sanitary, the galley etc. especially in passenger ships, need to be addressed and modelled, in this study as constant loads, during the design for the appropriate sizing of the power generation sets.

6.5.1.1 Generic three-phase induction motor model for whole ship applications

Following the first-principles modelling, the number of input parameters of a generic three-phase induction motor model is coming to nine, see Figure 5-1.

Two of them are supplied by the network itself and are characterised as global parameters, voltage and frequency, which are controlled by the power generation local control system. One parameter is depending on the pump, fan or propeller instantaneous performance which performs as boundary to the system, the torque. The rest parameters, stator, rotor and magnetic resistances and inductances, are the technical characteristics of each motor depending on the capacity, the rated speed, frequency and voltage of each motor.

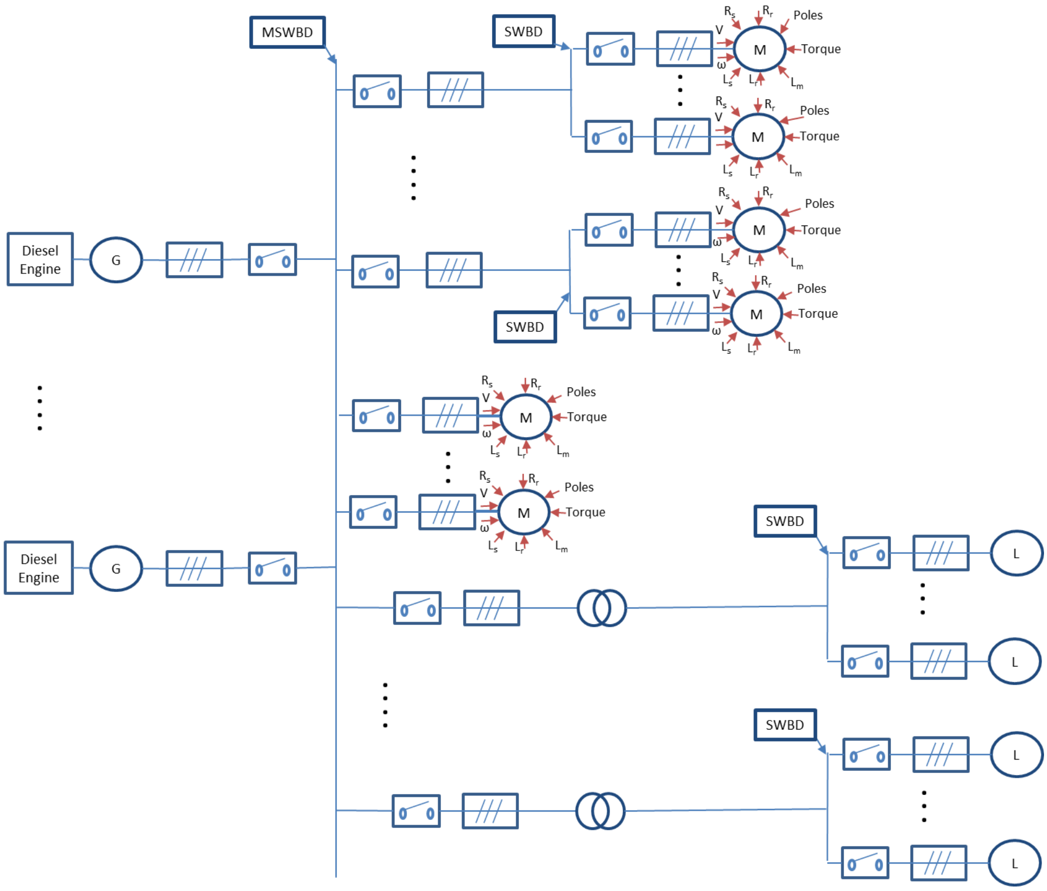


Fig 5-1. "Generic three-phase induction motor input parameters investigation"

Quasi-dynamic simulations results are presented below for both ship types. The input voltage and frequency were based on the power network performance and consequently both values are affected by it. In addition, for motor's magnetic inductance and poles parameters, quasi-dynamic simulations couldn't be performed due to zero value of the denominator through the regarding equations modifications. Consequently, both parameters will be necessary inputs of generic three-phase induction motor model during the design.

Cargo ship

The results of the quasi-dynamic simulations for the case of the cargo ship are shown in Figure 5-2 below. The results reveal the level of accuracy when especially R_s, but also L_s and L_r parameters are omitted. In specific, the simulations in Figures 5-3 show that the system power performance in the cases of R_s, L_s and L_r parameters reduction is highly aligned with the full detailed model results.

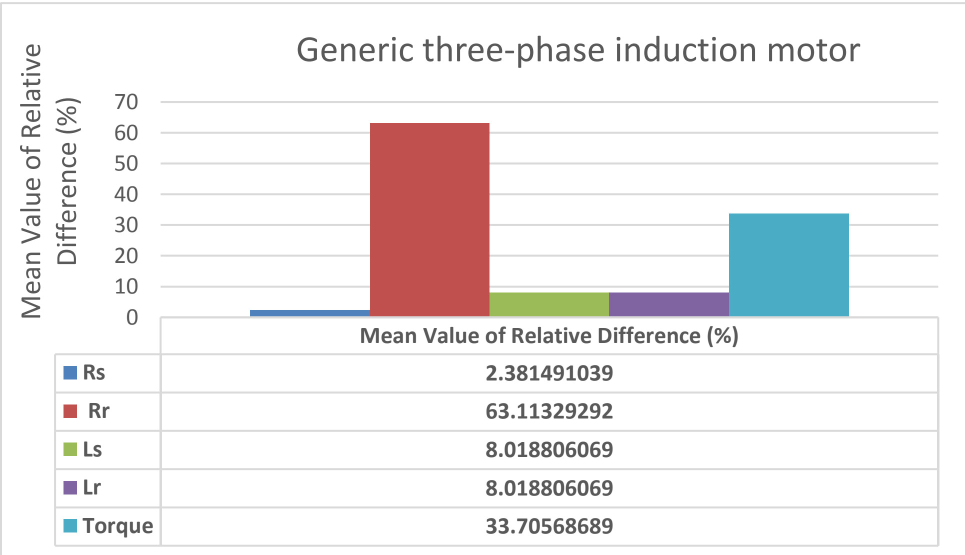


Fig 5-2. "Results of the generic three-phase induction motor parametric study for cargo ship"

On the other hand, the results for the cases of R_r and *Torque* parameters illustrate the unacceptable accuracy rate of both for their neglect during the design, something that is shown in Figures 5-4 and 5-5 as well.

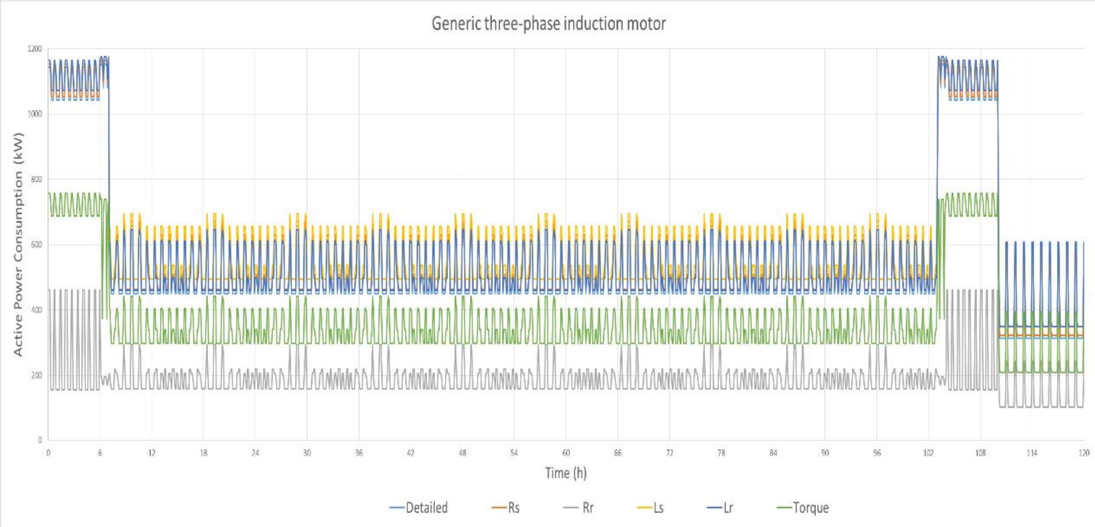


Fig 5-3. "Active power consumption of the generic three-phase induction motor parametric study for cargo ship"

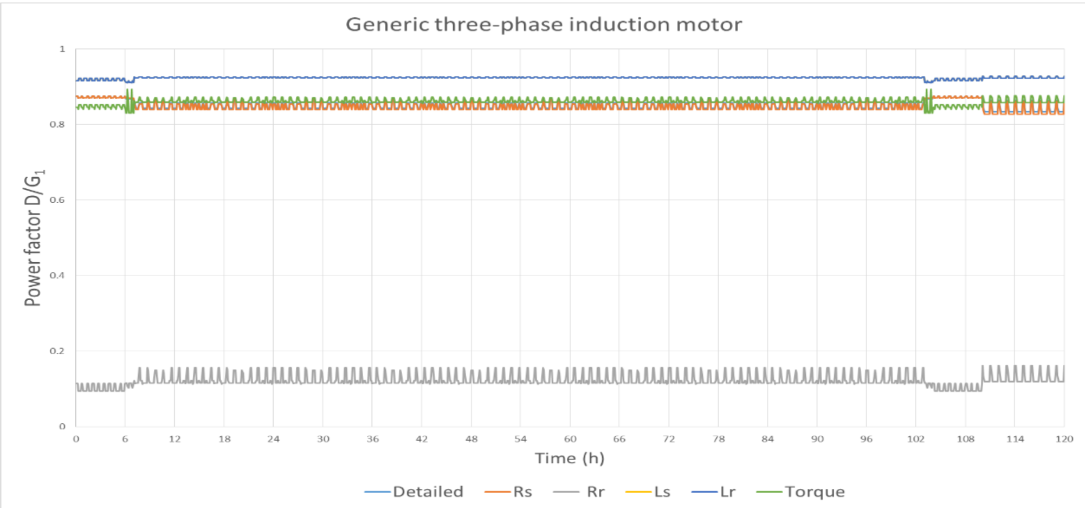


Fig 5-4. "D/G_1 power factor variation of the generic three-phase induction motor parametric study for cargo ship"

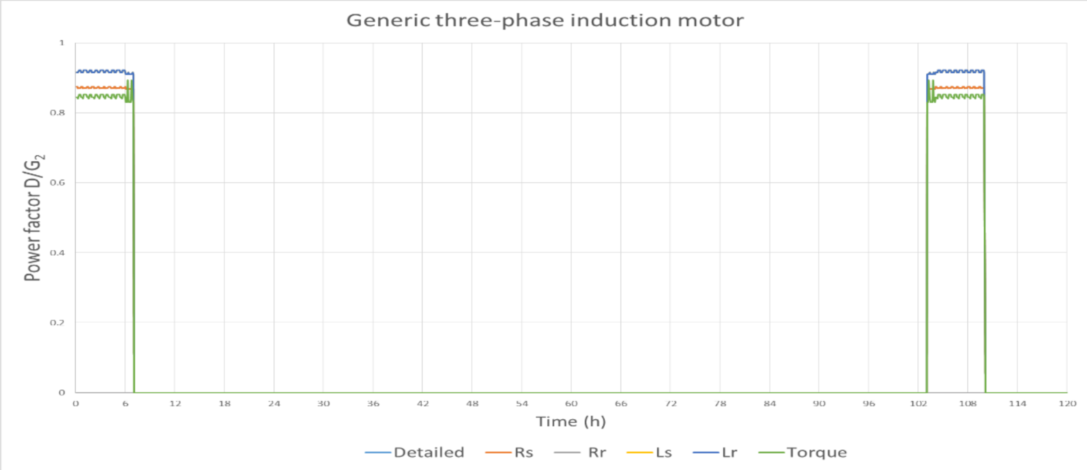


Fig 5-5. "D/G$_2$ power factor variation of the generic three-phase induction motor parametric study for cargo ship"

Passenger ship

The quasi-dynamic simulation results are presented in Figures 5-6 and 5-7 below. Qualitatively, the results align with the case of cargo ship however an additional increase in the results inaccuracy was revealed, something normal considering the length and complexity of passenger energy systems. Consequently, the parameters R_s, L_s and L_r can be neglected during the design, however this cannot be considered for the R_r and *Torque*.

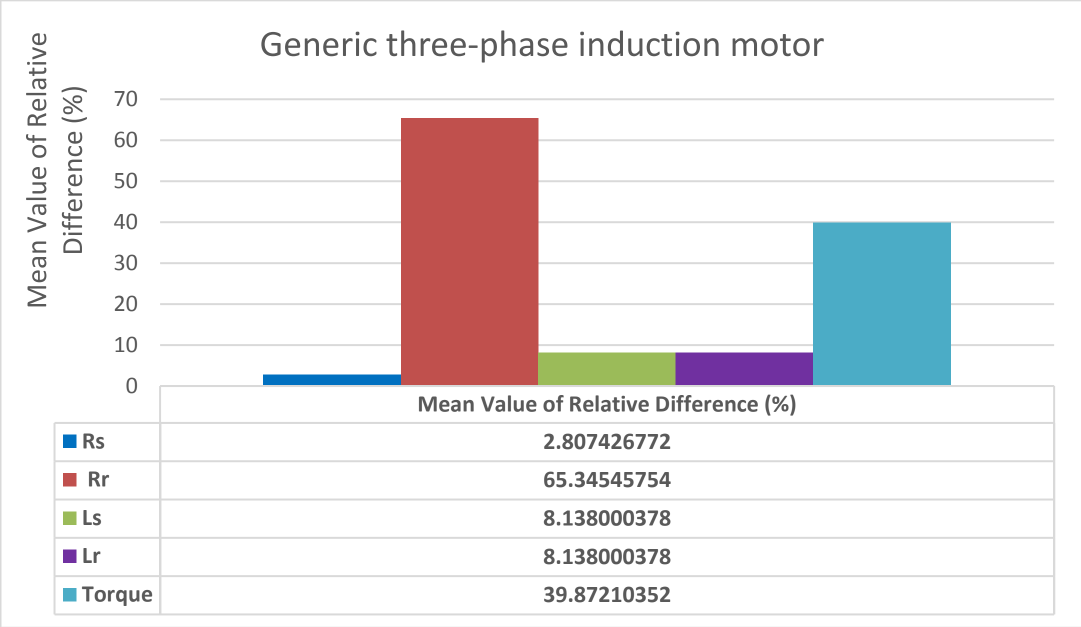


Fig 5-6. "Results of the generic three-phase induction motor parametric study for passenger ship"

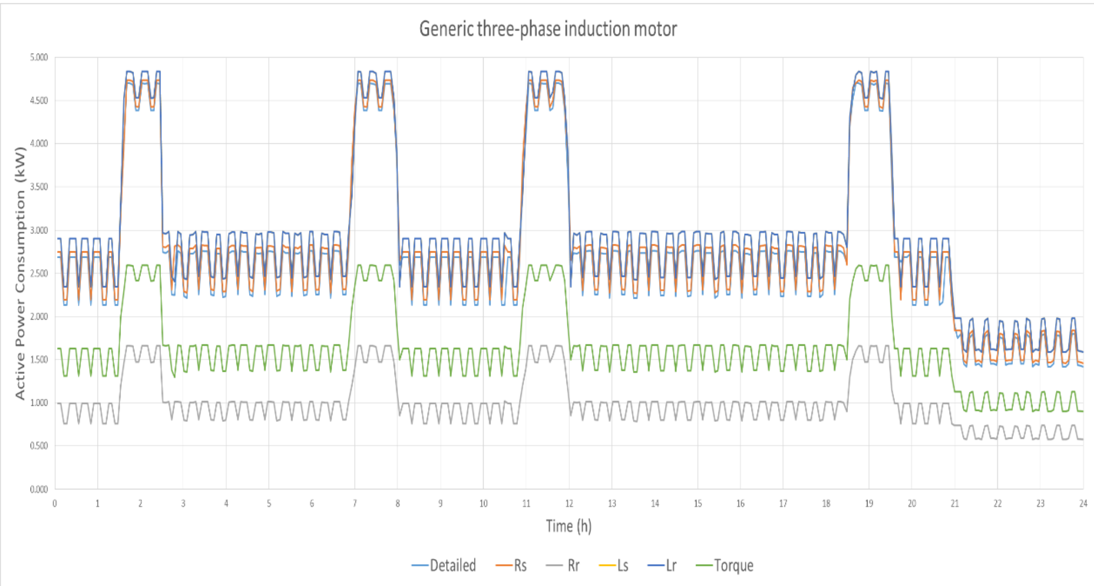


Fig 5-7. "Active power consumption of the generic three-phase induction motor parametric study for passenger ship"

In Figures 5-8, 5-9 and 5-10 the simulations results of the power factor for each systems generator are presented.

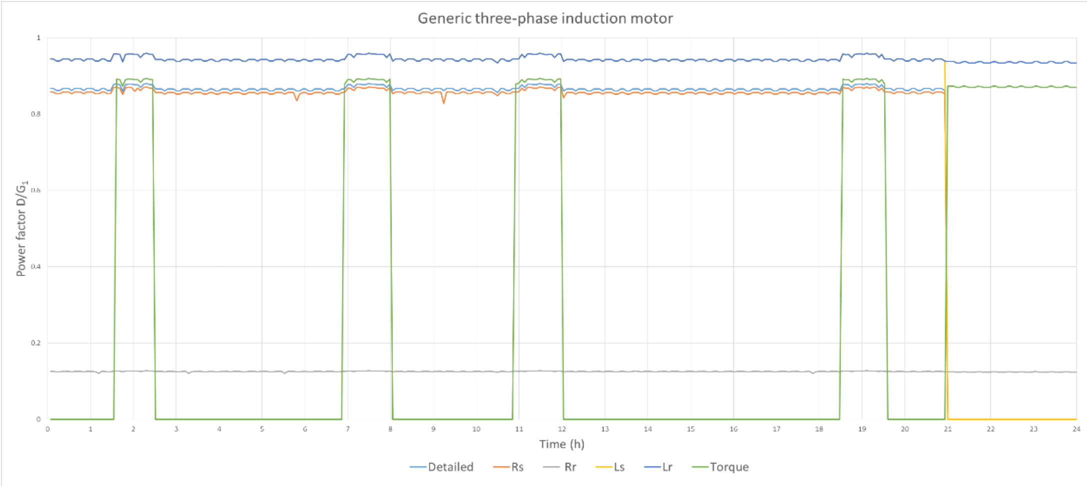


Fig 5-8. "D/G1 power factor variation of the generic three-phase induction motor parametric study for passenger ship"

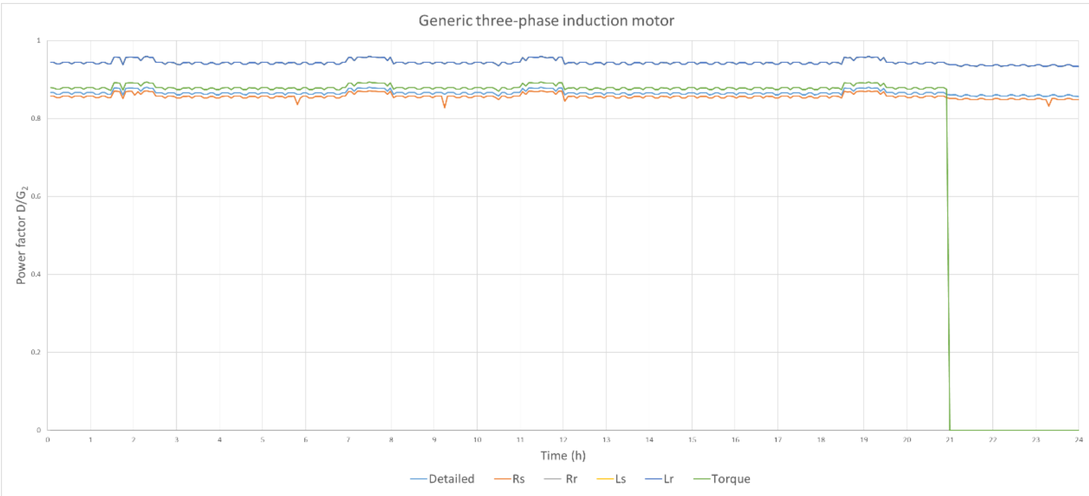


Fig 5-9. "D/G2 power factor variation of the generic three-phase induction motor parametric study for passenger ship"

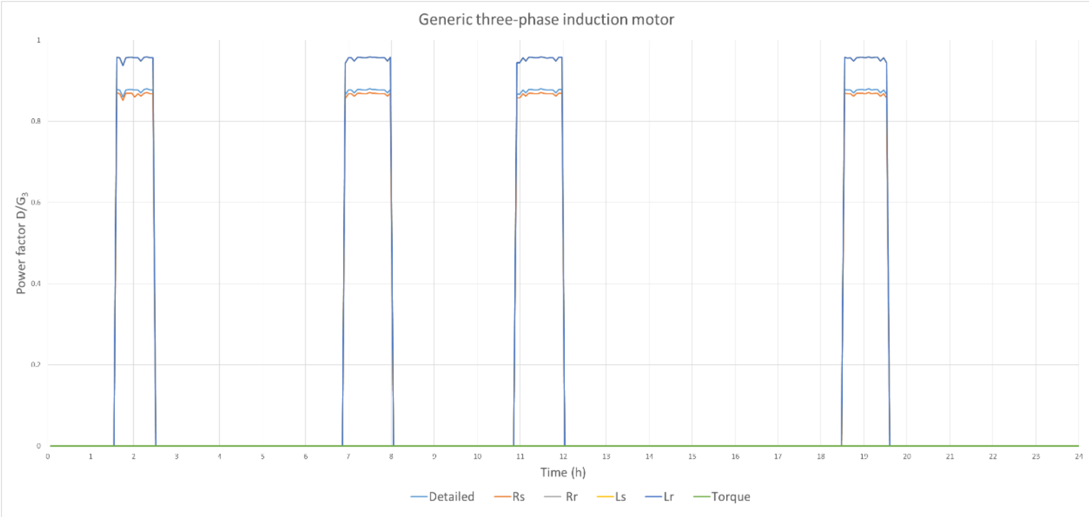


Fig 5-10. "D/G3 power factor variation of the generic three-phase induction motor parametric study for passenger ship"

5.5.1.2 Constant loads

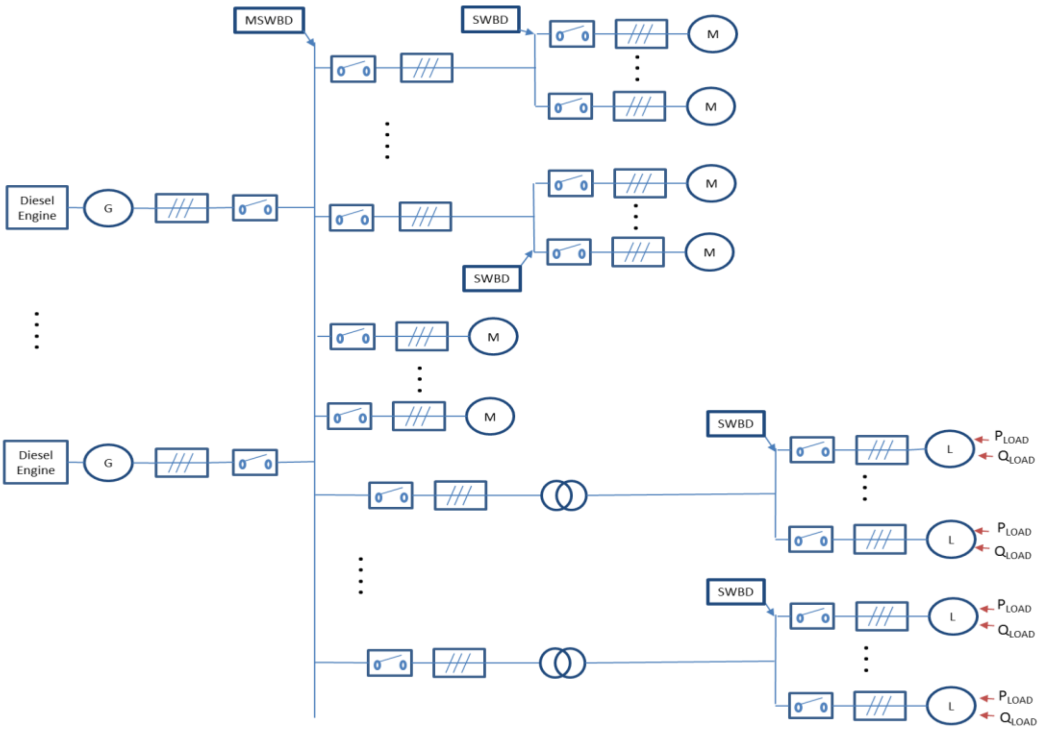


Fig 5-11. "Constant loads models input parameters"

Two input parameters were under investigation at the constant load model, the active and the reactive power, Figure 5-11. The below simulation results show the chance of disregarding the parameters during the conceptual design.

Cargo ship

The quasi-dynamic simulation results are shown in Figure 5-12 and illustrate that both parameters can be excluded during the conceptual design of the case of a cargo vessel as the inaccuracy values are negligible for one parameter and very small for the other.

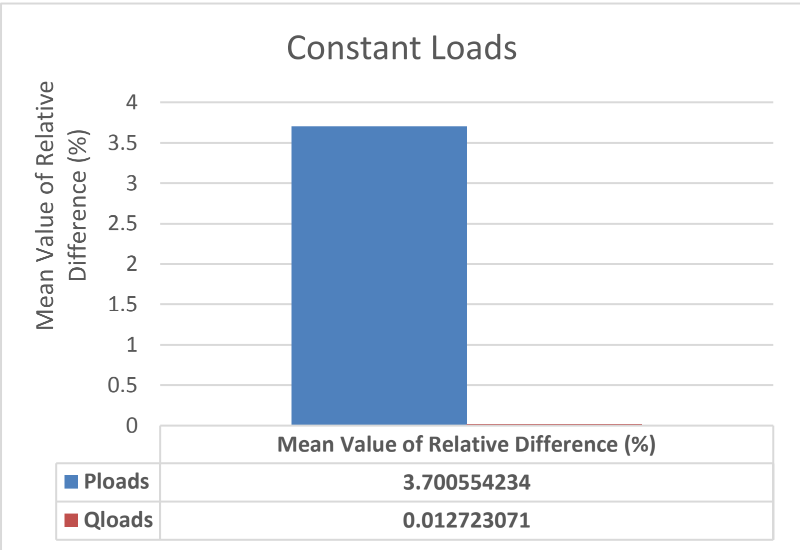


Fig 5-12. "Results of constant loads parametric study for cargo ship"

Passenger ship

Quasi-dynamic simulation results are presented in Figure 5-13. Following the cargo ship, passenger has slightly higher inaccuracy in the power consumption results but both parameters can be excluded from the design process.

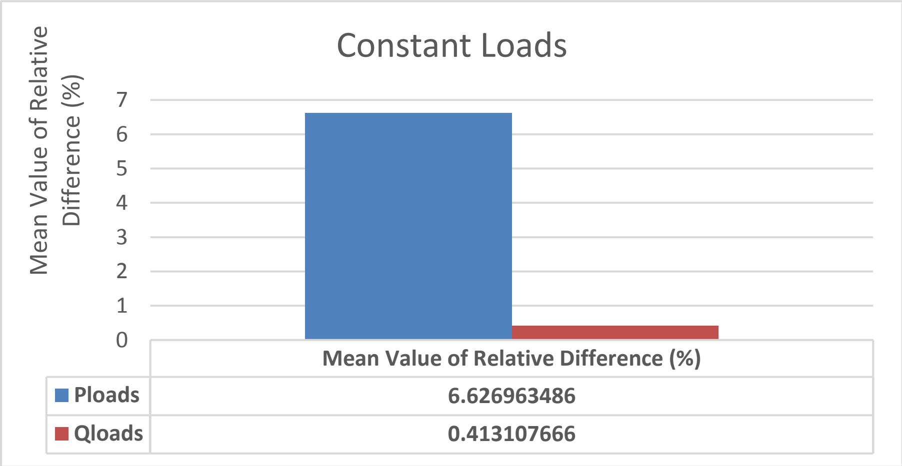


Fig 5-13. "Results of constant loads parametric study for passenger ship"

5.5.2 Power distribution and conversion systems

In this case the cabling system and the ideal power transformers of the system were neglected, see Figure 5-14, with the quasi-dynamic simulation results to be compared with the detailed model. The absence of systems transformers means that the voltage was not converted at the system. However, the constant loads that were topologically located after the secondary winding of the transformer, needed to be supplied with lower than the main switchboards voltages. Therefore, the supplying voltage to the constant loads was considered as the voltage of the main switchboard multiplied with the ratio of the number of turns of the secondary winding to the number of turns of the primary winding, i.e. N_2/N_1. For example, the constant loads that were topologically following a 440/110 V power transformer, multiplied the input, main switchboards, voltage with the value of 0.25.

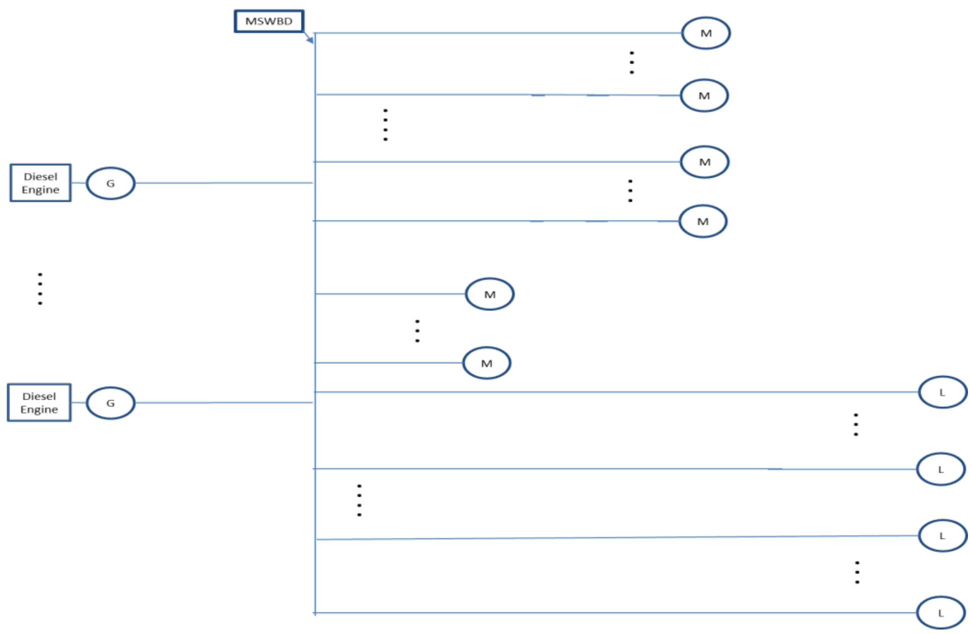


Fig 5-14. "Power distribution and conversion model representation"

Cargo ship

The simulation result is shown in Figure 5-15 and easily can be understood that the level of inaccuracy in the comparison with the detailed model is very low and consequently the whole system can be omitted during the design.

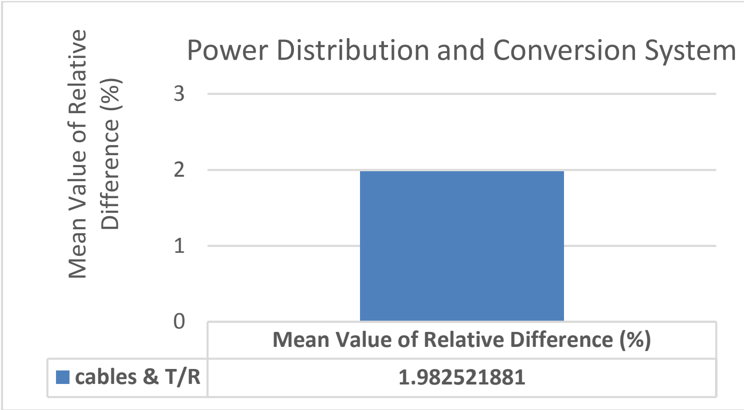


Fig 5-15. "Results of power distribution and conversion system parametric study for cargo ship'

Passenger ship

Following the cargo ship's results, the low level of inaccuracy of the result is giving the potential of neglecting the whole distribution and conversion system during the design.

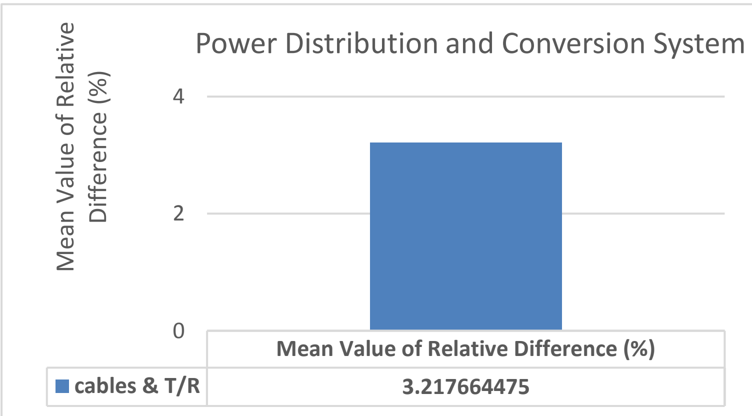


Fig. 5-16. 'Results of power distribution and conversion system parametric study for passenger ship'

5.5.3 Power generation systems

The power generation system was considered as an identical power source and by extension it supplied the network with the reference values of voltage and frequency as in Figure 5-17. The simulation results for the cases of cargo and passenger ship are presented below. In addition, since the systems generators have been substituted by the ideal source of power, power factor simulations are not performed.

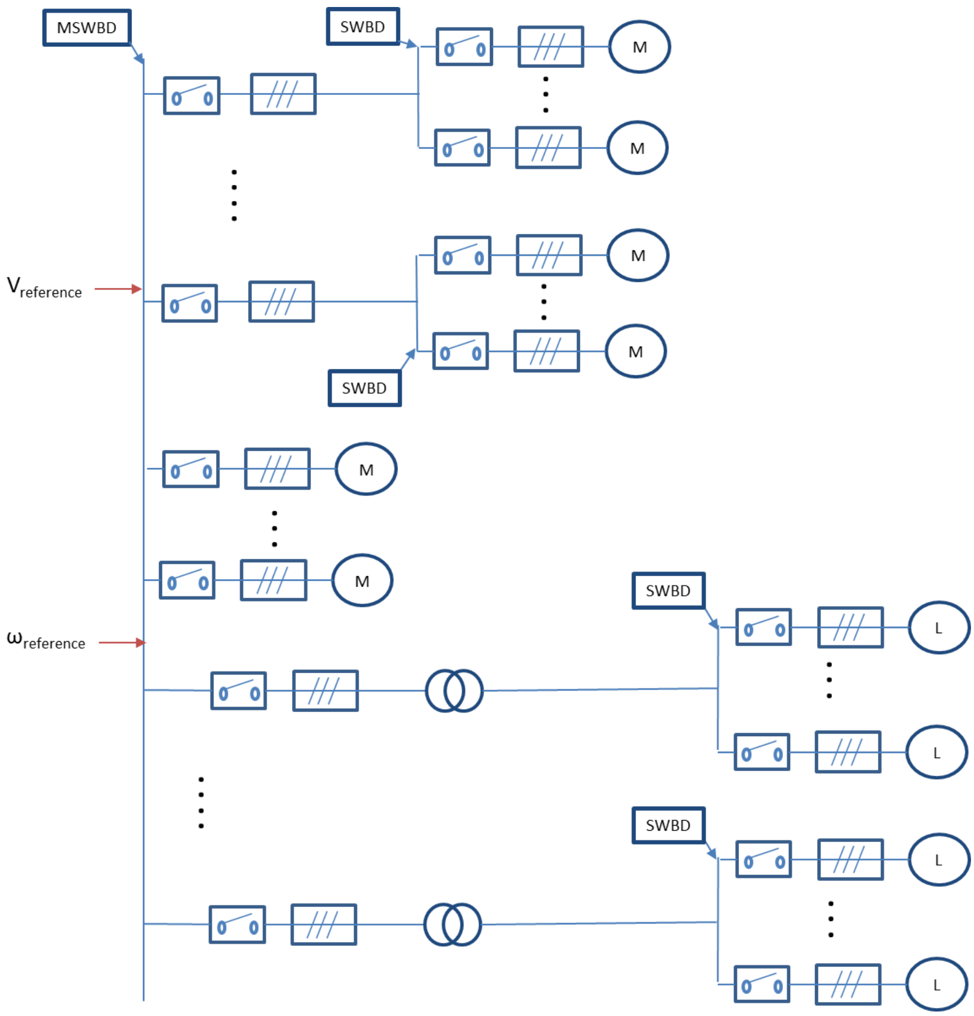


Fig 5-17. "Simplified power generation system model representation"

Cargo ship

The quasi-dynamic simulation results presented in Figure 5-18, show that the mean value of the relative difference is not insignificant but could be estimated as acceptable for the conceptual design. Considering the computational time and the effort for modelling the power generation system as well as the choice of the appropriate and accurate control strategy, the inaccuracy level in power consumption can be compensated.

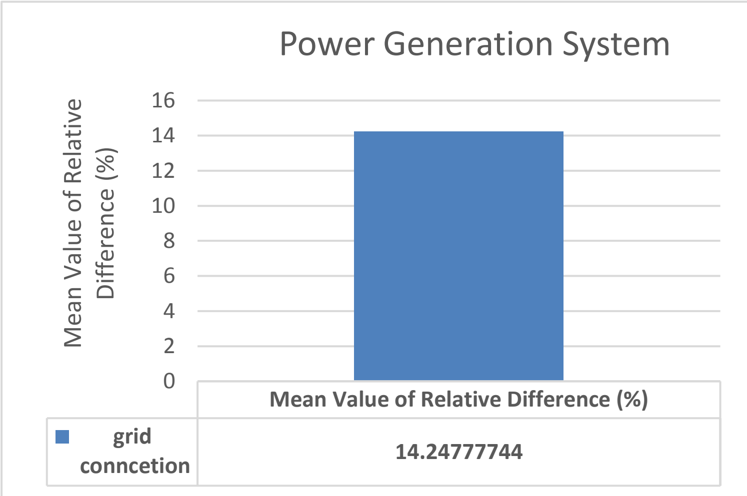


Fig 5-18. "Results of power generation system parametric study for cargo ship"

The quasi-dynamic simulations results of the Figures 5-19 shows that the level of inaccuracy throughout the whole range of the simulation

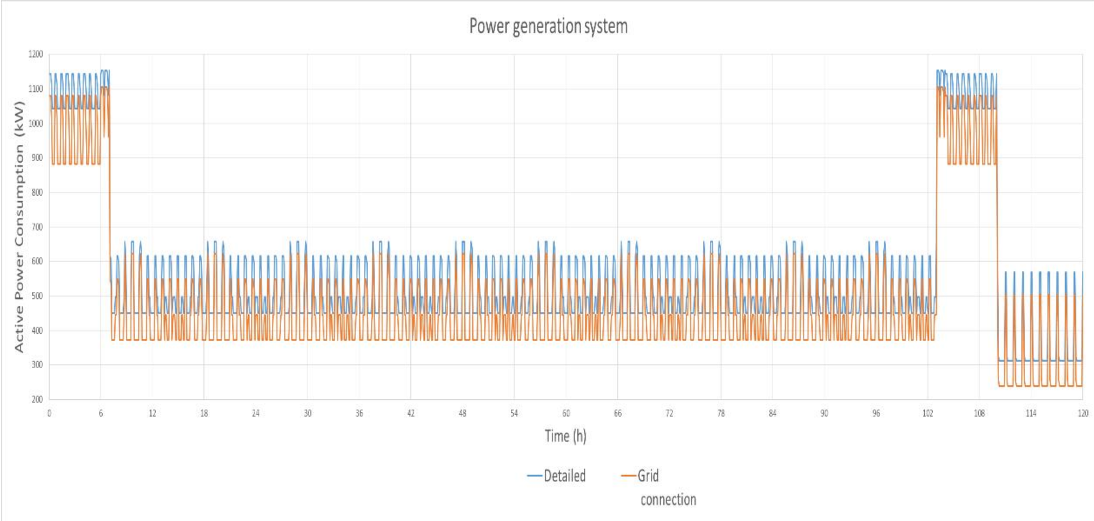


Fig 5-19. "Active power consumption of power generation system parametric study for cargo ship"

Passenger ship

The simulation results presented in Figure 5-20, show that the mean value of the relative difference is slightly higher than in the case of cargo ship but could be estimated as acceptable for the conceptual design. As in the case of the cargo ship, the computational time and the effort for modelling the power generation system and the local control systems can be compensated by the inaccuracy level in power consumption.

