CRISTIAN ANDRÉS MORALES VÁSQUEZ

A methodology to select the electric propulsion system for Platform Supply Vessels (PSV)

Dissertation submitted to Escola Politécnica da Universidade de São Paulo to obtain the degree of Master of Science in Engineering.

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Concentration Area:
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Advisor:
Prof. Dr. Helio Mitio Morishita

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ABSTRACT

The present work proposes a methodology to define the electric propulsion system for PSVs. This methodology was applied to a case study: the conceptual design of a PSV for operation at the pre-salt fields at Santos basin. First, four different alternatives of electric propulsion systems for the PSV are presented and sized. The first one has induction motors as main propulsion motors, the second one has synchronous motors as main propulsion motors; the third and fourth alternatives are the same as the first and second, respectively, with a batteries bank connected to the main switchboard. Each of the four arrangements was contemplated with two options for Diesel generators: high speed and medium speed generator sets. The mass, volume, fuel consumption, exhaust gases emissions and reference capital costs for each arrangement are estimated and analyzed. Moreover, an economic analysis through the Net Present Value (NPV) is performed. The methodology ends with the Analytic Hierarchy Process (AHP) to support the decision making procedure. Some of the parameters obtained for each arrangement (mass, volume, fuel consumption, exhaust gases and NPV) are used as criteria and sub-criteria for selection. Two scenarios are evaluated, the first scenario gives more importance to the financial component of the design; the second scenario sets the exhaust gases emissions as the more significant parameter. The results were different, the arrangements 1 and 2 with medium speed Diesel generator sets appear as the most suitable option from the economical point of view; whereas the arrangements with batteries and high speed Diesel gensets are the best options to reduce the exhaust emissions.

Keywords: Ship electric propulsion systems. Platform Supply Vessels. Batteries bank. Electric propulsion arrangements. Propulsion systems for PSVs.

RESUMO

O presente trabalho propôs uma metodologia para definir o sistema de propulsão elétrica para PSVs. A metodologia foi aplicada para um caso estudo: o projeto conceitual de um PSV para operar nos campos do pré-sal na Bacia de Santos. Primeiramente, as quatro diferentes alternativas de sistemas de propulsão elétrica para PSV são apresentadas e dimensionadas. A primeira alternativa tem motores de indução como motores de propulsão principal, a segunda alternativa tem motores síncronos como motores de propulsão principal; a terceira e quarta alternativas são as mesmas que a primeira e a segunda, respectivamente, com um banco de baterias conectado ao quadro principal. Cada um dos quatro arranjos foi considerado com duas opções para Diesel geradores: Diesel geradores de alta e média rotação. A massa, volumem, consumo de combustível, emissão de gases e os custos capitais de referência para cada arranjo são estimados e analisados. Adicionalmente, uma análise económica usando o Valor Presente Líquido (VPL) é feita. A metodologia finaliza com o Analytic Hierarchy Process (AHP) para apoiar o processo de escolha de alternativa. Alguns dos parâmetros obtidos para cada arranjo (massa, volumem, consumo de combustível, gases poluentes e o VPL) são utilizados como critérios de seleção. Dois cenários são avaliados, o primeiro cenário dá maior importância à parte financeira do projeto, o segundo cenário estabelece as emissões de gases poluentes como o parâmetro mais significativo. Os resultados foram diferentes, os arranjos 1 e 2 com Diesel geradores de média rotação se apresentam como a opção mais adequada desde o ponto de vista econômico; enquanto os arranjos com baterias e Diesel geradores de alta rotação são a melhor opção para reduzir as emissões de gases poluentes

Palavras-chave: Propulsão elétrica de navios. Barco de Apoio a Plataformas. Banco de baterias. Arranjos de propulsão elétrica. Sistemas de propulsão para PSVs.

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ABREVIATIONS

A1	Arrangement 1
A2	Arrangement 2
A3	Arrangement 3
A4	Arrangement 4
AC	Alternating Current
AHP	Analytic Hierarchy Process
CO_2	Carbon Dioxide
CPP	Controllable Pitch Propeller
CSI	Current Source Inverter
DC	Direct Current
DP	Dynamic Positioning
DWT	Deadweight
FAFW	Forced Air/Forced Water
FPP	Fixed Pitch Propeller
Genset	Generator Set
HFO	Heavy Fuel Oil
HTS	High Temperature Superconductor
IEC	International Electrotechnical Commission
IEEE	The Institute of Electrical and Electronic Engineers
IFO	Intermediate Fuel Oil
IGBT	Insulated Gate Bipolar Transistor
IGCT	Integrated Gate-Commutated Transistor
IMO	International Maritime Organization
IMP	Integrated Motor-Propeller
IPT	Instituto de Pesquisas Tecnológicas
ISO	International Organization for Standardization
LNG	Liquefied Natural Gas
MARPOL	International Convention for the Prevention of Pollution from ships

MCR	Maximum Continuous Rating
MDO	Marine Diesel Oil
MGO	Marine Gas Oil
NEMA	National Electrical Manufacturers Association
NOx	Nitrous Oxides
NPV	Net Present Value
O&M	Operation and Maintenance
OSV	Offshore Support Vessel
PMSG	Permanent Magnet Synchronous Generator
PSV	Platform Supply Vessel
SCAC	Separate Circuit After-Cooled
SFOC	Specific Fuel Consumption
SNAME	Society of Naval Architects and Marine Engineers
SOx	Sulfur Oxides
UFRJ	Universidade Federal do Rio de Janeiro
US	United States
USP	Universidade de São Paulo
VFD	Variable Frequency Drive
VSI	Voltage Source Inverter
ZEBRA	Sodium/Nickel Chloride Batteries

SYMBOLS

A_{BT}	Transverse bulb area
A_{Lt}	Installment amounts
A_T	Transom area
$Aux.power_n$	Auxiliary/hotel power sample
B	Beam
BL_{RC}	Basic line module rated current
BL_{RP}	Rated power of the basic line module
CA	Random consistency index
CO_2	Mass of released CO_2
C_B	Block coefficient
C_M	Master section coefficient
C_P	Prismatic coefficient
C_{stern}	Stern shape parameter
C_{WP}	Waterplane coefficient
D	Propeller diameter
$DP\ power_n$	Dynamic positioning power sample
$Engpow_n$	Power delivered by the Diesel engine at the sample n
$engload_{high1n}$	Loading of the high speed Diesel engine of the arrangement 1
$engload_{medium1n}$	Loading of the medium speed Diesel engine of the arrangement 1
$engload_{medium2n}$	Loading of the medium speed Diesel engine of the arrangement 2
$estrg$	Total energy storage
ef_{CO_2}	CO_2 emission factor
ef_{NOx}	NOx emission factor
ef_{SOx}	SOx emission factor
$fcost$	Cost of the fuel
$fexp_i$	Fuel expenses for period i
$fexp_1$	Fuel expenses for the first year

G_{PRkVA}	Power rating of the generator sets in kVA
G_{PRkW}	Power rating of the generator sets in kW
$Genpow_n$	Power at the output of the generator
$genload_n$	Generator loading
h	Number of Diesel generator sets in operation
h_B	Height of the centre of the transverse bulb area
$hsgenset_{cost}$	Cost of the high speed generator sets
IC	Inconsistency index
IM_{cost}	Induction motor cost
k	Discount rate
L	Length of waterline
L_{CB}	Longitudinal centre of buoyancy
L_{PP}	Length between perpendiculars
L_t	Bank loan
MCR	Maximum continuous rate
M_{DE}	Mass of Diesel electric propulsion installation
M_{DEW}	Mass of Diesel electric propulsion installation (Watson formula)
m	Order of the matrix
$mexp_i$	Maintenance expenses for the year i
$mexp_1$	Maintenance expenses for the first year
$mfactor$	Cost of maintenance
$msgenset_{cost}$	Cost of the medium speed generator sets
N	Total number of periods
NO_X	Mass of released NOx
N_L	Loan payback period
$NPV(k,N)$	Net present value
n	Number of the sample

η	Transformer Efficiency
η_{gen}	Generator efficiency
η_m	Motor efficiency
η_{maz}	Efficiency of the main propulsion motor
η_{mbow}	Efficiency of the bow thruster motor
$\eta_{motor\ module}$	Motor module efficiency
η_{switch}	Switchboard efficiency
$\eta_{trafoaz}$	Efficiency of the transformer for main propulsion
η_{VFD}	VFD efficiency
η_{VFDaz}	Efficiency of the VFD for main propulsion
η_{VFDbow}	Efficiency of the VFD for the bow thruster motor
P_{LL}	Transformer load losses
P_{NL}	Transformer no load losses
$Prop.power_n$	Propulsion load power sample
$P.F.$	Transformer power factor
P_m	Motor rated power
P_p	Total installed power for propulsion
$P.F._{load}$	Power factor at the output of the generators
$P.F._m$	Motor rated power factor
$P.F._{VFD}$	VFD power factor
RC	Consistency Ratio
R_L	Interest rate
R_t	Cash flow of the period t
S	Transformer apparent power
SY	Number of services per year
$SFOC_{high1n}$	Specific fuel oil consumption for the high speed Diesel engine of the arrangement 1

$SFOC_{medium1n}$	Specific fuel oil consumption for the medium speed Diesel engine of the arrangement 1
$SFOC_{medium2n}$	Specific fuel oil consumption for the medium speed Diesel engine of the arrangement 2
$SFOC_n$	Engine specific fuel consumption for the sample n
SM_{cost}	Synchronous motor cost
SO_X	Mass of released SOx
$Switchboard_{RC}$	Switchboard rated current
$Trafo_{cost}$	Transformer cost
$Trafo_{PR}$	Transformer power rating
T_A	Draft aft
T_F	Draft forward
t	Period of the cash flow
t_1, t_2	Time limit between samples
VFD_{AP}	Active power of the VFD
$VFDcost$	Cost of the VFD
VFD_{RC}	Main VFD rated current
$\%sulfur\ content$	Sulfur content of the fuel in percentage
$\%fvar$	Variation of the value of the fuel per year
$\%mvar$	Variation of the value of the maintenance per year
∇	Displacement
λ_{max}	Greater autovalue of the matrix

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1 INTRODUCTION

1.1 BACKGROUND

Brazil, with its recent oil discoveries at sea below the pre-salt layer[1], has increased its potential oil reserves up to 30 billion barrels. Taking this into account and the rising tendency of the global oil demand, Petrobras, the largest oil and gas company in Brazil, intends to exceed the current limit production of 2.1 mb/d (million barrels per day) (ANP, 2013) to reach the target of 4.2 mb/d by 2020 (GNBC, 2012). To achieve this goal, a huge logistic operation and a large infrastructure is required to develop and support the production activities in the pre-salt oil fields at Santos Basin, at distances above 300km from shore. In fact, it is expected that, until 2020, a large number of drilling and production units will be required along with more than 500 offshore support vessels (OSV) to sustain their operation (VAREIDE, 2011); most of them will be PSV[2] (RS PLATOU, 2012).

The platform supply vessels (PSV) are specialized ships built to serve platforms or drilling rigs in offshore production fields. Their principal task is to transport cargo, provisions or personnel from port to the platforms at sea, generally at several kilometers away from shore. In order to perform this task, the ship possesses a large free deck space for placement or storage of equipment; within the hull, the vessel can be equipped with tanks to store liquid or dry bulk cargo. A PSV is usually fitted with dynamic positioning systems, which are required for position keeping at sea close to the platforms or drilling rigs. In Figure 1.1 a typical PSV is shown.

Owing to the large distance from ports to the pre-salt fields at Santos Basin, the PSVs are required to have a large capacity for cargo, high reliability, and system redundancy, as well as meeting the strict safety standards. Nowadays the platform operators are demanding PSVs with electric propulsion systems and class 2 dynamic positioning systems (IMO, 1994) with high preference for vessels with deadweight (DWT) capacity above 4000DWT (WEISS, *et al.*, 2012).

In this context, the Universidade de São Paulo (USP), the Universidade Federal do Rio de Janeiro (UFRJ) and the Instituto de Pesquisas Tecnológicas (IPT) conducted a

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[1] Geological formation approximately 5 to 7km deep from the water surface and, approximately 300km far from the Brazilian coast; extended along the coastal line of Santa Catarina up to Espirito Santo.

[2] The Offshore Support Vessel (OSV) is a ship that provides logistic, operational and emergency assistance to the offshore production environment. The Platform Supply Vessel (PSV) is a special type of OSV that transport and stores materials, equipment and/or personnel to, from and between offshore installations.

research to develop a conceptual design of a PSV for supporting the exploration and production activities at Santos Basin. One of the preliminary results of the research was the proposal of a basic hull form (WEISS, *et al.*, 2012; COPPE/UFRJ, IPT e USP, 2012), which is required to be complemented by the definition of the propulsive installation. In this sense, the present work is focused on sizing and selecting the electric propulsion system for PSVs.

Figure 1.1 – A Typical PSV (ARCOVERDE, 2013).

1.2 LITERATURE REVIEW

Electric propulsion systems have been used for ship propulsion for more than 100 years, but it was not until the 1980 decade, with the advancement of power electronics, that the ship electric propulsion systems became popular and cost competitive when compared to conventional mechanical propulsion ones (ADNANES, 2003). Ships with high torque requirements at low rotational speed (icebreakers), with various operation types (PSVs), with hotel loads as big as the propulsion loads (cruisers), and with various electrical actuators (vessels with dynamic positioning), are the major users of the system (ADNANES, 2003; 2008; 2009; ALVES, 2007; PATEL, 2012).

The electric propulsion system offers several technologies and arrangements. The selection of elements for a particular ship depends on the total power range, commercial availability, the state of art and the specific conditions. In electric propulsion systems for PSVs, the most common components are the following (ADNANES, 2003; 2008; 2009; ALVES, 2007; PATEL, 2012):

- Prime movers: Diesel engines in the medium or high rotational speed range, with fixed or variable speed operation.
- Generator: wound rotor or permanent magnet synchronous generator.
- Transmission system: alternate current (AC) or direct current (DC) at low voltage level.
- Electric propulsion drives: variable frequency drive (VFD)
- Electric motor for propulsion: wound rotor or permanent magnet synchronous motor, and induction motor.
- Main propulsion and thruster units: Azimuth thruster with fixed pitch propeller, podded thruster with fixed pitch propeller, cycloidal propeller, tunnel thruster and integrated motor propeller.

Each of the previous components can be set in operation along with any other component, forming several electric propulsion arrangements.

In order to select an electric propulsion system for a vessel, various alternatives or arrangements are proposed to compare their characteristics. The most common alternatives for medium size/medium power vessels (in order from 1 to 10~12MW) are the electric propulsion systems with AC transmission and synchronous or induction motors as main propulsion motors (ALVES, 2007; PATEL, 2012). Dedes, Hudson & Turnock (2010; 2012) have also proposed electric propulsion systems with AC transmission and batteries banks for power compensation and reduction of fuel consumption. Fan (2013) proposed and performed the evaluation of DC transmission systems for PSVs comparing them to AC transmission systems and concluding that DC systems can provide better fuel consumption in dynamic positioning operation.

Regarding the sizing of the electric propulsion arrangements, the International Maritime Organization (IMO) settled some guidelines related to the selection of the Diesel generator sets and the system redundancy for class 2 dynamic positioning systems. The MARPOL (International Convention for the Prevention of Pollution from ships) 73/78 in their Annex VI (IMO, 2004) has established limits for NOx (Nitrous Oxides) emissions caused by Diesel engines in ships, decreasing the allowable emissions by stages or tiers; currently the tier II has entered into force. Additionally the sulfur content of fuels used in vessels cannot be higher than 3.5%. With respect to the class 2 dynamic positioning systems, the IMO (1994) settled regulations that made mandatory the redundancy in thrust and main propulsion systems, which are complemented by the regulations of the classification societies (ABS, 2006; 2011; 2013).

Some authors assess and compare electric propulsion arrangements using the typical power demand of a vessel for a typical operation (DEDES, HUDSON and TURNOCK, 2010; 2012; ARCOVERDE, 2013). The main parameter for evaluation is the fuel consumption of the Diesel generator sets to supply the demand, which is compared between all the arrangements. Also, it is suggested to estimate the exhaust gases emissions from the Diesel generator sets to determine the impact of each arrangement on the environmental pollution (PEREIRA, 2007; MEDEIROS, 2010). Two additional parameters for evaluation are important from the point of view of naval architects: the mass and the occupied volume of the arrangements. Depending on the ship type and its constraints, one parameter can be more important compared with the other (the ship can be restricted in mass and volume).

They are both important for determining their influence on the hull resistance (BOSE, 2008; MOLLAND, TURNOCK and HUDSON, 2011); therefore, a propulsion arrangement with low mass and volume is desired in any ship design. A final criterion for the arrangements selection, the economics, is proposed (DEDES, HUDSON and TURNOCK, 2010; 2012; ARCOVERDE, 2013). The economic evaluation uses the cash flow (sum of the total incomes and outgoings) during the lifetime of the vessel (composed by fuel, maintenance and other expenses) to identify the arrangements with the highest expenses.

To select the best arrangement, various selection methodologies are proposed by Garber (2002). The most recommended one is the analytic hierarchy process (AHP) methodology as pointed out by Garber (2002), Pereira (2007) and Moratelli (2010).

1.3 OBJECTIVE

In order to perform a profitable operation, ship-owners and platform operators are investing in several researches leading to improve the propulsive efficiency and reduce the fuel consumption of the vessels. As the electric propulsion systems become mandatory in PSVs in Brazil, a clear methodology or process to define the electric propulsion arrangements in early stages of the project is required.

The main objective of the present work is to propose a methodology to size and select the electric propulsion system for PSVs applied to a case study: PSVs for operation in the pre-salt oilfields at Santos Basin. The task is divided into the following stages:

a. Discussion and analysis of the main components of the electric propulsion system for PSVs.
b. Estimation of a typical operational profile and load profile for a PSV in Santos Basin.
c. Proposal and sizing of four electric propulsion alternatives: two arrangements with conventional electric propulsion systems and two arrangements with batteries bank as a relative new implementation in this type of vessel. Each alternative considering medium and high speed Diesel generator sets.
d. Estimation of the mass, volume and capital costs for each arrangement.
e. Estimation of the fuel consumption and exhaust gases emissions of each alternative for the reference load profile.
f. Development of an economic analysis through cash flow and the NPV to determine the expenses of each arrangement for the vessel lifetime.
g. Comparison and selection of the best arrangement fitted to the following criteria: low mass, volume, fuel consumption, exhaust gases emissions (NOx and SOx) and NPV. This procedure will be performed through the AHP methodology.

1.4 TEXT ORGANIZATION

Chapter 2 presents and discusses the general arrangement of the electric propulsion systems for PSVs. Each component is detailed, presenting also the available alternatives and their features.

In chapter 3, the operational requirements for the PSVs in Brazil are described. Later, the methodological approach is proposed and discussed. Furthermore, the first stages of the methodology are performed: characterization of similar vessels, estimation of the propulsion power and sizing of the electric propulsion arrangements.

Chapter 4 continues with the remaining stages of the methodology, the operational profile and the standard load profile are defined for the evaluation of the arrangements. Next, the performance analysis of the Diesel generator sets and the power of the system is made resulting in the estimation of the fuel consumption and the exhaust emissions for each arrangement. Afterwards, the economic evaluation and the selection of the electric propulsion arrangement for the PSV is done using the AHP methodology.

Finally, the conclusions and recommendations of this dissertation are presented in Chapter 5.

2 SHIP ELECTRIC PROPULSION SYSTEM DESCRIPTION

The general arrangement of the Electric Propulsion System for twin propeller vessels is shown in Figure 2.1. The source of power is the prime mover, which transforms the chemical power of the fuel into mechanical power. Then, the energy is again converted from the mechanical form to the electrical one through a generator; afterwards, the power is transmitted to the electric motor using cables, in alternate current or direct current form, passing through switchboards, transformers and frequency converters. The energy is once more converted from the electrical to the mechanical form to provide power to the propulsion unit, which provides the required thrust for the ship movement or station-keeping. An energy storage device can be added to this configuration for load compensation, for energy back up or for supplying energy to the loads when the vessel is in port or stand-by operation.

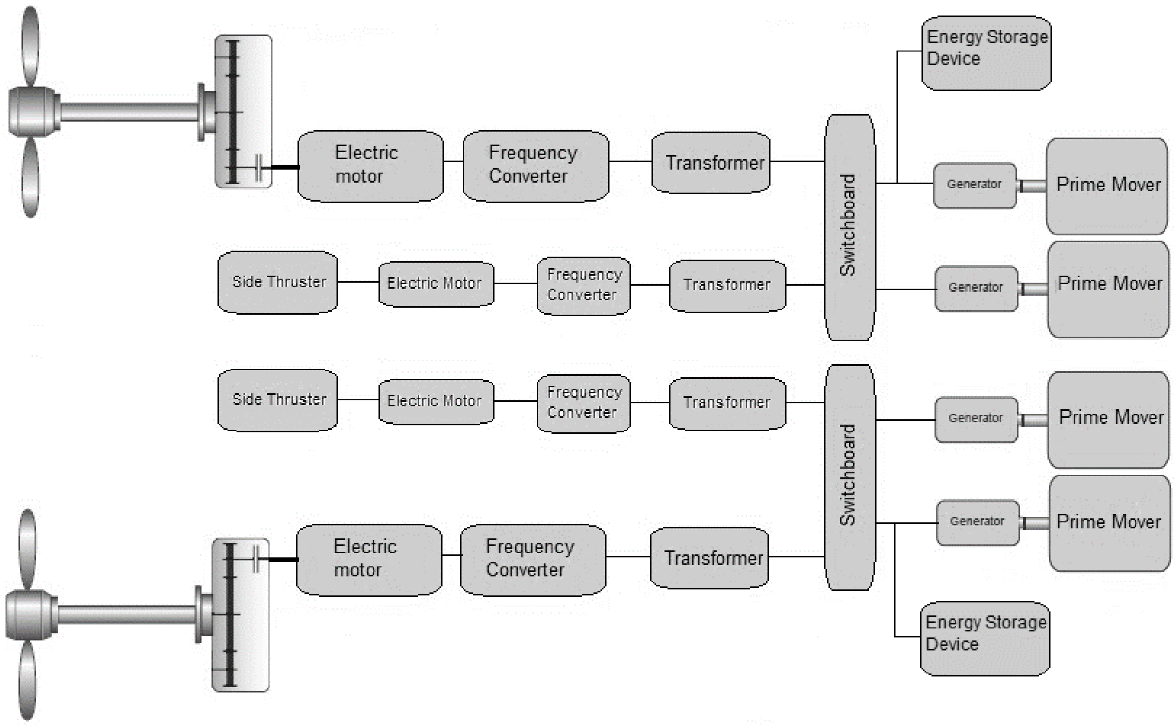

Figure 2.1 – Electric Propulsion General Arrangement.

Depending on the configuration of the arrangement the electric propulsion system can be classified according to three main concepts (PATEL, 2012): Separated Electric Propulsion System, Integrated Propulsion System and All-electric ship. In the first case there are two separated groups of generator sets, one group to supply exclusively the propulsion loads and the other one to supply the hotel and auxiliary loads. In the second case, the integrated propulsion system, all the generator sets operate interconnected supplying all the loads, as shown in Figure 2.1. Finally, in the all-electric ships, all the loads that use hydraulic or compressed air power on the ship are converted into the electrical type, thus eliminating the hydraulic and air systems on board.

The Electric Propulsion System has been extensively used in commercial vessels lately because of its several advantages; mostly cruisers, offshore support vessels, icebreakers, passenger vessels and warships are the major current users of this system. The features of this system, taking as a comparison basis the conventional mechanical propulsion system, as reported in the literature, are detailed in Table 2.1.

Table 2.1 - Advantages and Disadvantages of the Electric Propulsion System (ADNANES, 2003; SNAME, 2004).

Advantages
Since power is produced by various engines, it is possible to optimize engine loading by switching them on or off when needed.
Reduced vulnerability and high reliability owing to redundancy of equipment
Improved life cycle cost with reduced consumption and maintenance even in low demand.
The use of light engines reduces the weight and space necessary for the entire system.
Flexibility in locating of thruster devices, engines, generators and converters since energy transmission is made by cables, also improving the used space.
Better maneuverability due to the use of azimuthing thrusters or podded propulsion.
Less propulsion noise and vibrations, because shaft lines are shorter.
Despite of the conversion energy losses presents r**educed fuel consumption**
The use of electric motors allows ship speed variation with high efficiency.
Disadvantages
Increased investment cost (the cost tends to decrease with the increasing numbers of units manufactured).
Additional components between prime mover and propeller increase the transmission losses at full load.
Electronic converters produce electric harmonic distortion in the supply voltage and current that have to be minimized.