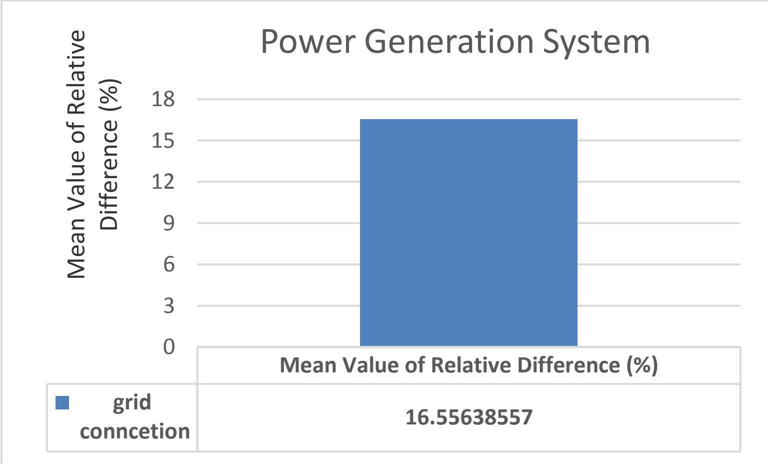


Fig 5-20. "Results of power generation system parametric study for passenger ship"

The simulations results of the Figures 5-21 show that the highest inaccuracy rate is shown up during all the operating conditions apart from the manoeuvring in which the most amount of power is consumed and all generation sets need to be in function.

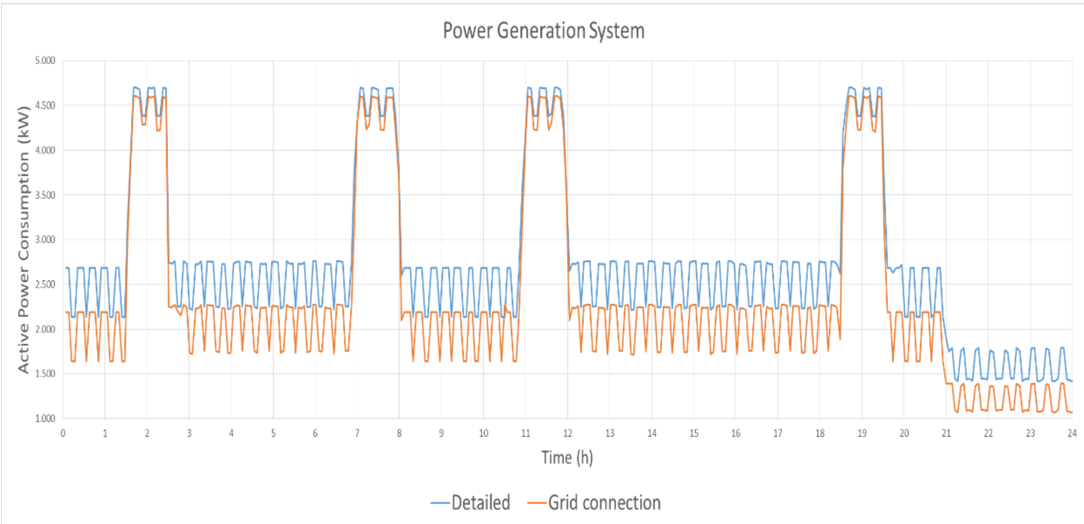


Fig 5-21. "Active power consumption of power generation system parametric studies for passenger ship"

5.5.4 Simplified marine electrical power system

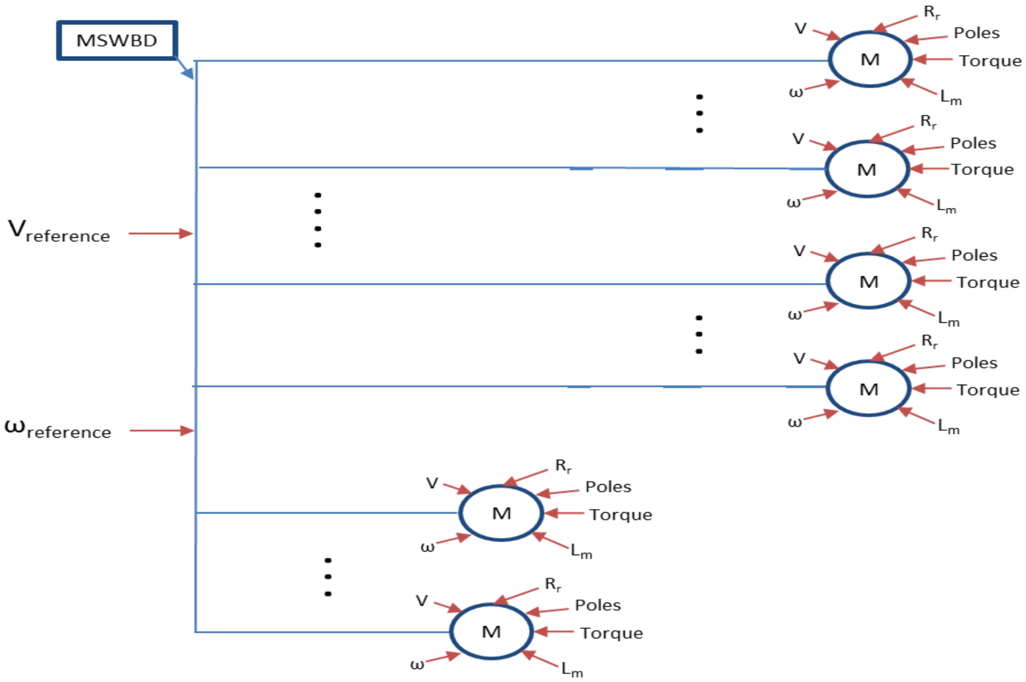


Fig 5-22. "Fully simplified electrical power systems model representation"

Having examined each of the above cases separately and through their results comparison deriving the parameters that can be neglected during the conceptual design, the gathering all of them in a fully simplified model was assessed in this section. The simplified diagram in Figure 5-22 depicts the configurations of the electrical systems after the simplifications and the comparison with the fully detailed model is described below for the types of the cargo and passenger ship. In addition, since the systems generators have been substituted by the ideal source of power, power factor simulations are not performed.

Cargo ship

The simulations results are shown in Figure 5-23. As the graph shows the accuracy of the simplified model is not insignificant but considering the time and the effort that could be saved during the conceptual design, the consistence of the model, as the Figure 5-24 shows, is at satisfactory rates.

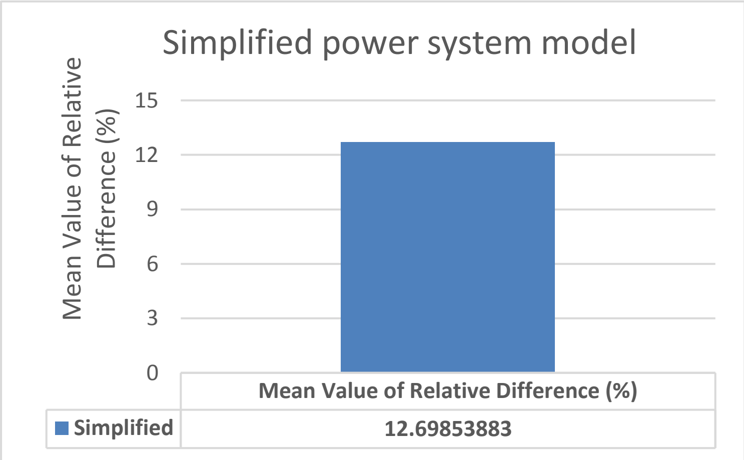


Fig 5-23. "Results of simplified power systems parametric study for cargo ship"

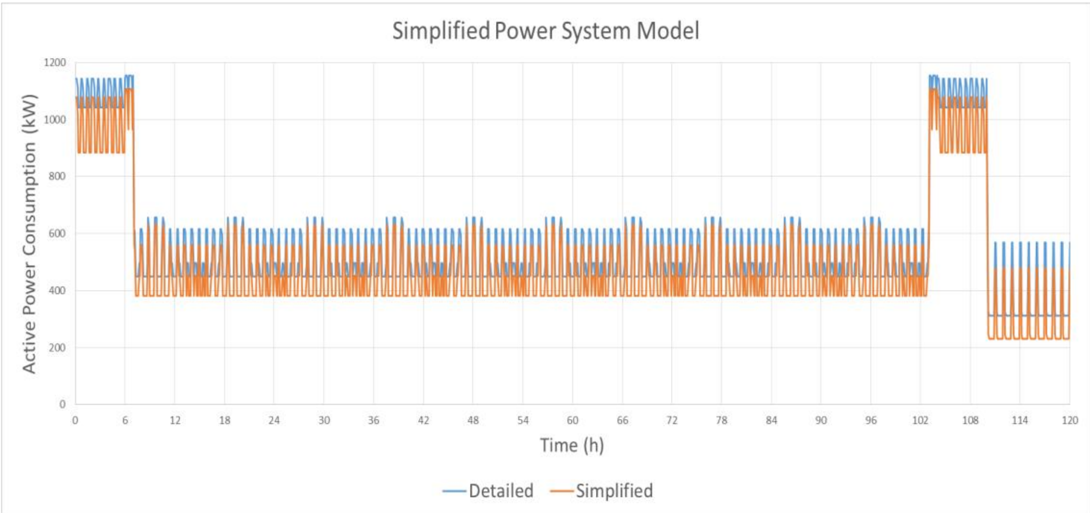


Fig 5-24. "Active power consumption of simplified power systems parametric study for cargo ship"

Passenger ship

Figures 5-25 and 5-26 show the simulations results. Aligning with the cargo ship case, the accuracy of the simplified model of the passenger vessel is not minor but designing time and effort considerations could render it adequate for the conceptual design.

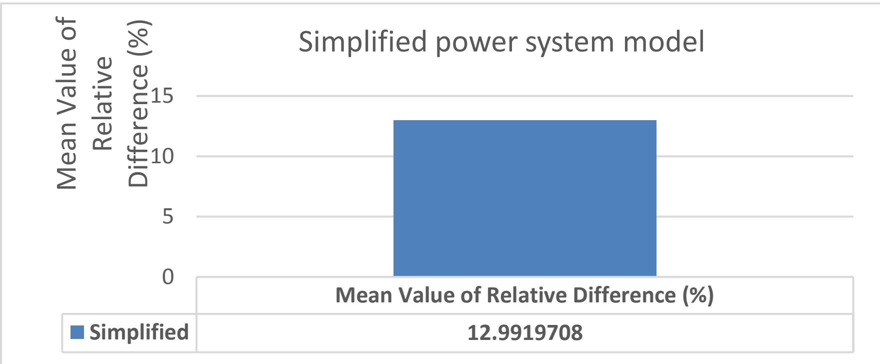


Fig 5-25. "Results of simplified power systems parametric study for passenger ship"

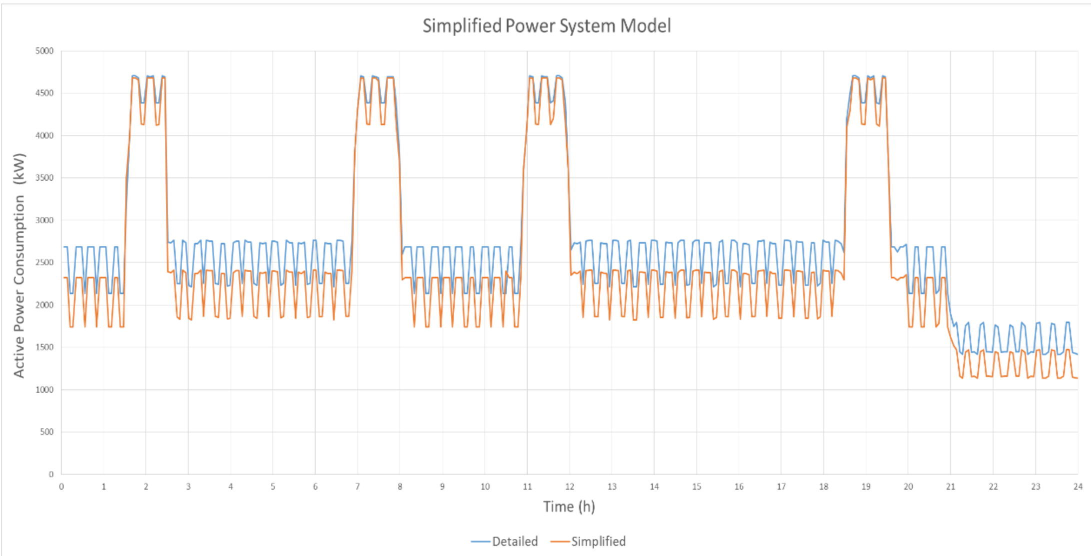


Fig 5-26. "Power consumption of simplified power systems parametric study for passenger ship"

5.6 Electrical energy systems modelling design guidelines

A very detailed electrical systems model with the appropriate control strategy would require time, data and effort for accurate results. However, simplifications cannot be done without performing a study of the parameters that are important and, finally, will allow for the appropriate for each case power generation sizing. Parameters neglect could not be arbitrary and their quantitative level of accuracy missing, should be estimated and be taken under consideration, in an attempt to compensate accuracy, consistency and time consuming for modelling the systems. Targeting to formalise the assumptions about the conceptual design of the marine electrical power network, general guidelines were developed based on the results of the investigation of this chapter for cargo and passenger ships. These guidelines will serve as a reference for cargo and passenger ship power generation sizing.

Cargo and Passenger ships

It is acceptable to model the electrical energy systems during the conceptual design for the power generation sizing needs through a fully simplified systems model in which:

1) the generic three-phase induction motor model of the power consuming system considering the whole range of ship applications will neglect the R_s, L_s and L_r parameters

2) the constant loads of the power consuming system can be neglected.

3) the power distribution and conversion systems can be disregarded holistically.

4) the power generation and the local control systems can be completely disregarded, something that might increase the inaccuracy levels but will preserve the consistency and the time to be spent during the design.

The above statements summarise the findings of this chapter and will be used in the course of the thesis to facilitate further calculations, simulations and case studies.

5.7 Closure

This chapter focused on the simplification of the electrical energy systems modelling during the design with the investigation of the validity of neglecting or keeping constant local and global parameters of the systems. Constant loads and R_s, L_s and L_r of the generic three-phase induction motors model parameters can be neglected with the same happening with the power distribution and conversion system. The power generation system can be excluded as well with the global controlled parameters to be kept constant in a more inaccurate assumption. Findings of this chapter are formalised in four statements that act as reference for the future designs and are a necessary step for the maximum capacity of the electrical power network and the power management system which is considered in the next chapter.

6 POWER MANAGEMENT SYSTEM ONBOARD SHIPS

6.1 Preamble

In an attempt to minimise the fuel consumption of the electrical power plant during the design, operation and retrofit, optimisation and exhaustive search decisions have to be made. The economic dispatch and the unit commitment are issues that have to be well defined for the vessels reduced operational and investment costs. This chapter focuses on the development of the PMS for cargo and passenger ships which is crucial for the fuel consumption minimisation during the design, retrofit and operation.

6.2 Need for Power Management System

With the detailed quasi-dynamic modelling of the electrical energy systems, the accurate estimation of the fuel consumption during the design and operation can be achieved. However, the need for controlling and reducing the use of fuel throughout any of the above stages, has facilitated the application of the PMS in the marine industry. Optimisation and exhaustive search assessment actions has to be introduced that has to be integrated in the power generation systems control strategy avoiding the violation of the classification societies technical limitations [75]. In this study, the focus of the PMS was targeting:

- the unit commitment
- the economic power dispatch

during the design and operational stages. In the literature, the second objective sometimes is considered as a part of the unit commitment approach [76].

Optimisation procedures could not be the same for the design and for the operational stages of the ship. Having this is mind, an optimisation procedure and an exhaustive search assessment are proposed in this study for the operational and design stages respectively. In other words, the static optimisation and exhaustive search that are proposed below for the system fuel minimisation and the appropriate sizing of the diesel-generators sets, are the PMS functionalities investigated in this study.

During operation

Through the detailed modelling of the electrical energy systems the fuel consumption of the network can be estimated during operation. However, due to fuel minimisation purposes, the operational and maintenance constraints, which can be translated to additional costs, have to be taken under consideration. Therefore, the fuel consumption minimisation process should solve two issues during the optimisation: which of the already installed power generation units should be online, i.e. operative, at each time step and which amount of power should each of the online units supply to the network through the main switchboard. The former case is applied to the unit commitment process and the second to the economic power dispatch between the online units. The static optimisation procedure outputs are limited by the constraints that could be technical and operational; all of them are extensively explained latter at this chapter.

In addition, the optimiser results should be integrated to the control of the power generation sets during the whole simulation time. Therefore, the unit commitment solutions will be integrated with the ideal circuit breaker controlling the corresponding diesel-generator unit, setting it 0 when the unit is offline and 1 when the unit is online or even in the stand-by setting. As for the economic power dispatch outputs, they are introduced as inputs to the frequency control scheme described in Figure 5-1 of previous chapter as the "load reference" block.

During design

PMS are also necessary during the design of the electrical power network and more specifically to the sizing of the power generation sets. Having identified the maximum operational power needs of the ship from the simplified system model developed in the previous chapter, the unit commitment optimisation process through the exhaustive search of the results could estimate the sizing and the number of power generation sets through the optimisation of the fuel consumption for each of the generation units combinations. As a consequence, subjected to constraints, the optimal sets could be chosen after exhaustive assessment and verified during its operation. However, the choice of the optimal sets is not only based on the minimum fuel consumption but primarily on the operational profile of the vessel with the choice of the most frequent area of operation and the PMS strategy that will be followed during operation, as it is explained latter in this work.

6.3 Optimisation during operation

6.3.1 Methodology

Provided that there is a number of power generation units that satisfies the expected ship electrical load, the unit commitment optimisation process aims to identify the necessary units that have to be online and the economic dispatch process the optimal load sharing among them at each time interval identifying the minimum cost that satisfies the predefined constraints. In specific, the optimisation is targeting not only the minimisation of the fuel consumption but simultaneously the calculated outputs to comply with the safety constraints as the adequate power generation reserve capacity for blackout prevention. In order to achieve that, a number of steps have to be followed and a number of constraints have to be initiated. The latter will be described latter at this chapter and the former is described below.

The sequence of the optimisation process can be followed as below:

1. Define the operating diesel-generators set

2. Define the objective function based on the number of online generation unit or units

3. Perform the optimisation for all possible load values according to technical and blackout prevention constraints taking under consideration the operational and maintenance costs as well. The process outputs indicate the economic power dispatch to the online units and the fuel consumption estimation at each time interval.

4. Repeat the process from step 1 to 3 until all allowable sets of generators are investigated.

5. Store the results from all possible generation sets combinations.

6. Export the set of the generators with the minimum operational cost at each load demand.

By following the above described algorithm, the derivation of the load dependent start and stop table for each possible power demand up to the installed generating power capacity is feasible. The table can be used as input to the control functions of the electrical power systems optimising the system in terms of energy efficiency during operation.

In order to understand and identify the applicability and suitability of the PMS during operation in cargo and passenger ships, three cases will be investigated with each power generating unit having different maximum power supplying limitations being ruled by technical constraints. This will result to different load dependent start and stop tables for each case and comparison to be feasible.

The comparison measure selected for this section was the amount of fuel consumed (kg) at each investigating case for both ship types including the operational, maintenance and stand-by costs. In addition to this, the power factor variation is presented during the whole simulation time in a matter of verifying the validity of the methodology. As in chapter 6, the simulated time was five days trip for the cargo vessel and one day trip for the passenger vessel with the details about the operational profile to be found in APPENDIX II.2 and APPENDIX III.2 respectively.

6.3.2 Optimisation concept

6.3.2.1 Objective function

In order to estimate the amount of fuel consumption in marine applications, the use of the specific fuel oil consumption with the electrical generated power curve was applied. So, the fuel consumption for each of the power generation units was calculated according to:

$$FC_i(\mathrm{P}_{i,\mathrm{load}}) = \mathrm{b}_i(\mathrm{P}_{i,\mathrm{load}}) \tag{6.1}$$

where $FC_i(P_{i,load})$ is the polynomial relation of fuel consumption-power production, $P_{i,load}$ is the active power loading of the i-th generator and b_i is the specific fuel oil consumption for each unit, usually indicated in g/kWh or g/h. The b_i is to be defined from the values given by the engine manufacturer using polynomial approximation as follows:

$$b_i(\mathrm{P}_{i,\mathrm{load}}) = \sum_{j=0}^{M} a_{i,j} \left(\frac{\mathrm{P}_{i,\mathrm{load}}}{\mathrm{P}_{i,\mathrm{rated}}} \right)^j \tag{6.2}$$

where $a_{i,j}$ are approximation constants for each generating set i and $\mathrm{P}_{i,rated}$ is the rated active power of the *i-th* generator. The unit power load is dimensionless, as can be seen from the term in the brackets. The 2nd degree polynomial (Ma = 2), was usually sufficient for the approximation. The total fuel consumption was determined as a summation of the individual fuel consumptions of the online and stand-by units adding the maintenance (low and high) costs:

$$Fuel = \sum_i FC_i(\mathrm{P}_{i,\mathrm{load}}) + C_l + C_h + C_{stand-by} \tag{6.3}$$

Having established the fuel cost minimisation objective function, the definition of the process constraints are following.

6.3.2.2 Optimisation constraints

The above described cost function has to be minimised subject to a number of constraints.

Power Balance

The power balance constraint was assuring the equality of the power generation with the power demand at each time interval.

$$P_L = \sum_i P_{i,d} P_L = \sum_i P_{i,\text{load}} \tag{6.4}$$

where P_L is the estimated system load demand and $P_{i,d}$ is the dispatched power of the *i-th* generator (in p.u.).

Minimum and maximum generators loading

Generators should not be loaded above or below a certain power level. For the high loading case, the mechanical and losses were considerably increased with the same happening for a potential thermal blackout to the system. The low loading of the generator and by extension the diesel engine can possibly cause damage to the functionality of the latter with certain loading values to be supplied by the engine manufacturers.

$$P_{i,\min} \le P_{i,\text{d}} \le P_{i,\max} \tag{6.5}$$

where $P_{i,min}$ and $P_{i,max}$ are the technically minimum and maximum, correspondingly, power produced by the *i-th* generator (in p.u.).

The blackout prevention constraint

The blackout prevention constraint defines the maximum allowable loading of the online generators where the system was protected.

$$\sum_{i=0}^{k} \mathrm{P}_{i,\text{rated}} - \mathrm{P}_L \geq \text{maximum}\, \mathrm{P}_{i,\text{rated}} \tag{6.6}$$

where maximum $P_{i,rated}$ is the systems generator with the highest power rated capacity and k the selected online generators. Through this constraint the existence of a redundant unit equal to the maximum rated power unit is applied, complying with the classification societies regulations about the resistance to single unit faults.

6.3.2.3 Maintenance costs

The operational and maintenance costs of the power generation system have to be minimised with the optimisation constraints as the engine performance should remain to acceptable and predefined loading range for its safety and economic operation. In order to minimise the fault susceptibility and the maintenance costs of the power generation system, 'operational penalties' were applied and are explained below.

Low load maintenance cost

To reduce the soot accumulation inside the engine and consequent maintenance costs, the low load engine operation has to be avoided, as defined by the constant $P_{i,min}$ in (6.5). Therefore, the low load cost can be defined to linearly penalize running the engine below 50% of the rated load:

$$C_l = \begin{cases} C_0 + \frac{C_0 - C_l}{P_{i,\min} - 0.5} \cdot P_{i,\mathrm{d}}, & P_{i,low} \leq P_{i,\mathrm{d}} < 0.5 P_{i,rated} \\ C_1, & 0.5 P_{i,rated} \leq P_{i,\mathrm{d}} \leq P_{i,high} \end{cases} \tag{6.7}$$

where $P_{i,low}$ and $P_{i,high}$ are the low and high, correspondingly, loading limits of the *i-th* generator (in p.u.), C_0, C_1 are the unit maintenance costs when a generator operates with its minimum power and over 50% of its rated power, respectively.

High load maintenance cost

The high engine loading should be avoided due to the fact that as the system operates closer to the blackout constraint, the available power becomes lower and the blackout capability decreases. Moreover, in order to reduce the engine susceptibility to faults, operators usually run the prime mover on lower loads than the maximum permitted $P_{i,max}$ in (6.5). The optimal engine loading for the minimum downtime is approximately between 50% and 90% rated load, i.e. $0.5\ P_{i,rated} \leq P_{i,d} \leq 0.9\ P_{i,rated}$, as given from the manufacturers and literature [77].

Therefore, the high load cost can be defined as a penalizing factor when running the engines closer to the blackout limit:

$$C_h = \frac{C_2}{P_{i,\max} - P_{i,\mathrm{high}}} \left(P_{i,\mathrm{d}} - P_{i,\mathrm{high}}\right), \quad P_{i,high} < P_{i,\mathrm{d}} \leq P_{i,\max} \tag{6.8}$$

where C_2 is the unit maintenance cost when it operates within the upper loading limit.

6.3.2.4 Stand-by cost

In general, the avoidance of the cold engine start is advised by manufacturers as it is highlighted as one of the worst engine transients. Therefore, practices such as keeping the engines preheated and lubricated are applied, however, with the concurrent increase of the stand-by cost. The stand-by cost refers to the cost of keeping the engine in the stand-by mode of the operation, where the engine is not running but should be pre-heated, pre-lubricated and in some occasions in the "slow-turning" mode. The amount of power that the stand-by engine consumes was defined as an additional cost and expressed as the 0.5% of the generator's power rating in kilowatts.

$$C_{stand-by} = 0.005\, P_{i,\mathrm{rated}} \tag{6.9}$$

6.3.3 Cargo ship

Optimisation process initialisation

The unit commitment and the economic power dispatch optimisation process during operation in cargo ships were applied through the algorithm described earlier in this chapter. Their initiation considered the definition of the cost function and the corresponding constraints. As a consequence of this process, the derivation of the load dependent start and stop table for the whole range of the operational power demand were feasible and their integration to the local control system results to potential energy savings.

For the optimisation process, the number of installed generators were three equally rated units each of them of 700 kW active rated power with one to be redundant. By doing so, the blackout prevention constraint was always accomplished by the stand-by mode of the redundant unit without being loaded at any demand except the case of a single unit fault. The fuel consumption-produced power curve of the diesel-generators sets is shown in APPENDIX IV.1 [78] and were used for all power generation units with the range of output active power to be from 450 to 855 kW. The curve was approximated by the polynomial function:

$$b_i(P_{i,\mathrm{load}}) = 89.843\left(\frac{P_{i,\mathrm{load}}}{P_{i,\mathrm{rated}}}\right)^2 - 147.02\left(\frac{P_{i,\mathrm{load}}}{P_{i,\mathrm{rated}}}\right) + 253.83 \tag{6.10}$$

Maintenance costs have been related to generator low-power operational costs. Therefore, low-power operation maintenance cost, C_0, has been assumed to be equal to 5% of the low-power operation cost, while high-power maintenance cost, C_2, equal to 90% of the low-power operation maintenance cost, with C_1 equals to 0. Regarding the maintenance low, $P_{i,low}$, and high, $P_{i,high}$, limitations, the former's value was equal to the technical minimum power constraint, i.e. $P_{i,min}$, at 25% of the generator's rated power and the latter value equals the upper energy efficient limit of the engine loading, i.e. 90% of the generator's rated power.

The above described objective function, maintenance and stand-by costs and constraints were applied to the three below examined cases. The differed constraint was the maximum generators loading which was applied as:

- case 1: $P_{i,max} = 1.1\ P_{i,rated}$
- case 2: $P_{i,max} = P_{i,rated}$

- case 3: $P_{i,max} = 0.9\ P_{i,rated}$

The investigation has been performed for the power range up to the installed services power capacity, excluded the redundant, i.e. 1,400 kW.

Optimisation results

The derivation of the load dependent start and stop table for the three investigating cases is shown in Table 6-1. This table represents the start and the stop of power generating sets in conjunction with the power dispatch among them and the fuel consumption at the corresponding load demand.

Table 6-1: Result of load dependent start and stop table for cargo ship during operation

Load (kW)	Case	D/G_1 (700 kW rated) (kW)	D/G_2 (700 kW rated) (kW)	D/G_3 (700 kW rated) (kW)	Specific Fuel Consumption (g/kWh)
175	1	175	0	offline	234.0
	2	175	0	offline	234.0
	3	175	0	offline	234.0
640	1	640	0	offline	222.9
	2	640	0	offline	222.9
	3	350	290	offline	413.7
710	1	710	0	0	243.0
	2	355	355	0	403.1
	3	355	355	0	403.1
780	1	390	390	0	393.0
	2	390	390	0	393.0
	3	390	390	0	393.0
1270	1	640	630	0	426.2
	2	640	630	0	426.2
	3	423.3	423.3	423.3	581.9
1400	1	770	630	0	459.3
	2	700	700	0	470.5
	3	466.7	466.7	466.7	581.3

The results show that the more the units in function, the more expensive the operation becomes. This statement is highlighted to the case of 710 and 1,400 kW load where the case 1 has the highest fuel savings working at the 110% of the unit rated power. In addition, the case 3 cannot afford the appropriate power after the 1,260 kW as the diesel-generators are obliged to work up to the 90% of their rated power. As a result, the blackout prevention constraint is violated.

At 640 kW load demand, the case 3 does not dispatch the power equally at the operating units but it keeps one unit at 50% of its rated power with the other unit to get the rest of the amount till the demand rises to 700 kW where the equal sharing is applied. That is because of the low loading maintenance cost for less than 50% of the rated capacity. Similarly for the high maintenance cost, at the operation of 1,270 kW demand the one unit is working to the 90% of its rated capacity and the rest above it until the upper technical limits are met.

Having derived the load dependent start and stop table for each of the investigating case, the fuel consumption of a five days trip of the cargo ship based on the corresponding operational profile was estimated. The above tables were used as input to the system and the simulation results are presented below.

In Figure 6-1 the results of the fuel consumption based on the same operational profile for all investigating cases was presented. The same amount of fuel is needed for the first two cases but for the third case which is the safest in terms of the equipment maintenance, the increase of 5.3% in the fuel consumption is shown. The simulation results of each case are presented in Figures 6-2, 6-3 and 6-5 for a better understanding. In Figures 6-4 and 6-6 the power factors of both system generators are presented.

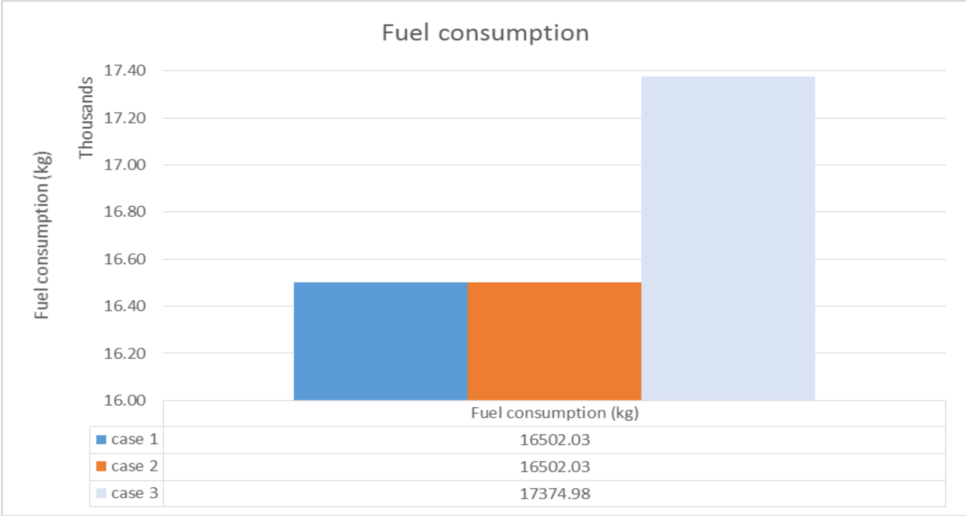


Fig 6-1. "Fuel consumption of investigating cases for cargo ship"

In Figure 6-2 the exact matching of the fuel consumption of case 1 and 2 are following the results of the Figure 6-1 with the Figure 6-3 to show the operation of two diesel-generator sets during loading/unloading and manoeuvring for both cases.

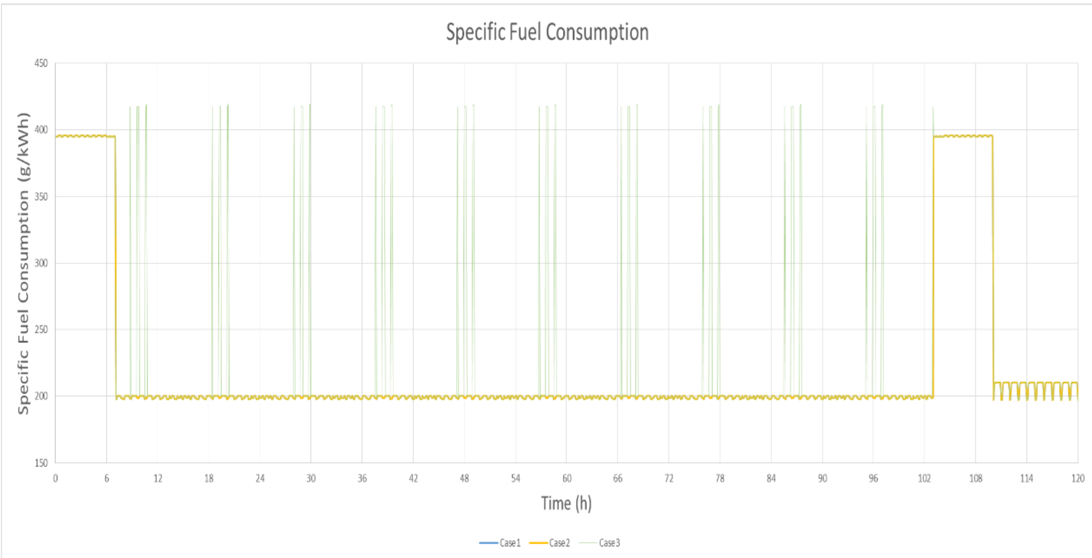


Fig 6-2. "Results for specific fuel consumption over time of investigating cases for cargo ship"

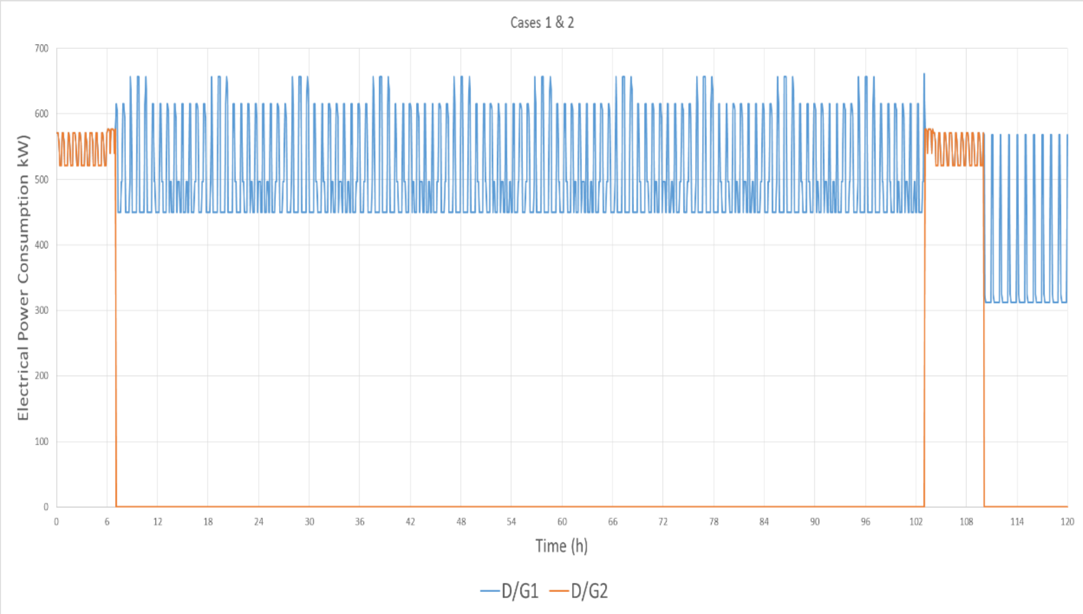


Fig 6-3. "Results for power dispatch of cases 1 and 2 for cargo ship"

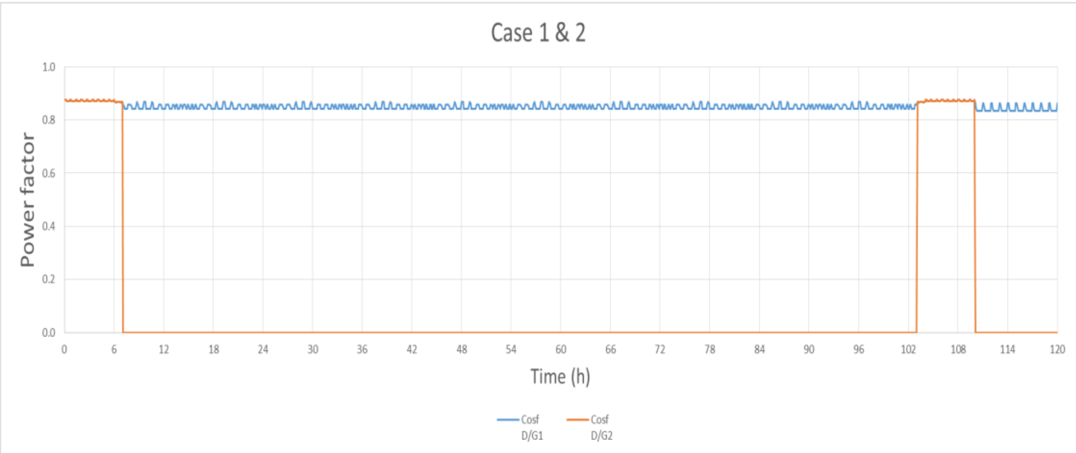


Fig 6-4. "Power factor variation of cases 1 and 2 for cargo ship"

For the case 3, the partial use of two generators also during the sea going state, where the power demand exceeds 630 kW (upper loading limit for this case), Figure 6-5, increases the fuel consumption.