This chapter describes all of the Electric Propulsion System components shown in Figure 2.1, focusing in those ones with major importance for application in offshore supply vessels.

2.1 ENGINE-GENERATOR SET

In Ship Electric Propulsion Systems, the source of electrical power is commonly a synchronous generator driven by a prime mover, which is generally an internal combustion engine fueled with Diesel or heavy fuel oil. Alternatively, high-speed gas turbines and steam turbines are used when high power-to-weight ratio is required (especially in warships) (ADNANES, 2003). Dual fuel engines, *i.e.* internal combustion engines that can be fueled with both Diesel fuel oil and liquefied natural gas (LNG), have also been used recently as prime movers, mainly in offshore support vessels and LNG carriers (WARTSILA, 2012).

The generators are of the synchronous type with wound rotor, rotating at fixed speed. In recent years, synchronous generators with permanent magnet rotor have been used as well, specially along with variable speed prime movers. Fuel cells for power generation are also being considered as a new technology for ship electric propulsion systems. This technology provides several advantages (SATTLER, 2000): low noise production, low maintenance, almost zero pollutant emissions, no rotating parts, etc. Nevertheless, the current state of the art of this technology makes it unsuitable for mid to high power applications in commercial ships because of some significant drawbacks (LEO, DURANGO and NAVARRO, 2010): high volume and weight, vulnerability to the marine environmental effects (corrosion and the constant movement of the ship), lack of infrastructure in the world to facilitate the widespread use if this technology and the high price of the generated energy (in kWh) compared to conventional systems. Several researches and tests for the application of this technology on surface ships have been conducted (LEO, DURANGO and NAVARRO, 2010; SATTLER, 2000; VIKING Lady Tests Fuel Cell Power, 2009; THE future is hybrid, 2012) leading to make this technology available for commercial vessels in the near future.

2.1.1 Prime Movers

2.1.1.1 Diesel Engines

The Diesel engines can be classified by their rotational speed into high, medium or low speed[3]. In medium-power ship electric propulsion systems the dominant technology for prime mover is the Diesel engine operating at fixed rotational speed in both, the high and medium speed range. Variable speed Diesel engines in both speed ranges have been also used in vessels (SIEMENS, 2011a; SIEMENS, 2012b). Features of each type of Diesel engines will be discussed below.

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[3] According to Dedes, Hudson and Turnock (2012), high-speed diesel engines have a rotational speed greater than 1000rpm, medium speed between 400-1000rpm and low speed lower than 140rpm.

- High speed Diesel engine

High-speed Diesel engines are engines commonly fueled with pure distillates from crude oil: Marine Gas Oil[4] (MGO), Marine Diesel Oil[5](MDO) or both. Compared to the Diesel engines in other speed ranges, they have the highest Specific Fuel Oil Consumption (SFOC), typically in a range of 195-260g/kWh as shown in the Figure 2.2 and the Table 2.2 for a typical engine (CUMMINS POWER GENERATION, 2008). For most engines, the SFOC curve has its minimum value at shaft loads equivalent to 80-85% of the rated load. Furthermore, their operational and maintenance costs are also the highest ones, approximately US$0.01 per kWh (ADNANES, 2003; KOZLOWSKI, 2002), as indicated in the Table 2.2. In contrast, they have the lowest capital costs, weight-to-power ratio and less occupied space.

The pollutant emissions, specifically nitrous oxide emissions[6] (NO_X) are also the lowest of the three types, commonly below of 11g/kWh as required by the IMO (IMO, 2004), which limits the NO_X released to the environment by high speed engines to a lower level than medium and low speed engines.

Regarding cooling, high-speed diesel engines for ship electric propulsion usually have a water jacket circuit for cooling the engine, which later exchange heat with another separate water circuit. This cooling method is known as Separate Circuit After-Cooled (SCAC) (CATERPILLAR, 2003). The second cooling circuit usually uses seawater as coolant.

Typical rotational speeds for commercial engines used for power generation at fixed speed are 1200, 1800, 3600rpm for 60Hz and 1000, 1500, 3000rpm for 50Hz (ENERGY AND ENVIRONMENTAL ANALYSIS, 2008).

Manufacturers categorize the high-speed diesel engines according to three rating designations, which define the maximum power rating of the engine: stand by, prime and continuous rating (CATERPILLAR, 2003).

- A diesel engine for stand by operation is manufactured to supply a varying load with an average load factor[7] ≤60% for a limited operational time, *e.g.* 500 hours

[4] In this dissertation the Marine Gas Oil is designated by the ISO 8217 4th edition 2010 as DMA.
[5] In this dissertation the Marine Diesel Oil is designated by the ISO 8217 4th edition 2010 as DMB.
[6] The NO_X emissions are related to the temperature of combustion and are dependent of the type of engine and its construction. The other significant exhaust gases from Diesel engines, SO_X and CO_2, depends on the quality and quantity of fuel burned instead of the engine type.
[7] Load factor as defined in Caterpillar (2003) is the product between the percentage of the total operational time at a specific load and the percentage of power required by the specific load referenced to the engine rated load.

per year; in an emergency case it can supply a peak demand of 100% of its rated power. Commercial engines are available at power ratings up to 4MW.

- A prime rating diesel engine with is manufactured to supply power to a varying load for an unlimited time. The average load factor must be kept between 60-70% and should be maintained for approximately 60% of the total operational time. The engine is capable of supplying peak demands for short time periods at a maximum of 120% of its rated power. Available commercial engines have power ratings up to 3.6MW.
- The diesel engine for continuous operation is built to provide rated power for a constant load for unlimited time. The typical load factor is between 70-100%. The engine can provide 100% of its rated power for 100% of the operational time or 120% of its rated power for short periods. Commercial units have power ratings up to 3.25MW.

• Medium speed Diesel engine

This type of engine rotates between a range of 400 to 1000rpm and can be fueled with MGO, MDO, Intermediate Fuel Oil[8] (IFO) and Heavy Fuel Oil [9] (HFO). When used for generating set, its fuel consumption tipically ranges between 185 and 210g/kWh, with the lowest value for shaft loads equivalent to 75-80% of the rated power, as can be noted in Figure 2.2 for a typical engine (MAN DIESEL & TURBO, 2013b). Since the engine can burn IFO or HFO and its rotational speed is lower than the high speed engine type, its operational and maintenance costs are cheaper, approximately $0.005 per kWh (KOZLOWSKI, 2002). Nevertheless, engine mass, capital cost and occupied volume are greater.

This type of engine is used mainly in electric propulsion systems in installations with medium to high power levels. In platform supply vessels with electric propulsion systems, this type of engine is used very seldom due to its high weight and capital cost compared to the high speed one (See section 3.2.1).

Commercial engines are available at power ratings up to 23000kW at 900, 720, 600, 514rpm for power generation at 60Hz and 750, 600, 500, 428rpm for power generation at 50Hz (MAN DIESEL & TURBO, 2012b). The engines with higher

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[8] In this dissertation the Intermediate Fuel oil is designated by the International Organization for Standardization [ISO] (2012) as residual fuel type from RME180 up to RMG700.
[9] In this dissertation the Heavy Fuel Oil is designated ISO (2012) as residual fuel type from RMK380 up to RMK700.

rotational speeds are preferred due to the lower weight of the engine and the generator, as will be discussed below.

The NO_X emissions of this type of engine are normally below 14g/kWh, usually higher than the emissions realeased by the high speed diesel engines due to the restrictions of the MARPOL 73/78 Annex VI (IMO, 2004).

In contrast to the high speed engines, the medium speed engines are not informed to have power ratings with average loads or time restrictions as the high speed ones.

- High and medium speed Diesel engines comparison

A comparison of the main features of each type of engine is presented in Table 2.2. The data of the SFOC, mass volume and type of fuel burned was taken from manufacturer catalogs (CUMMINS POWER GENERATION, 2008; MAN DIESEL & TURBO, 2013b). The capital costs of the high speed Diesel engine were obtained from trend-lines presented in Appendix A for a power rating of 1825kW, while for the medium speed Diesel engine was obtained from Dedes, Hudson and Turnock (2010).

Table 2.2 – High Speed and Medium Speed Diesel Engine Features Comparison.

	SFOC (g/kWh)	Mass	Volume	Capital Cost (US$/kW)	Maintenance cost (US$/kWh)	Fuel burned	NO_X Emissions (g/kWh)	Maximum power (kW)
High speed	195-260	1	1	≈264	0,01	MGO	≤11	3600 (prime)
Medium speed	187-210	≥2.4	1.1	≈350	0,005	MGO, MDO, HFO	≤14	11000

Figure 2.2 presents the typical SFOC curves of the two types of Diesel engines already discussed. The curves correspond to measures taken from commercial Diesel engines from different manufacturers operating at 1800rpm and 900rpm, fixed speed at the same reference conditions (CUMMINS POWER GENERATION, 2008; MAN DIESEL & TURBO, 2013b).

- Variable speed Diesel engines

The Diesel engine for propulsion and power generation is designed to provide torque between a range of shaft power and rotational speed, being able to work within an operational region known as the engine operational region or engine schematic layout diagram (MAN DIESEL & TURBO, 2012a), which is presented in Figure 2.3.

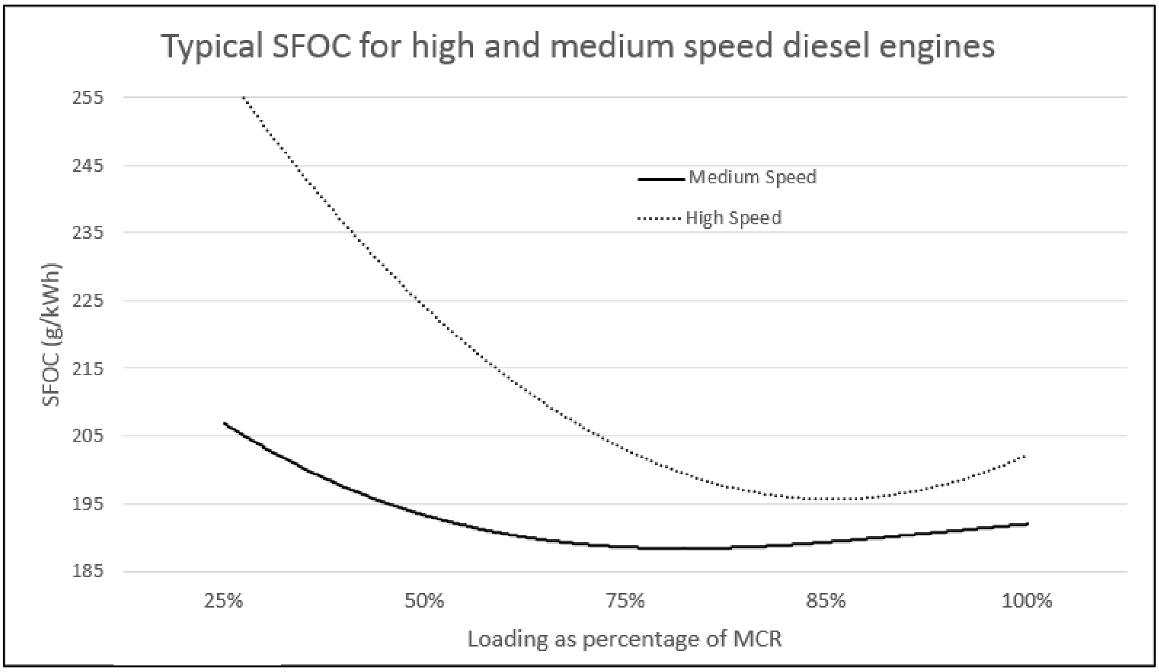


Figure 2.2 – Typical SFOC Comparison for High and Medium Speed Diesel Engines for generating sets operating at fixed speed.