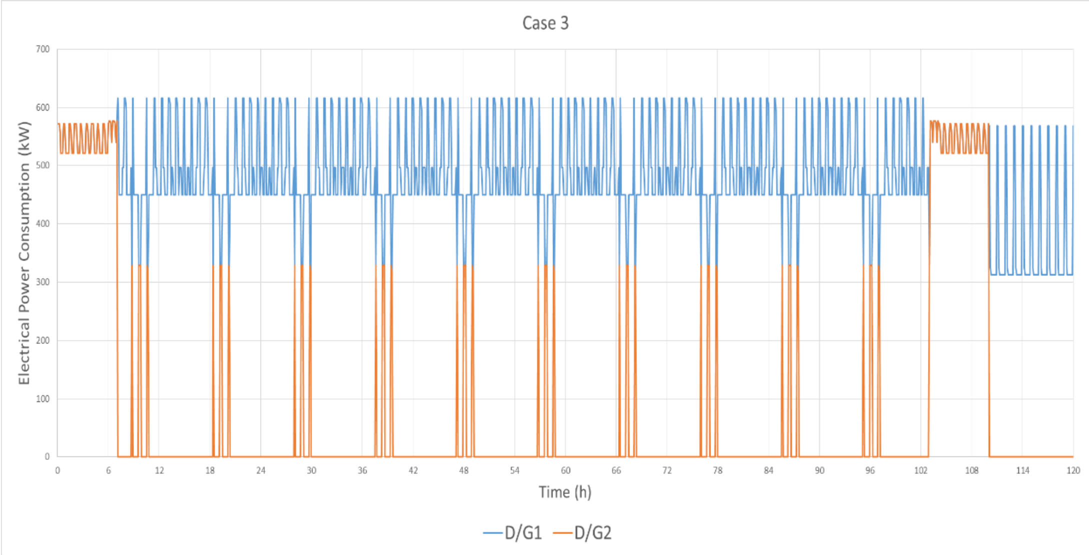


Fig 6-5. "Results for power dispatch of case 3 for cargo ship"

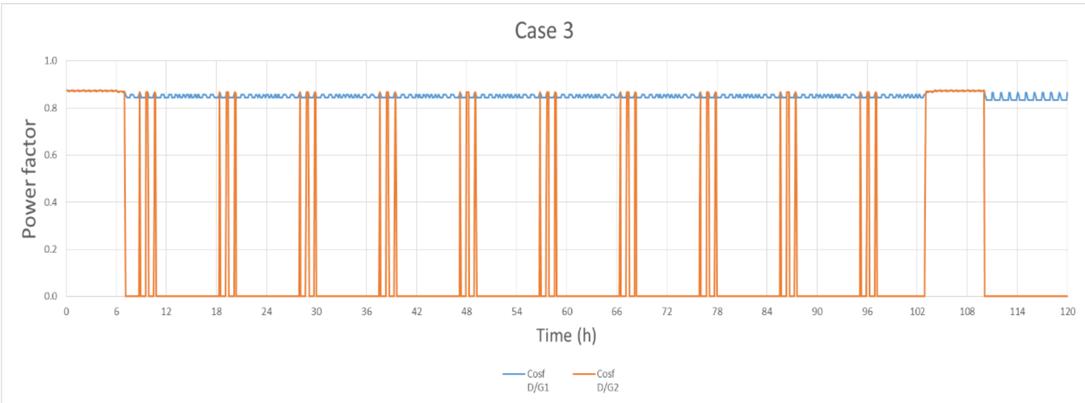


Fig 6-6. "Power factor variation of case 3 for cargo ship"

As a conclusion, the loading of the diesel-generation units under their power rating will definitely secure the equipment and the power system preventing it from additional maintenance or blackout, however the operational cost is increased. The generation units loading to the rated capacity or even 10% higher results to energy efficient systems operation.

6.3.4 Passenger ship

Optimisation process initialisation

For the optimisation process, the installed number of diesel-generator sets were 4, with two of them (D/G_1 and D/G_3) of 1,500 kW and the other two (D/G_2 and D/G_4) of 1,900 kW rated power, with D/G_4 to be considered as redundant. By doing so, the blackout prevention constraint was always accomplished by the stand-by mode of the redundant unit without being loaded at any demand except the case of a single unit fault. The fuel consumption-produced power curve of the diesel-generator sets is shown in APPENDIX IV.2 [79] and was used for all power generation units with the range of output power to be from 1,000 to 2,350 kW. The curve was approximated by the polynomial function:

$$\mathrm{b}_i(\mathrm{P}_{i,\mathrm{load}}) = 83.241\left(\frac{\mathrm{P}_{i,\mathrm{load}}}{\mathrm{P}_{i,\mathrm{rated}}}\right)^2 - 132.94\left(\frac{\mathrm{P}_{i,\mathrm{load}}}{\mathrm{P}_{i,\mathrm{rated}}}\right) + 243.43 \tag{6.11}$$

The parameters of the optimisation process initialisation were the same as described in the previous case of the cargo ship. Three optimisation cases were investigated again with the same constraints, maintenance and stand-by costs as previously. The investigation will be performed for the power range up to the installed services power generation capacity, excluded the redundant, i.e. 4,900 kW.

Optimisation results

The load dependent start and stop table for the unit commitment and economic dispatch is shown in Table 6-2. The results are commented below based on the range of the power demand as presented in the Table 6-2.

For the load demand ranges from 375 kW, low limit of D/G_1, to 1,340 kW for all examined cases, the loads are supplied by one low rated power diesel-generator. Slightly before the D/G_1 upper limit at 1,340 kW, the D/G_2 is providing power to the plant. At 1,710 kW demand, the third case meets its upper loading limit and the D/G_1 and D/G_2 are online until load demand equals 1,910 kW. After 1,910 kW, the D/G_1 gets online for the second examined cases, with the same happening for the first case when its high loading limit is met at 2,090 kW.

After 2,090 kW load, for all cases the D/G_1 and D/G_2 are online with unequal load sharing until the load demand reaches the 3,070 kW. At 3,080 kW demand, the D/G_3 gets in function for the third case, with the same happening for the second and third case after 3,400 kW and 3,740 kW respectively where the corresponding upper loading limits are met. During that range of operation, the equal rated diesel-generators are sharing the same amount of power.

The maximum limit for case 3 during the operation with three generators is at 4,410 kW power demand. After that point and up to the 4,900 kW load demand, the violation of the blackout prevention constraint is necessary and the D/G_4 gets online.

Table 6-2: Result of load dependent start and stop table for passenger ship during operation

Load (kW)	Case	D/G_1 1500 kW rated (kW)	D/G_2 1900 kW rated (kW)	D/G_3 1500 kW rated (kW)	D/G_4 1900 kW rated (kW)	Specific Fuel Consumption (g/kWh)
375	1	375	offline	0	offline	236.5
	2	375	offline	0	offline	236.5
	3	375	offline	0	offline	236.5
1340	1	offline	1340	0	offline	198.6
	2	offline	1340	0	offline	198.6
	3	offline	1340	0	offline	198.6
1720	1	offline	1720	offline	0	201.1
	2	offline	1720	offline	0	201.1
	3	768	952	offline	0	404.4
1920	1	offline	1920	0	0	219.1
	2	893	1027	offline	0	399.2
	3	893	1027	offline	0	399.2
2100	1	962	1138	offline	0	395.6
	2	962	1138	offline	0	395.6
	3	962	1138	offline	0	395.6
3080	1	1350	1730	offline	0	392.7
	2	1350	1730	offline	0	392.7
	3	967	1147	967	0	587.7
3420	1	1405	2015	offline	0	408.3
	2	1061	1298	1061	0	583.0
	3	1061	1298	1061	0	583.0
3760	1	1155	1449	1155	0	580.8
	2	1155	1449	1155	0	580.8
	3	1155	1449	1155	0	580.8
3980	1	1051	1878	1051	0	582.6
	2	1051	1878	1051	0	582.6
	3	1051	1878	1051	0	582.6
4420	1	1350	1720	1350	0	583.5
	2	1350	1720	1350	0	583.5
	3	0	1589	1242	1589	578.9
4900	1	1425	2049	1425	0	606.2
	2	1500	1900	1500	0	607.1
	3	1079	1371	1079	1371	758.7

Having derived the load dependent start and stop table for each of the investigating cases, the fuel consumption of a one day trip based on the operational profile of APPENDIX II.2 was evaluated. The results presented in

Table 6-2 were used as input to the system and the simulation results are presented below. As for case 3, the blackout prevention constraint were inactive for the cases that the optimisation could not be performed another way.

In Figure 6-7 the results of the fuel consumption during the vessel's trip is presented for the three investigated cases. It is obvious that the less fuel were consumed for the case 1, with the case 2 to need slightly more fuel for the same trip, 0.4%, and the case 3 to be by far the most expensive with 3.3% higher fuel usage, even though it violates the blackout proof constraint during the manoeuvring condition.

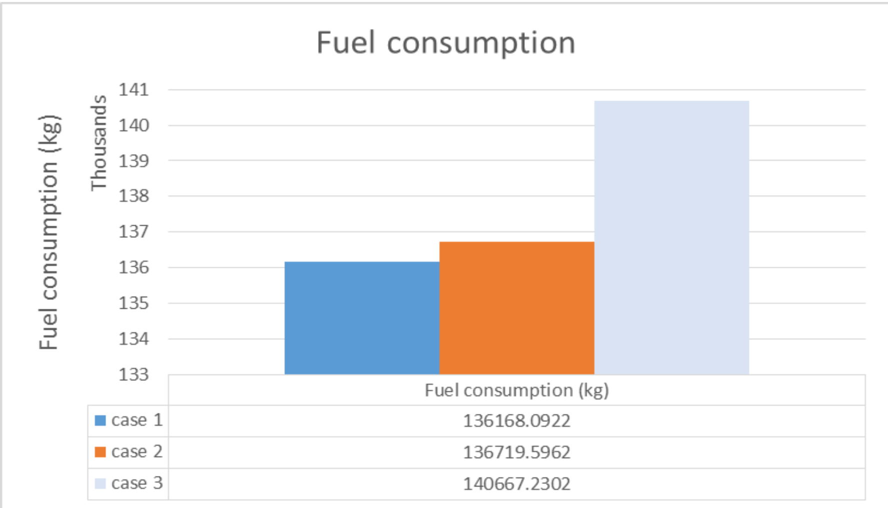


Fig 6-7. "Fuel consumption of investigating cases for passenger ship"

In Figure 6-8 the results are shown for the three cases throughout the whole route simulated. It could be identified that the first two cases are almost aligned contrary to the third which has significantly of higher fuel consumption rate.

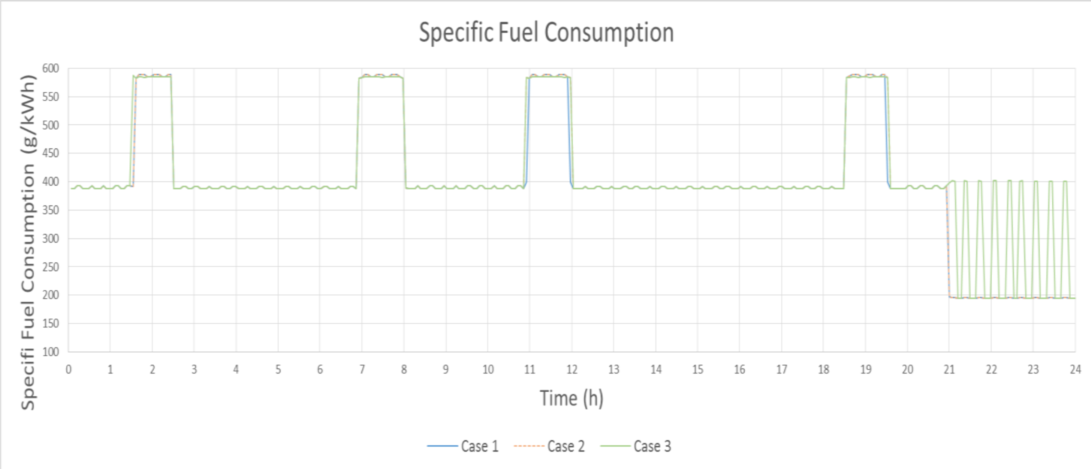


Fig 6-8. ""Results for fuel consumption over time of investigating cases for passenger ship"

Taking a closer look at the results of the simulation, Figure 6-9 and 6-11 show that for the cases 1 and 2 the D/G_2 is used throughout the whole simulated range with the D/G_1 to be used too apart from the port operating condition. The D/G_3 is used only during manoeuvring where the loading is increased. In Figures 6-10, 6-12 and 6-14 the power factors of both system generators are presented.

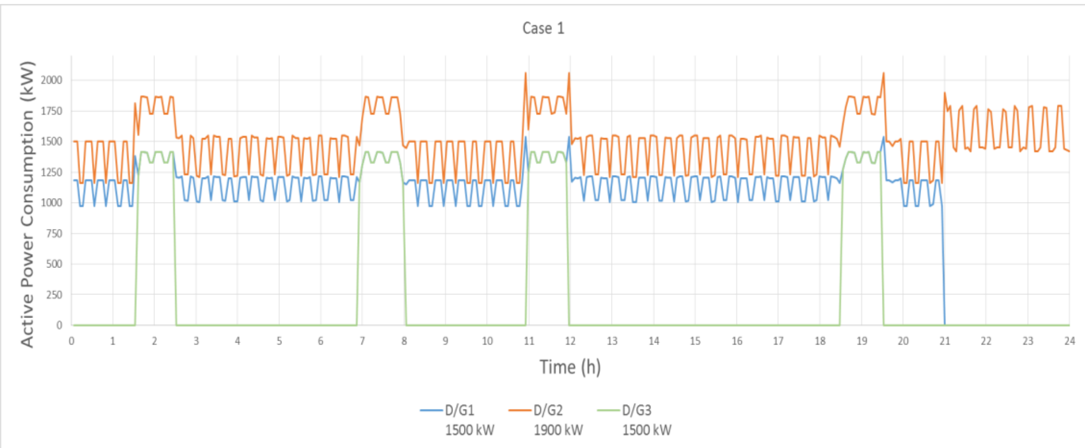


Fig 6-9. "Results for power dispatch of case 1 for passenger ship"

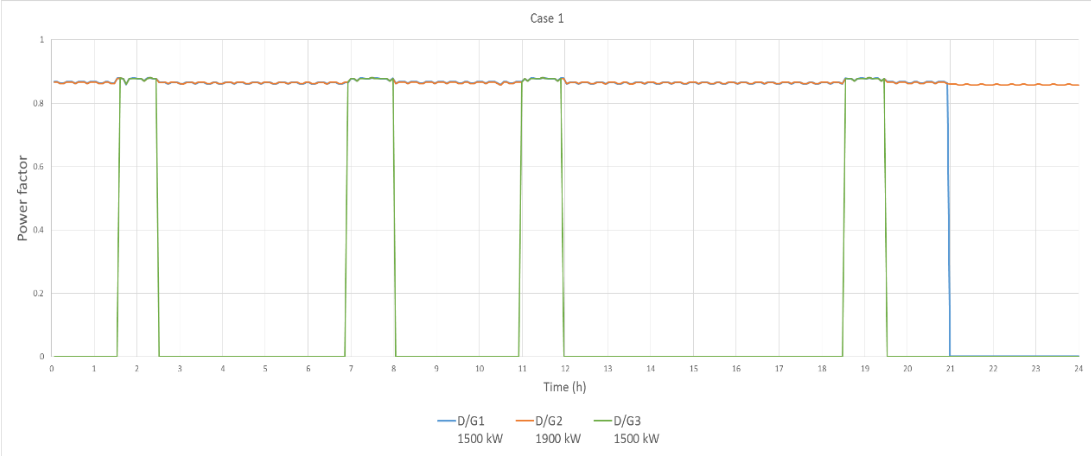


Fig 6-10. “Power factor results of case 1 for passenger ship”

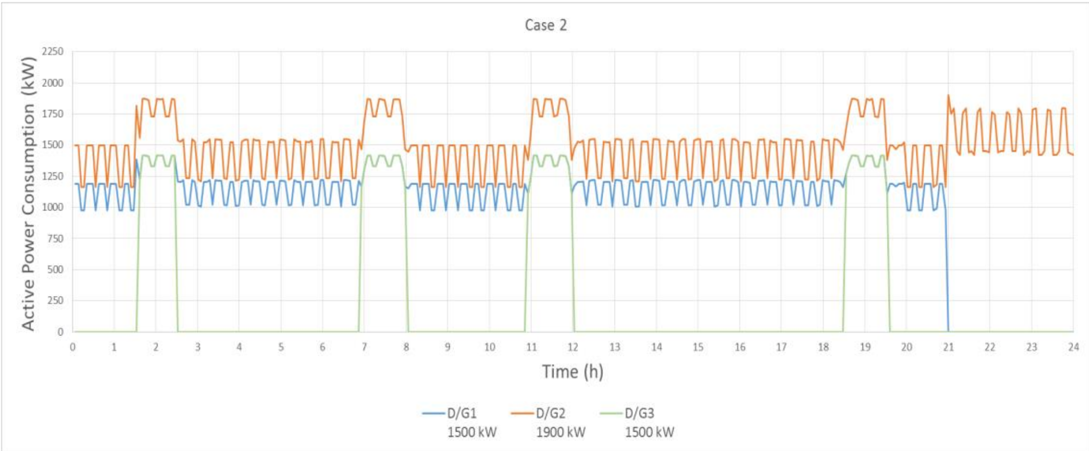


Fig 6-11. “Results for power dispatch of case 2 for passenger ship”

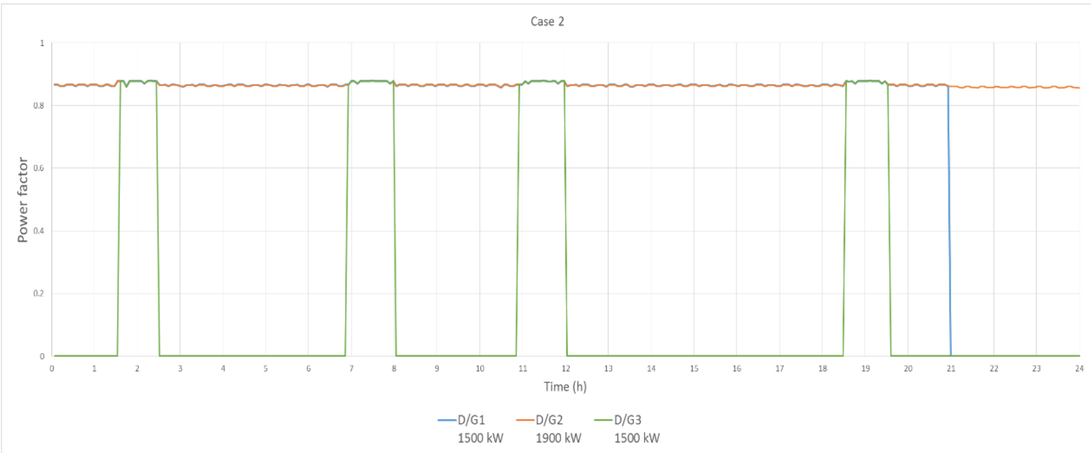


Fig 6-12. “Power factor results of case 2 for passenger ship”

The simulation results for the case 3 are shown in Figure 6-9 explaining the high fuel consumption. The D/G2 is online during the whole simulation with the D/G1 to be too but the port operation. However, during the manoeuvring state there is the need for higher power supply than the three available diesel-generators, because of their upper loading limit applied to this case. Therefore, the redundant units is set to be in function running in parallel with the D/G1 and D/G2. Therefore, the blackout proof constraint was violated with the fuel consumption to be reduced compared to the other cases.

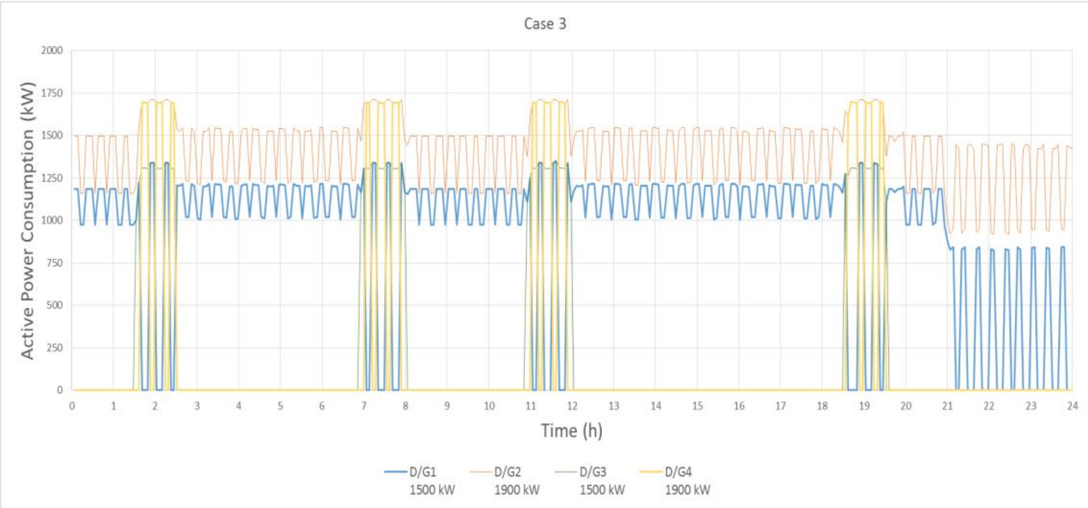


Fig 6-13. "Results for power dispatch of case 3 for a passenger ship"

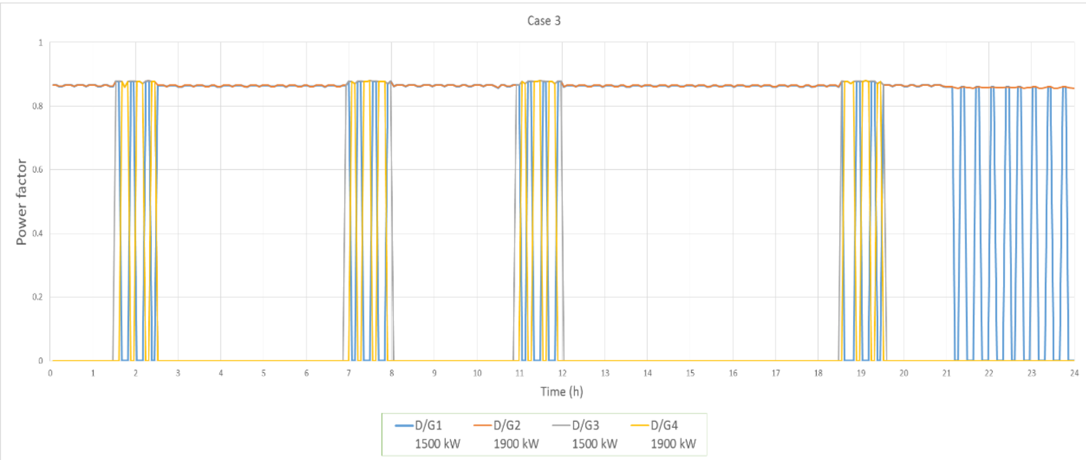


Fig 6-14. "Power factor results of case 3 for passenger ship"

To sum up, similar conclusions with the cargo vessel case can be summarised. In specific, the diesel-generator units loading under their rated power will definitely secure the equipment and the power system preventing it from additional maintenance, however the fuel cost is increased. The loading up to the rated capacity is way more efficient than the previous case, but the optimal is considered the 110% of the rated capacity. Although the suggestions are based on simulation results for this specific passenger ship, the consideration of the power utilisation system's load demand and the installed rating power capacity with the number of units, are parameters that affect the applicability and suitability of the PMS.

6.4 Exhaustive search optimisation during design

6.4.1 Methodology

Targeting the design optimisation of the electrical power systems, the number and the sizing of the power generation sets are of the highest importance. By taking advantage of the simulation results of the fully simplified electrical power systems model of chapter 6, the sizing estimation of the most energy efficient power generating sets during the design can be achieved. The adopted approach was different from the one for the operation. The steps of the exhaustive search optimisation process were as below:

1. Define the installed services power generating capacity
2. Define the operating generation unit or units

3. Define the objective function based on the number of installed services generation units

4. Perform the optimisation according to technical constraints for all possible load values. The process outputs indicate the optimal rating of each installed unit, the economic power dispatch and fuel consumption estimation at each time interval.

5. Create the design load dependent start and stop tables.

6. Repeat the process from step 2 to 5 until all allowable sets of generators are investigated.

Through the above described algorithm the design load dependent start and stop design tables can be created and used, afterwards, for sizing the power generation units. For the applicability of the above exhaustive search optimisation approach, one case for cargo and three for passenger ships will be investigated in order to identify the most energy efficient number of installed generators and their exact sizing over a range of load demand at each ship type through the design load dependent start and stop tables. A limited number of constraints, described later in this chapter, were applied during the optimisation process with the maintenance and stand-by costs to be neglected. In addition, during this approach the existence of redundant generation unit was not feasible since the sizing was considering the services generating units under normal operation. After that derivation, the size of the redundant units was selected equal to the highest rated power unit.

6.4.2 Exhaustive search optimisation concept

6.4.2.1 Objective function

In order to perform the optimisation the objective function was defined. The same as previously, in (6.1) - (6.3), was applied without including the stand-by and maintenance costs. In addition, in equation (6.2) the denominators, i.e. the generators power ratings, were not known at this case.

6.4.2.2 Exhaustive search optimisation constraints

For the exhaustive search optimisation process during the design, a number of constraints was applied some of them in common with the previous methodology. The

- power balance constraint (6.4) and
- the minimum and maximum generators loading constraints (6.5)

are also used at this method with the blackout prevention constraint to neglected.

Furthermore, the *installed services power constraint* was introduced. It ensured that the total installed power of the optimised power generation units equals the highest load demand defined by the operational profile of the vessel.

$$\sum_i \mathrm{P}_{i,rated} = \mathrm{P}_{L,\max} \tag{6.12}$$

where $P_{L,max}$ is the maximum load demand of the system derived by the simplified system model of chapter 5. The maintenance and stand-by costs are not taken under consideration at this process.

6.4.3 Cargo ship

The below cases were introduced to demonstrate the applicability of the optimisation procedure during the design of cargo ships. As in the previously examined case for cargo ships at operational stage, the same cargo vessels was used. One sizing case was investigated since the assumption in this study was that the total installed services power generation units cannot be less than one and more than three in number excluding redundancies. The diesel-generator sets choices are presented in APPENDIX IV.

In addition to the sizing case, two scenarios were examined considering the PMS loading strategy during vessel's operation as described in the previous section. The scenarios of installed service power generation units being loaded up to their rating power, strategy 1, and up to ten percent more than that, strategy 2, were investigated and analysed coupled with their corresponding fuel consumption. Consequently, decisions about the operation of the vessel are vital during the design process with the power generation equipment loading and the area of vessel operation to be on high priority.

6.4.3.1 Exhaustive search optimisation process initialisation

As defined in chapter 5, the maximum power load demand of the simplified electrical power system equals to the value of 1,100 kW, see Figure 5-19. Therefore, this value can be used as input for the total installed services power, $P_{L,max}$. In addition, the applied cost function was defined by the equation (6.10) with the corresponding rated generating power ranging from 450 - 855 kW. Because of the 1,100 kW installed power generating capacity limitation, the case of two installed units was investigated without considering the redundant unit. In conjunction with the high loading limit, which is examined as strategy 1 and 2, the low loading limit of each generator was employed and equal to the 25% of the units rated power.

6.4.3.2 Exhaustive search optimisation results

PMS loading strategy 1

Results of the optimisation for the power generation units loading up to their rated power are presented in Table 6-3. In most load cases the sizing of generators is not equal, with one unit to be of 650 kW and the other of 450 kW rated power. The equality is possible to take place at the range of 440 - 480 kW load demand. As for the fuel consumption, the lowest rate is achieved during the operation of 360-520 kW load demand.

Table 6-3: Design load dependent start and stop table for strategy 1 of cargo ship

Load (kW)	D/G_1 (450-855 kW)		D/G_2 (450-855 kW)		Specific Fuel consumption (g/kWh)
	Generator loading (kW)	Generator power rating (kW)	Generator loading (kW)	Generator power rating (kW)	
200	200	450	0	650	206.2
240	240	450	0	650	201.0
280	280	450	0	650	197.1
320	320	450	0	650	194.7
360	360	450	0	650	193.7
400	400	487.7	0	612.3	193.7
440	440	537.1	0	562.9	193.7
480	480	581.2	0	518.8	193.7
520	520	635.6	0	464.4	193.7
560	560	650	0	450	193.9
580	580	650	0	450	194.2
600	600	650	0	450	194.7
640	640	650	0	450	196.2
680	590	650	90	450	422.4
720	630	650	90	450	423.7
760	437.2	650	322.8	450	390.2
780	450.7	650	329.3	450	389.4
820	477.7	650	342.3	450	388.3
860	504.8	650	355.2	450	387.6
900	527.9	650	372.1	450	387.4
940	558.9	650	381.1	450	387.6
980	585.9	650	394.1	450	388.3
1020	650	650	370	450	390.3
1060	650	650	410	450	391.1
1100	650	650	450	450	393.3

PMS loading strategy 2

Results of the optimisation for the power generation units loading 10% higher of their rated power are presented in Table 6-4. The results reveal the compliance with the previous examined loading case. The different sizing area is noticed between the 650 - 710 kW load demand where the D/G_1 meets its upper loading limit and the corresponding fuel consumption is less than the half of the previous case.

Table 6-4: Design load dependent start and stop table for strategy 2 of cargo ship

Load (kW)	D/G_1 (450-855 kW)		D/G_2 (450-855 kW)		Specific Fuel consumption (g/kWh)
	Generator loading (kW)	Generator power rating (kW)	Generator loading (kW)	Generator power rating (kW)	
200	200	450	0	650	206.2
240	240	450	0	650	201.0
280	280	450	0	650	197.1
320	320	450	0	650	194.7
360	360	450	0	650	193.7
400	400	487.7	0	612.3	193.7
440	440	537.1	0	562.9	193.7
480	480	581.2	0	518.8	193.7
520	520	635.6	0	464.4	193.7
560	560	650	0	450	193.9
580	580	650	0	450	194.2
600	600	650	0	450	194.7
640	640	650	0	450	196.2
680	680	650	0	450	198.4
720	630	650	90	450	423.7
760	437.2	650	322.8	450	390.2
780	450.7	650	329.3	450	389.4
820	477.7	650	342.3	450	388.3
860	504.8	650	355.2	450	387.6
900	527.9	650	372.1	450	387.4
940	558.9	650	381.1	450	387.6
980	585.9	650	394.1	450	388.3
1020	650	650	370	450	390.3
1060	650	650	410	450	391.1
1100	650	650	450	450	393.3

6.4.4 Passenger ship

The below case were applied to demonstrate the applicability of the optimisation procedure during the design of passenger ships. As previously in this chapter the same passenger vessel was used. Three sizing cases were investigated based on the number of installed services power generation sets under the limitation of maximum three diesel-generators sets that can be operational, in other words four units included the redundant. The choices of the diesel-generator sets is presented in APPENDIX IV.

Also, two scenarios were examined for each sizing case considering the PMS loading strategy during vessel's operation as described previously for the cargo ship examined case. The scenarios of installed service power generation units being loaded up to their rating power and up to 10% more than that were investigated presenting their corresponding fuel consumption.

6.4.4.1 Exhaustive search optimisation process initialisation

As defined in chapter 5 by the derivation of the simplified electrical power system, the maximum power load demand equals to the value of 4,700 kW, Figure 5-21. Therefore, this value were used as input for the total installed services generating power capacity. In addition, the applied cost function was defined by the equations (6.10) and (6.11) with the corresponding rated generating power ranging from 450-855 kW and 1,000-2,350 kW as described in APPENDIX IV.1 and APPENDIX IV.2 respectively.

For comparison purposes three cases, were investigated. In the first case, the installation of two power generation units was initiated with the only choice of both to be from the second diesel-generation category. The second and third case were based on the installation of three power generation units; one case comprised two sets from the second diesel-generation category and one set from the first diesel-generator category and the other case comprises three sets from the second diesel-generation category. Due to the limitations for 4,700 kW installed generating power and up to three installed service units, the above combinations of power generating sets satisfy this constraint. It is worthy to mention that the redundant unit was not involved in this process, as previously in cargo ship section. The low loading limit of each generator equals the 25% of its rated power with the upper limit depending on the PMS loading strategy.

The technical constraints that applied are the same with the cargo vessel's case during the design with no maintenance and stand-by costs to be taken under consideration.

6.4.4.2 Exhaustive search optimisation results for case 1

PMS loading strategy 1

Results of the optimisation for the power generation units loading up to their rated power are presented in Table 6-5. Due to the limitation of the installed generating power capacity, both units are equally sized with the maximum power rating of the second diesel-generator category, i.e. 2,350 kW. One generator is online up to the upper loading constraint and after that load, equal sharing is performed. It is clear that the redundant unit will also be of the same power rating as the operating units.

Table 6-5: Design load dependent start and stop table for case 1, strategy 1 of passenger ship

Load (kW)	D/G_1 (1000-2350 kW)		D/G_2 (1000-2350 kW)		Specific Fuel consumption (g/kWh)
	Generator loading (kW)	Generator power rating (kW)	Generator loading (kW)	Generator power rating (kW)	
600	600	2350	0	2350	214.9
800	800	2350	0	2350	207.8
1000	1000	2350	0	2350	201.9
1200	1200	2350	0	2350	197.3
1400	1400	2350	0	2350	193.8
1600	1600	2350	0	2350	191.5
1800	1800	2350	0	2350	190.4
2000	2000	2350	0	2350	190.6
2200	2200	2350	0	2350	191.9
2350	2350	2350	0	2350	193.7
2400	1200	2350	1200	2350	394.5
2500	1250	2350	1250	2350	393
2600	1300	2350	1300	2350	390.7
2800	1400	2350	1400	2350	387.5
3000	1500	2350	1500	2350	385.0
3200	1600	2350	1600	2350	383.0
3400	1700	2350	1700	2350	381.6
3600	1800	2350	1800	2350	380.9
4000	2000	2350	2000	2350	381.2
4300	2150	2350	2150	2350	383.0
4700	2350	2350	2350	2350	387.5

PMS loading strategy 2

Table 6-6: Design load dependent start and stop table for case 1, strategy 2 of passenger ship

Load (kW)	D/G_1 (1000-2350 kW)		D/G_2 (1000-2350 kW)		Specific Fuel consumption (g/kWh)
	Generator loading (kW)	Generator power rating (kW)	Generator loading (kW)	Generator power rating (kW)	
600	600	2350	0	2350	214.9
800	800	2350	0	2350	207.8
1000	1000	2350	0	2350	201.9
1200	1200	2350	0	2350	197.3
1400	1400	2350	0	2350	193.8
1600	1600	2350	0	2350	191.5
1800	1800	2350	0	2350	190.4
2000	2000	2350	0	2350	190.6
2200	2200	2350	0	2350	191.9
2350	2350	2350	0	2350	193.7
2400	2400	2350	0	2350	194.5
2500	2500	2350	0	2350	196.2
2600	1300	2350	1300	2350	390.7
2800	1400	2350	1400	2350	387.5
3000	1500	2350	1500	2350	385.0
3200	1600	2350	1600	2350	383.0
3400	1700	2350	1700	2350	381.6
3600	1800	2350	1800	2350	380.9
4000	2000	2350	2000	2350	381.2
4300	2150	2350	2150	2350	383.0
4700	2350	2350	2350	2350	387.5

The results are presented in Table 6-6. As in the PMS loading strategy 1, both units are equally sized without any exception to any load demand. Difference is shown in the area of operation of 2,350-2,858 kW with one diesel-generator to supply the network and the fuel cost to be decreased. Furthermore, the redundant unit will be of the same power capacity as the operational units.

6.4.4.3 Exhaustive search optimisation results for case 2

PMS loading strategy 1

Table 6-7: Design Load dependent start and stop table for case 2, strategy 1 of passenger ship

Load (kW)	D/G_1 (450-855 kW)		D/G_2 (1000-2350 kW)		D/G_3 (1000-2350 kW)		Specific Fuel consumption (g/kWh)
	Generator loading (kW)	Generator power rating (kW)	Generator loading (kW)	Generator power rating (kW)	Generator loading (kW)	Generator power rating (kW)	
600	600	733.7	0	1983.2	0	1983.2	193.7
800	800	855	0	1922.5	0	1922.5	194.9
860	0	855	860	1495	0	2350	194.4
1000	0	855	1000	1495	0	2350	191.8
1200	0	855	1200	1503.7	0	2341.3	190.4
1400	0	855	1400	1753.3	0	2091.8	190.4
1600	0	855	1600	2003.6	0	1841.4	190.4
1800	0	855	1800	2254.1	0	1591	190.4
2000	0	855	2000	2350	0	1495	190.6
2200	0	855	2200	2350	0	1495	191.9
2350	0	855	2350	2350	0	1495	193.7
2400	491	591	1909	2056	0	2053	385.5
2500	0	855	1250	1922	1250	1923	393
2600	0	855	1300	1922	1300	1923	383.2
2800	0	855	1400	1923	1400	1923	381.5
3000	0	855	1500	1923	1500	1923	380.8
3200	0	692.6	1600	2003.7	1600	2003.7	380.7
3400	0	450	1700	2125	1700	2125	380.7
3600	0	450	1800	2125	1800	2125	381.1
4000	0	450	2000	2125	2000	2125	384.1
4260	378	450	1941	2125	1941	2125	576.6
4700	450	450	2125	2125	2125	2125	584.1

The results for case 2 following the loading strategy 1 are presented in Table 6-7. For the load demand ranging up to 2,350 kW, the D/G_2 is online and its sizing meets its upper loading limit. For loads ranging from 2,360 kW up to the maximum demand, the almost equal D/G_2 and D/G_3 power rating is shown with the D/G1 to be sized considering efficient point for the rest of the power demand.

PMS loading strategy 2

Table 6-8: Design load dependent start and stop table for case 2, strategy 2 of passenger ship

Load (kW)	D/G_1 (450-855 kW)		D/G_2 (1000-2350 kW)		D/G_3 (1000-2350 kW)		Specific Fuel consumption (g/kWh)
	Generator loading (kW)	Generator power rating (kW)	Generator loading (kW)	Generator power rating (kW)	Generator loading (kW)	Generator power rating (kW)	
600	600	733.7	0	1983.2	0	1983.2	193.7
800	800	855	0	1922.5	0	1922.5	194.9
860	0	855	860	1495	0	2350	194.4
1000	0	855	1000	1495	0	2350	191.8
1200	0	855	1200	1503.7	0	2341.3	190.4
1400	0	855	1400	1753.3	0	2091.8	190.4
1600	0	855	1600	2003.6	0	1841.4	190.4
1800	0	855	1800	2254.1	0	1591	190.4
2000	0	855	2000	2350	0	1495	190.6
2200	0	855	2200	2350	0	1495	191.9
2350	0	855	2350	2350	0	1495	193.7
2400	0	855	2400	2350	0	1495	194.5
2500	0	855	2500	2350	0	1495	196.2
2600	0	855	1300	1922	1300	1923	383.2
2800	0	855	1400	1923	1400	1923	381.5
3000	0	855	1500	1923	1500	1923	380.8
3200	0	692.6	1600	2003.7	1600	2003.7	380.7
3400	0	450	1700	2125	1700	2125	380.7
3600	0	450	1800	2125	1800	2125	381.1
4000	0	450	2000	2125	2000	2125	384.1
4260	0	450	2130	2125	2130	2125	387.6
4700	450	450	2125	2125	2125	2125	584.1

The calculated results for case 2 following the loading strategy 2 are presented in Table 6-8. The results reveal the difference, compared to the previous strategy, in units sizing and fuel consumption for load demand 10% higher than the D/G2 rated power, i.e. 2,350-2,585 kW. For the rest demand, the same sizing is applied as in the previous strategy.

6.4.4.4 Exhaustive search optimisation results for case 3

PMS loading strategy 1

Table 6-9: Design load dependent start and stop table for case 3, strategy 1 of passenger ship

Load (kW)	D/G_1 (1000-2350 kW)		D/G_2 (1000-2350 kW)		D/G_3 (1000-2350 kW)		Specific Fuel consumption (g/kWh)
	Generator loading (kW)	Generator power rating (kW)	Generator loading (kW)	Generator power rating (kW)	Generator loading (kW)	Generator power rating (kW)	
600	600	1000	0	1850	0	1850	193.6
800	800	1001.8	0	1849.1	0	1849.1	190.4
1200	1200	1503.7	0	1598.1	0	1598.1	190.4
1400	1400	1753.3	0	1473.4	0	1473.4	190.4
1600	1600	2003.6	0	1348.2	0	1348.2	190.4
1800	1800	2254.1	0	1223	0	1223	190.4
2000	2000	2350	0	1175	0	1175	190.6
2200	2200	2350	0	1175	0	1175	191.9
2300	2300	2350	0	1175	0	1175	193.1
2350	2350	2350	0	1175	0	1175	193.7
2400	1200	1503	1200	1503	0	1694	380.7
2500	1250	1565	1250	1565	0	1570	380.7
2600	1300	1628	1300	1628	0	1444	380.7
2800	1400	1753.2	1400	1753.2	0	1193.5	380.7
3000	1500	1850	1500	1850	0	1000	380.7
3200	1600	1850	1600	1850.0	0	1000	381.4
3400	1700	1850	1700	1850.0	0	1000	383.1
3600	1800	1850	1800	1850.0	0	1000	385.8
3800	1267	1566.7	1267	1566.7	1267	1566.7	571.1
4000	1333	1566.7	1333	1566.7	1333	1566.7	571.7
4200	1400	1566.7	1400	1566.7	1400	1566.7	573.3
4400	1466.7	1566.7	1466.7	1566.7	1466.7	1566.7	575.8
4700	1566.7	1566.7	1566.7	1566.7	1566.7	1566.7	581.2

The results for case 3 are shown in Table 6-9. For the range of operation up to 2,350 kW where D/G1 is online, the sizing of the rest offline units is equal. For the range of 2,360 – 3,700 kW where D/G1 and D/G2 are in function, both are equally sized and also equally loaded. Moreover, during the load demand range from 3,800 to 4,700 kW, all units are equally sized and equally loaded.

PMS loading strategy 2

Table 6-10: Design load dependent start and stop table for case 3, strategy 2 of passenger ship

Load (kW)	D/G_1 (1000-2350 kW)		D/G_2 (1000-2350 kW)		D/G_3 (1000-2350 kW)		Specific Fuel consumption (g/kWh)
	Generator loading (kW)	Generator power rating (kW)	Generator loading (kW)	Generator power rating (kW)	Generator loading (kW)	Generator power rating (kW)	
600	600	1000	0	1850	0	1850	193.6
800	800	1001.8	0	1849.1	0	1849.1	190.4
1200	1200	1503.7	0	1598.1	0	1598.1	190.4
1400	1400	1753.3	0	1473.4	0	1473.4	190.4
1600	1600	2003.6	0	1348.2	0	1348.2	190.4
1800	1800	2254.1	0	1223	0	1223	190.4
2000	2000	2350	0	1175	0	1175	190.6
2200	2200	2350	0	1175	0	1175	191.9
2300	2300	2350	0	1175	0	1175	193.1
2350	2350	2350	0	1175	0	1175	193.7
2400	2400	2350	0	1175	0	1175	194.5
2500	2500	2350	0	1175	0	1175	196.2
2600	1300	1628	1300	1628	0	1444	380.7
2800	1400	1753.2	1400	1753.2	0	1193.5	380.7
3000	1500	1850	1500	1850	0	1000	380.7
3200	1600	1850	1600	1850.0	0	1000	381.4
3400	1700	1850	1700	1850.0	0	1000	383.1
3600	1800	1850	1800	1850.0	0	1000	385.8
3800	1900	1850	1900	1850.0	0	1000	389.4
4000	2000	1850	2000	1850.0	0	1000	394.0
4200	1400	1566.7	1400	1566.7	1400	1566.7	573.3
4400	1466.7	1566.7	1466.7	1566.7	1466.7	1566.7	575.8
4700	1566.7	1566.7	1566.7	1566.7	1566.7	1566.7	581.2

The calculated results for case 3 following the loading strategy 2 are presented in Table 6-10. The difference of the results with the previous strategy are shown to the loading area of 2,350 -2,585 kW where the upper loading limit is met for the D/G_1. In addition, during the area ranging from 3,700-4,070 kW the D/G_1 and D/G_2 which are online remain at their previous sizing condition, i.e. 1,850 kW, receiving higher load thanks to the increased upper limits setting for this strategy.

6.5 Power management system optimiser guidelines

Fuel optimisation of the on board electrical energy systems is applicable during operation and design as it was studied in this chapter. However, the considerations focusing on electrical systems energy efficiency could possibly result at decisions that could possibly reduce the safety of the equipment and the systems themselves. The findings of this chapter were categorised and compiled based on the ship type and life-cycle stage and will serve guidelines for ship power management system design.

Cargo ship

Operation

- Same fuel saving potential is applied by setting the systems diesel-generators upper load limit at their rated power with 10 % higher than that.

- Setting the diesel-generators upper load limit at level lower than their rated, results to increased fuel consumption.
- The blackout prevention constraint is violated for load demand higher than 90% of the installed generating capacity when generators load limit is set lower than the generators power rating.

In the latter case, even though the operation is safer and the maintenance costs are reduced, the need for extra generating power during high load demands, requires the additional operability of the redundant unit.

Design

In the choice between low and high power rating diesel-generator sets:

- Two sets of low power rating diesel-generators were applied with the exact sizing to be based on the designers choice of the area of vessel's operation and the decided PMS loading strategy during operation

Although equal sizing of diesel-generators sets is widely applied for cargo ships, the choice of the area of ship operation is of high importance with the possibility of generators sizing inequalities as well as the appropriate choice of the PMS loading strategy during operation. A set of maximum power rating diesel-generators set has to be added as redundant unit for blackout prevention constraint compliance.

<u>Passenger ships</u>

Operation

- The highest fuel saving potential is applied by setting the diesel-generators upper load limit at 10 % higher than their rated power.
- Setting the upper load limit at diesel-generators power rating increases slightly the fuel consumption.
- Setting the diesel-generators upper load limit at level lower than their rated, results to increased fuel consumption.
- The blackout prevention constraint is violated for load demand higher than 90% of the installed generating capacity when generators load limit is set lower than the generators power rating.

In the latter case, even though the operation is safer and the maintenance costs are reduced, the need for extra generating power during high load demands, requires the additional operability of the redundant unit.

Design

In the choice between low and high power rating diesel-generators sets the possible combination were investigated:

- Two sets of high power rating diesel-generators
- Two sets of high and one set of low power rating diesel-generators
- Three sets of high power rating diesel-generators

However, the choice of the most appropriate and energy efficient depends on the area of ship operation decided by the designers, which is of high importance for the number and the exact sizing of the power generating set, as well as on the PMS loading strategy that will be followed during vessel's operation. In addition to this, a set of maximum power rating diesel-generators set has to be added as redundant unit for blackout prevention constraint compliance.

6.6 Closure

This chapter focused on the application of the power management system in cargo and passenger ships. The optimisation and exhaustive search processes, which are constrained by technical, maintenance and stand-by limitations, targets the fuel minimisation during operation and the optimal sizing of the diesel-generators sets power capacity during systems design. Through the unit commitment and the economic power dispatch process, the load dependent start and stop tables were derived which can be integrated to the control system for the case of operation or can be used for power generations sets sizing for the case of design. In addition, regarding guidelines were proposed for both ship types concerning PMS during operation and design.

7 SAFETY-CRITICAL SYSTEMS AVAILABILITY DURING EMERGENCIES

7.1 Preamble

In an attempt to design the electrical energy systems of passenger ships considering the safety as another key objective following the energy efficiency, this chapter is focusing on the logical and topological modelling of the safety-critical systems, with the latter being applied to statistical flooding damages. This allows for quantitative safety performance assessment of the systems using probabilistic rules during emergencies. Systematic investigation for the identification of the vulnerable zones is performed with additional proposed design solutions considering systems transverse and vertical onboard topology optimisation.

7.2 Post-damage systems availability

7.2.1 Principles of the availability assessment

Regarding the current introduced SRtP regulations, design flexibility of the safety critical systems is afforded by the AD&A framework and therefore the decisions are taken by the designers. This relative autonomy gives not only a chance to make the best use of their corresponding knowledge and experience but it also implies that it might not be wise to follow minimal requirements when more robust and safer design does not have to be more expensive (in the time of an accident potential consequences could be mitigated by built-in safety measures).

Compliance with the regulations could be achieved either by analysing systems' availability using deterministic approach, i.e. involving "all casualty scenarios" or by employing probabilistic methods to generate the scenarios. Even though both methods can be used against requirements, there are fundamental distinctions that make significant difference to the scope of application.

Firstly, the deterministic cases are screened prior to analysis and therefore contain only subset of all possible scenarios, called as "all casualty scenarios" previously, whereas the scenarios generated with use of probabilistic methods contain all the scenarios with screening performed in the time of analysis and with the vetting driven by the probabilities of scenarios occurrence. The difference may seem to be slight but it may have major impact on the quality of the results as the latter case do not require any form of judgment and consequently the outcome is not biased by scenario selection. Moreover, being linked with the probabilistic framework of ship damage stability, the probabilistic assessment could enhance ships absolute survivability. In addition, the probabilistic assessment provides valuable information about vulnerability of the vessel to the considered fire or flooding casualties, as it is investigated latter at this chapter for the flooding case.

Another advantage that the probabilistic-based approach has is related to the damages penetration. Considering both transverse and vertical extend, their link with the systems equipment could potential define areas for the latter's location onboard with enhanced availability. The current regulations set "safety" limits as 1/10 and 1/20 of the ship's beam (i.e. symbolised as B/10 and B/20 respectively) for transverse (measured from the shell) and vertical (measured from the bottom) penetrations respectively. Therefore, all system's components located within these boundaries are considered not to be mechanically damaged. However, these limits are set to enable deterministic assessment, with this study to investigate areas of increased availability onboard through the application of probabilistic assessment.

7.2.2 Methodology

The probabilistic-based approach adopted for the design of the safety-critical systems comprises the below parts:

- modelling
- damage scenarios
- availability analysis

The above parts are explained below.

Modelling

The modelling part was following the principles described in section 4.3 of chapter 4 for the safety-critical systems. All systems were supplied by the main power distribution system with the emergency system to supply the most of the redundancies, with minor exceptions supplied by the main. The onboard topological diagram of the above systems conventional design for this study's passenger vessel is shown in APPENDIX III.4. For this chapter's investigation purposes, the absence of the emergency system and the corresponding redundancies were considered with the outcomes to be used for the former and latter sizing and corresponding onboard topology optimisation.

Damage scenarios

For the reliability analysis of the electrical distribution energy systems, the systems and the components failures at emergencies have to be initiated. The casualty that will be involved in this study is the most frequent in shipping, i.e. the collision (or grounding). Damage occurring as a result of collision or grounding relates to breaching of the hull structure with subsequent flooding of spaces below water level and exposed to damage opening. The interior of the vessel is divided into a number of WT compartments separated by watertight partitions: transverse and longitudinal bulkheads and decks. All spaces (rooms) within WT compartments were assumed to be floodable, i.e. all the rooms within the damaged zone were considered as being affected. All statistical damages were considered in the availability analysis and a weighted average was calculated. Concerning the SRtP compliance, statistical applied damages are limited to those affecting only single WT compartment.

There are standard approaches for evaluating probabilities of flooding ship spaces which are based on statistical data of damage location, length, vertical extent and penetration. Such a multivariable probability distribution is integrated over domains formed by WT partitions with the integrals obtained for each compartment and all possible combinations of compartments to be called p-factors and be denoted as p_i. Damage scenarios were generated with use of software NAPA for single and group of transverse zones through the use of subdivision tables. The p-factors for all damage cases along with a list of compartments being damaged were passed as input for probabilistic assessment of systems availability.

Availability analysis

After the components placement within the vessel environment, with the parallel creation of dependency structures, the computational stage for solving the above created logical expressions was following. For analysis purposes, the dependency structures were transformed into an acyclic graph BDD [80]. In principle, a BDD was a graphical representation of the so-called truth table, i.e. of a set of all possible solutions (false and true) of given logical expression which was structured by functions and components. All the system components and functions were subjected to individual damage scenarios, which were defined as a combination of probability of occurrence p_i and a list of spaces (rooms) affected. At this point, the difference with the deterministic approach has to be highlighted since through the latter the probabilities are dropped, i.e. p_i=*1* for all the cases.

More specifically, all the system components and functions were grouped into a vector quantity ***S*** with binary components where S_{ji} (*j=1,…,N* and *i=1,…,n)* stands for a state (0 or 1 for availability or unavailability respectively) of the *j-th* system in the *i-th* damage scenario. So, the probability of system being unavailable can be expressed by means of matrix notations:

$$F = \begin{bmatrix} F_1 \\ \vdots \\ F_N \end{bmatrix} = \frac{1}{\sum_{i=1}^{n} p_i} \begin{pmatrix} S_{11} & \cdots & S_{1n} \\ \vdots & \ddots & \vdots \\ S_{N1} & \cdots & S_{Nn} \end{pmatrix} \begin{bmatrix} p_1 \\ \vdots \\ p_N \end{bmatrix} \tag{7.1}$$

The element p_i denotes probability of the *i-th* scenario and F_j stands for aggregated probability of *j-th* system being unavailable. The normalising factor[1] was used as p-factors should be sum up to one in case of all possible damages were considered. However, for the case of SRtP compliance, only damages occurring in any single WT compartment were assessed and so the normalising factor equals the sum of the probability of damage occurrence in each specific WT compartment. Furthermore, the precise meaning of the components F_j of the vector F (probability of *j-th* system being unavailable) was an average probability of system being unavailable given any considered damage scenario has happened [31].

[1] Normalising is called the $\left(\sum_{i=1}^{n} p_i\right)^{-1}$ factor including in the denominator of the equation (8.1).

To this end, targeting to increase the safety-critical systems post-damage availability during emergencies, a passenger ship was used as application case, the same as in previous chapters, with the propulsion, steering and bilge and ballast systems to have been under investigation. Systematic investigation for the identification of the critical components and zones was performed with the application of all possible flooding damages coupled with their probability of occurrence. Having identified the critical areas, aspects of optimising the systems safety performance within them were evaluated focused on the systems onboard topology in terms of transverse and vertical extent.

7.3 Systematic investigation

Investigation about the identification of the most vulnerable ship zones for each of the examined safety-critical system was performed at this section. The below systems were investigated:

- propulsion system
- steering system
- bilge and ballast system

with the emergency system to be absent at this stage. For the purposes of this study, the same passenger ship as in chapter 6 were employed with its GA to initiate the WT subdivisions as shown in Figure 7-1. In addition, the conventional design of the safety-critical systems considering their dependencies and their onboard location of the systems components with their source of power are shown in APPENDIX III.3 and APPENDIX III.4

respectively. The data about the location and the cables routing of the power distribution and utilisation systems and components have been provided within the EC-funded REFRESH project.

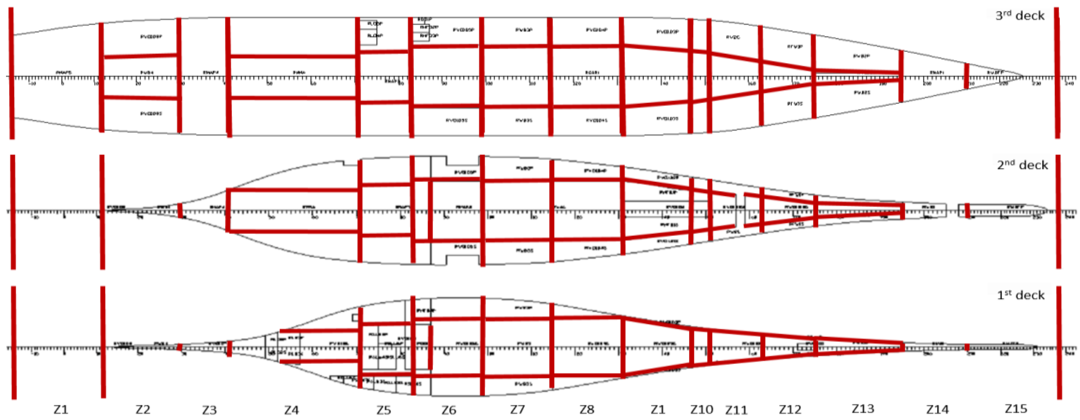


Fig 7-1. "WT arrangements of the vessel being subject of this study"

After the accomplishment of the modelling part, through the use of subdivision tables, all possible collision damage scenarios were generated with use of NAPA software coupled with their probability of occurrence. Therefore, by knowing the conventional design of the safety-critical systems onboard and all damage scenarios with the corresponding p-factors, the probabilistic assessment was performed for identifying each systems most vulnerable zones that were characterised as critical. Each vessel zone was bounded by transverse bulkheads with 15 zones to be in total, Figure 7-1. The vertical extent of the flooding damages were up to the third deck. Furthermore, it was assumed that any systems component placed in a damaged room was damaged as well and, also, the damage propagation is out of the scope of this work.

For probabilistic assessment visualisation results purposes, the technique of triangles upon vessel's starboard side view which is widely applied for vessels survivability was adopted. The triangles corresponds to a set of damages within a domain starting with the single zone damages, then to two adjacent zones and continuing up to six adjacent zones damages covering the whole longitudinal zone range of the vessel. According to the evaluation results, the triangles were coloured considering their criticality and severity for each examined system. In this study, four colours were selected filling each triangle for categorising them and, in turn, the corresponding zone or zones:

a) green

b) yellow

c) orange

d) red

The green colour ranges for resulted values of 0-0.01 probability of being unavailable and represented the safest zone or zones. The yellow colour represented a slight higher rate of probability being unavailable, 0.01-0.03, with the orange colour, 0.03-0.05, indicating high level of severity and, therefore, corrected actions should be done. The most vulnerable areas were filled with red colour where corrected actions or even redundancies have to be considered for increasing the level of systems availability therein, Figure 7-2.

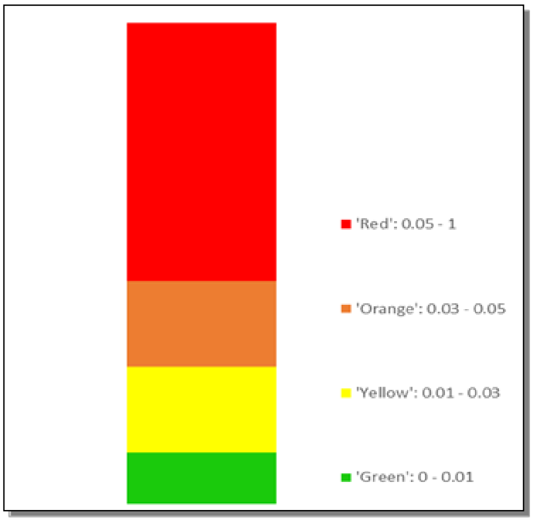


Fig 7-2. "Categorisation of damaged zones severity"

The aggregated calculation results for the safety-critical systems are presented in Table 7-1. The results are presented as damages within any single WT compartment, for SRtP compliance, and as all possible casualty scenarios according to probabilistic framework. The results show the different level of safety and accuracy when the rules compliance is the only objective.

Based on the Table 7-1 results the propulsion and the bilge and ballast systems are almost at the same levels of safety with the steering systems to have surprisingly high probability of being unavailable. For the better understanding of the aggregated results, the use of triangles was initiated as described above with the results of the propulsion, steering and bilge and ballast systems to be shown in Figures 7-3, 7-4 and 7-5 respectively.

Table 7-1. Average probability of system being unavailable given flooding damages

System	Damage scenarios	
	Single WT compartment	All damages
Propulsion	0.21	0.28
Steering	0.54	0.68
Bilge & Ballast	0.2	0.26

Through the power distribution and utilisation systems topology shown in APPENDIX III.3 and diagrammatically in APPENDIX III.4, it is noticed that the functionality of the propulsion system was performed mostly at the E/R and the A/R, zones 4 and 5 respectively. Therefore, both zones could be considered as the most vulnerable according, also, to the results in Figure 7-3. However, although the engine room has high unavailability rate at emergencies considering the single WT compartment damages, the auxiliary room has rather low as the yellow triangle reveals. Nevertheless, considering two and three adjacent zones damages, the real unavailability rates were derived including not only the auxiliary room as critical but also the zone 6 wherein the power flow path for higher decks fans, i.e. supply and exhaust engine and auxiliary room fans, was included.

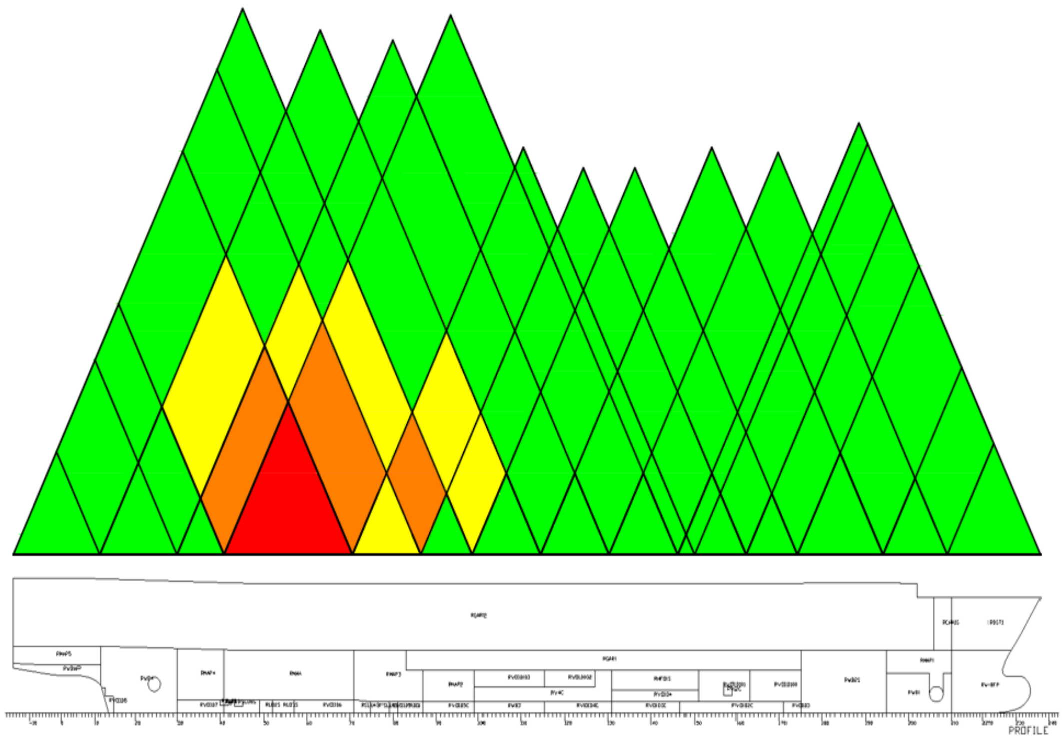


Fig 7-3. "Propulsion system availability triangles for the conventional design case"

For damage scenarios considering more than three adjacent zones to be damaged, their probability of occurrence is highly reduced and consequently even grouped zones including the critical are marked as safe. The rest zones of the vessel are marked as safe regarding the propulsion system limited extent.

The calculated triangles of the steering system are shown in Figure 7-4. The high average probability of being unavailable shown in Table 7-1 is easily explained with the large number of red, orange and yellow triangles. Because of the systems topological extent throughout the ship's longitudinal axis, the critical areas could considered not only the zones 4, 5 and 6 as in propulsion case, but also in the stern side zones where the steering gears and the stern thruster were located, i.e. zones 1 and 2. In addition, in the bow side of the vessel the zone where the bow thruster was located and zones around it are marked as critical with the zones 7-9, comprising power cables, to be under consideration for the former's power supply.

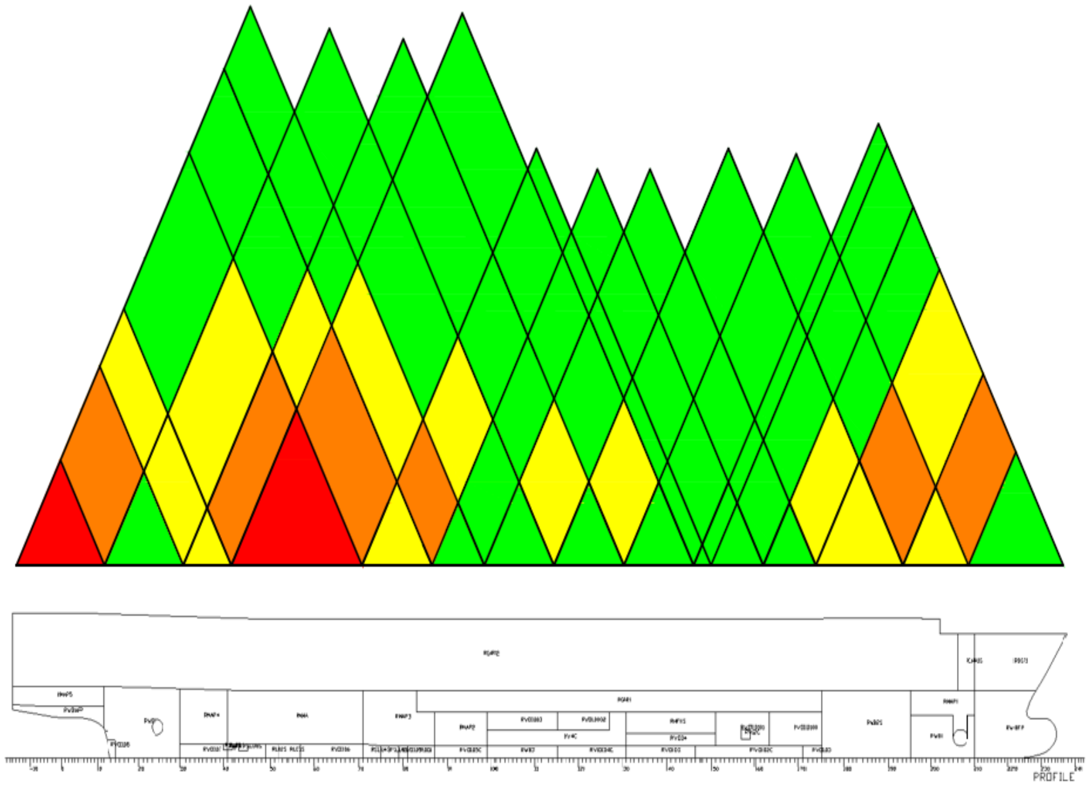


Fig 7-4. "Steering system availability triangles for the conventional design case"

Results about the bilge and ballast system are shown in Figure 7-5. As expected from the aggregated results, the bilge and ballast system's results are almost the same with the propulsion system case with the only difference that zones

6 and 7 are not as vulnerable as previously due to the lack of upper deck's connection.

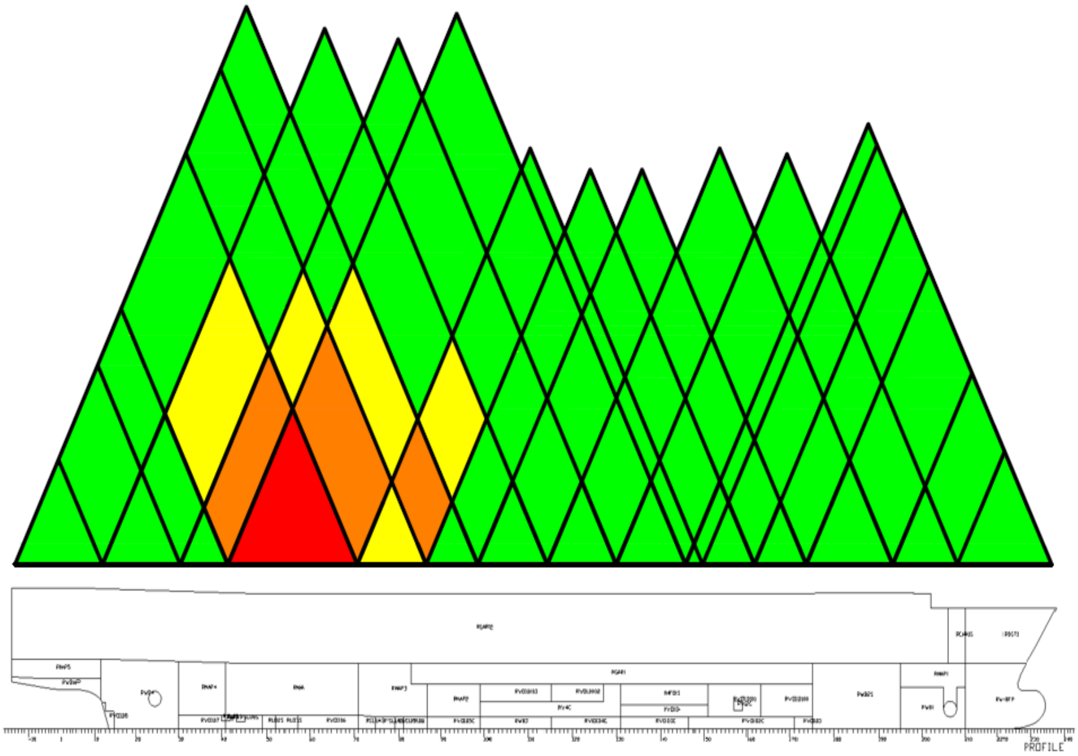


Fig 7-5. "Bilge and ballast system availability triangles for the conventional design case"

7.4 Onboard systems topology and geometry optimisation

Having identified the critical zones for each safety-critical system, design solutions about the increase of the availability therein should be investigated and proposed without disregarding the cost of them as well. In this study, the onboard topology of the electrical power distribution system was investigated considering the cases of its transverse relocation closer to the ship's reference frame and its re-routing through safer zones and decks. Apart from the power distribution system, considerations about the power utilisation system topology was investigated through the system's relocation following the distribution. In order the above to be achieved, the identification of areas with low level of damage vulnerability had to be initiated through the performance of systematic probabilistic assessment. The optimisation results were presented, in tables and triangles formats, and compared using the systems availability as comparison metric.

In case of zones with considerably high level of unavailability after the optimisation modifications, the use of components redundancies should be applied through the emergency system. Targeting parallel to the safety increase the cost reduction as well, the assumption made in this study was that the power utilisation equipment redundancies should be as less as possible, in other words the systems relocation and re-routing, even in high rates, was preferred than the corresponding units redundancies, as a qualitative cost metric. Moreover, it was assumed that all components within specific bounded areas were considered damaged only in damage scenarios overlapping the latter area. So, in a damaged room only equipment which therein location overlaps the damage penetration was considered as unavailable. Also, the assumption that all rooms and spaces were considered as possible re-routing paths and relocation areas for the investigated systems regardless of their existing usability was made. Again, damage propagation was out of the scope of this work.

7.4.1 Systems transverse onboard topology optimisation

The transverse onboard topology of the power distribution and utilisation systems was investigated as an attempt to maximise the safety-critical systems post-damage availability in the already identified critical zones without the application of redundant utilisation units. The approach followed aiming the identification of an area within the zones, including the critical, where the aggregated flooding damage probability to be reduced.

Based on the probabilistic index, areas closer to the ship's longitudinal reference frame have, firstly, lower probability of being damaged and, secondly, being affected by lower number of damage scenarios. Therefore, the relocation of the systems into that area would increase the quantitative levels of their availability. Focusing on the number and location of longitudinal bulkheads especially at the critical zones, an 'enhanced-availability area' has been chosen, with transverse limits at B/3 and longitudinally covering the whole ship range and not only the critical zones. The aggregated probability 'invading' this area is 0.43 which is much less than the absolute one for all possible damage scenarios.

By locating the systems into the defined 'enhanced-availability area' and applying statistical damages, the probabilistic safety performance was calculated and analysed. Two cases were investigated below: firstly, only the power distribution system and secondly, both power distribution and power utilisation systems to be relocated within. The calculation results were presented and compared between them and with the conventional case as well.

Power distribution system

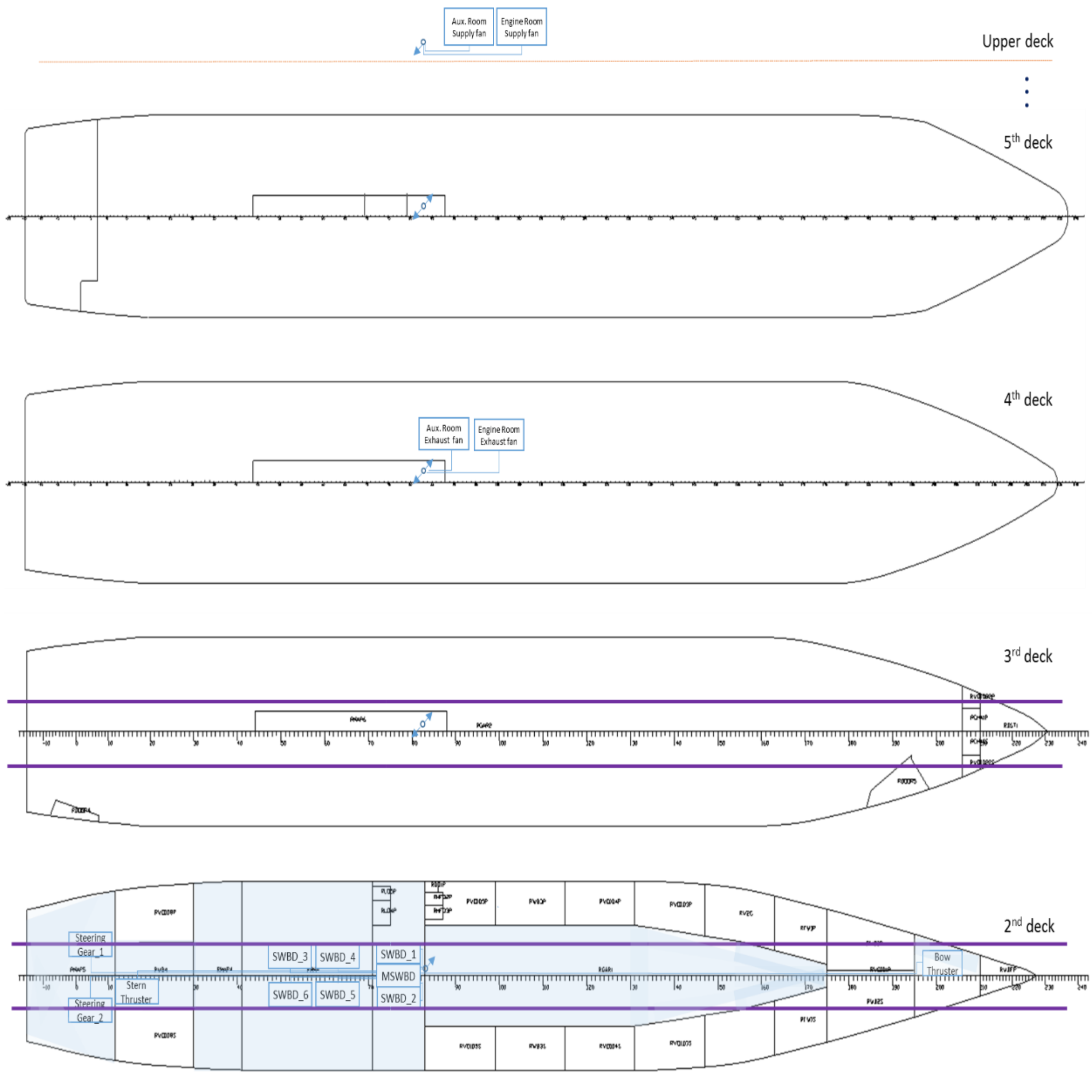


Fig 7-6. "Onboard systems topology for the power distribution system transverse extent case"

The onboard modelling of the modified power distribution system was presented in the Figure 7-6. According to that, the distribution system's switchboards and power cables were relocated within the 'enhanced-availability area', with the flow paths for the propulsion, steering and bilge and ballast systems to have been relocated through the longitudinal reference frame of the vessel for reduced vulnerability. The 'enhanced-availability area' was bounded by the purple lines with the power utilisation system to have been located within the light blue coloured areas. The power flow to the upper decks fans of the propulsion system was remaining through the same path since it was located within the 'enhanced-availability area' geometrical limitations.

The aggregated results for the propulsion, steering and bilge and ballast systems are shown in Table 7-2. Compared with the conventional case, the bilge and ballast system's availability remains at the same level, with the propulsion to be slightly better regarding all possible damages results. Concerning the steering system, due to its longitudinal extent throughout the whole vessel, its availability rate is 47% higher than the conventional case but still improvements are needed. A more detailed sight of the results are present in Figures 7-7, 7-8 and 7-9 for the propulsion, steering and bilge and ballast systems respectively in triangles format.

Table 7-2. Average probability of systems being unavailable given flooding damages.

System	Damage scenarios	
	Single WT compartment	All damages
Propulsion	0.21	0.27
Steering	0.35	0.47
Bilge & Ballast	0.2	0.26

Propulsion system's availability seem slightly improved with the yellow triangle in zones 6-7 to be green now. However, the area around the E/R and A/R is exactly of the same safety level as in the conventional case, regardless of the power distribution systems relocation. This happens due to the fact that even though only damages within the 'enhanced-availability area' are influencing the distribution system, the utilisation system's components, i.e. motors and fans, are still affected by all damages into the corresponding zones. The same consequence applies to the bilge and ballast system in which the distribution system's relocation did not improve the availability assessment results.