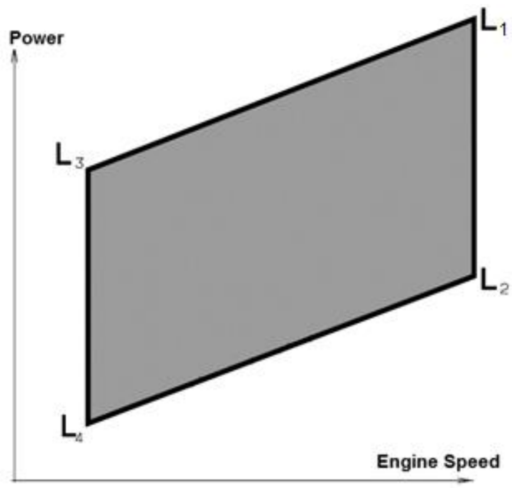


Figure 2.3 – Engine Operational Region or Engine Schematic Layout Diagram (MAN DIESEL & TURBO, 2012a).

In electric power generation applications, the engine speed controller is usually programmed to operate in the limit of the operational region marked in Figure 2.3 as L_1-L_2 at a constant speed. In this way, the engine presents the typical SFOC shown in Figure 2.2.

If the engine is operated within the complete operational region, its SFOC will vary as the function of the load and the rotational speed, forming a SFOC map with several curves or areas of constant SFOC for different loads and rotational speeds, as shown in Figure 2.4 for a typical Diesel engine (MAN DIESEL & TURBO, 2013a). In the figure, it is possible to see that as the curves get closer to the minimum point the lowest the SFOC values are.

A Diesel engine for power generation, operating at a variable speed, can take advantage of what was mentioned above and function within the curve with the lowest SFOC value for the demanded load by adjusting the rotational speed; hence, the engine will be more efficient from the fuel consumption perspective compared to the fixed speed ones.

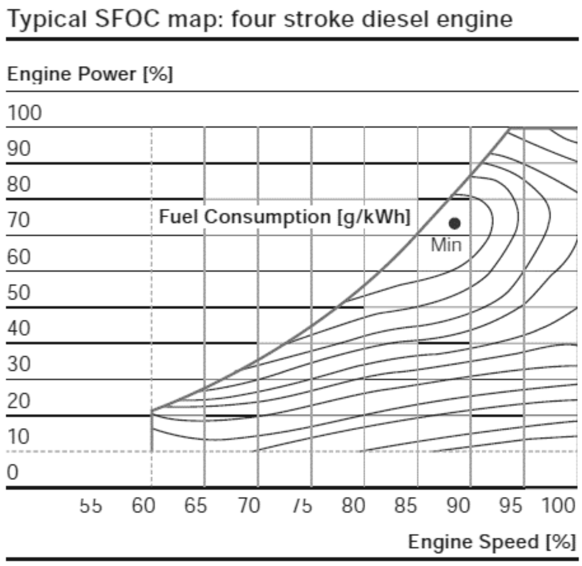


Figure 2.4 – Typical SFOC Map of Diesel Engine As a Function of Rotational Speed and Shaft Power (MAN DIESEL & TURBO, 2013a).

Figure 2.5 is presented in order to clarify the difference between the SFOC of both types of engines (fixed speed and variable speed). The figure shows two typical SFOC curves as a function of the shaft load for fixed and variable speed engines, both in the high speed operational range, with similar power ratings and with the fixed speed engine operating at a rated speed. The curves are part of a brochure of a new system offered by a manufacturer (SIEMENS, 2011a). As it can be seen, the SFOC curves have similar values for shaft loads over 40% of the power rating; however, below this point, the SFOC of the fixed speed engine starts to become greater, specially for shaft loads below 15% of the rated load.

Diesel engines for power generation at variable speed operation are available in all speed ranges. For electric propulsion systems, their implementation is an important subject aiming to reduce the fuel consumption and the pollutant emissions. Currently, various important manufacturers of ship electric propulsion systems, such as ABB, MAN Diesel & Turbo, Siemens and Caterpillar, are offering the variable speed engine for power generation in offshore support vessels, passenger vessels and military ships. In fact, Siemens along with Caterpillar have already installed an electric propulsion system with variable speed Diesel engines to an offshore supply vessel, the Edda Ferd (MARINELOG, 2012; SIEMENS, 2011a). In the future, Siemens expects to install this type of engine in other vessels with electric propulsion systems (SIEMENS, 2012b).

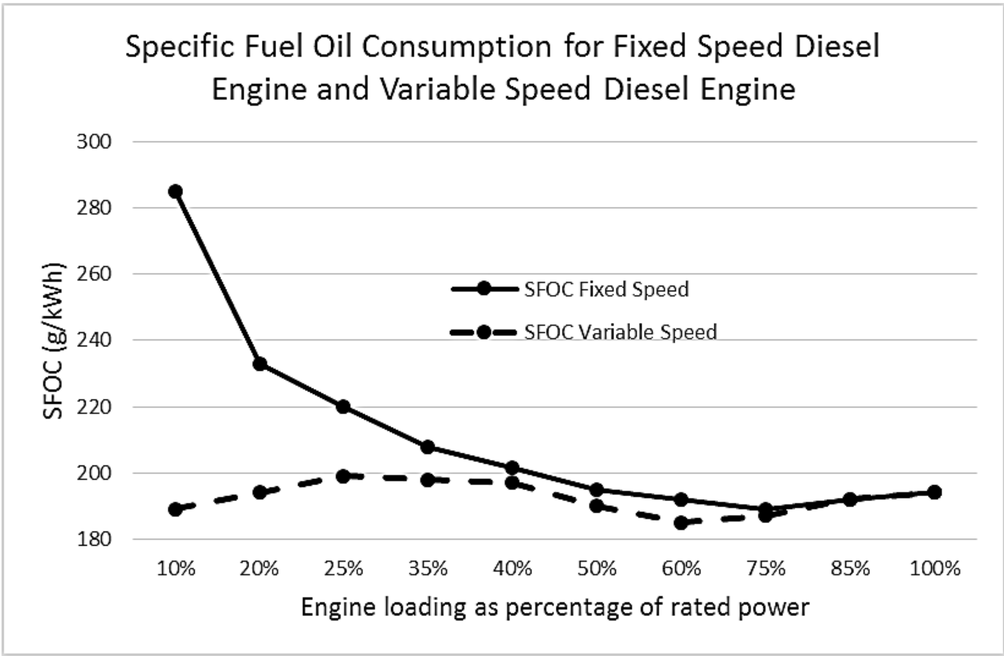


Figure 2.5 – Comparison of SFOC for Similar Power Fixed Speed Diesel Engine at Rated Speed and Variable Speed Diesel Engine (SIEMENS, 2011a).

2.1.1.2 Dual-Fuel Engines

Dual-fuel engines are internal combustion machines, which operate with both the Otto and the Diesel cycle in order to burn LNG and HFO or MDO. The dual-fuel engine is a relatively recently developed technology, which exploits the advantages of the diesel fuel and the environmentally friendly features of the LNG for mechanical power supply.

A dual-fuel engine burning LNG releases 85% less NO_x, 25% to 30% less CO_2 and zero SO_x gases, since the molecules of LNG are formed by less hydrogen atoms compared with Diesel fuels. This type of engine is becoming an important alternative to reduce the pollutant emissions from vessels.

The dual fuel engines are commercially available in the medium speed range (LEVANDER, 2011) for power generation at fixed or variable speed operation and at power ratings up to 17.5MW. The weight of the units is approximately the same compared to Diesel engines of similar power rating. Nonetheless, their SFOC is higher for low shaft loads (PAPAGIANNAKIS and HOUNTALAS, 2004).

Despite the advantages of this engine, some drawbacks limit its implementation. First of all, distribution stations with adequate infrastructure are required. Furthermore, LNG storage in ships requires high volume containers, occupies space and requires cryogenic equipment, demanding high investment amounts (LEVANDER, 2011). In other countries, the LNG supply is exclusively used for power generation on shore, restricting the ships access to its use.

2.1.2 Generators

The generator units transform the mechanical power given by the prime mover into electrical power. In ship electric propulsion systems the most used generator unit is the wound rotor synchronous generator, operating at fixed rotational speed (ADNANES, 2003). More recently, synchronous generators with permanent magnet rotors have been used, especially along with variable speed diesel engines (SIEMENS, 2011a; SIEMENS, 2012c). Induction generators have been also considered for variable speed power generation (WANG, NAYAR and WANG, 2010); nevertheless, their implementation in ships is still distant. High temperature superconductor (HTS) generators are emerging as an efficient energy technology for power generation in ships. Currently, several researches and investements are being held aiming to implement this type of machines on ships, especially in warships (GIERAS, 2008; SIVASUBRAMANIAM, *et al.*, 2008) owing to their high efficiency, reduced weight and volume. In the following decades, this technology is expected to be commercially available for power generation in ships (GIERAS, 2008).

2.1.2.1 Wound rotor synchronous generator

The wound rotor synchronous generator is the most common alternator for power generation in the world. It is used from small generator sets, with a few kW, to giant power plants, with power ratings in a magnitude order of GW. The generator consists in a stator, in which the three phase armature windings are installed, and a rotor, in which the field windings are mounted. The rotor receives the torque from the prime mover; the rotational movement induces a voltage in the armature windings to supply the electrical loads. In ship power generation, wound rotor synchronous generators are commonly used along with fixed speed diesel engines to produce power at 50 or 60Hz; it is also possible to use them with variable speed diesel engines by modifying the voltage and frequency controller.

In medium power electric propulsion installations, commercial generators produce power with fixed voltage at low and medium voltage levels up to 6600V; 440V and 690V are the most typical voltage levels provided by the generators in platform supply vessels with electric propulsion systems (See section 3.2.1). Moreover, available rotational speeds are found from 600rpm up to 3600rpm depending on the pole number, as shown in Table 2.3. The rated rotational speed of a fixed speed Diesel engine intended to work along with synchronous generator must correspond to the respectively rated speed of the generator considering the values presented in Table 2.3.

Table 2.3 - Rotational Speeds for Wound Rotor Synchronous Generators Depending on the Pole Number for 60 and 50Hz Power Generation.

Pole Number - *P*	**Required rpm for 60Hz - n_m**	**Required rpm for 50Hz - n_m**
2	3600	3000
4	1800	1500
6	1200	1000
8	900	750
10	720	600

The rotational speed of the wound rotor synchronous generator also defines its mass as shown in Figure 2.6. The graph, taken from Hau (2006), shows different curves of the generator mass vs. the generator power for various rotational speeds for a 50Hz power generation; for 60Hz power generation, the curves can be taken as a guide since the behavior is similar. It can be noticed that, for the same output power, the generator mass becomes greater as the rotational speed decreases. In fact, a higher pole number (which implies a lower rotational speed) requires more copper and more steel, hence, the generator becomes heavier as the rotational speed decreases.

Commercial wound rotor synchronous generators are specified considering their power rating in kW and the minimum rated power factor that they are capable to supply. Usually the power specifications are given in kW for a minimum rated power factor of 0.8; if the global power factor of the load is below this value, the active power that the generator can supply will be lower than those indicated in the nameplate.

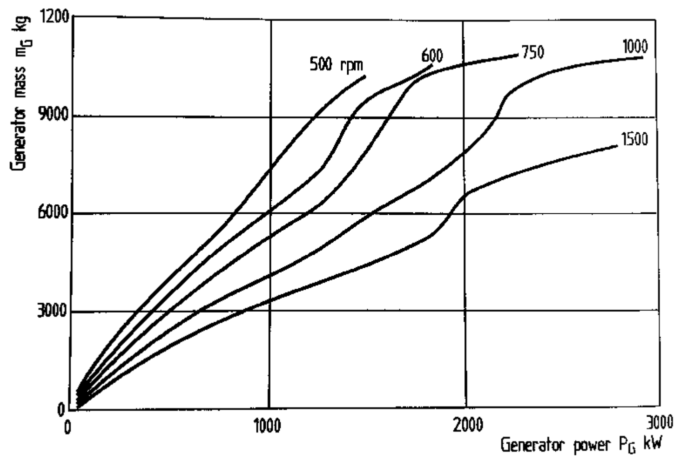


Figure 2.6 – Wound Rotor Synchronous Generator Mass vs. Rated Power for Various Rotational Speeds for Power Generation at 50Hz (HAU, 2006).