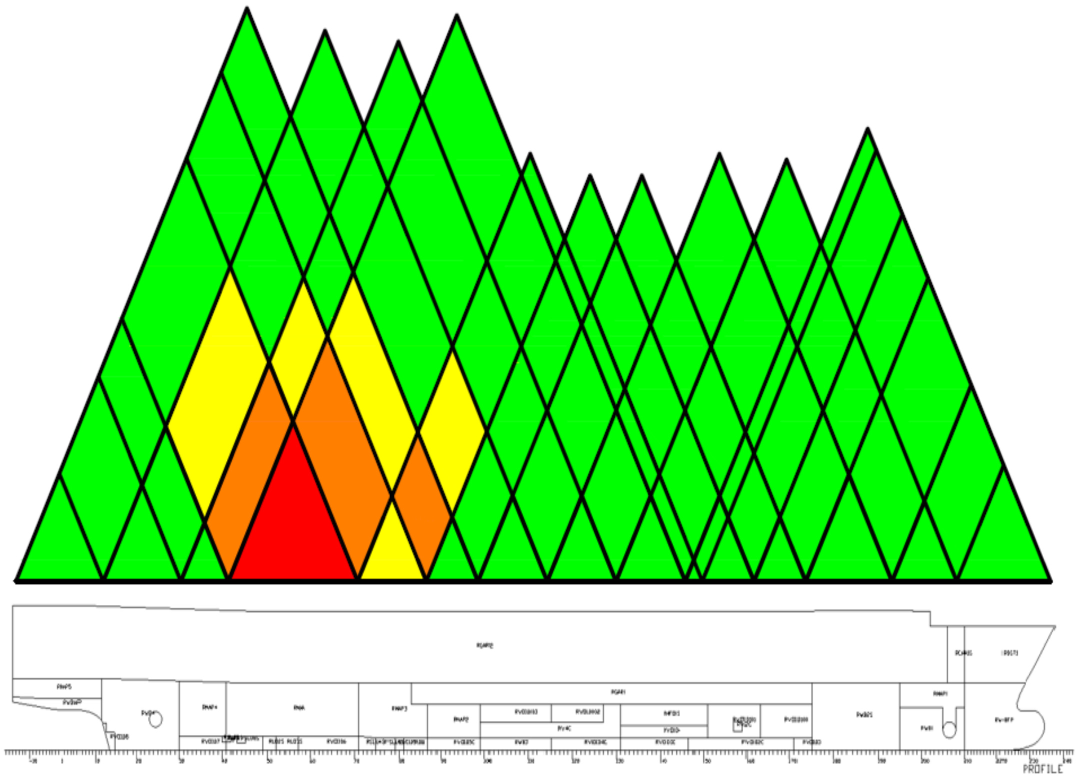


Fig 7-7. "Propulsion system availability triangles for the power distribution system transverse extent case"

The most improved availability is of the steering system. At the stern and bow zones of the vessel, the availability improvement is limited but with huge enhancements in the areas inside and around the E/R and A/R, i.e. in zones 3-7. This is a result of the lack of utilisation components into that zones for the steering system and consequently the distribution system's relocation increased vastly the level of availability. However, still the level of unavailability in zones 1-3 and 13-15 are high.

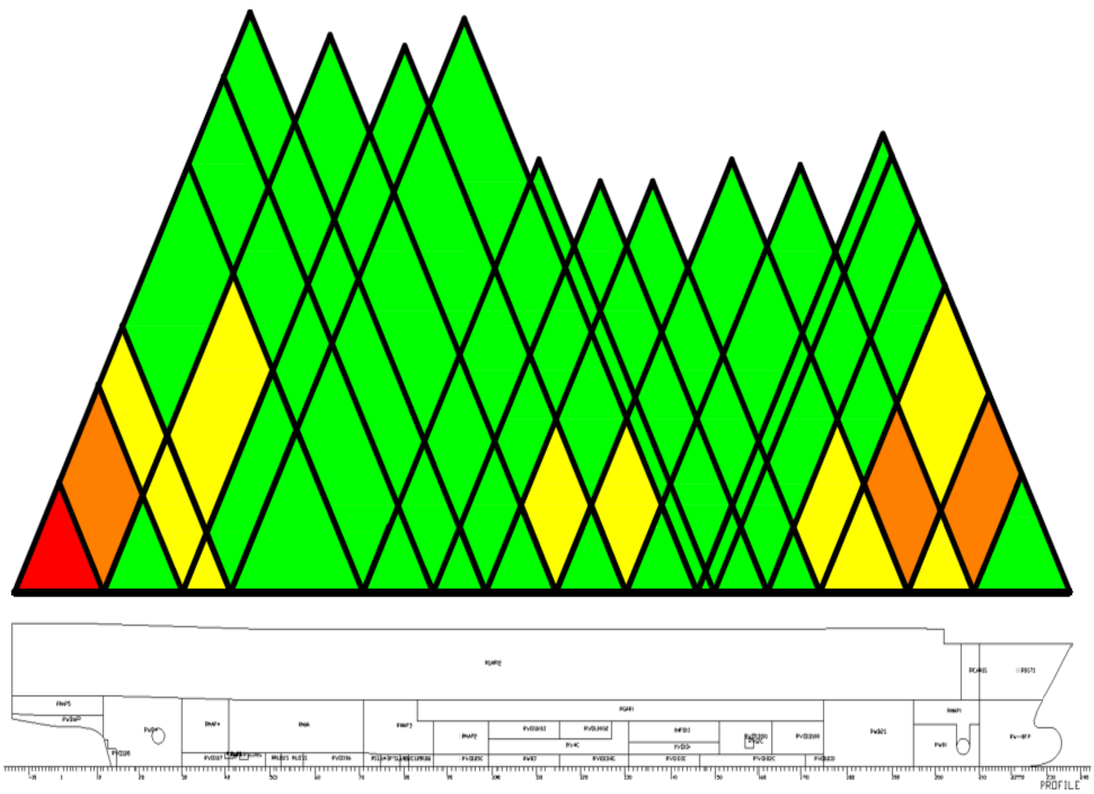


Fig 7-8. "Steering system availability triangles for the power distribution system transverse extent case"

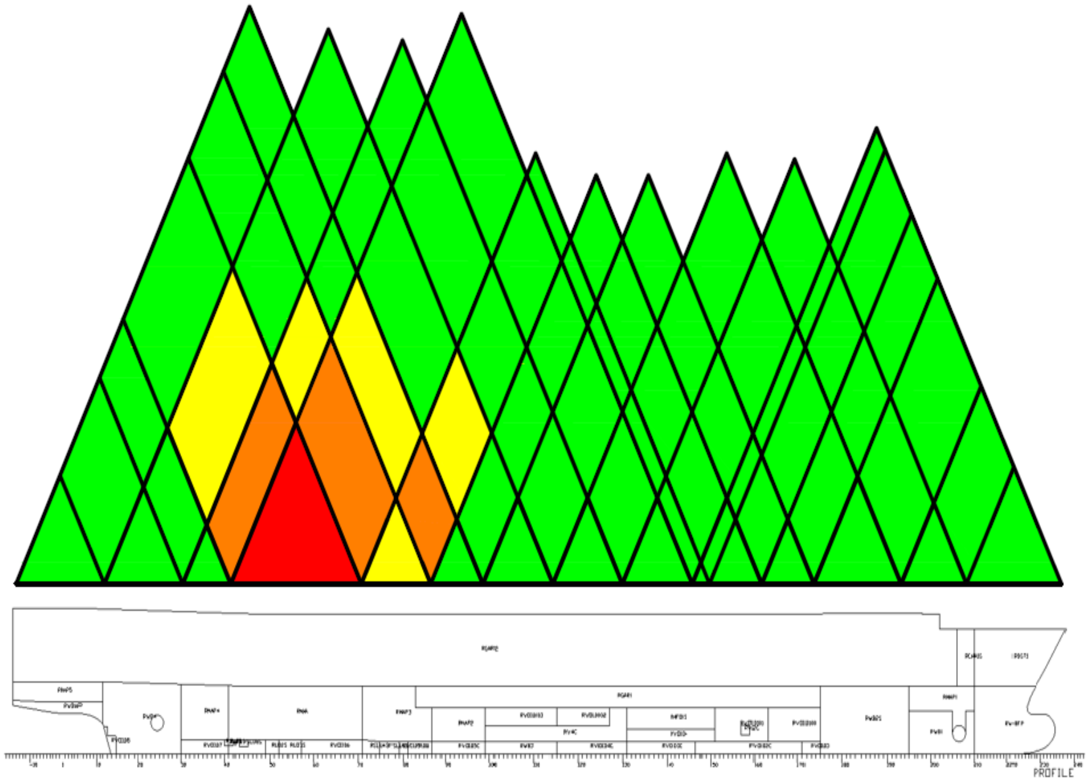


Fig 7-9. "Bilge and Ballast system availability triangles for the power distribution system transverse extent case"

Power distribution and utilisation systems

In the previous section only the power distribution system were optimised through its relocation to the 'enhanced-availability area'. Having identified that the power utilisation system's topology onboard was responsible for the low availability rates for the propulsion and the bilge and ballast systems, its optimisation was considered in this section through its relocation, simultaneously with the power distribution system, to the 'enhanced-availability area'. The onboard modelling of the power distribution and utilisation systems are presented in the Figure 7-10.

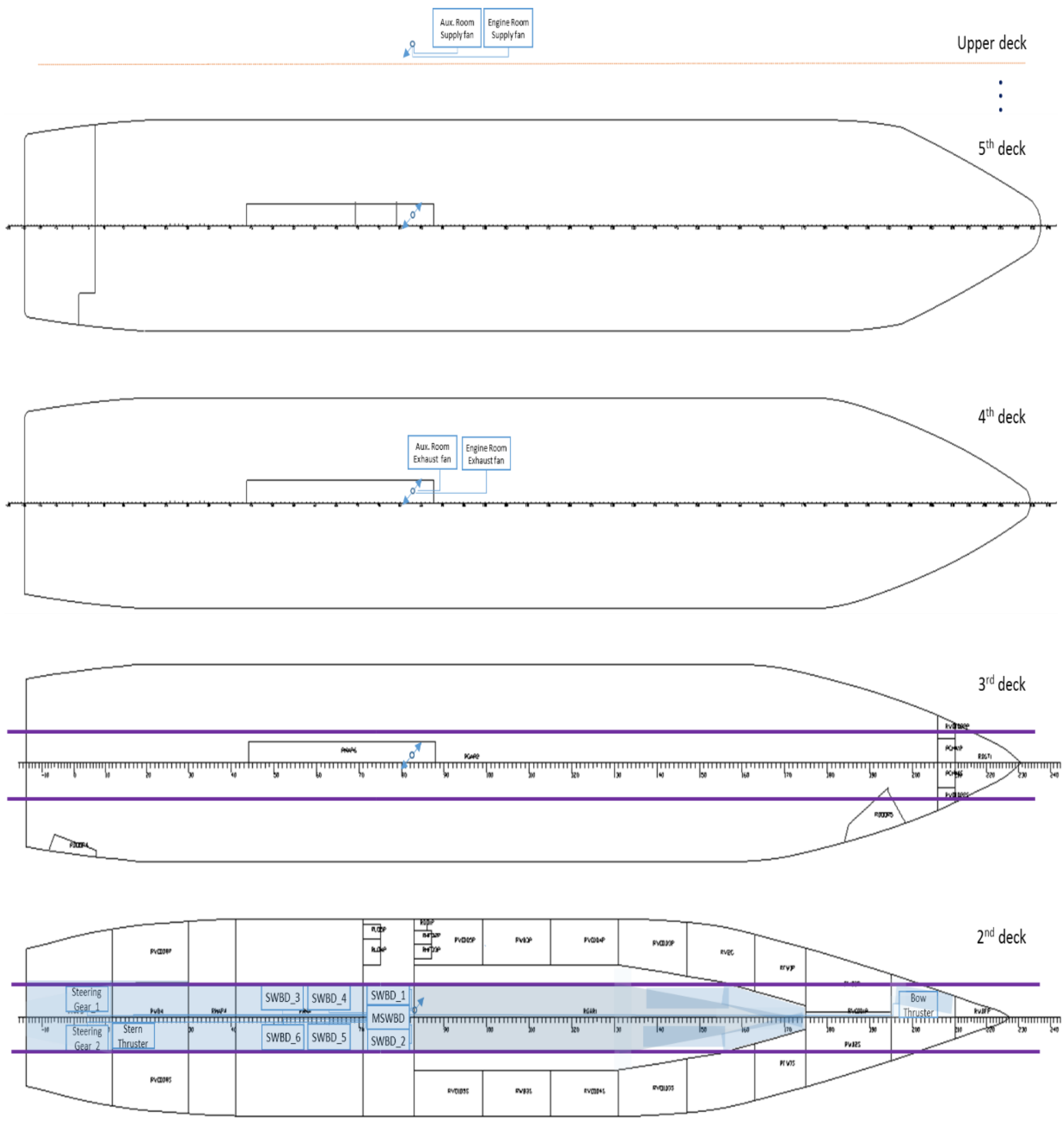


Fig 7-10. "Onboard systems topology for the power distribution and utilisation systems transverse extent case"

The aggregated calculated results of the investigation are presented in Table 7-3. It is easily understood that both propulsion and bilge and ballast systems have almost zero probability of being unavailable after flooding damages application. For the case of steering system, even though the results based on the single WT compartments damage is the same as in the previous section, regarding the application of all possible damages results it is 27% reduced. The triangles below explain the above results in detail.

Table 7-3. Average probability of systems being unavailable given flooding damages.

System	Damage scenarios	
	Single WT compartment	**All damages**
Propulsion	0.03	0.06
Steering	0.35	0.37
Bilge & Ballast	0.02	0.04

In Figures 7-11 and 7-13 where the results for the propulsion and bilge and ballast systems are shown, it is obvious that both systems are unaffected by the flooding damages for the whole ship range. Consequently, the placement of the power utilisation system units closer to the longitudinal reference frame of the vessel maximised the availability.

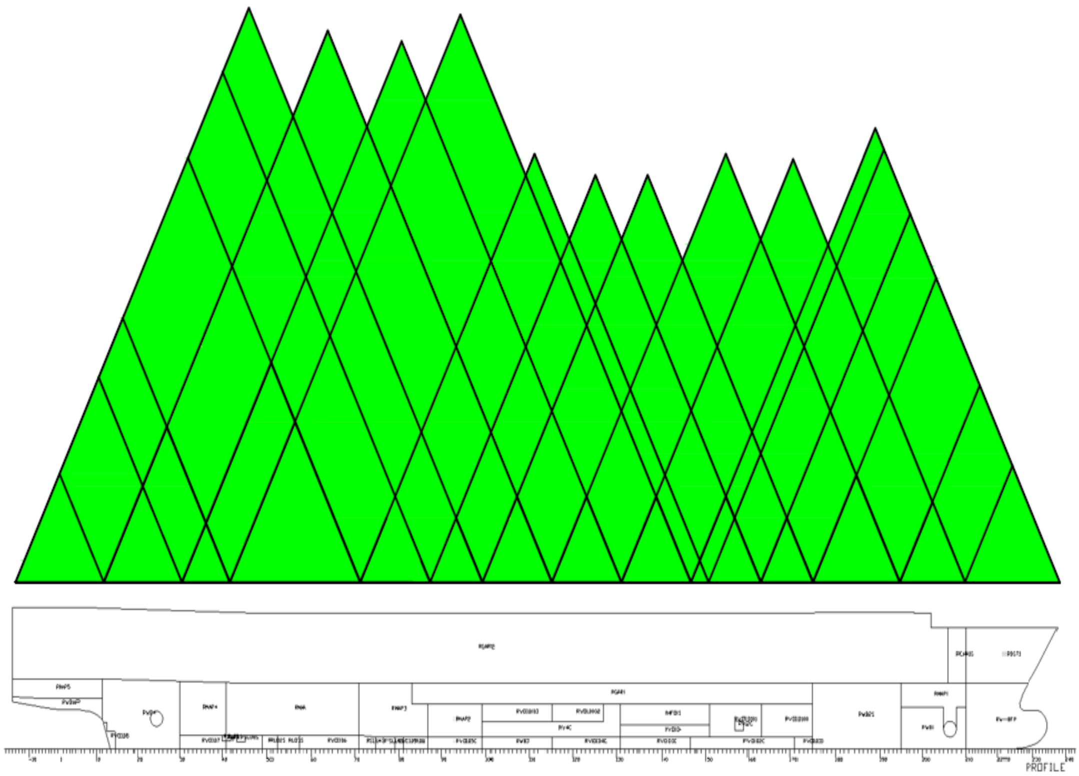


Fig 7-11. "Propulsion system availability triangles for the power distribution and utilisation systems transverse extent case"

In Figure 7-12 the triangles for the steering system are shown. It is seen that improvements exist not only in the bow but also in the stern zones of the vessel. Since the stern and bow thrusters entered the 'enhanced-availability area' the orange triangles became yellow and green, with similar results not applying for the steering gear motors case. The latter is a conclusion of the high probability of the zone being damaged regardless of its penetration. Additional optimisation is needed for further safety improvements, something that was investigated on the next section of this chapter.

Furthermore, through the results visualisation for the steering system, it could be highlighted that the single WT compartments colours are the same as of the previous section without happening the same for the rest damage scenarios and probabilities. This proves the insufficiency of taking under consideration during the assessment only a limited number of damage scenarios and their corresponding probabilities.

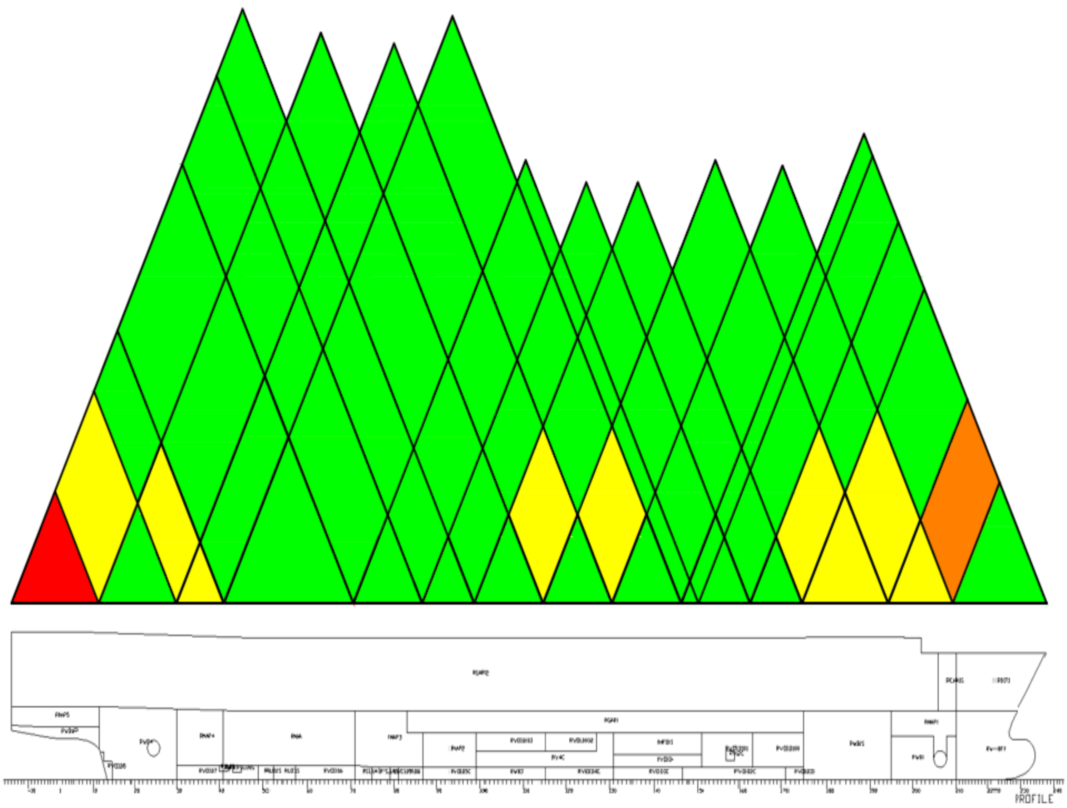


Fig 7-12. "Steering system availability triangles for the power distribution and utilisation systems transverse extent case"

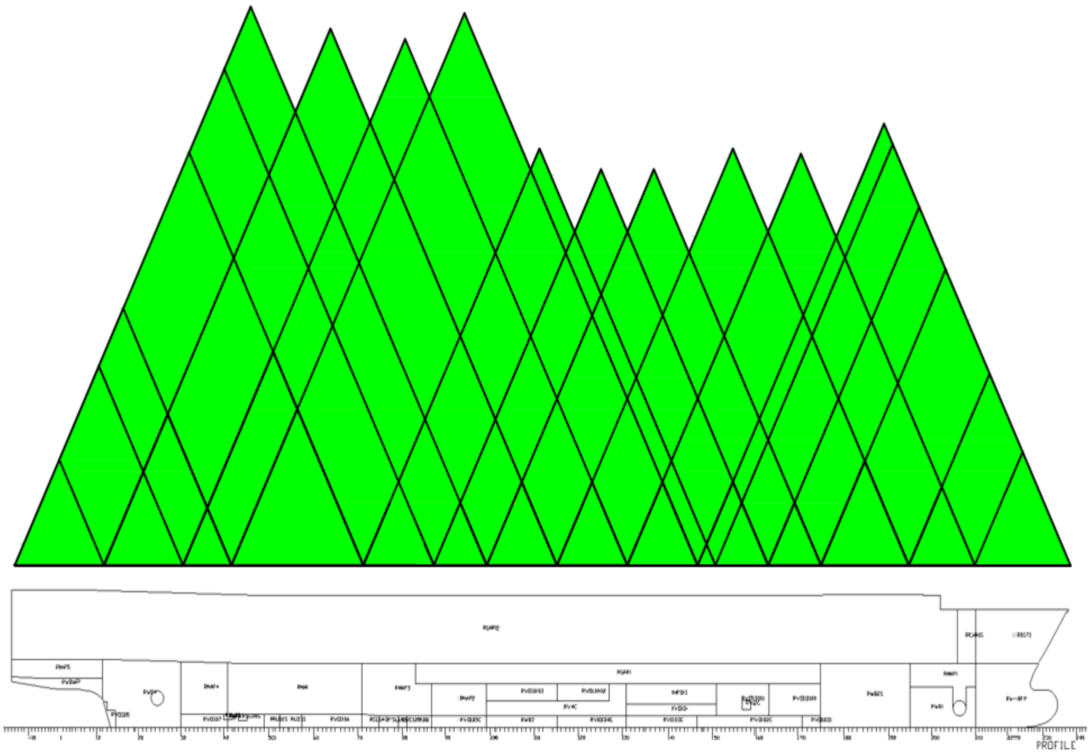


Fig 7-13. "Bilge and ballast system availability triangles for the power distribution and utilisation systems transverse extent case"

7.4.2 Systems transverse and vertical onboard topology optimisation

In the previous section the investigation of the safety-critical systems onboard topology optimisation over one dimension, the transverse, was performed. The results reveal the need for further optimisation for the steering system with the alternative of applying utilisation units redundancies being supplied by the emergency distribution system. However, the latter choice increased the initial invested cost and further optimisation was examined. In this section the investigation of the vertical topology optimisation only for the steering system was performed in conjunction with, firstly, the relocation only of the distribution system to the 'enhanced-availability area' and, secondly, the relocation of the utilisation system into it as well. The optimisation results were presented, analysed and compared with previous examined cases.

Power distribution system

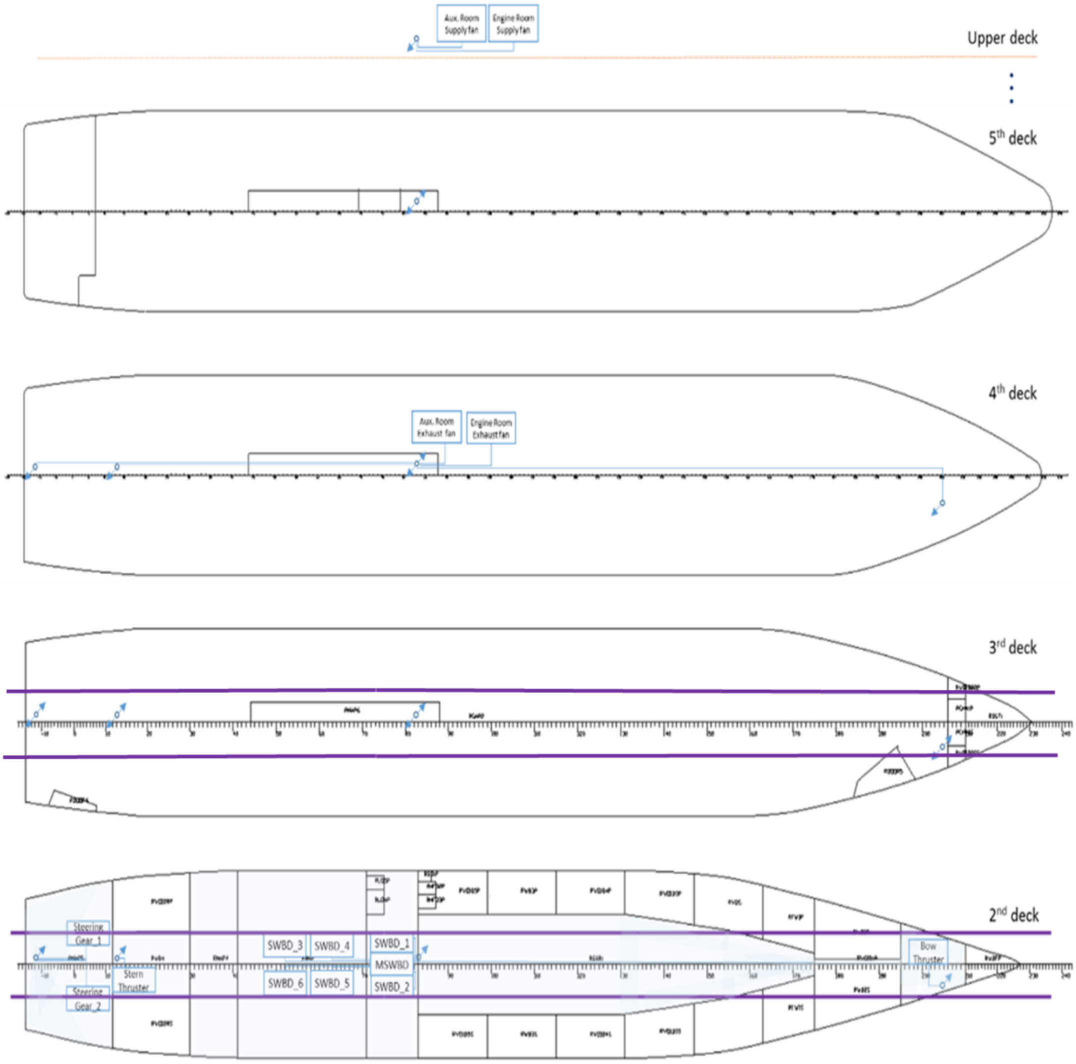


Fig 7-14. "Onboard steering systems topology for the power distribution system transverse and vertical extent case"

The modelling of the power distribution system is presented in the Figure 7-14. According to that, the distribution system switchboards and power cables were relocated within the 'enhanced-availability area' as in the previous section, with the difference that the power flow paths for the stern and bow side of the vessel, where the steering gears and the thrusters were located, was re-routed through the fourth deck of the ship where no flooding damages were considered. By doing so, the damages occurred from the power supply source, MSWBD, until the power utilisers zones were disregarded. As a consequence, the system's availability should have been increased, but, with the simultaneous increase of the power cables lengths.

The aggregated results for the steering system are presented below in Table 7-4. The results reveal the increase of the safety level compared to the previous cases for both single WT compartments and all possible damages scenarios results.

Table 7-4. Average probability of steering system being unavailable given flooding damages.

System	**Damage scenarios**	
	Single WT compartment	**All damages**
Steering	0.23	0.34

The visualisation of the results in triangle format, Figure 7-15, shows that through the power distribution system's re-routing, the zones between the MSWBD and the steering systems utilisers increased their availability rates. The highly unavailability zones remain those that the utilisers are within, i.e.

zones 1, 2 and 14, since all possible damages occurred therein were affecting the results.

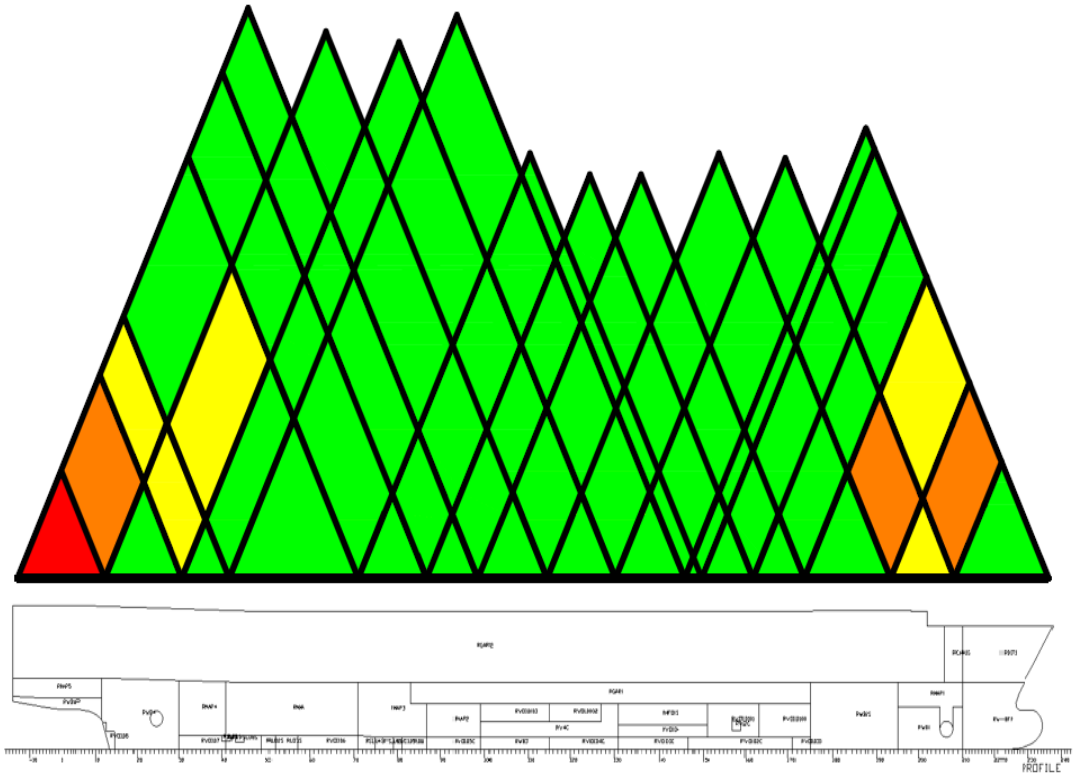


Fig 7-15. "Steering system availability triangles for the power distribution system transverse and vertical extent case"

Power distribution and power utilisation system

In this section the modelling of the power distribution system follows the previous investigation principles for the steering system but additionally the systems utilisers were relocated to the 'enhanced-availability area' for maximising the safety levels. The onboard modelling of the power distribution and utilisation systems were presented in the Figure 7-16.

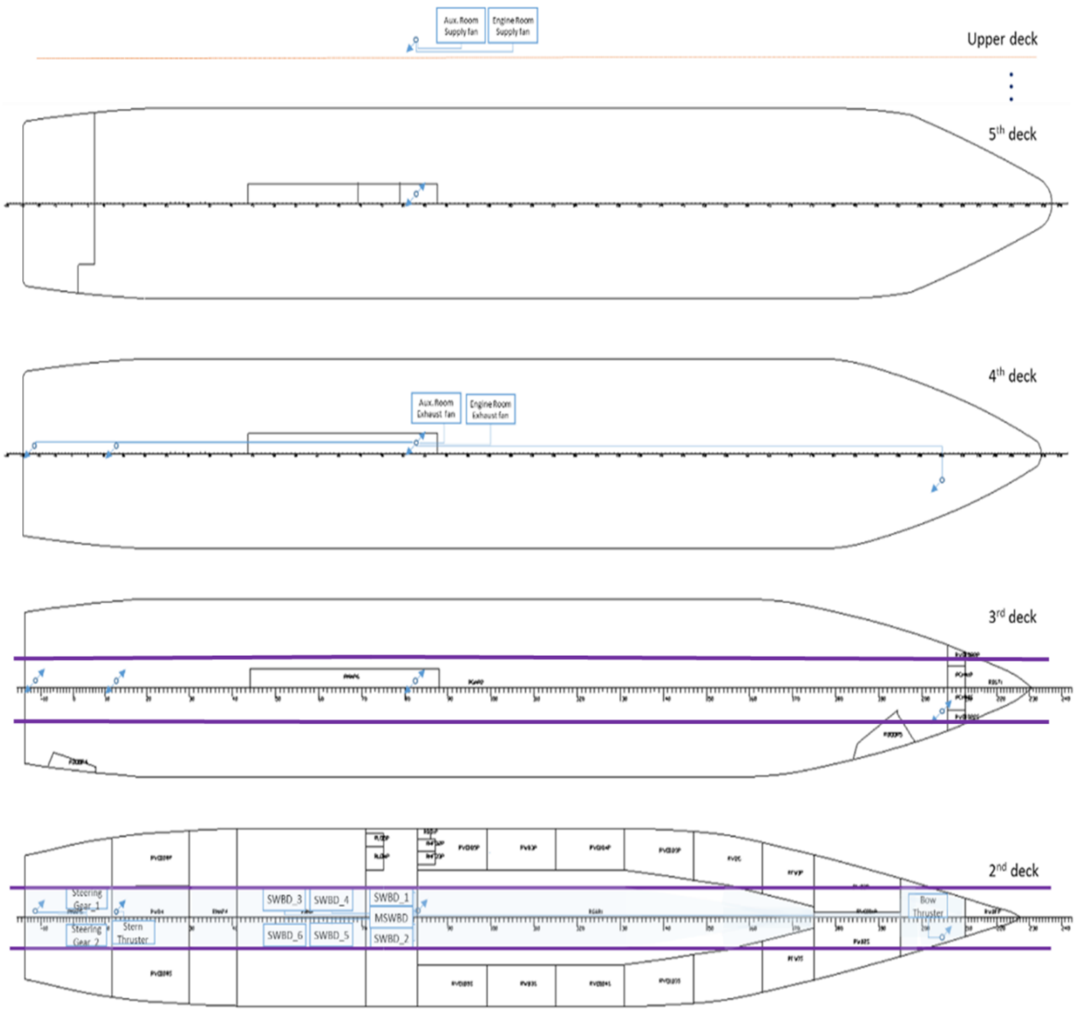


Fig 7-16. "Onboard steering systems topology for the power distribution and utilisation systems transverse and vertical extent case"

The probabilistic assessment results for the steering system are shown in Table 7-5 with the single WT compartment availability results to be almost equal to all possible damages. Although the former's value is the same with the previous examined case the latter's is reduced by 30%. Analysing the results through the triangles form, Figure 7-17, in both bow and stern sides the probabilities of being unavailable have been reduced but depending on designers decisions, need for improvements might be advised.

Table 7-5. Average probability of steering system being unavailable given flooding damages.

System	Damage scenarios	
	Single WT compartment	All damages
Steering	0.23	0.24

In order to further reduce the unavailability rates of the steering system, the need of units redundancies is inevitable, however, with their placement in different than the operating unit zones and always topologically into the 'enhanced-availability area'. Similar principles with the above resulted should be applied for the emergency distribution system topologies supplying the redundant units.

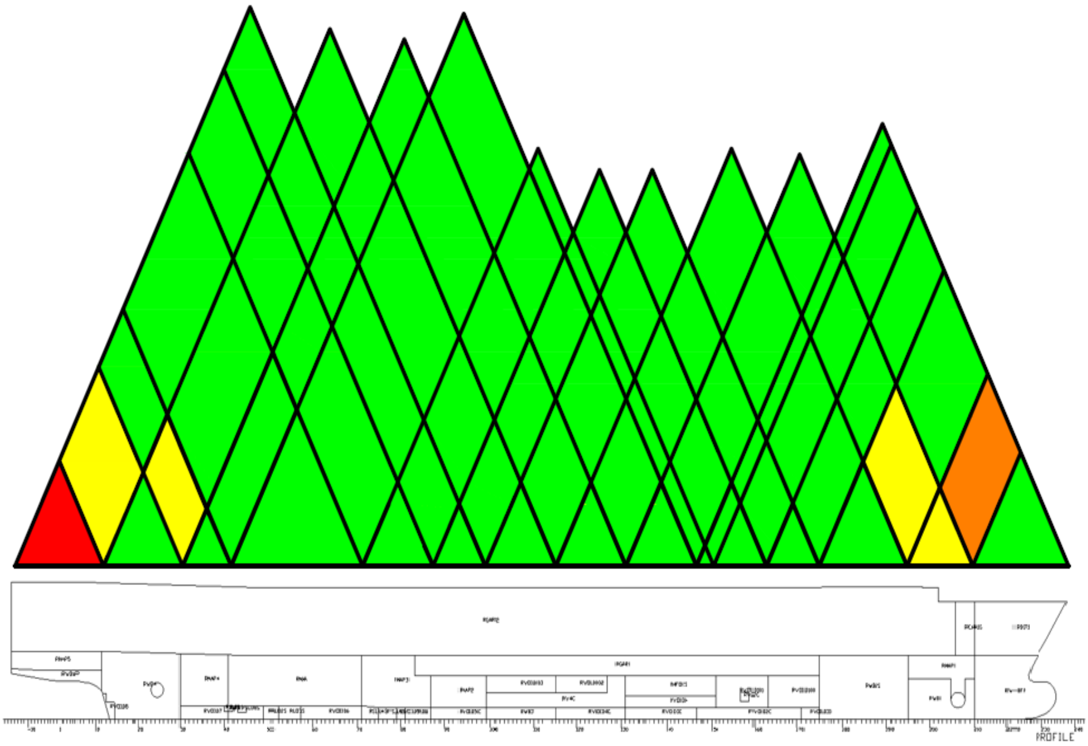


Fig 7-17. "Steering system availability triangles for the power distribution and utilisation systems transverse and vertical extent case"

7.5 Safety-critical systems design guidelines

New SRtP regulations compliance requires quantitative performance assessment of the pre-defined safety-critical systems for the passenger vessels. The approach that is applied should provide as much information and accuracy as possible for efficient designs and the according decisions during it. In addition, the identification of the critical zones of the vessel is of major importance for the systems topologies and through that the optimisation of the vulnerable areas should be investigated instead of the application of direct redundancies. Having performed a number of design cases and analysed the corresponding results, the below guidelines were derived that will serve as a reference for ship safety-critical systems design.

1) The probabilistic assessment based on the probabilistic rules applied in damage stability studies, offering the necessary results accuracy and could be easily be integrated to the ships absolute survivability during the design.