Another characteristic to be contemplated is the variation of the efficiency as a function of the output power. The efficiency of the generator is influenced by its load and its power factor as presented in Figure 2.7, for a typical generator in the high speed range (CUMMINS POWER GENERATION, 2008). The figure shows typical efficiency values of the generator vs. the electrical load demand for various power factors. It can be noticed that the efficiency has its maximum peak between 60%-80% of the rated load; while for output power below 35% the efficiency decreases. Furthermore, as the load power factor is reduced, the efficiency lowers.

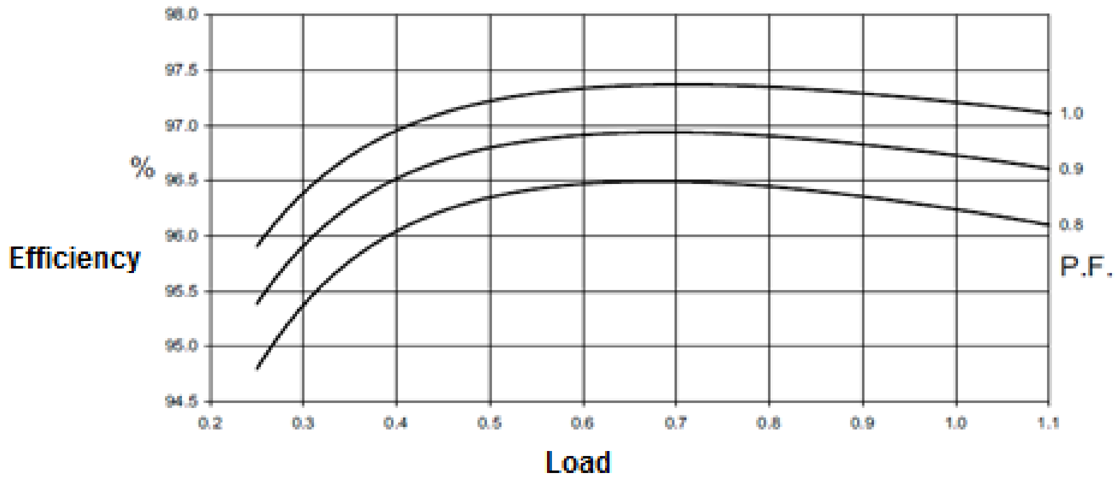


Figure 2.7 – Efficiency Curves of a Typical Round Rotor Synchronous Generator as a Function of Output Load and Power Factor (CUMMINS POWER GENERATION, 2008).

Since the generator transforms energy, the rotor and the stator windings transport electrical currents, which produce Joule heating as a product of the resistance losses[11] in the wires and the core, which have to be dissipated. In order to dissipate the heat produced by the losses, the air-to-water cooling method (IC81W) is used by manufacturers for synchronous generators intended to operate in ship electric propulsion systems. This cooling method uses air to extract the heat directly from the generator, and afterwards, it exchanges the heat with a water-circuit inside the generator case.

2.1.2.2 Permanent magnet synchronous generators

This type of generator has the same stator construction as the previous generator, but with a coreless permanent magnet rotor instead of a wound rotor. The permanent magnet material, made from rare earth magnets, produces a constant magnetic field, without any energy supply, which induces a three-phase voltage in the stator windings.

Since the rotor is coreless, the permanent magnet synchronous generator (PMSG) has a lower weight compared to the conventional wound rotor generator with similar characteristics, typically 20 to 30% lower. Furthermore, its rotational inertia is also reduced and its length is 30% smaller. Additionally, due to the lack of power supply to the rotor, its efficiency is greater than similar wound rotor synchronous generator (AMLER, KOERNER and KRACHT, 2010).

In a wound rotor synchronous generator, the output power demand is supplied by requesting torque to the prime mover, maintaining the rotational speed fixed in order to keep the electrical frequency at 50 or 60Hz; the output voltage is regulated by controlling the field excitation current in the rotor winding. In PMSGs, since the magnetic field produced by the rotor is constant, the voltage and the power output depend on the rotational speed and the torque of the prime mover. Hence, in order to supply the load power demand, the generator requires a speed variation, changing also the electrical frequency of the output voltage.

Currently, commercial units are available at power ratings up to 8MW with rotational speeds from 0rpm to 3000rpm (ABB, 2012a).

Since the PMSGs produces electric power with variable voltage and frequency, in ship electric propulsion systems, they are required to have a rectifier or an inverter at

[11] Joule heating, known as ohmic heating or resistive heating is the process by which the passage of an electric current through a conductor releases heat.

the output in order to keep constant the voltage and the electrical frequency (MAN DIESEL & TURBO, 2013a; HANSEN, LINDTJORN and VANSKA, 2011).

2.2 ENERGY STORAGE SYSTEMS

Energy storage systems for implementation in surface vessels have been proposed as an efficient and clean alternative to optimize and compensate the changing operational conditions of the Diesel engines at the sea due to the waves, wind and speed (ASPIN and HAYMAN, 2009). Energy storage systems are used mainly to compensate disturbances in the electric system caused by load variations and to maintain the diesel engines loaded at their optimal operational point in which the SFOC is minimum (CHEN, *et al.*, 2010). The energy storage technologies reported by the literature as suitable for the marine electric applications are the batteries and the super-capacitors. Currently, some vessels with electric and electric-mechanical propulsion systems have already implemented batteries to reduce pollutant emissions by using the stored energy in standby or port operation (ASPIN and HAYMAN, 2009); however, super-capacitors are under consideration owing to their lower weight, volume and electrical characteristics (CHEN, *et al.,* 2010).

2.2.1 Batteries

As energy storage devices, batteries are a reliable and, depending on its type, a low cost solution that can store a large amount of energy with a high power density. There are several types of battery technologies commercially available, as presented in Table 2.4 (DIVYA and OSTERGAARD, 2009; LINDEN and REDDY, 2002). As it is presented in the table, the Litium-Ion batteries have the best characteristics, but their cost is the highest one, which, consequently, limits their application in marine propulsion systems (DEDES, TURNOCK and HUDSON 2010, 2012). The sodium/Nickel Chloride batteries (ZEBRA) have also good performance characteristics with a significant lower cost than the Lithium-Ion ones, however, they require a high temperature to operate. The Vanadium Redox batteries are another alternative performing with lower efficiency and energy density, but with a long lifetime exceeding 10000 charge cycles. Sodium Sulphur batteries present likewise good characteristics, but require an ambient temperature of 325°C to operate, an issue that also limits its implementation. The Lead Acid batteries are reported as being used in marine propulsion systems (SCOTT, 2011; ASPIN and HAYMAN, 2009), they have the lowest cost, but present the worst energy density..

Table 2.4 - Rechargeable Battery Technology and Its Features (DIVYA and OSTERGAARD, 2009; LINDEN and REDDY, 2002)..

Battery type	Efficiency	Specific energy (Wh/kg)	Life time	Cost	Typical application	Features	Power Levels
Lead Acid (Flooded Type)	72-78%	25Wh/kg @-5 to 40°C	1000-2000 cycles @70% depth of discharge ≈6 years	\$3.2/kg* \$1200/kW†	Emergency power, utilities, UPS.	Heavy and high maintenance rate, flat discharge profile.	Tens of Megawats - 10MW
Lead Acid (Valve Regulated)	72-78%	30-50Wh/kg @-5 to 40°C	200-300 cycles @80% depth discharge 3-6 years	\$1500/kW†	Vehicles, aircraft, marine, utilities.	Portable, reduced maintenance, flat discharge profile.	Houndreds of Kilowats - 300kW
Nickel Cadmium (NiCd)	72-78%	45-80Wh/kg @-40 to 50°C	3000 cycles @100% depth of discharge 5-20 years	\$2400/kW†	Industrial and Emergency power applications.	Heavy, poisonous, high discharge rate, flat discharge profile.	Tens of Megawats - 27MW
Sodium Sulphur (NaS)	89%	100Wh/kg @325°C	2500 cycles @100% depth of discharge 15 years	\$3200/kW†	Stationary and utilities.	High temperature operation.	Megawatt scale - 9.6MW
Lithium ion	100%	90-190Wh/kg @-30 to 60°C	3000 cycles @80% depth of discharge 5-20 years	\$90/kg* \$3800/kW†	Portable and consumer electronic equipment, electric vehicles and space applications.	High cost due to internal package and protection, sloping discharge profile.	Tens of Kilowatts
Vanadium Redox	85%	30-50Wh/kg @0 to 40°C	10000 cycles @75% depth of discharge	\$15/kg* \$2600/kW†		Negligible self-discharge.	Megawatt scale - 1.5MW
Zinc Bromine	75%	70Wh/kg @0 to 40°C	1500 cycles	\$2500/kW†		Bulky, low power, hazardous components.	Megawatt scale- 1MW
Silver Cadmium	95%	70Wh/kg @-25 to 70°C	300-800 cycles 3-4 years		Portable equipment requiring a lightweight, high capacity battery; space satellites.	High cost, high energy density, low maintenance.	
Sodium/Nickel Chloride	100%	115Wh/kg @270 to 350°C	2500 cycles	\$12.7/kg*	Electric vehicles.	High energy density, High temperature operation.	

* Data taken from (DEDES, HUDSON and TURNOCK, 2010)
† Data drawn from (COREY, 2010)

In marine electric propulsion systems, several researches and implementations of batteries have been conducted. Dedes, Hudson and Turnock (2010; 2012) and Manzoni, Metzger and Crugnola (2008) have been studying the implementation of batteries in ships, concluding that the ZEBRA batteries are the most feasible technology to reduce emissions with a possible high return on the initial investment. Furthermore, a tugboat was built with electric propulsion systems along with lead acid batteries in a system known as hybrid propulsion system (SCOTT, 2011; ASPIN and HAYMAN, 2009). Moreover, Siemens (2012b) designed and is currently building hybrid electric propulsion systems for tugs in various projects in Singaporean shipyards. The system, which its battery type is not informed, receives energy from permanent magnet synchronous generators with rectified output, transmitting the energy in direct current form.

A batteries bank is normally defined in terms of the total energy that is capable to storage, in kWh, the rated voltage and the discharge current in A/h. If the batteries are sized, the previous parameters must be defined.

2.2.2 Super-capacitors

The Super-capacitors are a new type of energy storage device, which is being increasingly used in industry and automotive applications. They differ from the conventional capacitors by their larger area for charge storing and the closer distance between electrodes compared to conventional capacitors, achieving a much greater capacitance within the same volume. When compared to batteries, super-capacitors have several advantages: they can be fast charged; charging cycles of super-capacitors are in the order of thousands of times instead of hundreds of times as the batteries; and, besides that, they can deliver frequent pulses of energy without any detrimental effects, whereas batteries experience reduced lifetime if exposed to frequent huge power pulses. Nonetheless, batteries can store a higher amount of energy than super-capacitors, which makes them more suitable for ship electrical systems (CHEN, *et al.,* 2010).

Some researches and projects are being conducted in order to assess the performance and the implementation of super-capacitors in isolated electric systems such as offshore support vessels. Chen, *et al.,* (2010) studied the hybrid electric propulsion system with super-capacitors for its implementation in offshore support vessels, as well as Lee, Lee, and Sul (2009), who have studied the application of super-capacitors for disturbance compensation in variable speed engine generator sets for fuel efficiency.

2.3 ENERGY TRANSMISSION AND VOLTAGE LEVELS

Alternate current and direct current are the two available transmission systems for ship electric propulsion. The former is normally chosen for ship electric propulsion systems with fixed speed prime movers combined with wound rotor synchronous generators, while the latter is mostly used with variable speed engines along with PMSGs and direct current rectifiers or inverters (MAN DIESEL & TURBO, 2013a; FAN, 2013; SIEMENS, 2012b).

2.3.1 Alternate current transmission

In marine electric systems, AC transmission is normally fixed in voltage, and frequency at 50 or 60Hz. As mentioned above, the AC power at fixed frequency and voltage is normally produced by fixed speed generator sets.

The recommended voltage levels and shipboard electric practices have been settled by the Institute of Electrical and Electronic Engineers [IEEE] (2002). The recommended rated voltages for AC transmission in ships are classified by the installed power as presented in Table 2.5.

Table 2.5 – Recommended Voltage Levels for AC Transmission in Ships (IEEE, 2002).

Installed Power	Generated Voltage[15]	Utilization Voltage[16]
<100kW	120V	115V
100kW to 1MW	230V, 240V	220V, 230V
1MW to 10MW	450V, 480V, 600V, 690V	440V, 460V, 575V, 660V
>10MW	2400V, 4160V, 6600V	2300V, 4000V, 6000V

2.3.2 Direct current transmission

Unlike AC power transmission, direct current transmission is not frequency standardized since the frequency of the system is theoretically 0Hz. Besides, compared to the AC transmission system, the DC one is relatively easier to use and to control owing to the constant voltage magnitude in time, which eliminates most of the dynamic events present in AC. Moreover, depending on the distance and power

[15] The generated voltage is the recommended rated voltage at the output of the generator.
[16] The utilization voltage is the recommended voltage level available at the point of connection to the load.

transmitted, the system can be cheaper, since only three wires are required (positive, negative and earth) instead of five wires necessary for AC transmission. Nevertheless, because of the use of electronic rectifiers at the output of the variable speed generator set and the robust protection devices, the implementation of this system may be more complex than AC systems, increasing the power losses, the possibility of failure and the investment costs. The IEEE (2010) recommends several voltage levels for large power DC shipboard systems: 1.5kV or +/-0.75, 3kV or +/-1.5, 6kV or +/-3kV and so on.

2.4 TRANSFORMERS, FILTERS AND POWER CONVERTERS

Transformers and filters are used in electric propulsion systems as equipment for harmonic distortion reduction while the power converters are used to vary the frequency and voltage of the power supplied to the loads. Voltage source inverters (VSI) or variable frequency drives (VFD), current source inverters (CSI), cycloconverters and AC/DC converters are the power converters reported by literature as suitable for ship electric propulsion systems (ALVES, 2007; ADNANES, 2003; PATEL, 2012). Cycloconverters are used mainly along with synchronous motors in icebreakers in which severe duty torque is required from the motor at low rotational speed; the converter supplies very high currents at low voltage with frequencies below half of the rated frequency. The CSI is also used with synchronous motors mainly in cruisers or high power ship electric propulsion systems; the CSI requires a motor with a leading power factor in order to achieve load commutation, this capacitive power factor can be supplied only by synchronous motors. The power factor produced by the CSI depends on the output frequency, it is 0-0.9 lagging and can control the motor speed at a minimum of 5-10% of the motor rated speed. The VFD is the most used power converter in the industry and in propulsion motor drives, it can operate with induction or synchronous motors and is able to control speed from 0 to more than 100% of the rated rotational speed; currently, most of the low and medium-power electric propulsion drives (like those used in offshore support vessels) uses VFDs along with induction motors for propulsion (ALVES, 2007; ADNANES, 2003; PATEL, 2012). AC/DC converters are used in ships for DC transmission, the converter is located at the output of the variable speed generator set in order to transform the variable voltage/frequency power supply in constant DC voltage supply (MAN DIESEL & TURBO, 2013a).

In this section, special focus will be given to transformers, filters and voltage source inverters since they are the most used elements for propulsion motor drives in offshore support vessels (ALVES, 2007; ADNANES, 2003; PATEL, 2012). Moreover, AC/DC converters will be also discussed as they are used in DC transmission in ships.

2.4.1 Transformers

The purpose of the transformer is to isolate and separate the electric propulsion system into several parts, changing the voltage supplied to the loads for their adequate operation. The transformers are normally built to receive a three-phase power supply at the primary winding at a certain voltage level and to give almost the same power at the secondary winding with other voltage level. The three coils of each side of the transformer can be connected in Δ (Delta) or Y connection.

For propulsion motor drives, transformers are used for phase shifting to supply 12-pulse and 24-pulse power converters. A transformer for 12-pulse converter possesses three sections: a primary, a secondary and a tertiary winding. The primary is normally three-phase connected in Δ, the secondary winding is Y connected while the tertiary is typically Δ connected. The objective of this configuration is to give a 30° phase shifting between the output of the secondary and the tertiary circuit for supplying the power converter, leading to the reduction of several harmonic components. A 24-pulse power converter uses two transformers, each one with two secondary circuits, and is used occasionally in applications with severe harmonic restrictions. In ship propulsion systems, the transformer for 12-pulse operation is the most used configuration to supply power converters (ADNANES, 2003).

As settled by classification societies, transformers intended to operate in ships are required to be the dry and air cooled type, with or without forced cooling (ABS, 2013). The most common cooling system for transformers for marine applications is the FAFW (Forced Air/Forced Water) cooling, in which the air is forced to circulate to remove the heat directly from the windings and the core; later, the hot air exchanges the heat with an external water circuit which can use seawater as a second coolant (ABB, 2004). Additionally, the rated ambient temperature is required to be 45°C minimum for transformers designed to operate inside machinery rooms; the rated temperature rise over the ambient temperature of the insulated windings is not to exceed 180°C at the hottest spot temperature rise (ABS, 2013).

Transformers for supplying power converters experiment additional load losses than transformers feeding linear loads. In fact, due to the nonlinear properties of the power converters, several current harmonic components are produced, which increment the copper and iron losses of the transformer (ABS, 2006; SHAREGHI, PHUNG, *et al.*, 2012). These losses produce a significant temperature rise, which can lead to overheating and early life failure of the transformer. Moreover, the efficiency is also reduced, since it depends on the transformer losses, as defined in the equation drawn from Yadav, Srinivasula and Sindhuja (2013):

$$\eta = \left(1 - \frac{P_{NL} + P_{LL}}{S \times P.F.}\right) \tag{2.1}$$

Where η is the efficiency; P_{NL} are the no load losses (independent losses from harmonic components); P_{LL} are the load losses (dependent on the harmonic components); S is the transformer rated power in kVA and P.F., is the load power factor.

Since transformers are important for the propulsion motor drives, it is necessary to minimize the risk of failure. The classification societies recommend the use of K-factor transformers, which are specifically designed for nonlinear loads and for operating with lower losses at harmonic frequencies. The transformers can include some modifications like additional cooling ducts, different magnetic cores, modification of the insulation of windings, etc. In new transformers, the k-factor is required to be calculated up to the 25^{th} harmonic component taking in account the recommendations settled in ABS (2006).

2.4.2 Filters

A passive filter is a circuit formed by inductances, capacitances, and sometimes a resistance too. The inductances and capacitances are sized in order to attenuate harmonic components greater than the fundamental component, by tuning the cut frequency to the most significant harmonic frequency. The current with fundamental frequency passes through the filter experiencing an almost-zero impedance, while the harmonic components are attenuated by the increased impedance. If there are several harmonics with significant magnitudes, various filters can be connected in parallel, each one tuned for one harmonic frequency

The passive filters present some drawbacks: sometimes it is difficult to correctly tune the cut frequency for attenuation owing to the several harmonic components.

Moreover, if several significant harmonic components are going to be attenuated, it could be necessary to demand more than one filter, which occupy additional space and increase the weight of the installation. As a solution to this situation, some manufacturers have developed passive filters identified as wide-spectrum filters, which uses small inductances and capacitances with a wide spectrum of harmonic attenuation; the solution has already been implemented in some ship electric propulsion systems (See Annex I).

Active filters are formed by power electronic converters with IGBTs (Insulated Gate Bipolar Transistors) feeding a capacitor. The power electronic converter is similar to a VSI, as will be discussed below. The switching devices, in parallel with the capacitor, compensate the harmonic components produced by the propulsion motor drive, drawing a totally sinusoidal current from the source. However, as a consequence of the high switching frequency of the IGBTs, a high frequency filter is required at the source side. The cost of active filters is considerably higher than the passive filters one; they are used occasionally in ship propulsion systems (ADNANES, 2003).

2.4.3 AC/DC converters

AC/DC converters or rectifiers are the elements that convert electric power in AC form to power in DC form. There are two main types of rectifiers depending on the electronic devices used: uncontrolled rectifiers and active rectifiers.

2.4.3.1 Uncontrolled Rectifiers

Uncontrolled rectifiers are the most basic units; they use diodes as electronic devices for power conversion, which do not permit any control in the rectification process. They have been extensively used in industry and in general applications owing to their low cost and lack of control requirement, becoming the easiest power converter to work with. Depending on the number of diode bridges, the converter can be 6-pulse, 12-pulse or 24-pulse. The 6-pulse converter uses 6 diodes, two per leg of the bridge, as shown in Figure 2.8a the 12-pulse rectifier uses 12 diodes separated in two 6-pulse bridges, which are supplied by a transformer with two secondary windings as discussed before. The 24-pulse converter uses four 6-pulse diode bridges supplied by two transformers with two secondary windings as previously detailed. The Figure 2.8 shows the 6-pulse, 12-pulse and 24-pulse power converter with diodes.

The 6-pulse diode rectifier produces harmonic components in the current at 5^{th}, 7^{th}, 11^{th}, 13^{th}…; the 12-pulse rectifier reduces the current harmonic components generated, producing the 11th, 13th, 23rd, 25th… the 24-pulse produces harmonic components at 23rd, 25th, 47th, 49th… Therefore, the greater the pulse number the better from the point of view of harmonic component production.

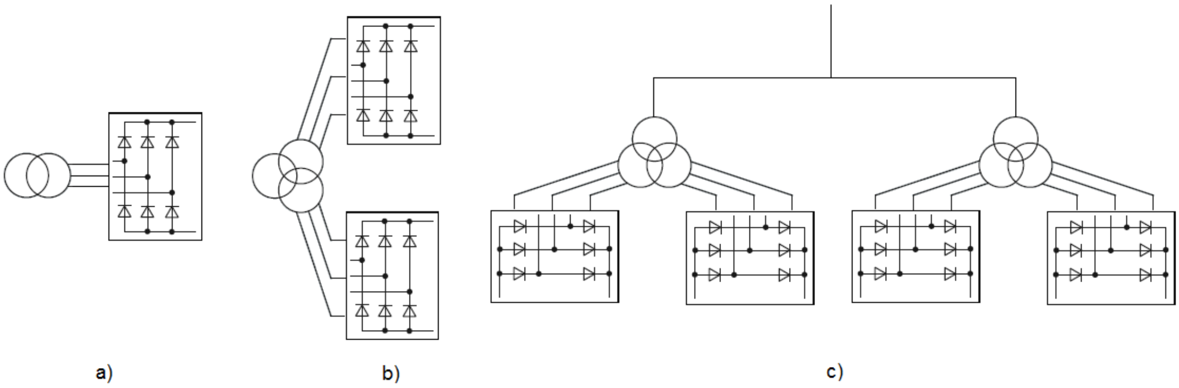


Figure 2.8 – Uncontrolled diode rectifiers: a) 6-pulse rectifier, b) 12-pulse rectifier and c) 24-pulse rectifier.

Uncontrolled diode rectifiers are restricted to operate at 50°C as maximum ambient temperature. In ship electric propulsion systems, the preferred cooling method is the water-cooling one, which uses water to directly remove heat from the heat-sinks of the devices (SIEMENS, 2011b). Diode rectifiers have a typical efficiency of 99% and are slightly affected by load variations; power factor is maintained almost constant for all load values and is normally above 0.95 (SIEMENS, 2011b; JARC and CONNORS, 1985).

2.4.3.2 Active rectifiers

Active rectifiers use thyristors, SCRs, IGBTs or IGCTs (Insulated Gate-Commutated Transistor) as switching devices instead of diodes. Currently, active rectifiers are equipped commonly with IGBTs or IGCTs (SIEMENS, 2011b) , which offer a better control of DC voltage and significantly reduce losses. Besides, the IGBTs or IGCTs allow adjusting the power factor to be equal to 1 or leading, without being affected by load variations. The rectifiers can also accept input power with variable voltage and frequency within a tolerance range, maintaining the DC voltage level (SIEMENS, 2011b).

Unlike uncontrolled rectifiers, active rectifiers do not require to be connected in 12-pulse or 24-pulse configurations; few harmonic components are produced in the standard 6-pulse configuration. Moreover, it can be operated without an input transformer, which also saves space and reduces the weight of the installation.

The rated efficiency for this equipment is normally 97.5% and is load dependent. As the uncontrolled rectifier, the ambient temperature is not to exceed 50°C and the most used cooling method is also water-cooling, which directly removes the heat from the devices (SIEMENS, 2011b).

2.4.4 Variable Frequency Converters

The VFD is the most used power converter in the industry and in ship electric propulsion systems (ADNANES, 2003). The converter is formed by a rectifier unit responsible for receiving three-phase power at fixed frequency; the unit delivers DC voltage, which feeds an inverter unit in parallel with a capacitor. Finally, the inverter transforms the electrical power in DC form to AC form at variable voltage and frequency.