Since all possible damage scenarios were applied compared to a limited number of them in case of deterministic approaches, the results accuracy level was significantly increased. In addition, the same probabilistic index is used during ship design for survivability purposes and could be an integrated part of this process.

2) The critical zones that have the highest probability of being damaged post-casualty are considered the:

    a. engine room

    b. auxiliary room

c. steering room

d. bow thruster’s room

e. stern thruster’s room

The above zones should be taken under careful consideration during the topological systems design due to the importance of power distribution and utilisation components that include and the functions that they serve.

3) Through the topological placement of the power distribution and utilisation systems further (measured from the shell) than the transverse limit of B/3, the probability of systems being unavailable is highly reduced.

As examined extensively in this chapter, the relocation of the distribution systems within the ‘enhanced-availability area’ increases the safety levels of the steering system. However, with the power utilisation system included, the propulsion and the bilge and ballast systems have slight unavailability rate.

4) Further optimisation of the steering system which is spread throughout the whole longitudinal axis of the ship, could be achieved by re-routing the power distribution of the bow and stern zones through decks not influenced by flooding damages.

By re-routing the power distribution system through decks not damaged by the flooding damages, higher level of post-damage availability is achieved but the considerations of higher energy losses should be considered due to increased power cable length.

5) For even further improvements to systems availability, redundant units should be applied and powered through the emergency distribution system, with both aligning with the number 3 guidelines and avoiding being placed into critical zones (number 2 guidelines).

In an attempt to further improve the availability rates of the systems, redundant components should be applied under the constraints that their supplying network and the redundant components will be located within the 'enhanced-availability area' for eliminating the damage probabilities. In addition, the redundancies should be located to zones different from the operating units, which are usually critical, where the vulnerability level is increased.

7.6 Closure

Following the probabilistic assessment for quantifying the safety-critical systems post-damage availability, the level of accuracy of this approach was analysed and discussed. Through the systematic assessment the identification of the critical zones were derived for each system. The topological optimisation of the systems through the identification of critical zones were investigated by initiated the relocation of the power distribution and utilisation systems and additionally the former's re-routing. Results were presented, analysed and compared for each examined case with the derived five guidelines to be discussed at the end of this chapter.

8 CONCEPTUAL DESIGN

8.1 Preamble

The aim of this chapter is to propose design methodology for the electrical energy systems of commercial ships based on quasi-dynamic energy modelling and, for passenger ships, probabilistic assessment with additional demonstration of their application. Two design scenarios were created one for each ship type, which serve as the basis for the development of two electrical power network models. Modelling were following the previous chapters description, simulation and calculation results were presented and decisions were made for the sizing and the on board location of the under investigation systems and corresponding components.

8.2 Performance-based design methodology

With the electrical energy systems modelling and optimisation principles and guidelines at hand, the electrical systems design for commercial ships is now feasible. Through the quasi-dynamic energy modelling concept the energy performance of the vessels is evaluated and additional for the case of passenger ships the post-casualty energy systems availability is assessed for safety purposes during emergencies. Therefore, in an attempt to facilitate and couple the key design objectives, a design methodology is proposed here that is demonstrated in two case studies later in the chapter. Design for both vessels follows a similar methodology and is initially divided in two stages: early and detailed design. Because of the supplementary safety design considerations of the energy systems for the passenger ship, extra safety part was added to the detailed design stage based on corresponding investigated guidelines.

8.2.1 Early design

During early design, the primary objective is to acquire the estimation about the maximum amount of electric power requirements supplying the whole electrical power network in order to size appropriately the power generation sets. The components and systems modelling principles were applied as described in chapter 4 following the simplified electrical energy systems design guidelines of chapter 5.

Once the holistic model is ready based on the vessels systems architecture, simulation is performed for the whole area of operation. A specific route is assumed and the equipment's operation during each state is taken under consideration. Quasi-dynamic simulations results are identifying the power demand of the systems throughout the trip, highlighting the maximum amount of systems power requirements. This serves as the necessary services installed generating power capacity of the power generation systems, excluding the redundancies.

Simulation results and design decisions are presented and compared with the corresponding conventional, steady-state calculations.

8.2.1 Detailed design

Both ship types

During this stage, all components and systems are detailed modelled. For the power generation system, the sizing of the diesel-generator sets is decided during this stage. Based on the decision from the early design stage about the maximum installed services power capacity, also the decision about the area of ship's operation and the pursuing PMS loading strategy during operation, the exact sets sizing derived by the load dependent start and stop design tables of chapter 6 is feasible. In case of absence of clear choice, the use of installation cost is introduced and the choice is based on the most reduced initial investment. Based on the sizing of the diesel-generators sets, the choice of the corresponding auxiliary equipment is usually made, something that is out of the scope of this study. After the sizing decision, detailed modelling is initiated as following the principles of chapter 4. The power distribution and conversion as well as the power utilisation systems are modelled as presented in chapter 4 and according to each vessels systems architecture.

In addition, having decided the PMS loading strategy that will be followed during operation the derivation of the load start and stop table for vessel operation is considered, aligning with the guidelines of chapter 6, and its integration with the local control of the power generation sets. The latter sets is, also, initiated for rules and regulations compliance through the trial and error method that was used to tune the PID controller parameters and ensure the stability of the power network. Fine tuning and optimisation of the controllers is out of the scope of this work.

The results of the quasi-dynamic simulations reveal the outcomes of the design decisions made during the early and the detailed design stages. The active power over time with the unit commitment and load sharing will be related to the fuel consumption of the electrical systems design decisions, with the latter to be compared with the conventional cases considering the current sizing and the corresponding fuel consumption. Furthermore, the quasi-dynamic simulation results about the system's frequency and voltage as well as the loads demand as a function of time are also presented.

Passenger ship

During the conceptual design of the electrical energy systems, the safety performance of the safety-critical systems has to be assessed in emergencies. The modelling of the dependency functions is following the description in chapter 4 and through the guidelines of chapter 7, the topology and geometry of the above systems into ship environment is feasible. Quantitative comparison assessment is applied with the conventional design. In addition, through the pursuing of the chapter 7 guidelines, the sizing of the emergency generation is derived and qualitatively compared with the conventional one. Through the optimisation actions of the cabling system flow paths, the change of the corresponding distribution lines lengths is applied. Therefore, by approximating the lines lengths through the vessels GA, the according modifications to the detailed model of the electrical power network at the detailed design stage are applied.

8.2.3 Design decisions

In the framework of performance-based design, this methodology does not set thresholds that define a good or acceptable design. On the contrary, based on the results of the simulations and the corresponding calculated design tables, the designer can make decisions depending on ship specific objectives.

One of the decisions that have to be made is the sizing of the power generation sets. In order to achieve this aim, a number of requirements are needed included other decision. Initially, the maximum power demand of the electrical network from the early design stage has to be identified through the peak in the power-time result diagram. In addition, the decision about the area of vessel operation has to be made, which in this study is depended on power consumption during the most frequent area of operation derived by the early design simulation results. However, the need for one more decision is needed in order the application of the start and stop design tables of chapter 6 to be feasible. It considers the PMS loading strategy during vessels operation. For this decision, guidelines of chapter 6 are employed. Having the above results and decisions at hand, the diesel-generators sizing is applicable, with an exception of possible investment cost consideration where additional decision has to be done based on minimum cost. It is worth to mention that the power generation sizing decisions were achieved based on the proposed methodology outcomes and consequently may not align with real manufacturers rated characteristics of the corresponding equipment.

Decisions apart from the power generation sizing, are also considering the topology and geometry of the power utilisation and distribution systems for the case of passenger vessels. As in chapter 7, reduced cost is of high priority with the unit redundancies to be considered as the most expensive choice compared to the re-routing even addition of redundant power flow paths. As a consequence, the topology and geometry of the equipment is also affecting the sizing, topology and geometry of the emergency power generation and distribution systems.

Following the described methodology, the electrical energy systems of a cargo and passenger vessel are modelled in the next section and their energy and safety, in the latter case, performance are assessed. The results are presented, analysed and compared with the traditional design approaches.

8.3 Cargo ship

An electrical power network of a cargo ship with mechanical propulsion and no use of thrusters was selected for investigation. Design and architecture specifications were provided within the EC-funded TARGETS project. For this design scenario was assumed to transfer goods from China to the US with the route to last for five days. The components of the electrical energy systems, their architecture and the operational profile of them are extensively described in APPENDIX II.1 and APPENDIX II.2 respectively.

8.3.1 Early design

Initially, the electrical power network is modelled following the principles presented in chapter 4 and the guidelines of chapter 5 for design simplifications. The system configuration presented in Figure 5-17 of chapter 5 were applied with the reference voltage and the reference frequency of the network to be 440 V and 60 Hz respectively. A five days simulation were carried out based on the assumed vessels operational profile. The quasi-dynamic simulation produced the electrical power demand – time variation shown in Figure 8-1. Through this graph, the derivation of the maximum installed services generating power capacity is feasible by identifying the peak value of the electrical power consumed.

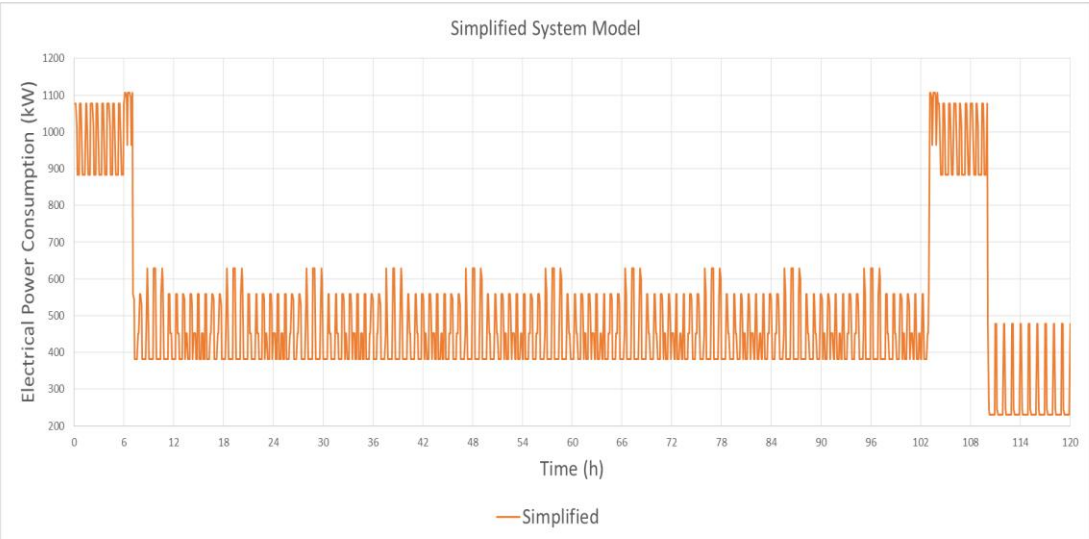


Fig 8-1. "Active power demand for cargo ship electrical systems during early design"

The results show the increased power needs of the system for the loading and unloading condition during the trip with the highest demand to be in manoeuvring state. Following the methodology for the early design, the maximum power demand derived by the quasi-dynamic simulation results, i.e. 1,100 kW, is considered as the total installed services power generating capacity without estimating the redundant unit power capacity.

Furthermore, from the simulation results it is easily identified that the most frequent operating condition is the sea going which last for four days. Taking in for granted, the design decision for the area of operation could be considered the sea going state, where the load demand is approximately at the range of 380 - 640 kW.

Comparison with the conventional case can be considered the electric load analysis which is mainly steady-state calculations. Potentially, the decision about the maximum installed services power capacity is higher than the proposed resulting from the multiplication of the highest power consumption operating condition and the load diversity factor, which is assumed as 0.9 for this case. The latter means that the aggregated load demand of all working units during the operating state with the highest demand, in other words during manoeuvring, are multiplied with the 90% of their rated power and they conclude to the maximum installed generating power capacity. Based on the manoeuvring state presented in APPENDIX II.2, the calculations conclude to the value of 1,400 kW and the Table 8-1 summarises the comparison with the proposed.

Table 8-1: Conventional and Proposed Installed Services Power

Case	Installed Services Power (kW)
Conventional	1,400
Proposed	1,100

With these design decisions, the early design stage comes to an end. The design decision about the installed services power will be used in the detailed design section in order to size the power generating units. The detailed modelling of the electrical energy systems and the results will be compared with the corresponding conventional case in detailed design as well.

8.3.2 Detailed design

In this step of the design process, exact sizing of the power generating sets and explicit electrical power network modelling is introduced based on the design decision of the early design stage and the guidelines of chapter 6 in order to produce more detailed information about the systems power demand and fuel consumption. In addition, a comparison assessment between the proposed and the conventional design is performed to verify the applicability of the proposed methodology.

At this stage, design decision about the exact sizing of the power generation sets should be taken based on the results of the early design and the guidelines of chapter 6. To begin with, in order to size the power generating sets, the choice of the area of operation has to be defined and also the loading strategy of the PMS that will be followed during operation. Concerning the former issue, traditionally the safeguarding of the worst case scenarios ends up to the design point choice as the highest power needs state, in this study case is the manoeuvring. However, by doing so, the potential oversizing is possible, see Table 8-1, and the sizing of the power generation sets will not be according to the different operating states power needs, so as to meet the diesel-generators efficient operating point.

The design decision about the operating area for the cargo ship of our study will during the seagoing where the vessels spends the most of the operating time and considering the Figure 8-1 the approximated power demand varies from 380 - 640 kW, as identified in the early design stage. Having decided the area of operation, the next choice will be of the loading condition of the power generation sets for the PMS operation. Considering the guidelines of chapter 6 during the PMS operation, the amount of fuel that is consumed is the same for the cases of loading the generation sets at their rated power and the 10% excess of it. However, due to the uncertainty level of the early design results of the simplified systems model, as has been proved in chapter 5, the choice of the second scenario can safeguard the power generation system energy efficient functionality, filling the gap of the uncertainty level deriving from the simulation results and offering higher fuel savings during operation.

Having acquired the above important design decisions for the design of the electrical power systems on board, the use of the design load dependent start and stop table 6-4 of chapter 6 can be employed for the exact sizing of the power generation sets, something that will lead to the total installed power of the systems with the presence of a redundant unit as well. Through exhaustive search, the choice of the Table 6-4 instead of Table 6-3 was the outcome from the design decision of pursuing the PMS loading strategy 2, 110% of the rated power as upper loading limit for the generating sets, during operation. However, throughout the range of chosen operation, the suggested sizing varies. So, under the thought that the results from the detailed model will be slightly increased, as derived from chapter 5, and also that the efficient area of operation of the diesel-generator is the 50-90% of its rated capacity, the highest load demand during the seagoing state, i.e. 640 kW, is chosen for the exact sizing of the power generating sets, with one unit to be 650 kW and the other 450 kW according to the Table 6-4.

By proposing the exact sizing of the power generating sets in this study, a redundant units has also to be defined for the regulations compliance. According to the latter, the sizing of it equals to the unit with the highest rated power for the scenario of its single fault. In other words, one more unit of 650 kW active power is added to the system safeguarding it against unsafe functionality. Contrary to the proposed method, the traditional power generation units sizing approach is based on the equal sizing of them disregarding the actual power needs at each operating conditions. Therefore, the steady-state calculations are based on the identification of the operating state with the highest power demand, i.e. manoeuvring, multiplying this demand with the diversity factor, as presented in the early design stage, and then divide the installed services power with the number of units that will be installed, i.e. by two in this study, for equal power generation sizing. Also, one redundant unit is applied of equal size as the rest. In Table 8-2 the summary of the proposed and the conventional sizing is presented with the total installed power, which in turn means investment, is higher in the conventional case.

Table 8-2: Conventional and Proposed Diesel-Generators sizing

Case	D/G_1 (kW)	D/G_2 (kW)	D/G_3 Redundant (kW)	Installed Services Power (kW)	Total Installed Power (kW)
Conventional	700	700	700	1400	2100
Proposed	650	450	650	1100	1750

After the step of the sizing the power generation sets, the detailed modelling of the electrical power systems was initiated based on the previous design decisions. The simplified grid-connected systems model was replaced by the detailed systems model comprising the appropriate functions for the frequency and voltage control of the power generation units, as described in chapter 4, and the PMS loading strategy during operation. In specific, detailed components modelling of the power generation, power utilisation and power distribution and conversion systems was applied. The electrical power system configuration presented in APPENDIX II.1 was used for this case study. In addition, the parameterisation methodologies and manufacturers and software built-in data were applied for the three-phase synchronous machines, the power transformers and the three-phase induction motors as described in chapter 4. For the diesel-engine set, the equations described in chapter 4.2.1 were used with the fuel oil consumption of APPENDIX.IV.1 to be employed after the exclusion of the generators efficiency and the conversion to torque as state variable. Furthermore, the cables lengths where estimated by the vessels GA and for the lines electrical resistance, R_{const}, and inductance, L_{const}, per meter constants manufacturers data where applied. Constant system loads active and reactive demand at each time interval is presented in the operational profile in APPENDIX II.2.

Moreover, the load dependent start and stop table has to be created for the proposed diesel-generator sets. The PMS operation strategy that will be followed was decided above and for the derivation of the corresponding table the same process as in chapter 6 were applied. The derived table is presented above in Table 8-3 and it was used as input to the frequency control scheme. The PI parameters of the frequency and voltage control schemes were tuned through the informal trial and error method so that the system power demand to be as close as possible for both cases at each time interval.

Table 8-3: Load dependent start and stop table for cargo ship

Load (kW)	D/G_1 (650 kW rated) (kW)	D/G_2 (450 kW rated) (kW)	D/G_3 (650 kW rated) (kW)	Specific Fuel Consumption (g/kWh)
112.5	0	110	offline	240.0
200	0	200	offline	224.7
300	0	300	offline	199.0
420	420	0	offline	199.6
500	500	offline	0	197.1
600	600	offline	0	199.2
720	410	310	0	395.3
800	464	336	0	392.1
900	532	368	0	390.6
1000	595	405	0	392.9
1100	695	405	0	406.5
1210	715	495	0	427.7

The quasi-dynamic simulation results are shown in the figures below. In Figure 8-2 and 8-3 the supplying active and reactive power of each power generating set, respectively, is presented with the highest rated diesel-generator set to be used during all operating conditions. The lowest rated power generation set is online in parallel with the highest during the loading and unloading operating states as well as during the manoeuvring. During the port operation, the operation of both sets was initiated but not simultaneously depending always on the instantaneous load demand and the PMS optimiser outputs. The corresponding power factors for each of the systems generator are shown in Figure 8-4.

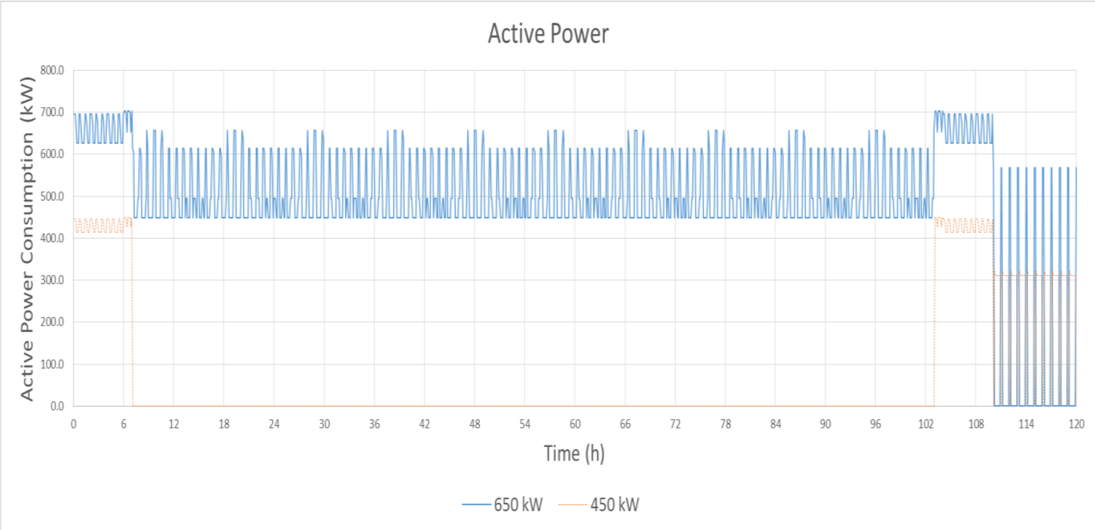


Fig 8-2. "Active power for proposed design of cargo ship electrical systems"

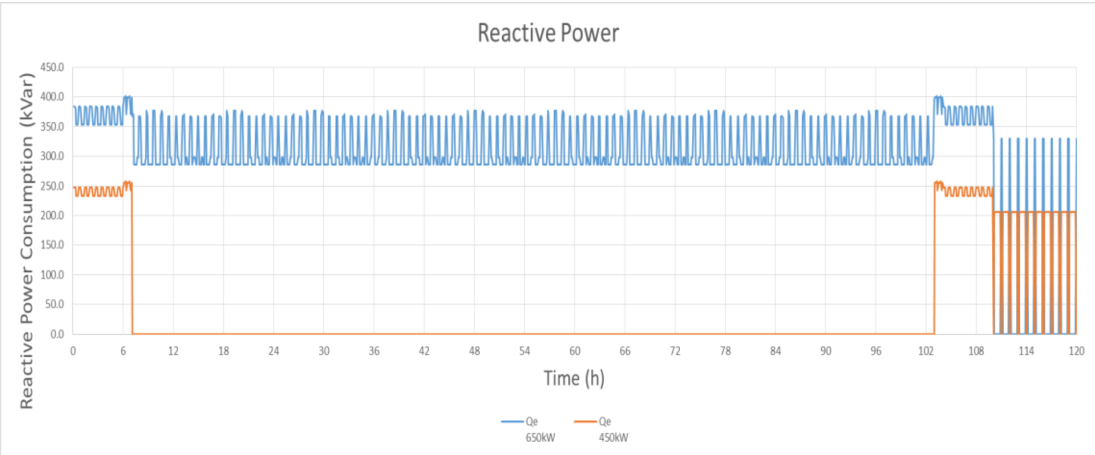


Fig 8-3. "Reactive power for proposed design of cargo ship electrical systems"

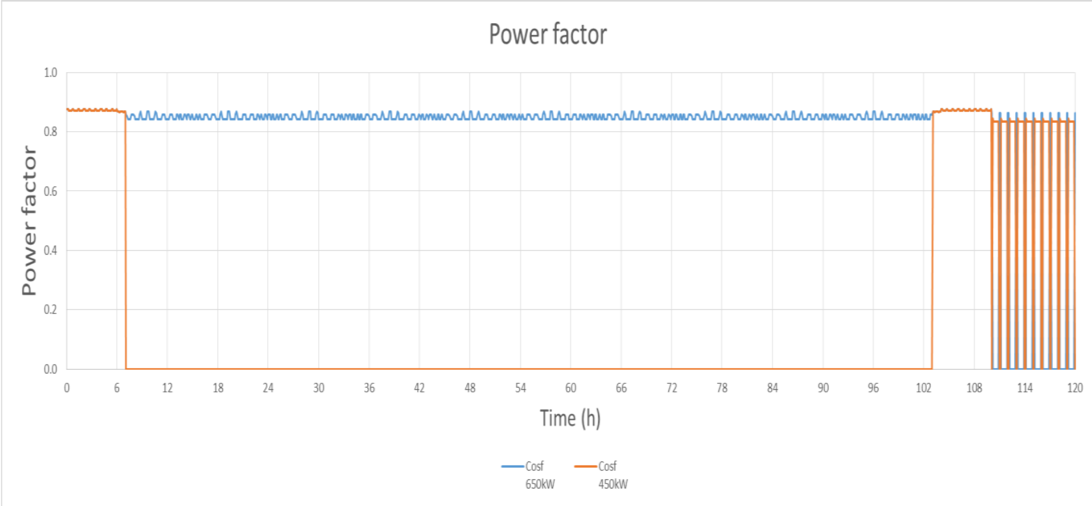


Fig 8-4. "Power factors for proposed design of cargo ship electrical systems"

In the Figures 8-5 and 8-6 the results for the frequency and voltage applied to the main switchboard of the systems is shown during the route simulation.

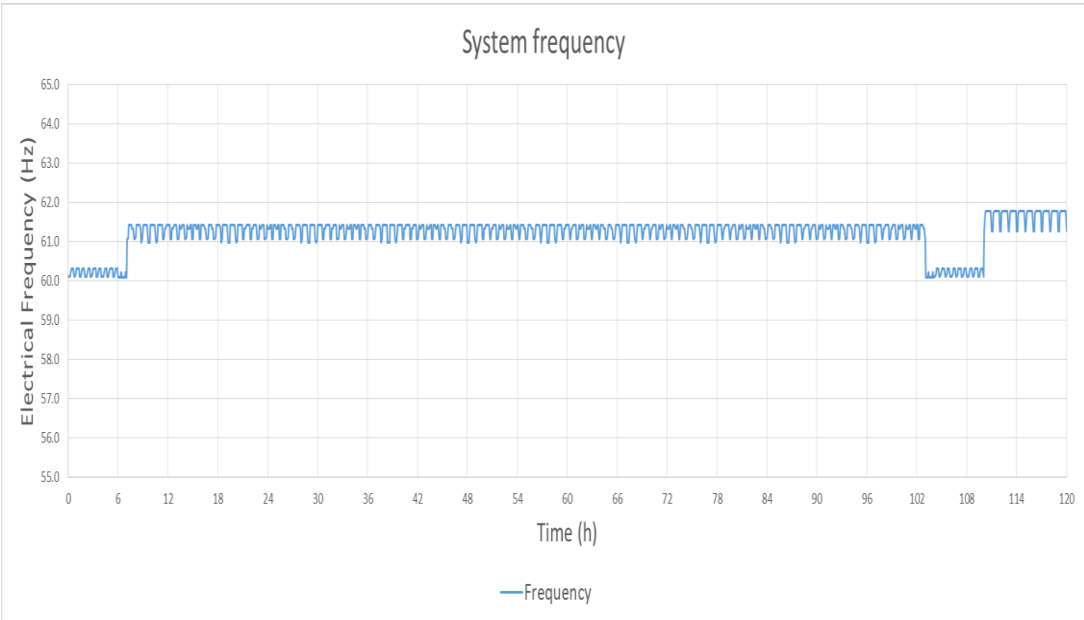


Fig 8-5. "Electrical frequency applied to the bus of the cargo ship electrical systems"

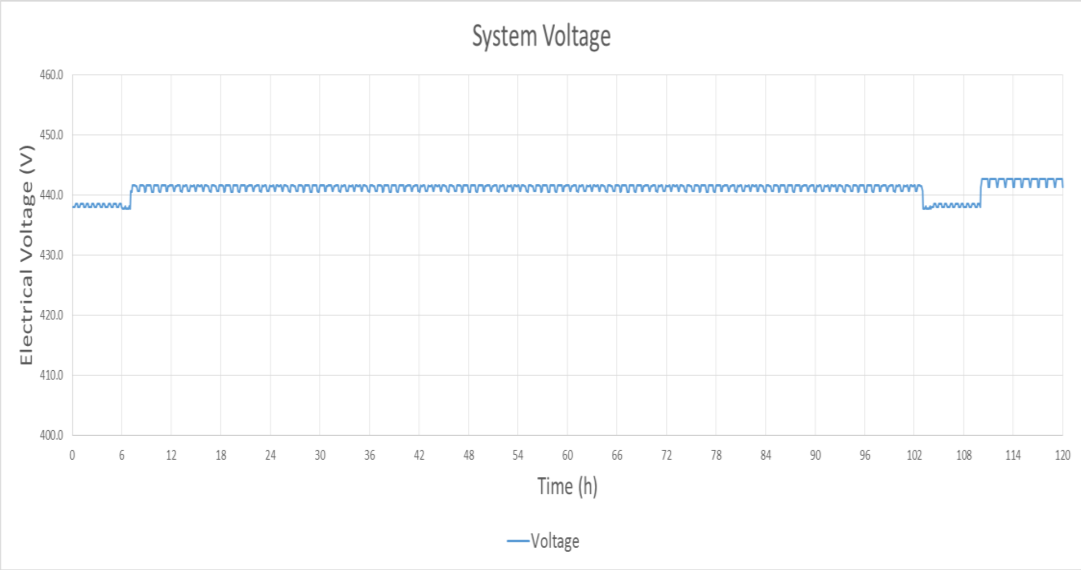


Fig 8-6. "Electrical voltage applied to the bus of the cargo ship electrical systems"

The fuel consumptions for both conventional and proposed cases are shown in Figure 8-7. For the conventional case, the quasi-dynamic simulation results used for the needs of chapter 5 for the detailed systems modelling were applied. The results reveal that the fuel consumption during peak load demands, i.e. during loading, unloading and manoeuvring, is higher for the proposed case since the conventional design meets its efficient operating point safeguarding against worst case scenarios. However, during the seagoing state the fuel consumption is slightly lower for the proposed design case since this was defined as the area of operation of the vessel. In addition, for operation at low load the proposed generation sets sizing offers higher fuel savings due to the lower power rating of the generation sets and, in turn, the energy efficient operating point.

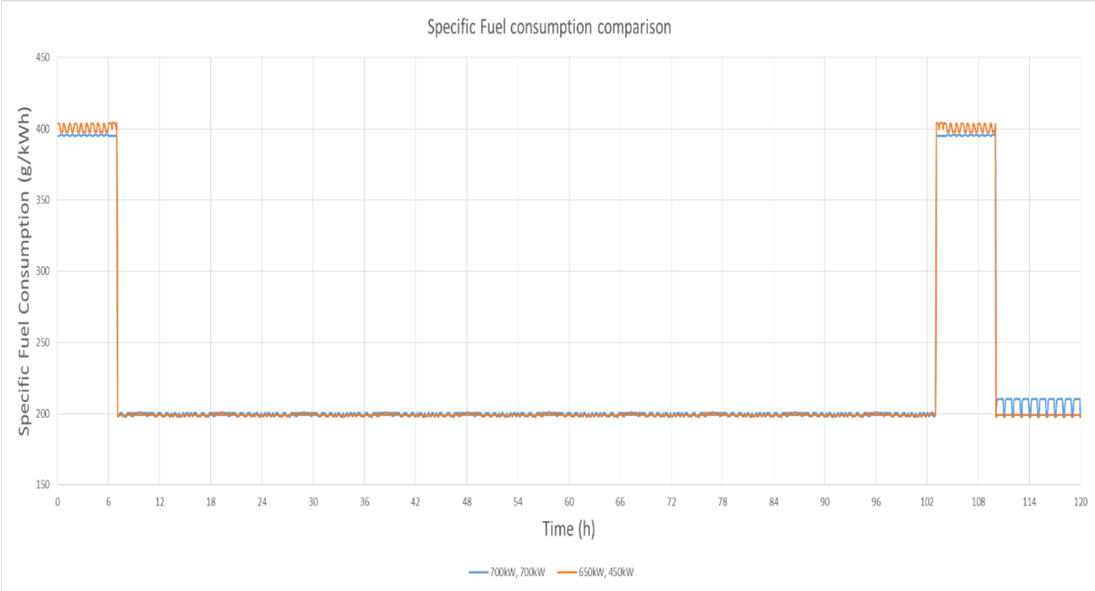


Fig 8-7. "Specific fuel consumption comparison of proposed and conventional cargo ship electrical systems design"

The results of the performance-based proposed design methodology prove that the design of the electrical energy systems on board ships can achieve enhanced energy efficient even with lower installed total and service power. The definition of the area of operation and mostly the PMS loading strategy during operation, are vital factors affecting the electrical systems design decisions.

8.4 Passenger ship

An electrical power network of a passenger ship with mechanical propulsion and the presence of one bow and one stern thruster was selected for investigation, same ship were used for chapter 5 investigation purposes. Design and architecture specifications were provided within the EC-funded REFRESH project. For this study, the daily itinerary of the under consideration passenger ship has the area of operation located in Greece starting from Athens going to Heraklion, city of Crete island, and the heading back to the starting point the same day. The components of the electrical energy systems, their architecture and the operational profile of them are extensively described in APPENDIX III.1 and APPENDIX III.2 respectively.

8.4.1 Early design

Following the energy modelling principles described in chapter 4 as well as the design simplification guidelines of chapter 5, the modelling of the 'fully simplified' electrical power system is initiated for the needs of the early design. It is worthy to mention that since the power distribution and conversion system is completely neglected according to chapter 5 results, the re-routing and relocation considerations following chapter 7 results about increased availability are not taken under consideration at this stage. The system configurations and 'fully simplified' modelling have discussed extensively in at section 5.4.4 of chapter 5, having as reference frequency and voltage of the network 60 Hz and 440 V respectively. Based on the guidelines of chapter 5 for the modelling simplifications during the design and the operational profile of the vessel for a daily trip, the quasi-dynamic simulation results for the electrical power demand–time variation are shown in Figure 8-8.

The information, during the early design stage, derived by the quasi-dynamic simulation results considers the peak value of the power demand during the most power consuming operating state of the vessel. This value will be used as the maximum installed service generating power during the detailed design for the sizing of the power generating sets and the redundancies.

The results reveal the highest power demand to be during the manoeuvring state with the loading and unloading condition to almost equal to the seagoing state in term of power consumption. Therefore, following the methodology for the early design, the maximum power demand from the simulation results, i.e. 4,700 kW, is considered as the total installed services power generating capacity without estimating the redundant unit power capacity.

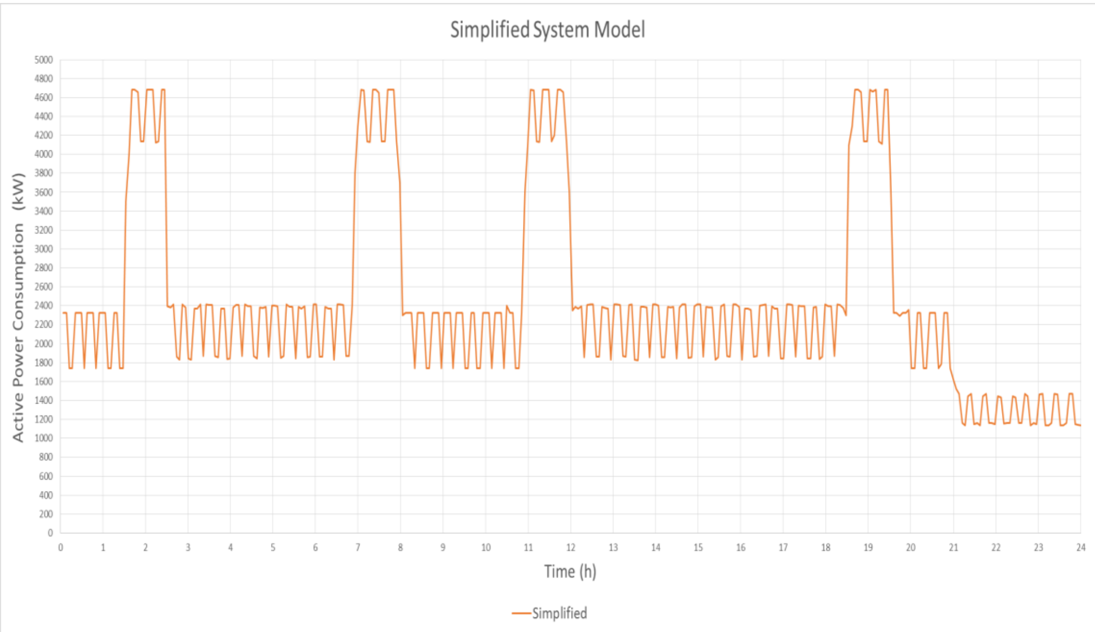


Fig 8-8. "Active power demand for passenger ship electrical systems during early design"

Another outcome from the quasi-dynamic simulation results is the most frequent area of ship operation. According to the results, it is the sea going state which is slightly of higher power demand than the loading and unloading state. Considering the design decisions that are to be done during the early design stages, sea going operating condition could be chosen as design area where the load demand is ranging from 1,800 – 2,400 kW.

Having identified through time domain simulation the maximum services power that needs to be installed, a comparison with the steady-state calculations could be presented. The derived generator's sizing for the traditional case was calculated through the identification of the most power consuming operating state from the electric load analysis and finally the application of an empirical factor for the exact components operation. In specific, in APPENDIX III.2 where the operation of each components at all operating states is described, the summation of the power demand of all components operating during the manoeuvring state results to an aggregate load which in turn is multiplied by the diversity factor of 90 % and conclude to the maximum installed services power capacity of 4,900 kW. As a result, the maximum load demand is slightly lower than the conventional with details about the exact sizing of the generation sets to be dealt in the detailed design stage.

Table 8-4: Conventional and Proposed Installed Services Power

Case	Installed Services Power (kW)
Conventional	4,900
Proposed	4,700

The above decisions bring the early to an end. The decisions about the installed services power and the most frequent area of operation will be used in the detailed design with is initiated at the next section.

8.4.2 Detailed design

In this step of the design process, explicit electrical power network modelling is introduced based on design decisions of the early design stage in order to produce more detailed information about the systems power demand and the fuel consumption. In addition, topological modelling of the safety-critical systems is initiated quantifying their safety performance and coupling energy efficiency and safety of the systems during design without underestimating the cost. Comparison of the proposed design with the conventional design is performed to verify the applicability of the proposed methodology.

At this stage, design decisions about the diesel-generators sets number and sizing should be taken based on the early design conclusions and following the guidelines of chapter 6. However, in order to align with the guidelines, design decision about the area of operation and the loading strategy of PMS during design and operation has to be made. For the needs of this study, following the early design results, the sea going state is selected as the most design area and additionally concerning the PMS loading strategy it is based primarily on the minimum fuel consumption and not on the according equipment's maintenance. Consequently, for the choice of the most appropriate sizing of generation sets the fuel cost at the decided operating point is the metric. Noticing the chapter's 6 design tables for both diesel-generation sets loading cases and following the according guidelines, the units

110% rated power loading strategy is selected due to reduced fuel consumption.

Furthermore, applying exhaustive search to the design load dependent start and stop tables 6-4, 6-5 and 6-6 at the chosen area of operation, the same fuel consumption is applied for all cases because of the use of one generator of 2,350 kW rating power. Even though the sizing of one diesel-generator is derived, no precise suggestions could be applied for the rest. Through the raked initial investment comparison of the equipment, the cost-based decision could be made. Therefore, considering the Tables 6-4, 6-5 and 6-6 and the corresponding costs of Table 8-5, the choice of the Table 6-6 is chosen for this study. In other words, the sizing of the diesel-generators sets are:

- D/G_1 = 2,350 kW
- D/G_2 = 1,175 kW
- D/G_3 = 1,175 kW

Table 8-5: Ranking of the diesel-generator sets

Cost ranking	Range of Installed Power (kW)
1	450-653
2	654-855
3	1,000-1,225
4	1,226-1,450
5	1,451-1,675
6	1,676-1,900
7	1,901-2,125
8	2,126-2,350

By proposing the exact sizing of the power generating sets in this study, a redundant units has also to be defined for regulations compliance. According to the latter, the sizing of it equals to the unit with the highest generating rated power for the scenario of its single fault. In other words, one more unit of 2,350 kW active power is added to the system safeguarding its functionality. Contrary to the proposed method, the traditional sizing of the generation sets is based on steady-state calculations, without sizing of the equipment considering the real needs but safeguarding against worst case scenario with potential oversizing as shown in the early design section. In Table 8-6 the summary of the proposed and the conventional sizing is presented with the total investment cost for the diesel-generators sets to be equal.