The rectifier unit can be uncontrolled or active as discussed before. The function of the capacitor is to smooth the voltage variations to the inverter and block the high frequency switching ripple from the inverter module for not entering the network. The inverter section possesses the same structure as an active rectifier, but with the inverse function, which is to switch the devices to produce an alternate current at a desired frequency and voltage. The switching devices of the inverter are normally IGBTs or IGCTs (ALVES, 2007; ADNANES, 2003; PATEL, 2012). The Figure 2.9 presents the schematic circuit of a typical VFD with diode rectifiers at the input.

When used for speed variation in propulsion motor drives, the power output of the inverter is controlled by the voltage and the frequency according to the speed demands from the main control unit. When operating below the rated speed, the voltage and the frequency are reduced in the same proportion to avoid saturation of the motor core; for operation above the rated speed, the voltage is kept constant and the frequency is varied, delivering torque within the limits of the rated power.

The efficiency of the VFD varies as a function of the load and the output frequency as reported by Rooks and Wallace (2004), Benhaddadi, et al. (2012), Burt, et al. (2006) and Gong et al. (2012). These four references conducted a series of tests in variable speed drives in order to measure the efficiency of the motor drive for various loads and speeds. The tests were made using premium[17] and standard three-phase induction motors in the order of dozens up to hundreds of horsepower; in all tests the power converter was a VFD with output frequency varied within a range of 25% to 110% of the rated frequency and a load variation within 10% to 100% of the converter rated load. The results of the tests gave several curves of VSI efficiency as a function of frequency and load, all the curves have similar behavior between references, nonetheless, with little variations between values owing to the equipment used to perform the tests. From the results, typical efficiency curves for VFD as a function of load and frequency can be plotted as presented in Figure 2.10.

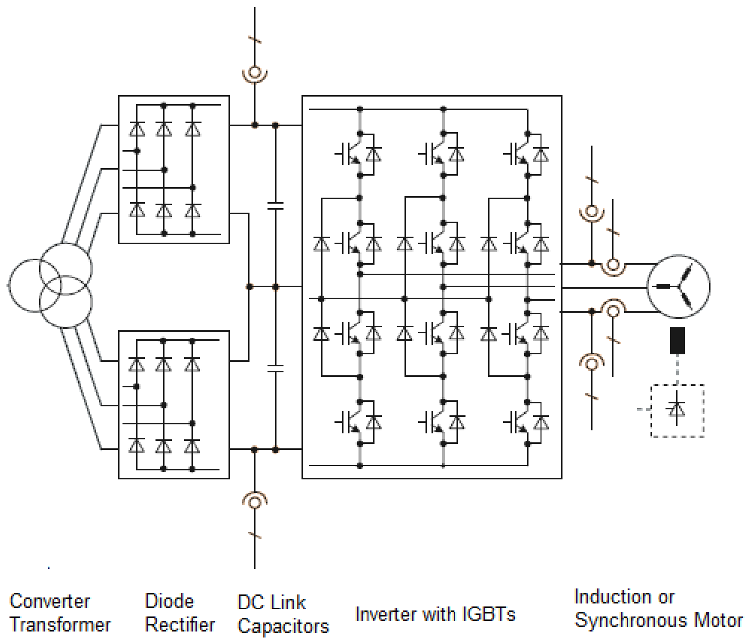


Figure 2.9 – Typical Schematic of a Variable Frequency Drive (SIEMENS, 2011b).

The power factor of the VSI has the same behavior as the one presented for the rectifier units, where diodes are used as power devices, keeping it normally >0.95; while when IGBTs are used, the power factor can be unitary or leading. Furthermore, when supplying induction motors or loads with lagging power factor, the VSI converter can provide reactive power from the stored energy in the capacitor without affecting the power factor at the input.

[17] Premium induction motors are motors designed to operate with higher efficiency than standard induction motors leading to energy conservation. Premium motors are defined by the International Electrotechnical Commission (IEC) and the National Electrical Manufacturers Association (NEMA) as IE3 and NEMA premium motors, respectively.

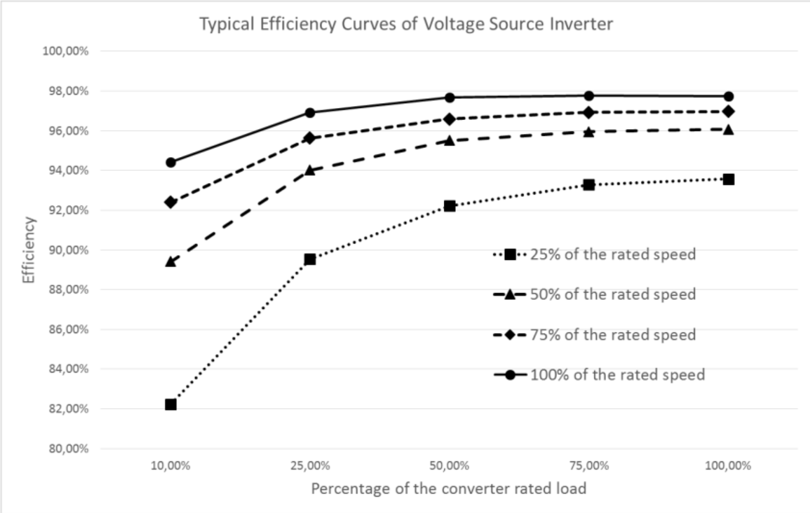


Figure 2.10 – Typical Efficiency Curves of Voltage Source Inverter (GONG, *et al.*, 2012)

As rectifiers, VSIs are not to operate with ambient temperatures above 50°C. The cooling method preferred in ship electric propulsion applications is the water-cooling method. The units commercially available are offered by manufacturers in modules: the module that receives the alternate current input, the module for rectification and the inverter module. If additional power rating is required, additional modules can be mounted without replacing the complete converter (SIEMENS, 2011b).

2.5 ELECTRIC PROPULSION MOTORS

Electric motors are used in ship electric propulsion systems to drive propellers and thrusters. Various technologies have already been used for propulsion in ships: induction motors, synchronous motors, permanent magnet motors and, more recently, high temperature superconductor motors (HTS).

Induction motors[20] are the most used motor type for medium to large power applications in industry and also in ships; currently, most of the electrically propelled vessels use induction motors for propulsion (ALVES, 2007; ADNANES, 2003; BASSHAM, 2003).

Synchronous motors are used mainly in ships with high or very high power propulsion systems or when the propulsion demand requires high torque at low rotational speeds. Currently, icebreakers and cruisers are the major users of this type of propulsion motor.

[20] In this dissertation, the term induction motor refers to squirrel cage induction motor.

Permanent magnet synchronous motors, which are a relatively new technology for ship electric propulsion systems, offer higher efficiency and lower weight compared to induction and synchronous motors. The motor has the same stator construction as the synchronous motor but with a coreless permanent magnet rotor. As main propulsion motor, it is mostly used in vessels equipped with the azipod propulsion system at powers up to 4500kW per unit (ABB, 2010). Moreover, the motor has been used lately in side thrusters for station keeping in integrated motor propellers (or rim driven thrusters), a new technology for lateral thrust with lower weight and noise production, and higher efficiency than conventional side thrusters. Currently, the application of large permanent magnet motors is focused mainly in pod units for large passenger vessels or naval ships; for other types of vessels their use is limited owing to the high cost of the magnetic materials. Several researches are being conducted leading to the development of large units, up to 36MW for their implementation in warships (GIERAS, 2008).

HTS motors have also been object of significant research and improvement for their use in ship electric propulsion systems. The motor possesses the same stator construction as conventional motors whereas the rotor is formed by electromagnets made with high temperature superconducting wires. The motor has several advantages compared to the conventional ones: is more compact, lighter, more efficient and quieter (KALSI, 2004); its efficiency is maintained almost constant for all load variations unlike conventional motors (KALSI, *et al.*, 2006; SNITCHLER, GAMBLE and KALSI, 2005). Nevertheless, since the superconductor material requires temperatures around of 32K[21] in order to maintain the superconductor characteristics, the motor is required to be cooled, which significantly complicates the installation and limits its implementation in commercial vessels. The motor is not commercially available yet, but several researches are in progress, which have already developed 5MW and 36.5MW prototypes for testing, aiming to be used in future US (United States) Navy Destroyers and in podded propulsion units (KALSI, *et al.*, 2006; KALSI S., 2004; OKAZAKI, *et al.*, 2006; WOODRUF, *et al.*, 2005; SITCHLER, GAMBLE and KALSI, 2005).

[21] Approximately -241°C

This section will focus in conventional induction and synchronous motors since, at the present moment, they are the most suitable alternatives for commercial vessels with medium power electrical systems.

2.5.1 Induction Motor

Three-phase induction motors are mostly used in low to medium power applications at high, medium and low rotational speeds. Manufacturers recommend their use for shaft powers below of 1MW with 22poles to 7MW with 4poles, taking as a guide all the power ratings below the bottom line shown in Figure 2.11 (ABB, 2011). For higher power requirements synchronous motors are considered to be a more cost effective solution (ABB, 2011); nonetheless, there is an overlapping area in which the evaluation of the two alternatives must be performed in order to determine the most suitable solution.

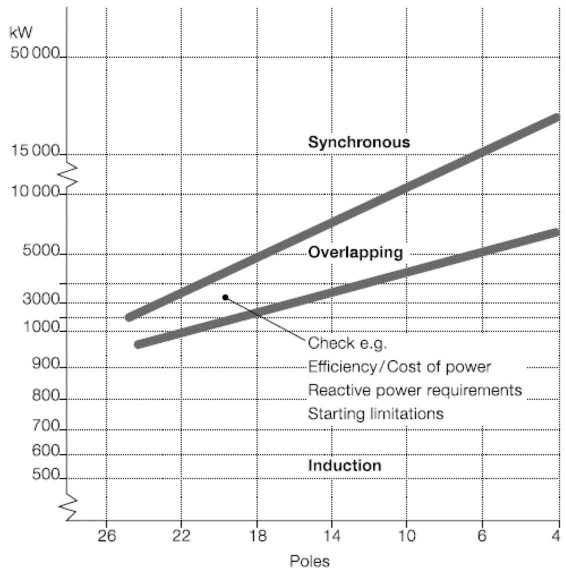


Figure 2.11 – Guide for Selection of Induction and Synchronous Motors as a Function of the Pole Number and Demanded Power (ABB, 2011).

Induction motors have several features which make them the most common solution in the industry and in medium power ship electric propulsion systems: low maintenance rates –almost zero in some cases, low operational and capital costs, high reliability, rapid operational response, relatively high efficiency, etc.

The rotational speeds of the motor are related to the pole number; when used in applications with fixed frequency supply at 50 or 60Hz their rated speeds as a function of the pole number are close[23] to the values presented in Table 2.3. When the input frequency is varied the motor can rotate at speeds above or below the rated speed. The rated voltage levels available for use in ship electric propulsion systems are the same as presented in Table 2.5.

The mass of the motor is related to the rotational speed (or pole number in a similar way as discussed for synchronous generators and as presented in Figure 2.6; it rises with the increment of the pole number. Furthermore, while the rated voltage level of the motor increases from low voltage to medium voltage the mass increases too as it can be seen in the manufacturer catalog (SIEMENS, 2013a). Additionally, comparing water jacket cooling motors with air-cooling motors in a manufacturer catalog (SIEMENS, 2013a), it can be seen that the formers are heavier than the latter.

Rated efficiencies of commercial induction motors can be as high as 97.1%; however, they are slightly reduced as the pole number increases, something that can be seen in the catalogs (SIEMENS, 2013a). Besides, their efficiency is also affected by shaft load and input frequency changes as reported by Rooks and Wallace (2004), Benhaddadi *et al.* (2012), Burt *et al.* (2006) and Gong *et al.* (2012), who studied the influence of shaft load and input frequency variations on the efficiency of induction motors. The studies show that for constant supply frequency, the efficiency as a function of the shaft load maintains almost the same value between 20% and 100% of the motor rated load and significantly drops for shaft loads below 20%; if the supply frequency is varied, then the efficiency curve slightly changes when compared to the others. In order to clarify the aforementioned explanation, Figure 2.12 shows efficiency curves as a function of the shaft load for various supply frequencies of a 3HP induction motor as published by Benahaddadi, *et al.,* (2012); the curves present the typical efficiency performance of an induction motor depending on the load and the supply frequency. The exact values can vary from motors depending on the rated power; hence, the greater the power rating, the higher the efficiency.