Table 8-6: Conventional and Proposed diesel-generator sets sizing

Case	D/G_1 (kW)	D/G_2 (kW)	D/G_3 (kW)	D/G_4 Redundant (kW)	Aggregated gen-sets ranking
Conventional	1900	1500	1500	1900	22
Proposed	2350	1175	1175	2350	22

Having identified the exact sizing of the power generation sets, the detailed modelling of the electrical power system is the step forward based on the previous design decisions. However, in order to model the power distribution and conversion system, the approximated cable lengths, not the switchboards since they are neglected for the energy performance, have to be known. The latter's parameter is referring to the topology and geometry of them onboard, something that comes as outcome from the probabilistic assessment of safety-critical systems. For the coupled parameter, will need the initiation of the topological and logical modelling of the safety-critical systems with the systems topological optimisation as well. The safety performance results will be compared with the conventional case and also cable lengths results will be used as input to the detailed energy modelling of the electrical power system. The passenger vessels of this study is the same as used in chapter 7 and the WT arrangements are shown in Figure 7-1 of chapter 7.

The logical and topological modelling of the safety-critical systems is following the principles of chapter 4 with the use of Boolean algebra. The safety-critical systems that will be evaluated are modelled as system functions and each of them may include a number of sub-system functions. Both systems and sub-systems are comprised by physical components placed in specific locations in the vessel and being supplied by specific (main, load-centre or emergency) switchboards. The systems and sub-systems that are modelled for the purposes of this study are:

- Propulsion
    - Ventilation
    - Air
    - Fuel
    - Lubrication
    - Cooling
    - CPP
- Steering
    - Rudder

    - Thruster

- Bilge and Ballast

- Emergency

with their dependency diagrams to be presented in APPENDIX III.3.

The emergency system has been added for examining its availability post-casualty. Based on the topological results and corresponding guidelines of chapter 7, the onboard location of the systems has been chosen and is shown in Figure 8-9. According to this, the power distribution and utilisation systems are located within the 'enhanced-availability area', i.e. after the B/3. Moreover, considering the steering system and the additional safety level that the guidelines suggest, the bow and stern thrusters are supplied through the 4th deck from the MSWBD, since usually there are no redundant units for them. The steering gear units of the rudder sub-system are supplied by the MSWBD with additional redundant units being supplied by the EMSWBD.

In the conventional design, the existence of redundant units supplied either by the MSWBD or EMSWBD is initiated with the onboard systems topology and geometry to be presented in APPENDIX III.4. The main power distribution and utilisation systems are as presented in section 7.3 of chapter 7 with additional redundancies and the emergency distribution system. The EMSWBD supplies two redundant steering gears, one ME air compressor, one A/R and one E/R supply fan and, also, one Bilge, Fire and Ballast pump, with all redundant units to be located next to the operated at the same room.

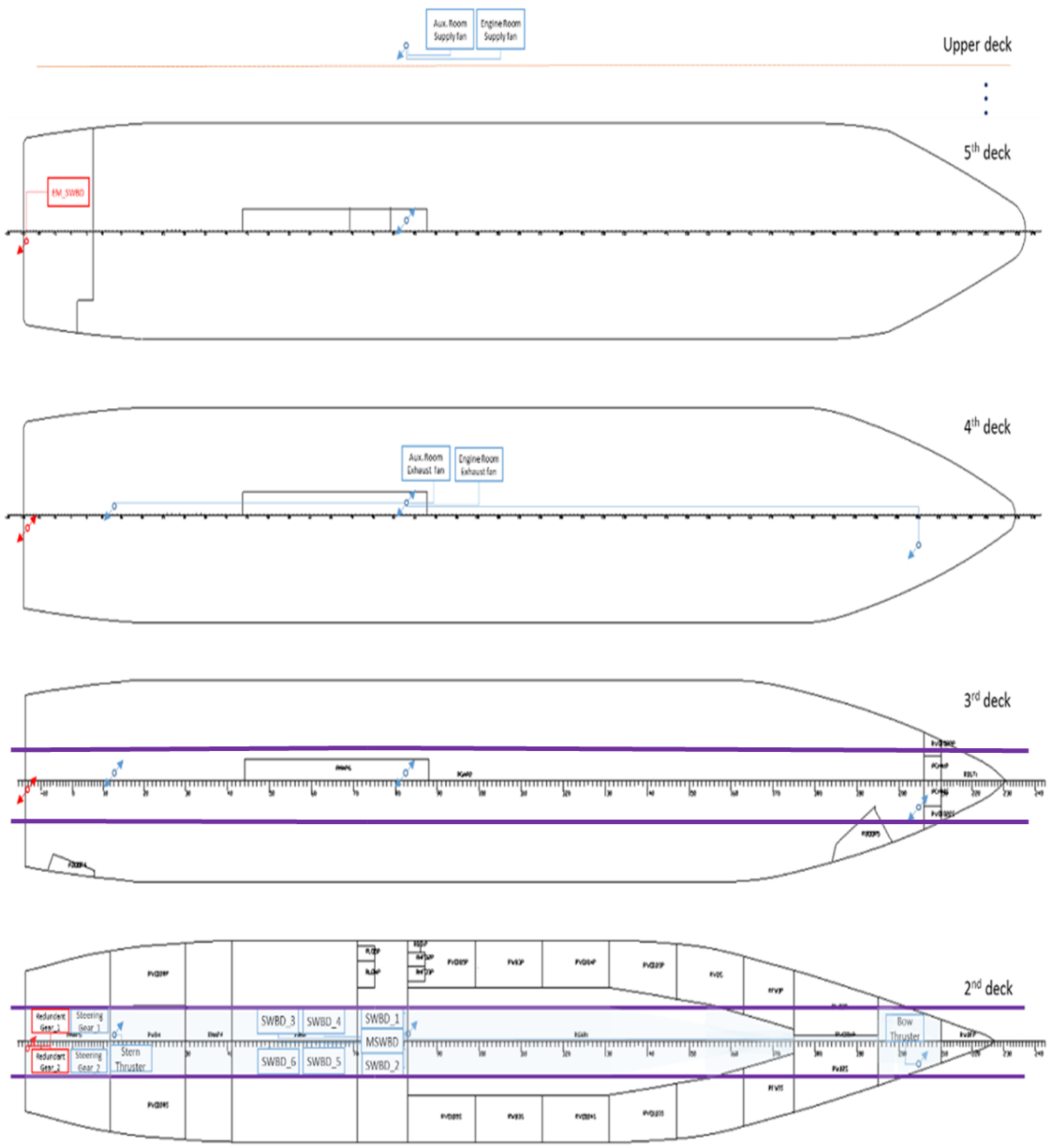


Fig 8-9. "Onboard topology of the safety-critical systems for the proposed case"

Having finished the modelling part, the designs are assessed with respect to collision damages, firstly within any single WT compartment, evaluating potential compliance with the SRtP, and secondly for any possible damage scenarios, for a robust systems design. The flooding damage scenarios coupled with their probabilities of occurrence were produced through NAPA software and for the availability assessment the design draught scenarios were used, same as used in chapter 7. Damage propagation is not examined and it is assumed that all rooms and spaces are considered as possible power flow paths for the power distribution system regardless of their existing usability.

The post-damage systems availability assessment is shown in Table 8-7 for compliance with SRtP and in Table 8-8 for evaluation of designs applied to all possible flooding damages. The results show the difference level of safety of the compared designs and additionally the level of accuracy when the design is based only on the SRtP compliance and when considering the systems safety as a holistic issue. As it is obvious from the results, the proposed design is by far the safest with the redundant components to have been minimised, only to the steering gears cases, and replaced with re-routing paths for the case of bow and stern thruster. By doing so, the steering systems availability has been increased 65 % with the rudder and thruster sub-systems to be less than 10% and 20% respectively possible to be unavailable.

Table 8-7. Average probability of systems being unavailable given collision and flooding within any single WT compartment.

System	Conventional	Proposed	Sub-systems	Conventional	Proposed
Propulsion	0.2	0.03	Ventilation	0.05	0.02
			Air	0.2	0.02
			Fuel	0.2	0.02
			Lubrication	0.2	0.02
			Cooling	0.2	0.02
			CPP	0.2	0.02
Steering	0.54	0.23	Rudder	0.4	0.15
			Thruster	0.39	0.08
Bilge & Ballast	0.2	0.02			
Emergency	0.85	0.15			

The propulsion system is reduced at around 70% compared to the conventional case without use of redundancies but only the relocation of the power distribution and utilisation systems to the 'enhanced-availability area'. The probability of all propulsion system sub-systems being unavailable after a flooding damage is 5% except for the ventilation which come to 6%. Concerning the bilge and ballast system, the proposed design probability is reduced by almost 85% of the conventional without any redundancies. Dramatic changes can be noticed in the results of the emergency system where the reduction comes to 90% with the reduction of the redundant units and the extensive flow paths in critical areas. Apart from the increase in the availability, the reduction of costs, weights and lower rated capacity of emergency diesel-generator set is applied.

Table 8-8. Average probability of systems being unavailable given collision and flooding considering all the damage scenarios.

System	Conventional	Proposed	Sub-systems	Conventional	Proposed
Propulsion	0.27	0.06	Ventilation	0.17	0.06
			Air	0.26	0.05
			Fuel	0.26	0.05
			Lubrication	0.26	0.05
			Cooling	0.26	0.05
			CPP	0.26	0.05
Steering	0.68	0.24	Rudder	0.42	0.09
			Thruster	0.60	0.18
Bilge & Ballast	0.26	0.04			
Emergency	0.93	0.09			

After the specification of the onboard topologies of the safety-critical systems, the detailed modelling of the electrical power systems is introduced. The assumed grid connection is replaced by the frequency and voltage control of the power generation units, as described in chapter 4, and the decided loading strategy of the generation sets during operation is initiated through the use of guidelines of chapter 6. Specifically, detailed components modelling of the power generation, power utilisation and power distribution and conversion systems is applied, with the latter to be applied inputs by the proposed topological design optimisation approximated cable lengths. The electrical power system configuration presented in APPENDIX III.1 is used for this case study. In addition, the parameterisation methodologies and manufacturers and software built-in data were applied for the three-phase synchronous machines, the power transformers and the three-phase induction motors as described in chapter 4. Furthermore, for the distribution lines electrical resistance, R_{const}, and inductance, L_{const}, per meter constants manufacturers data were applied. Constant system loads active and reactive demand at each time interval is presented in the operational profile in APPENDIX III.2. In order a comparison case to be performed, the tuning of the frequency and voltage controllers, where pursuing same principles following the trial and error until stable parameters were identified. For the diesel-engine set, the equations described in chapter 4.2.1 were used with the fuel oil consumption of APPENDIX.IV.2 to be employed after the exclusion of the generators efficiency and the conversion to torque as state variable.

Table 8-9: Load dependent start and stop table for passenger ship

Load (kW)	D/G_1 1175 kW rated (kW)	D/G_2 2350 kW rated (kW)	D/G_3 1175 kW rated (kW)	D/G_4 2350 kW rated (kW)	Specific Fuel Consumption (g/kWh)
295	295	offline	0	offline	234.5
600	600	offline	0	offline	203.1
1000	1000	offline	0	offline	196.5
1180	offline	1180	offline	0	209.4
1500	offline	1500	offline	0	204.2
2000	offline	2000	offline	0	202.3
2500	offline	2500	0	0	217.1
2600	895.3	1704.7	offline	0	393.0
3000	975.3	2024.7	offline	0	392.9
3500	1057.5	2442.5	offline	0	405.8
3880	959.4	1961.2	959.4	0	583.0
4200	1042.5	2115	1042.5	0	585.0
4600	1057.5	2485	1057.5	0	598.7
4900	1157.5	2585	1157.5	0	616.4

The load dependent start and stop table has to be created for the proposed diesel generator sizing. The PMS loading strategy that will be used is the 110% of the rated generating power for each of the units. The derived table is presented above as Table 8-9 and it is used as input to the frequency control scheme of each three phase synchronous generator.

Quasi-dynamic simulation results are shown in the figures below. In Figure 8-10 and 8-11 the supplying active and reactive power of each power generating set, respectively, is presented with the highest rated diesel-generator set to be used during all operating conditions. From the rest two equal rated sets, one is partially online in parallel with the high rated during all operating conditions, except for the port operation. As for the other generation unit, it is in function during very high load demands, i.e. manoeuvring state. The corresponding power factors for each of the systems generator are shown in Figure 8-12.

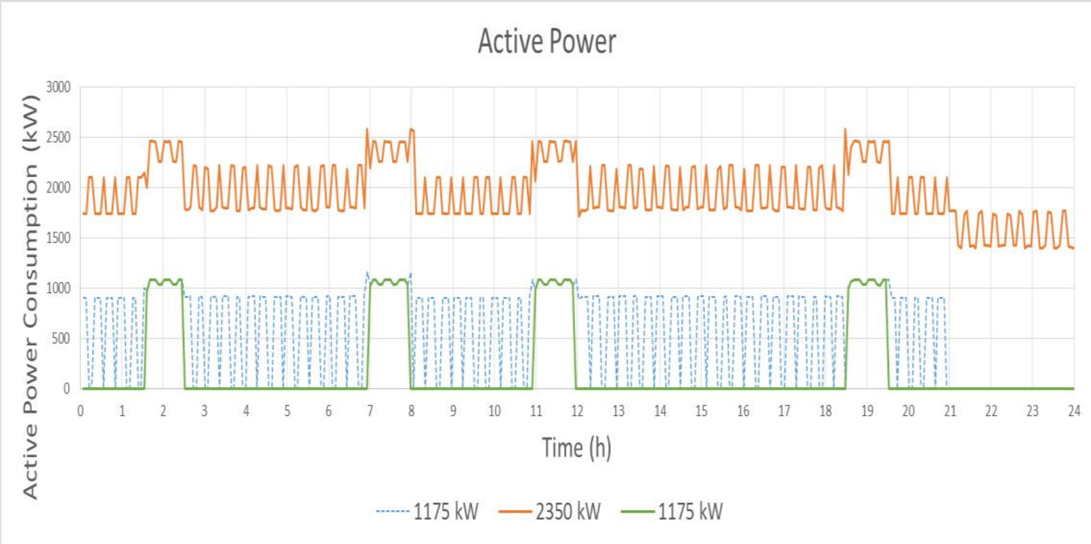


Fig 8-10. "Active power for proposed design of passenger ship electrical systems"

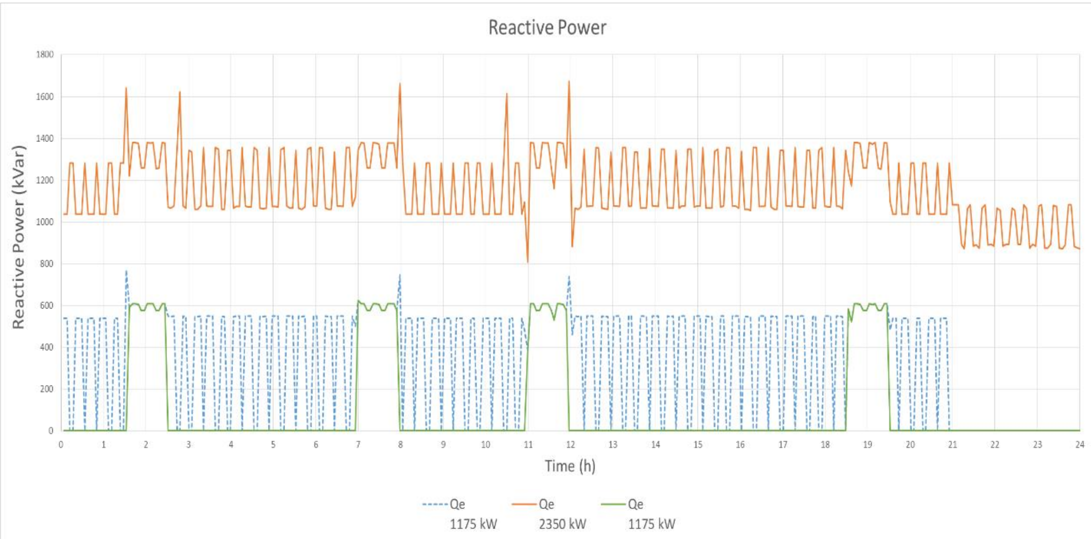


Fig 8-11. "Reactive power for proposed design of passenger ship electrical systems"

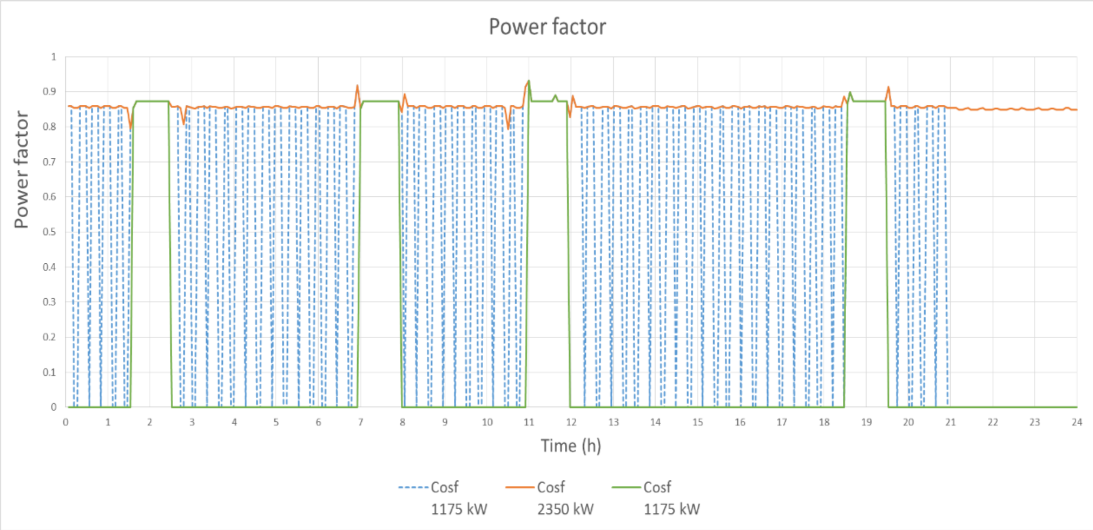


Fig 8-12. "Power factors for proposed design of passenger ship electrical systems"

In the Figures 8-13 and 8-14 the results for the frequency and voltage applied to the main switchboard of the systems are shown during the simulation.

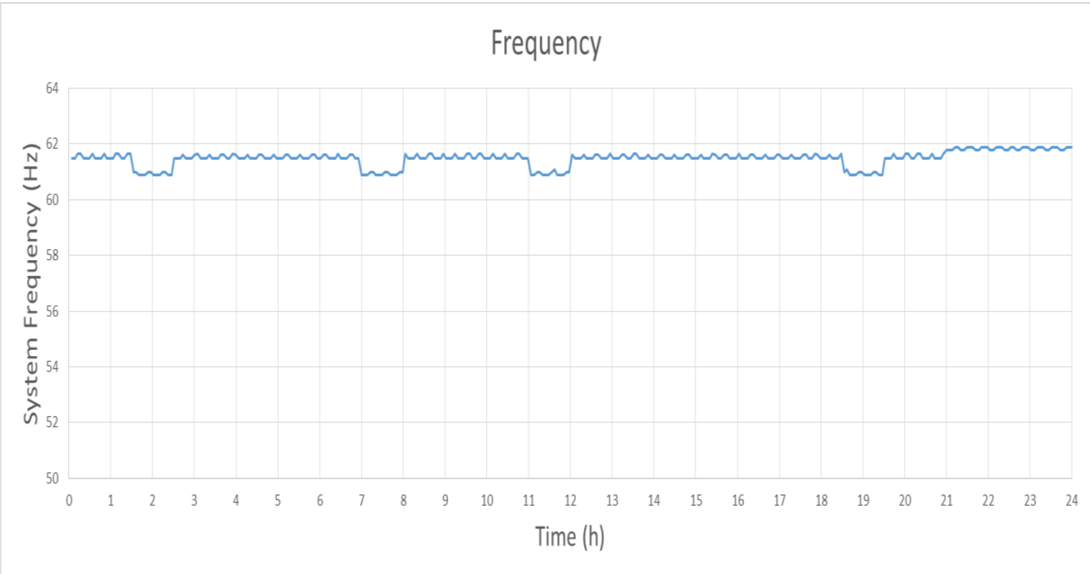


Fig 8-13. "Frequency for proposed design of passenger ship electrical systems"

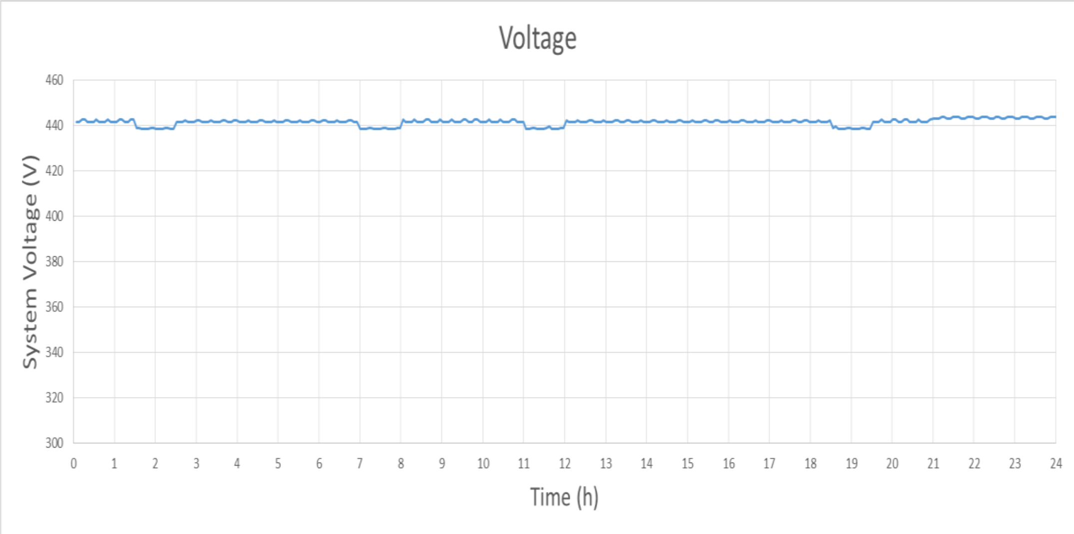


Fig 8-14. "Voltage for proposed design of passenger electrical systems"

The fuel consumptions for both conventional and proposed cases are shown in Figure 8-15. The results reveal that the fuel consumption during the high and low load demand, i.e. manoeuvring and at port condition respectively, is higher for the proposed case since the conventional design meets the efficient operating points. However, during the seagoing and the loading and unloading states, where the operation is more frequent during the trip duration, the fuel consumption is lower for the proposed design case since seagoing was defined as the area of operation of the vessel. Concerning the power consumption during loading and unloading states, the power demand is very close to the seagoing and consequently almost efficient operation is achieved.

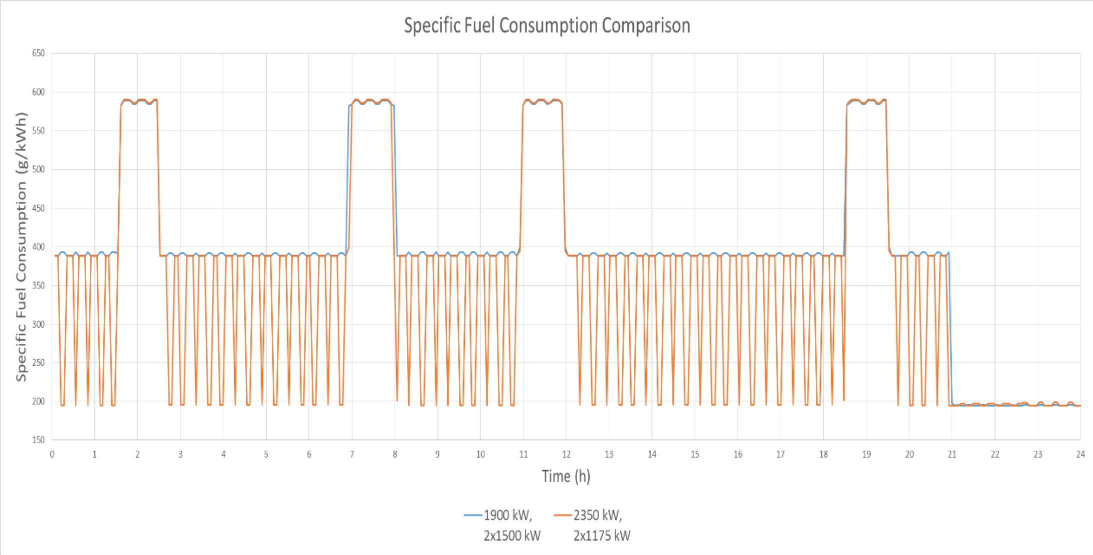


Fig 8-15. "Specific fuel consumption comparison of conventional and proposed passenger ship electrical systems designs"

The results of the performance-based proposed design methodology prove that the design of the electrical energy systems on board ships can achieve enhanced energy efficient even with the same investment cost at the power generation. In addition, cost and safety improvements can be achieved through the probabilistic assessment with the optimised onboard topologies of the power distribution and utilisation systems, with the concurrent reduction of the emergency power generation sizing and the geometrical extent of the emergency power distribution system.

8.5 Closure

In this chapter electrical systems design methodologies for cargo and passenger vessels were proposed based on quasi-dynamic electrical modelling and, considering the latter case, the probabilistic assessment during emergencies. The sizing of the power generation units and the onboard topology and geometry of the main and emergency power distribution and utilisation systems were identified and compared with the conventional configurations. This chapter closes the work of this thesis and is followed by discussion and recommendations.

9 DISCUSSION AND RECOMMENDATIONS

9.1 Preamble

This chapter summarises the contributions of this thesis in the field of energy efficiency and safety during ship design and operation, and proposes areas for future work that were not investigated in this research.

9.2 Contribution to the field

This work started four years ago in an attempt to address the ever-growing need for energy efficiency and safety in the shipping sector especially for the case of passenger ships. The uncertainty of fuel prices and the introduction of mandatory environmental regulations, targeting the increasing carbon footprint of shipping, caused the maritime research and industry to be dealing with the fuel efficiency, which had never before been the key objective during ship design. In addition, safety considerations during design were always driven the shipping industry, however underestimating the need for the vessel's operability post-casualty. This gap were filled by the SRtP regulations with their mandatory compliance to the pre-defined safety-critical systems availability after a fire or a flooding damage.

The first contribution of this work was the critical review of the state of the art of electrical energy systems onboard and of current design approaches. Critical review is not normally cited among the contributions of a PhD dissertation but this constitutes the first such review, at least from the perspective of quasi-dynamic energy modelling and the probabilistic performance assessment at emergencies, for commercial ships with literature to exist for warships [81], for electrical systems. As such, it revealed many deficiencies of existing deterministic design approaches such as the use of arbitrary components performance factors for the sizing of the power generation system, the lack of systems dynamic performance over time (with the use of steady-state calculations instead), the neglect of interaction between energy systems, the power distribution design far from their 'applied' environment and lastly the absence of the nature of the damage during systems safety performance assessment. The drawbacks of regulations-based design were also pointed out, and the need for multi-objective performance-based design was justified.

The second contribution, was the introduction of quasi-dynamic energy modelling as a platform to assess and improve the performance of ship energy systems. The remarkable absence of technology in the design calculations of new ships, made the adoption of practices applied to related industries, with the electrical energy systems modelling to have been proposed to simulate the performance of onboard energy systems with the use of first principles and the manufacturers data.

The third original contribution was the introduction of probabilistic assessment as an approach to evaluate and improve the safety performance of passenger ship critical systems and additionally ensures consistency between survivability of vessel and onboard systems. The lack of tool estimating the safety performance of the systems within the ship environment, driven to the adoption of successfully applied methods to other ship disciplines, i.e. damage stability. The introduction of the quantitative performance-based approach considering probabilistic rules was proposed to quantitatively evaluate post-casualty availability of safety-critical systems in passenger ships.

The fourth original contribution was the reduction (simplification), consisting the omitting of switching elements, of the modelling process for electrical power network, which was achieved through the investigation of electrical, topological and geometrical parameters mostly affecting the power supply which in turn was applied for the sizing of the generation sets. This exercise led to the development of modelling guidelines for cargo and passenger ship electrical power network.

The fifth original contribution was the optimisation of the electrical power system during design and operation through the application of the PMS. Unit commitment and economic load sharing functionalities were employed with the application of technical, operational and maintenance constraints for the identification of energy-efficient solutions and the simultaneous integration to the frequency control scheme during operation. Design method were proposed based on a number of design decisions for the exact sizing of the power generation sets. Guidelines were derived for the choice of the most energy efficient concepts.

The sixth origin contribution was the investigation and optimisation of the energy systems onboard topologies in terms of safety and cost. Through the onboard topological and geometrical modelling of the safety-critical systems and the application of all possible flooding damages on them, investigation of the most vulnerable ship zones and the systems topology optimisation was feasible. Power distribution and utilisation systems topological and geometrical guidelines were proposed based on this study results.

Finally, a design methodology based on the quasi-dynamic energy modelling of electrical energy systems was proposed for cargo ships. For the case of passenger ships, a design methodology based on the probabilistic assessment of the safety-critical systems at emergencies and additionally on the quasi-dynamic energy modelling of electrical energy systems was proposed, with both to have been demonstrated in two case studies.

The research undertaken for the completion of this thesis, produced two conference papers [82,83] that were presented in two international conferences, in the framework of getting feedback from the academic and industrial community, and promoting this work. In addition, one journal paper [84] was produced as a part of the work submitted to the JOULES EU project.

9.3 Recommendations for future work

Time limitations did not allow the investigation of some topics that might have improved the energy efficiency and safety of onboard electrical systems. These are discussed below.

Extensive detailed validation

Although well-known first principles and available data were applied for modelling the electrical power network, limited components verification was applied in this work. Several calculations in this thesis have been compared with onboard measurements in the framework of EU projects, however, due to the large number of input parameters and the lack of resources, no systematic and thorough comparisons were performed. Validation of energy modelling developed platform requires extensive onboard monitoring that would give accurate values of component and system parameters over time.

Harmonic analysis

The growing complexity of marine electrical power systems through the extensive and ever-increasing use of electrical machines and power electronic systems, together with the demand for electrical integration between the propulsion and services, means that the impact of any waveform distortion needs to be carefully assessed to ensure proper electrical systems functionality. Waveform distortion is caused by non-linearity effects present in the electrical distribution system that cause energy imbalances. The performance of power systems harmonic analysis could result to an even more efficient systems design increasing the quality of power to the electrical network.

Integration with ship energy model

In the framework of two EU projects, electrical power network models were developed on this work, which were used for the estimation of the total power consumption of cargo and passenger vessels. In these holistic models, interaction between the electrical system with not only environment, for the case of thrusters, but also other energy systems considered as boundary conditions, such as the mechanical and thermal systems, were disregarded as estimated values were used for those boundaries. For the accurately modelling of these interactions, more effort should be spent towards the integration of all energy systems under a holistic ship energy model, which necessitates the identification of points of connection and exchange of information between a number of different modelling environments. The development of a modelling platform with the system simplification and optimisation of the design process achieved in this thesis, play a major role in this coupling since fast simulation, modelling time and multi-disciplinary optimisation are vital in a holistic modelling and optimisation platform targeting operation, retrofitting and design.

Assess alternative electrical energy systems configurations

This work has focused mainly on the development of a modelling and optimisation tool targeting the design of the electrical energy systems through a proposed methodology for each ship type. However, only traditional applications were considered especially for the power generation system, i.e. the diesel engines, since they are commonly applied in maritime industry. The investigation of new technologies, with their direct integration to the modelling platform, as primarily sources of power, such as alternative fuel, renewable technologies and shaft generators, as well as variable frequency drives for critical power utiliser units, could possibly result to even more energy efficient systems design and operation.

Additional functions of PMS

PMS in this thesis were applied for the fuel optimisation of the power generation sets during the design and operation with the former translating to diesel-generators sizing and the latter being integrated within the local frequency control system. Sophisticated PMS could be developed for the optimal control of the power network considering the quality of the delivered power, the load shedding, the load increase control, the optimal load transfer between different source of power, etc.

Use for life-cycle energy management

In this work energy modelling has been demonstrated as a design tool. However, with a holistic energy modelling tool at hand, the power consumption of a ship can be estimated during her life-cycle from very early stages in the design with rough assumptions about the vessel's operational profile.

Investigation of more safety-critical systems

The investigation performed in this thesis was considering the propulsion, the steering and the bilge and ballast systems as safety-critical with a number of corresponding sub-systems within. In addition, the existence of emergency system was employed for the holistic availability assessment including units redundancies. However, SRtP regulations comprise additional pre-defined systems that have to be examined in topological and geometrical manners for their post-casualty availability optimisation, such as navigation systems, lighting systems, external communication system, etc.

Further Topological optimisation

The power distribution and utilisation systems onboard topological optimisation were investigated under the constraint of flooding damages (collision) with the results and guidelines to be presented and analysed. However, having established the probabilistic-based approach further boundaries could be assessed, for regulations compliance as well, such as the grounding and fire damages as well as different systems configuration with the application of water and fire resistant cables to the critical system paths or even the use of two MSWBD for the cases of high number of vessel zones for increased systems availability and reduced redundancies.

Integration of probabilistic assessment with COPT approach

In this study, probabilistic assessment approach was applied in an attempt to increase ship systems safety from the naval architecture perspectives, as the statistical flooding damages were considered. Considering COPT as a method used in power systems engineering to calculate LOLP (loss of load probability) and ELL (expected load lost), their integration will allow the initiation of electrical systems inherent capabilities and additionally the consolidation of the probabilistic analysis followed in the thesis.

9.4 Closure

This chapter summarised the contributions of this thesis in the field of energy modelling during ship design and operation and systems availability at emergencies. Also, it was discussed further developments that would improve the application of energy modelling during the assessment of the life-cycle energy performance of ships and additional enhance the ship systems safety assessment during emergencies.

10 CONCLUSIONS

The continuous growth of the maritime, goods and passengers, transport has addressed the ship safety, energy efficiency and environmental pollution as major issues that shipping industry and research have to deal with. Through the introduction of MARPOL Annex XI and the mandatory implementation of EEDI and SEEMP in 2013, the need for reduced shipping's carbon footprint is leading to direct improvement of energy efficiency. Furthermore, with the SRtP regulations to have come recently into force imposing certain requirements regarding the performance of the safety-critical systems in emergencies, the need for increased system reliability is highly prioritised.

Regardless of the fact that the systems safety was addressed as one of the most dominant issues in shipping industry, especially for the case of passenger vessels, the deterministic design approaches without considering the nature of the damage and the application environment, never allow the shipping industry to deal effectively with this concept. In addition, contrary to systems safety, the energy efficiency was never addressed as key objective, with the design of ship energy systems to be characterised by antiquated calculations and rules-based processes. It is clear that available technologies and methodologies are disregarded while in other industries or even in the same applied for other purposes, well-established and successfully applied are available.

Dynamic energy simulations are widely applied in various engineering industries with limited extent taking place in maritime. First principles tools are able to capture almost every energy interaction between different energy disciplines, electrical equipment characteristics and the environment. Quasi-dynamic energy modelling concept were adopted in this work in an attempt to address the vessel's energy performance through the modelling of the electrical systems.

Initially the numerical modelling principles of the marine electrical power systems, and by extension components, were presented including the power generation, power distribution and conversion, power utilisation and local control systems. Considering the systems configuration and components parameterisation, the energy modelling platform capable of modelling the electrical energy systems of cargo and passenger ships was assembled. However, taking under consideration the large number of components comprises the electrical systems with a vast number of input parameters for each of them, especially in passenger ships, some form of simplification during the modelling process for the system design is required. For this reason a part of this thesis was focused on the input parameters reduction for the power utilisation, power distribution and conversion and power generation systems. Results shew that the derivation of a simplified electrical power systems model is feasible for cargo and passenger ships, neglecting the R_s, L_s and L_r parameters of the generic induction motor model, the constant loads, and the whole power distribution and conversion, power generation and local control systems. The rate of accuracy loss in the quasi-dynamic energy simulations was estimated and reviewed as acceptable for the early design stage. Based on these results, design guidelines were generated that simplify the modelling process.

Having performed a parametric study identifying the key design parameters of the electrical power network, the development of the PMS targeting the system's constrained optimisation during the design and operation was initiated. In the operation case, by changing the setting of the maximum load limit of the power generation units, the derivation of load dependant start and stop table was derived based on the fuel efficiency at each case. For the design case, pre-defined sets of power generation units were examined based on the fuel efficiency at each load demand with the PMS generation units loading strategy during operation to be considered as well as the area of ship operation. The design load dependant start and stop tables were derived and through the exhaustive assessment considering also appropriate design decisions, the power generation sizing was feasible. Guidelines were generated based on the corresponding exhaustive search optimisation results.

For the case of passenger vessels, parallel to the energy also the safety systems performance has to be quantified. In this thesis, the latter was achieved through the probabilistic assessment of the safety-critical systems availability by adopting the probabilistic framework applied in damage stability. The modelling of the safety-critical systems comprising the propulsion, the steering and the bilge and ballast systems, was initiated into the ship environment preserving physical, functional and spatial relations of them. Following the systems onboard modelling and the corresponding dependencies, the application of all possible flooding damage scenarios coupled with their corresponding probability of occurrence were apply with an aggregated average probability to be applied as concluded safety metric. In the view of rule compliance, only damages at any single WT compartments were considered.

For the identification of the critical zones, where the examined safety-critical systems have high vulnerability rate, systematic investigation were performed with the probabilistic assessment resulting to the below: engine, auxiliary, steering, bow and stern thrusters rooms. Having identified the critical zones, topological optimisation performed for the power distribution and utilisation systems attempting to either avoid the critical zone or identify 'enhanced-availability areas' so as to minimise the units redundancies. Results indicated that the systems placement further than the transverse limit of B/3, measured from the shell, have enormously reduced probability of being damaged and additionally the stern and bow zones could be supplied by the MSWBD through intact from flooding damages decks for increased availability. Emergency distribution systems with units redundancies were suggested to follow the same topological principles. Outcomes about the increased level of results accuracy for designs targeting the robust systems design over those based only on the SRtP compliance were presented and analysed. Based on the investigation results, design guidelines were derived and presented.

At this point, methodologies for the design of the electrical energy systems onboard in commercial ships was proposed and compared with the conventional design, with its use were demonstrated in two case studies, one for a cargo and one for a passenger ship. Results shew the importance of systems modelling simplifications and optimisation through the estimation of power consumption over time and for the case of passenger vessels the optimal location of the systems onboard for redundancies, i.e. cost, minimisation. Further recommendations for future work were made that are expected to improve the validity, accuracy and energy and safety performance of electrical systems in the marine environment during design, retrofit and operation.

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APPENDIX I – PARK TRANSFORMATION

The transformation between the *abc*-frame and the *qd0*-frame in which the q-axis leads the d-axis and the transformation is expressed in terms of the angle, θ, between the *q*-axis and the *a*-axis, is given by:

$$\left[T_{qd0}\right] = \frac{2}{3}\begin{bmatrix} \cos\theta & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ \sin\theta & \sin(\theta - \frac{2\pi}{3}) & \sin(\theta + \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \tag{I.1}$$

$$\left[T_{qd0}\right]^{-1} = \begin{bmatrix} \cos\theta & \sin\theta & 1 \\ \cos(\theta - \frac{2\pi}{3}) & \sin(\theta - \frac{2\pi}{3}) & 1 \\ \cos(\theta + \frac{2\pi}{3}) & \sin(\theta + \frac{2\pi}{3}) & 1 \end{bmatrix} \tag{I.2}$$

The transformation equations for voltages and currents are shown:

$$\left[V_{qd0}\right] = \left[T_{qd0}\right]\left[V_{abc}\right] \tag{I.3}$$

$$\left[I_{qd0}\right] = \left[T_{qd0}\right]\left[I_{abc}\right] \tag{I.4}$$

The inverse counterparts are shown as:

$$\left[V_{abc}\right] = \left[T_{qd0}\right]^{-1}\left[V_{qd0}\right] \tag{I.5}$$

$$\left[I_{abc}\right] = \left[T_{qd0}\right]^{-1}\left[I_{qd0}\right] \tag{I.6}$$

APPENDIX II – CARGO SHIP

II.1. Electrical systems

II.1.1 Configurations

The components of the electrical power systems for the studied cargo ship are presented below.

Table II-1: Electrical systems configurations of studied cargo ship

System	Sub-System	Component	Number of units (in use)	Power (kW)	Source	
Propulsion	Ventilation	Engine Room Supply fan	1 (1)	15	MSWBD	M_1
		Engine Auxiliary Blower	2 (2)	75	SWBD_1, SWBD_2	M_2 M_3
		Engine Room Exhaust fan	2 (2)	11	MSWBD	M_4 M_5
	Air	ME Air Compressor	2 (2)	45	SWBD_1, SWBD_2	M_6 M_7
	Fuel	FO Transfer pump	1 (1)	11	SWBD_1	M_8
		FO Purifier	1 (1)	7.5	SWBD_1	M_9
	Lubrication	LO pump	1 (1)	90	SWBD_2	M_{10}
	Cooling	ME HT FW cooling pump	1 (1)	18.5	SWBD_3	M_{11}
		SW cooling pump	1 (1)	70	SWBD_3	M_{12}
Steering	Rudder	Steering Gear	2 (2)	80	MSWBD	M_{13} M_{14}
Bilge & Ballast		Bilge, Fire & Ballast pump	1 (1)	90	SWBD_4	M_{15}
		Ballast pump	2 (2)	300	SWBD_3, SWBD_4	M_{16} M_{17}
Machinery		Windlass	2 (2)	90	MSWBD	M_{18} M_{19}
		Moor Winch	2 (2)	90	MSWBD	M_{20} M_{21}
		Air condenser Ref Mach	1 (1)	33	SWBD_4	M_{22}
Lighting, Galley, Navigation		Lighting		80	SSWBD	L_1
		Galley and Sanitary		13	SSWBD	L_2
		Navigation and Communication		10	SSWBD	L_3
Power Generation		Diesel - Generator	3(2)	700		G_1 G_2 G_3
Power Distribution and Conversion		Power Transformer (440/220 V)	1 (1)	100 (kVA)	MSWBD	

II.1.2 Single line diagram

The line diagram of the electrical power systems for the studied cargo ship is presented below (red colour defines the redundant units).

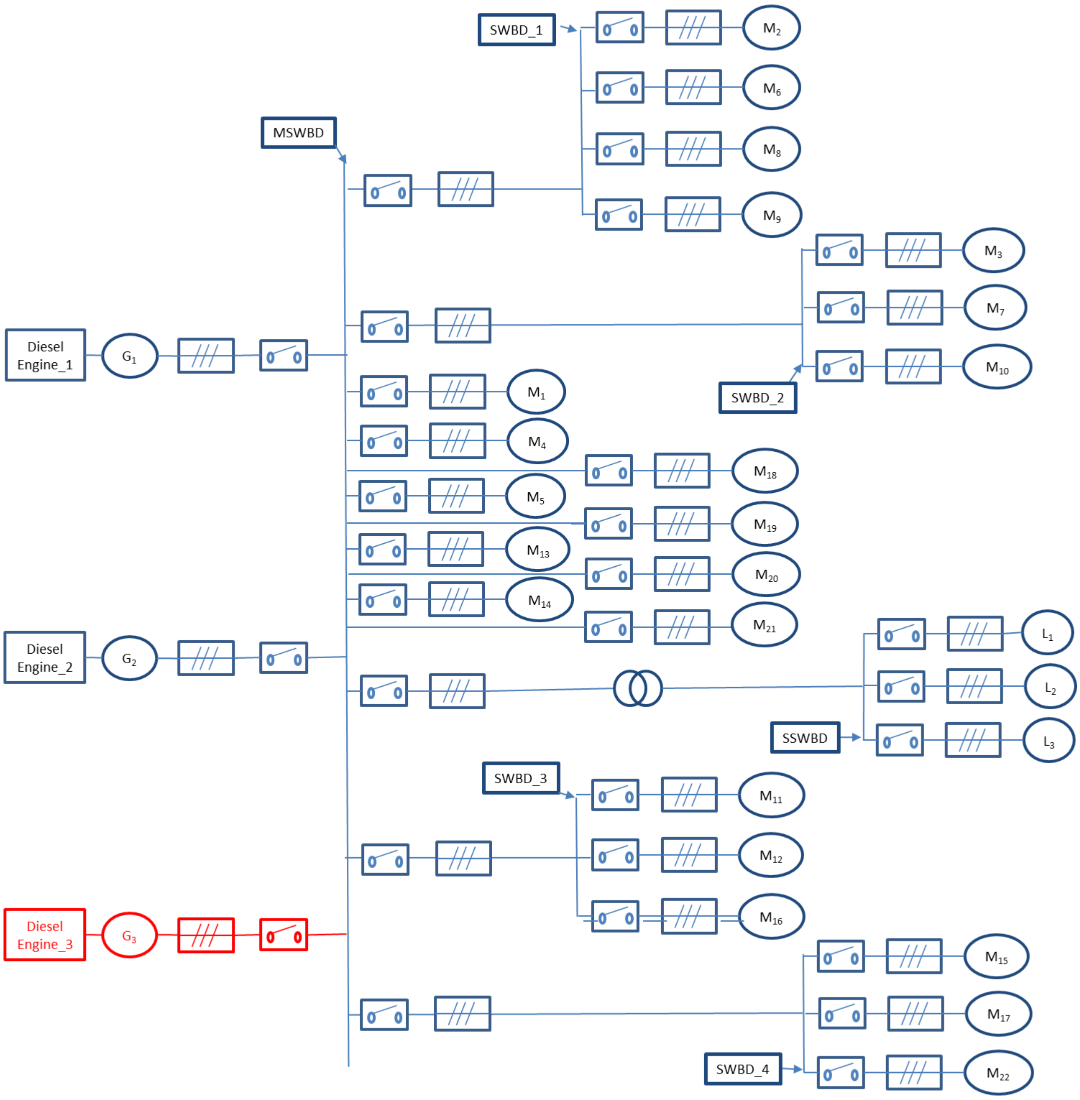

Fig II-1. "Single line diagram of studied cargo ship"

II.2. Operational profile

The operational profile of the investigated cargo ship is assumed to be five days for one way trip, from one port to the other. Being at sea going state for most of the time, the operating conditions are described below as they were considered throughout the simulations:

- Loading: 6 hours
- Manoeuvring: 1 hour
- Sea going: 96 hours
- Manoeuvring: 1 hour
- Unloading: 6 hours
- Rest At port: 10 hours

The above operational profile is based on TARGETS project data and author's assumptions.

The electrical power systems components functionality with their corresponding duration and frequency at each operating state is described below. The rated power performance was considered for all components during their operation.

Table II-2: Operational profile of studied cargo ship electrical components

Component	Loading/ Unloading		Manoeuvring		Sea going		Rest at port	
	frequency	Duration (hours)	frequency	Duration (hours)	frequency	Duration (hours)	frequency	Duration (hours)
Engine Room Supply fan	1	6	1	1	1	96	1	10
Engine Auxiliary Blower	-	-	1	1	-	-	-	-
	-	-	1	1	-	-	-	-
Engine Room Exhaust fan	1	6	1	1	1	96	1	10
	1	6	1	1	1	96	-	-
ME Air Compressor	9	0.4	2	0.4	10	0.5	10	0.3
	9	0.2	2	0.2	10	0.25	10	0.15
FO Transfer pump	9	0.3	2	0.3	10	0.2	10	0.15
FO Purifier	1	6	1	1	1	96	1	10
LO pump	-	-	1	1	1	96	-	-
ME HT FW cooling pump	-	-	1	1	1	96	-	-
SW cooling pump	1	6	1	1	1	96	1	10
Steering Gear	1	6	1	1	1	96	-	-
	-	-	1	1	-	-	-	-
Bilge, Fire & Ballast pump	1	6	1	1	-	-	-	-
Ballast pump	1	6	-	-	-	-	-	-
	1	6	-	-	-	-	-	-
Windlass	-	-	1	1	-	-	-	-
	-	-	1	1	-	-	-	-
Moor Winch	-	-	1	1	-	-	-	-
	-	-	1	1	-	-	-	-
Air condenser Ref Mach	9	0.3	2	0.3	10	0.25	10	0.15
Lighting	9	0.2	2	0.2	12	0.2	10	0.12
Galley and Sanitary	9	0.2	2	0.2	10	0.2	10	0.2
Navigation and Communication	9	0.2	2	0.2	10	0.2	10	0.2

APPENDIX III – PASSENGER SHIP

III.1. Electrical systems

III.1.1 Configurations

The components of the electrical power systems for the studied passenger ship are presented below.

Table III-1: Electrical systems configurations of studied passenger ship

System	Sub-System	Component	Number of units (in use)	Power (kW)	Location	Source	
Propulsion	Ventilation	Engine Room Supply fan	2(1)	110	Upper deck	MSWBD	M_1
		Auxiliary Room Supply fan	2(1)	33	Upper deck	MSWBD	M_2
		Engine Room Exhaust fan	1(1)	11	4th deck	MSWBD	M_3
		Auxiliary Room Exhaust fan	1(1)	11	4th deck	MSWBD	M_4
	Air	ME Air Compressor	2(1)	33	Engine Room	SWBD_4	M_5
	Fuel	ME FO Booster pump	2(2)	11	Engine Room	SWBD_3	M_6 M_7
		DE FO Booster pump	2(2)	11	Auxiliary Room	SWBD_1	M_8 M_9
		DO Transfer pump	1(1)	11	Auxiliary Room	SWBD_1	M_{10}
		FO Transfer pump	1(1)	18.5	Auxiliary Room	SWBD_1	M_{11}
	Lubrication	LO pump	4(2)	132	Engine Room	SWBD_3, SWBD_5	M_{12} M_{13} M_{14} M_{15}
		Reduction Gear LO pump	2(2)	18.5	Engine Room	SWBD_4, SWBD_5	M_{16} M_{17}
		LO Purifier	2(2)	15	Auxiliary Room	SWBD_2	M_{18} M_{19}
	Cooling	ME LT FW cooling pump	2(2)	132	Engine Room	SWBD_5, SWBD_6	M_{20} M_{21}
		ME HT FW cooling pump	2(2)	70	Engine Room	SWBD_3	M_{22} M_{23}
		SW cooling pump	3(2)	45	Engine Room	SWBD_4, SWBD_6	M_{24} M_{25} M_{26}
		DE LT FW cooling pump	2(2)	11	Auxiliary Room	SWBD_2	M_{27} M_{28}
	CPP	CPP Propeller pitch setting pump	2(2)	33	Engine Room	SWBD_4, SWBD_6	M_{29} M_{30}
Steering	Rudder	Steering Gear	4(2)	15	Steering Room	MSWBD	M_{31} M_{32}
	Thruster	Bow Thruster	1(1)	1,310	Bow Thruster Room	MSWBD	M_{33}
		Stern Thruster	1(1)	1,030	Stern Thruster Room	MSWBD	M_{34}
Bilge & Ballast		Bilge, Fire & Ballast pump	2(1)	75	Engine Room	SWBD_4	M_{35}
		Engine Room Fire & Bilge pump	1(1)	110	Auxiliary Room	SWBD_2	M_{36}
		Ballast pump	2(1)	132	Auxiliary Room	SWBD_1, SWBD_2	M_{37} M_{38}
		Drencher	1(1)	132	Engine Room	MSWBD	M_{39}
Emergency		Auxiliary Room Supply fan	1		Upper	EMSWBD	M_{45}

					deck		
		Engine Room Supply fan	1		Upper deck	EMSWBD	M_{46}
		ME Air Compressor	1		Engine Room	EMSWBD	M_{47}
		Steering Gear	2		Steering Room	EMSWBD	M_{48} M_{49}
		Bilge, Fire & Ballast pump	1		Engine Room	EMSWBD	M_{50}
HVAC		Chiller	3(3)	300	Pump Room	MSWBD	M_{40} M_{41} M_{42}
		Air Cond. FW pump	1(1)	22	Pump Room	SWBD_1	M_{43}
		Air Cond. SW pump	1(1)	15	Pump Room	SWBD_2	M_{44}
Lighting, Galley, Navigation		Lighting (220V)		90		TR_1	L_1
		Lighting (100V)		70		TR_3	L_2
		Navigation & Communication (220 V)		10		SSWBD	L_3
		Galley, Sanitary & Entertainment (220 V)		90		SSWBD	L_4
Power Generation		Diesel - Generator	2(1)	1900	Auxiliary Room		G_1 G_2
		Diesel - Generator	2(2)	1500	Auxiliary Room		G_3 G_4
Power Distribution and Conversion		Power Transformer (440/220 V)	1(1)	100 (kVA)	4^{th} deck	MSWBD	TR_1
		Power Transformer (440/220 V)	1(1)	100 (kVA)	4^{th} deck	MSWBD	TR_2
		Power Transformer (440/100 V)	1(1)	75 (kVA)	4^{th} deck	MSWBD	TR_3

III.1.2 Single line diagram

The line diagrams of the electrical power systems for the studied passenger ship are presented below.

In Figures III-1 and III-2 the emergency and the main power systems line diagrams are presented respectively.

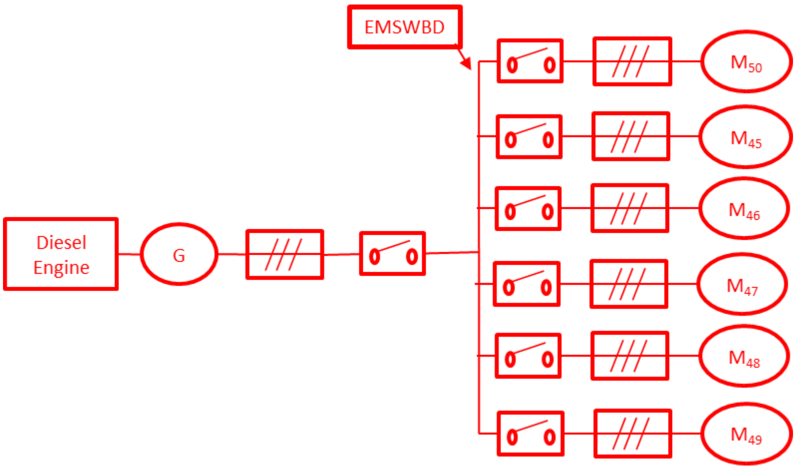

Fig III-1. "Single line diagram of the emergency power system of studied passenger ship"

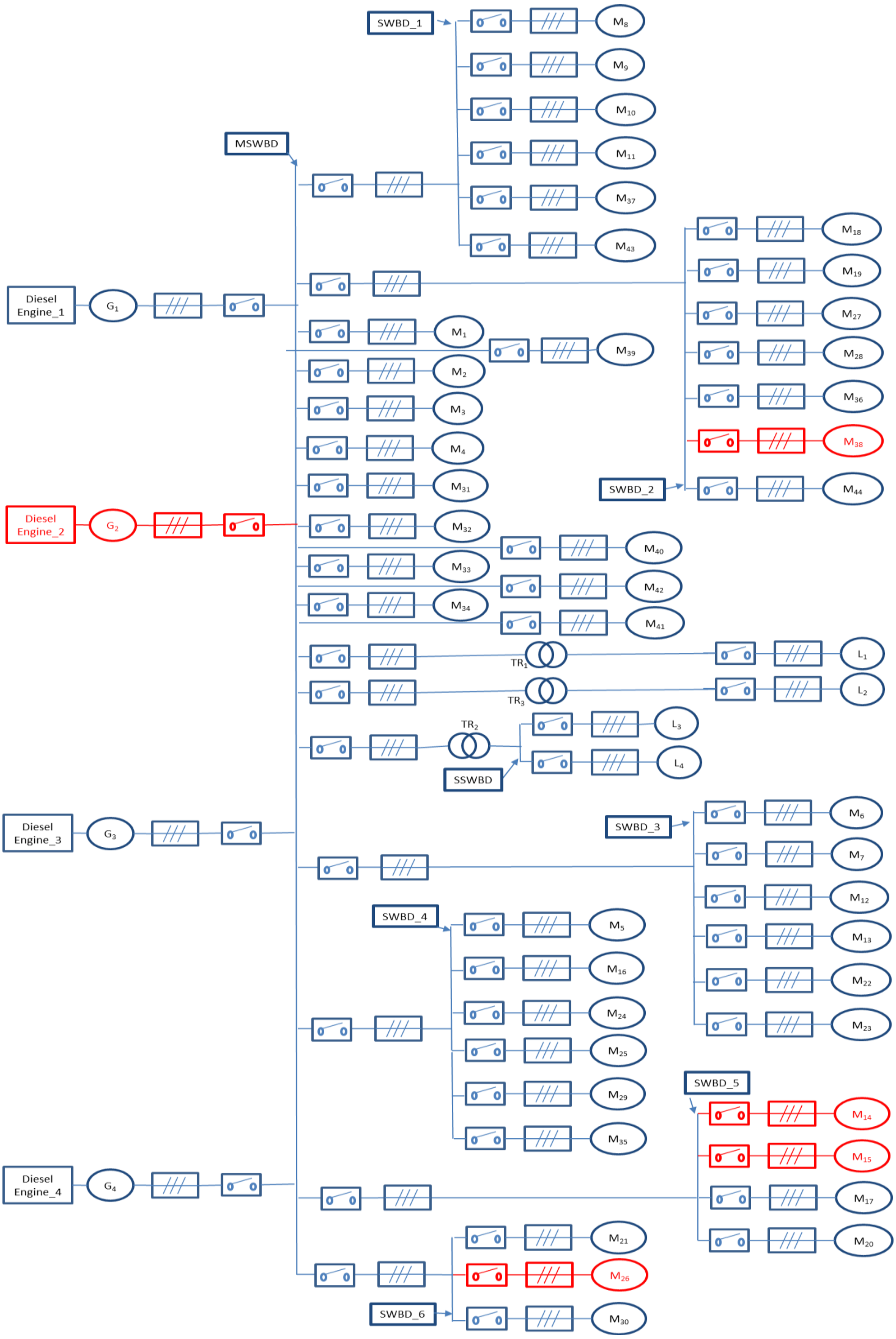

Fig III-2. "Single line diagram of the main power system of studied passenger ship"

III.2. Operational profile

One day return trip of the examined passenger ship is considered in this study. It travels to two different ports before returning to the initial in 24 hours time. The exact operational profile is described as:

- Loading: 1.5 hours
- Manoeuvring: 1 hour
- Sea going: 4.5 hours
- Manoeuvring: 1 hour
- Unloading: 1.5 hours
- Loading: 1.5 hours
- Manoeuvring: 1 hour
- Sea going: 6.5 hours
- Manoeuvring: 1 hour
- Unloading: 1.5 hours
- Rest at port: 3 hours

The above operational profile is based on REFRESH project data and author's assumptions.

The electrical power systems components functionality with their corresponding duration and frequency at each operating state is described below. The rated power performance was considered for all components during their operation except for the thrusters which are operating at lower rated power during the whole manoeuvring condition.

Table III-2: Operational profile of studied passenger ship electrical components

Component	Loading/ Unloading		Manoeuvring		Sea going		Rest at port	
	frequency	Duration (hours)	frequency	Duration (hours)	frequency	Duration (hours)	frequency	Duration (hours)
Engine Room Supply fan	5	0.2	6	0.15	8	0.5	8	0.25
Auxiliary Room Supply fan	5	0.2	8	0.11	10	0.45	6	0.45
Engine Room Exhaust fan	5	0.2	8	0.12	10	0.5	10	0.1
Auxiliary Room Exhaust fan	5	0.2	6	0.1	10	0.5	10	0.25
ME Air Compressor	5	0.2	8	0.12	10	0.5	5	0.2
ME FO Booster pump	5	0.2	8	0.12	20	0.15	10	0.2
DE FO Booster pump	5	0.2	3	0.2	20	0.2	5	0.2
	-	-	3	0.2	20	0.2	-	-
DO Transfer pump	-	-	3	0.2	20	0.2	-	-
FO Transfer pump	5	0.2	3	0.2	20	0.2	5	0.2
LO pump	5	0.2	3	0.2	20	0.2	-	-
	5	0.2	3	0.2	20	0.2	-	-
Reduction Gear LO pump	5	0.2	3	0.2	20	0.2	5	0.2
	5	0.2	3	0.2	20	0.2	5	0.2
LO Purifier	5	0.2	3	0.2	20	0.2	5	0.2
	5	0.2	3	0.2	20	0.2	-	-
ME LT FW cooling pump	-	-	3	0.2	20	0.2	-	-
	-	-	3	0.2	20	0.2	-	-
ME HT FW cooling pump	-	-	3	0.2	20	0.2	-	-
	-	-	3	0.2	20	0.2	-	-
SW cooling pump	5	0.2	3	0.2	20	0.2	5	0.2
	5	0.2	3	0.2	20	0.2	5	0.2
DE LT FW cooling pump	5	0.2	3	0.2	20	0.2	5	0.2
	5	0.2	3	0.2	20	0.2	-	-
CPP Propeller pitch setting pump	-	-	3	0.2	20	0.2	-	-
	-	-	3	0.2	20	0.2	-	-
Steering Gear	-	-	3	0.3	20	0.25	-	-
	-	-	3	0.3	20	0.25	-	-
Bow Thruster	-	-	8	0.12	-	-	-	-
Stern Thruster	-	-	8	0.12	-	-	-	-
Bilge, Fire & Ballast pump	2	0.2	3	0.1	5	0.1	5	0.2
E/R Fire & Bilge pump	2	0.2	3	0.1	5	0.1	5	0.2
Ballast pump	5	0.2	-	-	-	-	-	-
Drencher	5	0.2	-	-	-	-	-	-
Chiller	5	0.2	3	0.2	20	0.2	10	0.15

	5	0.2	3	0.2	20	0.2	5	0.15
	5	0.2	3	0.2	-	-	-	-
AC FW pump	5	0.2	3	0.2	20	0.2	10	0.15
AC SW pump	5	0.2	3	0.2	20	0.2	10	0.15
Lighting (225V)	5	0.2	3	0.2	20	0.2	10	0.15
Lighting (100V)	5	0.2	3	0.2	20	0.2	10	0.15
Navigation & Communication	5	0.2	3	0.2	20	0.2	10	0.15
Galley, Sanitary & Entertainment	5	0.2	3	0.2	20	0.2	10	0.15

III.3. Dependency diagrams of safety-critical systems

Boolean structures of the safety-critical systems for the studied passenger ship are presented below.

III.3.1 Propulsion system

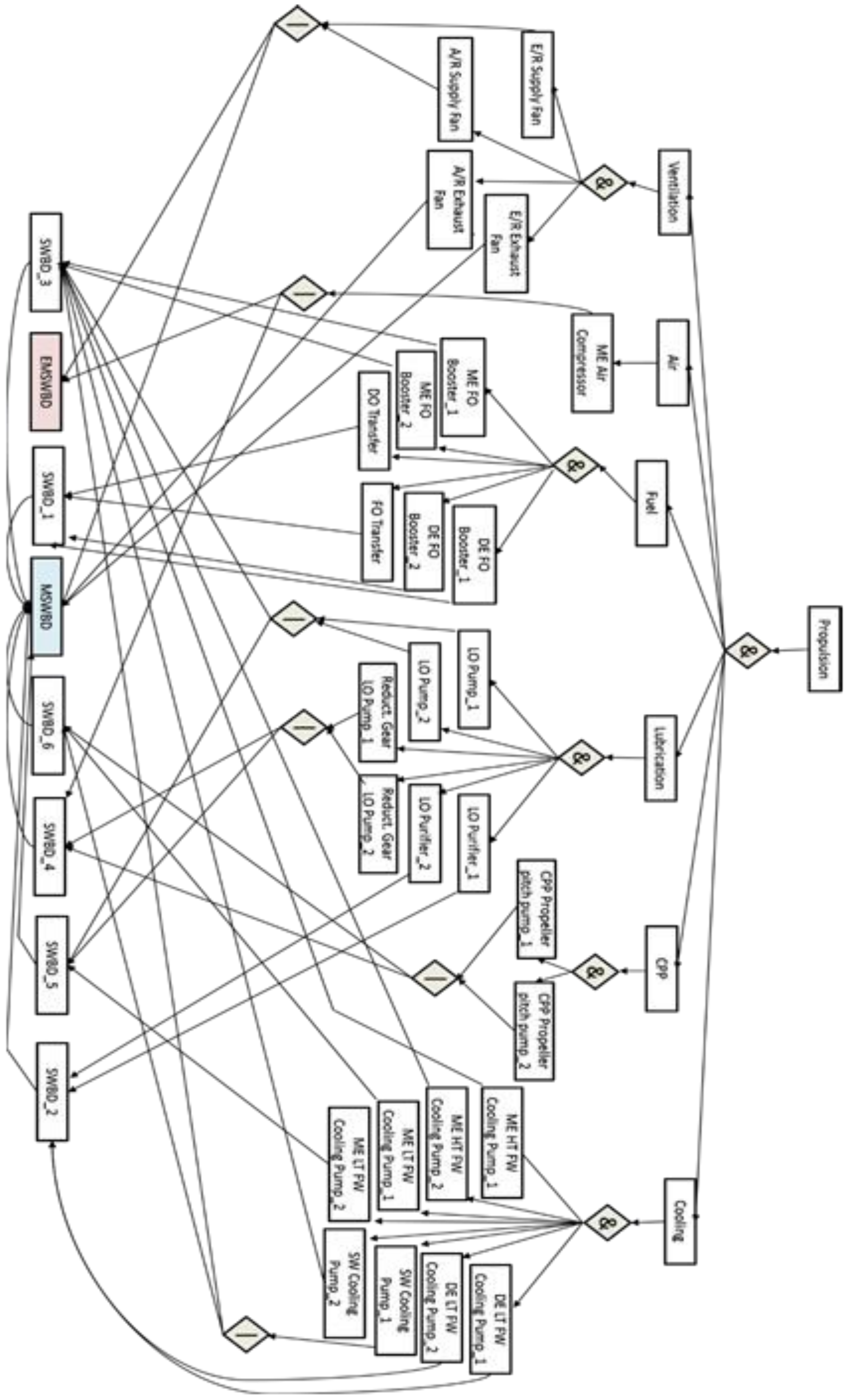

Fig III-3. "Dependency diagram of the propulsion system of studied passenger ship"

III.3.2 Steering system

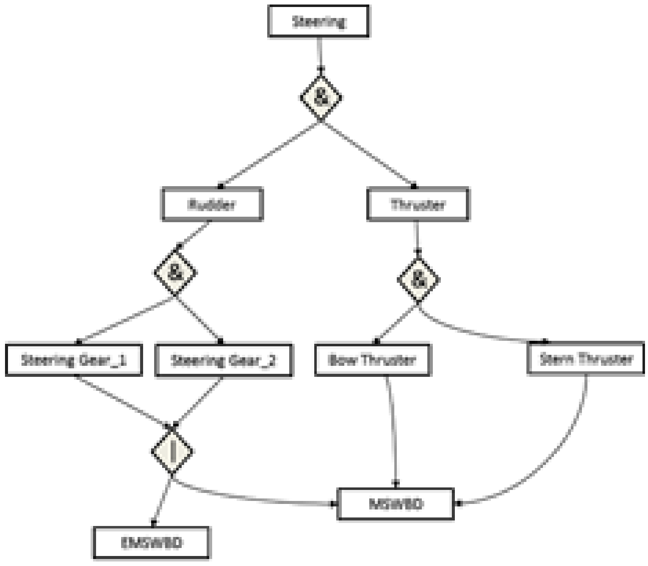

Fig III-4. "Dependency diagram of the steering system of studied passenger ship"

III.3.3 Bilge and Ballast system

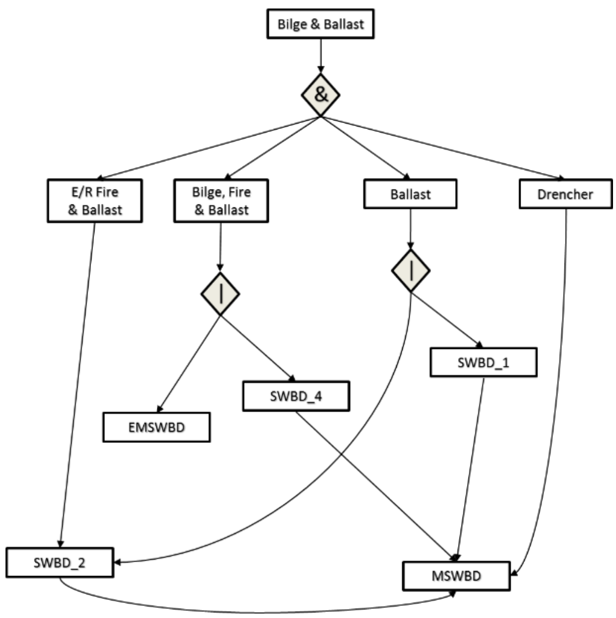

Fig III-5. "Dependency diagram of the bilge and ballast system of studied passenger ship"

III.3.3 Emergency system

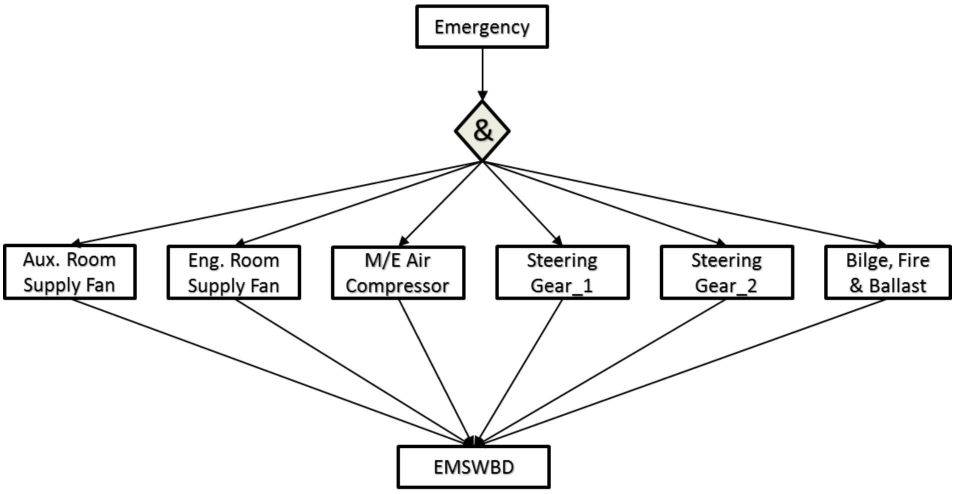

Fig III-6. "Dependency diagram of the emergency system of studied passenger ship"

III.4. Topology and geometry of safety-critical systems for conventional case

The onboard topology and geometry of the safety-critical systems for the studied passenger ship is shown below.

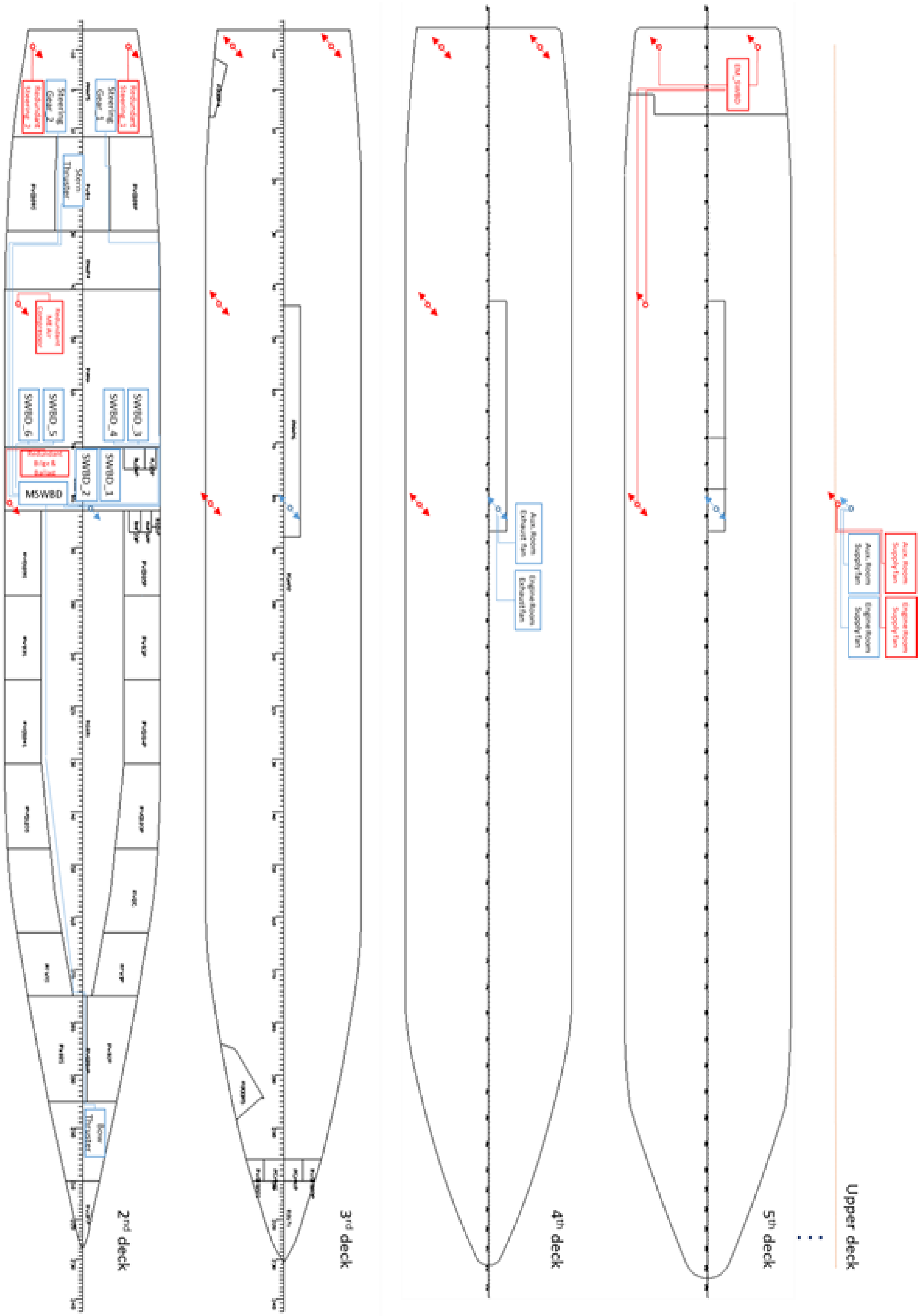

Fig III-7. "Onboard topology and geometry of the studied passenger ship systems"

APPENDIX IV – DIESEL-GENERATOR SETS

IV.1. Low capacity D/G set

The below curve describes the behavior of the diesel-generator set producing a range of output power from 450 kW to 855 kW.

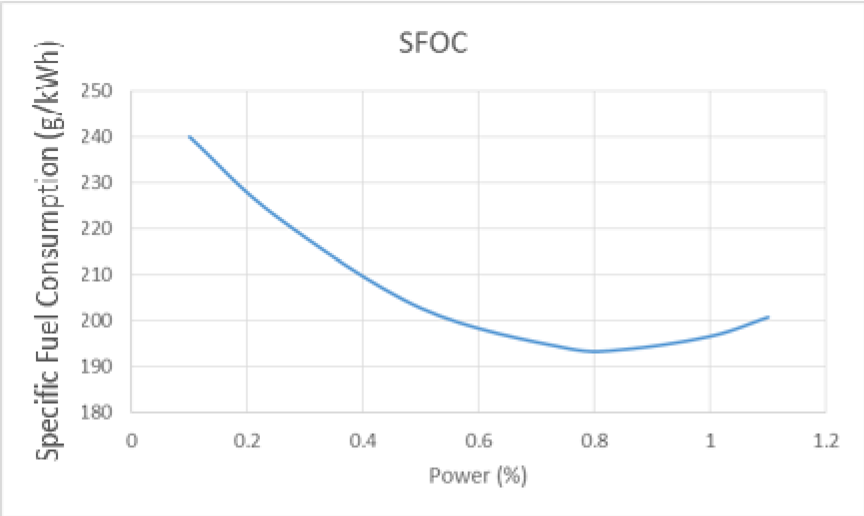

Fig IV-1. “Fuel consumption-produced power curve of low capacity D/G case”

IV.2. High capacity D/G set

The above curve describes the behavior of the diesel engines producing a range of power from 1,000 kW to 2,350 kW.

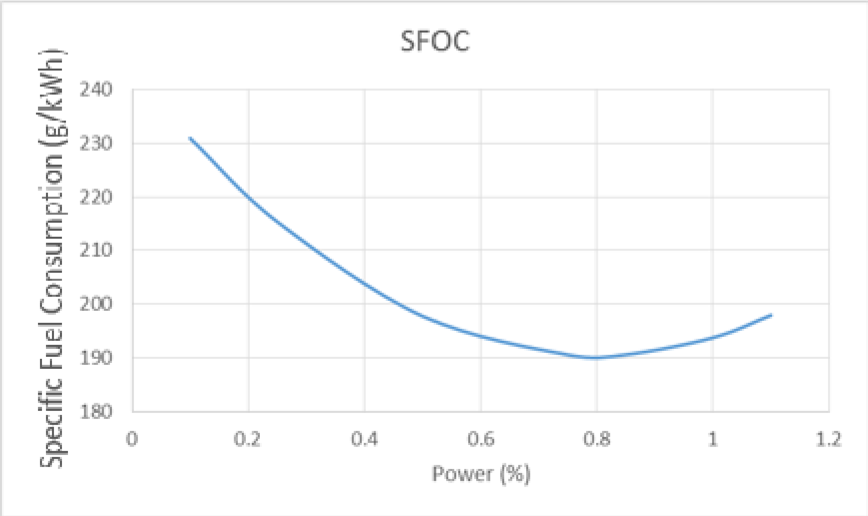

Fig IV-2. "Fuel consumption-produced power curve of high capacity D/G case"