The reference curve for efficiency was obtained from tests over a 3HP induction motor, however, the behavior shown in Figure 2.12 is similar to other induction motors, even with high power ratings. Hence, the curves can be used as reference for induction motors with several power ratings.

[23] Induction motor experiences slip when is operating at rated frequency and rated torque; the slip is the difference between synchronous speed and the real rotational speed of the induction motor. This value is normally under 0.5% at rated load and is load dependent.

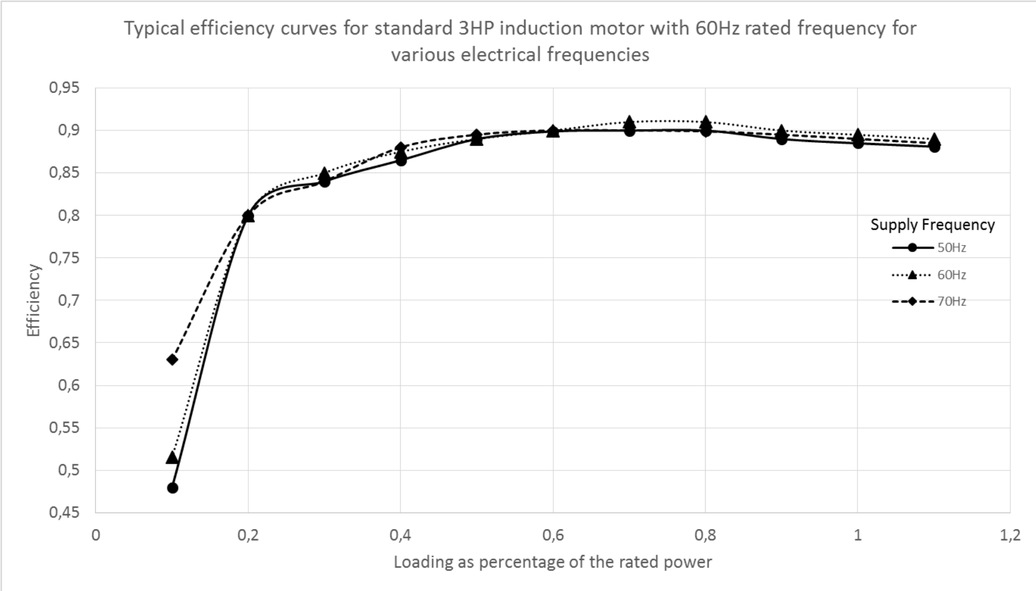


Figure 2.12 – Typical Efficiency Curves for Standard 3HP Induction Motor with 60Hz Rated Frequency for Various Supply Frequencies (BENHADADDI, *et al.,* 2012).

The power factor of the induction motor is also influenced by the load variation, but is independent of changes in supply frequency as concluded by Burt, *et al.* (2006). Again, the author performed some tests and measured electrical characteristics at the input of several motors connected to a unique power converter; the measured quantities were the voltage, the current and the active power. The measurements gave several power factor curves as a function of the shaft loads of the motors; the author plotted a typical curve of power factor variation as a function of the load for induction motors as presented in Figure 2.13 which can be taken as reference.

Induction motors for ship electric propulsion applications are commonly offered with jacket water-cooling method (IC71W) (WEG, 2013), in which the water directly removes heat from the stator and the rotor windings and exchanges this heat with another external water circuit. Three-phase induction motors with jacket water cooling are offered by manufacturers at power ratings up to 2800kW (WEG, 2013).

2.5.2 Synchronous Motors

Three-phase synchronous motors are mostly used in high power applications at a high, medium and low rotational speed range, as shown in Figure 2.11. In ship electric propulsion systems they are usually implemented as main propulsion motors in large passenger vessels and icebreakers, benefiting from their features.

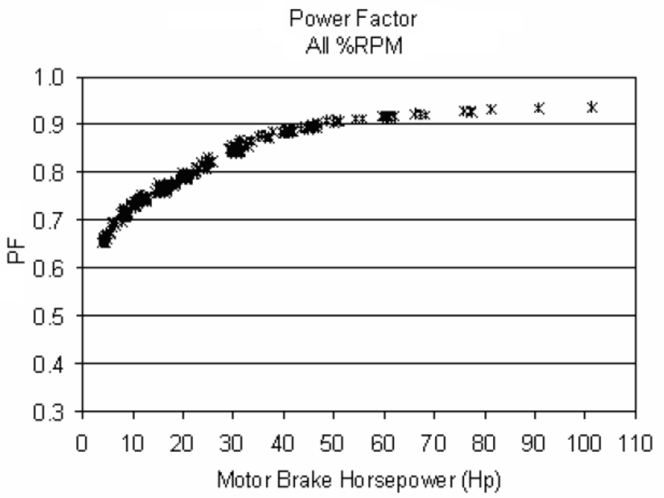


Figure 2.13 – Typical Power Factor Curve vs. Motor Output Horsepower for Induction Motor. Taken from Burt, *et al.* (2006)

2.5.3 Comparison between Induction and Synchronous Motors

In the following table the main features of each motor are summarized and compared. This table was constructed taking into account the information exposed by Rasilo, Belahcen and Arkkio (2012), Singh (2004) and WEG (2005).

Table 2.6 – Comparison of the Main Features of Induction and Synchronous Motors.

	Induction	Synchronous		Induction	Synchronous
Reactive power	Consumes	Can Produce	Maintenance	minimal	small
Power Factor	0.8-0.9 lag	Lead-Lag	Cost	1	1.25
Efficiency	High	1-1.6 greater	Mass	1	1
Speed	with slip	synchronous	Efficiency Variation	Load and supply freq.	Load

2.6 PROPULSION UNITS

In ship electric propulsion systems, the propulsion units are used for vessel thrust and station keeping. In electrically propelled OSVs and tugs, azimuth thrusters are commonly used along with induction motors for main propulsion; in large passenger vessels and icebreakers podded units with synchronous motors are mostly implemented. Shaft propulsion is occasionally used, while cycloidal propulsion units are getting more attention due to their advantages over other units. For station keeping, tunnel thrusters have been extensively used as side thrusters; however, integrated motor propeller units with permanent magnets have been emerging as a new technology in the field.

Shaft propulsion, as shown in Figure 2.14a, is the most used propulsion unit for conventional mechanical propulsion. In ship electric propulsion units it is mostly used when the power rating of the motor is larger than the available azimuth or podded thrusters, when dynamic positioning capabilities are not required or when they can be supplied by cheaper tunnel thruster units (ADNANES, 2003). Shaft propulsion offers high transmission efficiency compared to the other propulsion units; nevertheless, presents several drawbacks for electric propulsion: shaft lines are required to pass through the vessel compromising the efficient use of the available space, it does not have the possibility of performing directional thrust; as a consequence, it is normally used along with rudders or tunnel, when used with electric motor, it commonly requires reduction gearboxes increasing the system complexity.

Azimuth propulsion has been extensively used, especially in tugs and offshore supply vessels with low to medium power electric propulsion systems. A typical azimuth thruster installation is shown in Figure 2.14b. The unit will be discussed in detail below.

Podded propulsion consists in a pod unit in which the propulsion motor is located inside, as shown in Figure 2.14c. The unit can rotate 360° for thrusting the vessel. The electric motor can be of the induction, synchronous or permanent magnet type and it is available at power ratings as high as 30MW (BERGH and HELLDÉN, 2007). The podded unit presents various advantages when compared to azimuth thrusters: higher transmission efficiency, less space occupied within the hull and a lack of reduction gears (ADNANES, 2003). However, it has the following drawbacks: since the unit does not possess reduction gears, motors with low rotational speed are required, thus heavier and more expensive motors are required, compared to the motors necessary for azimuth thrusters. The system is normally installed in large passenger vessels and icebreakers in which the cost and the weight of the unit can be compensated by the size of the vessel or its operational requirements (ADNANES, 2003).

The Cycloidal propeller, Figure 2.14d, is an exclusive propulsion system developed by Voith Turbo, which delivers thrust in all directions. Is a fast and precise vessel propulsion system combining propulsion and steering in a single unit without requiring any rudders; trust and steering forces between zero and the maximum value can be generated in any direction (VOITH, 2011). In Voith Schneider propellers, each propeller blade performs an oscillatory motion around its own axis, which is superimposed on the uniform rotary motion. The propeller is fitted in the vessel so that only the blades protrude from the hull. The system can work with a diesel engine or an electric motor with fixed speed or variable speed operation offering a precise and improved maneuverability compared to other types of propulsion (VOITH, 2011).

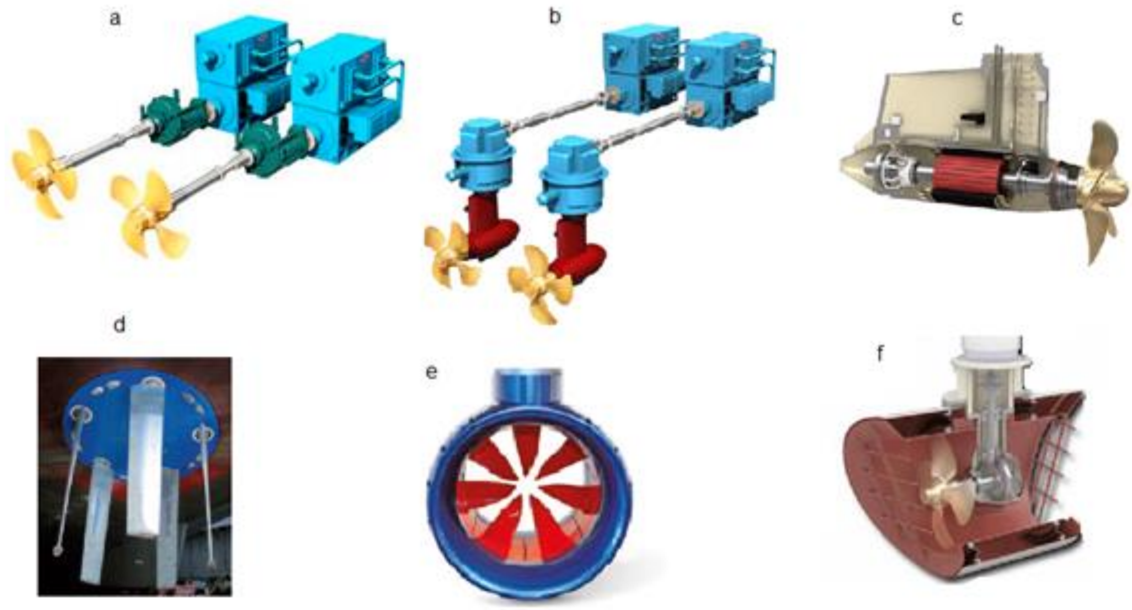


Figure 2.14 – .Propulsion Units Used in Ship Electric Propulsion Systems: a. Shaft Propulsion (STADT, 2013a), b. Azimuth Propulsion (STADT, 2013b), c. Podded Propulsion (HOLGERSSON, 2013), d. Cycloidal Propulsion (VOITH, 2011), e. Integrated Motor Propeller (VOITH, 2012) and f. Tunnel Thruster (ROLLS ROYCE, 2012).

The integrated motor-propeller (IMP) consists of a shrouded propeller, around which the rotor of an electric motor is mounted, Figure 2.14e. The thruster possesses various advantages compared to the conventional propulsors or thrusters: The motor effectively utilizes passive seawater cooling; therefore, an active cooling and a heat exchanger system are not necessary; Some IMPs have no central shafts and no supporting struts, so that the water inflow to the propeller is more uniform and undisturbed, which is beneficial regarding the efficiency, noise and vibration. Reliability is increased and maintenance costs are reduced. IMPs use variable speed permanent magnet synchronous motors along with fixed pitch propellers. Power ratings offered by the manufacturers are up to 1500kW (BRUNVOLL, 2012; VOITH, 2012).

Tunnel thrusters, Figure 2.14f, produce fixed-direction transverse thrust and are commonly used in vessels with dynamic positioning operation requirements. The implemented motors are normally induction motors, vertically mounted with an L-

Shaped gear or horizontally mounted with a Z-Shaped gear for higher rotational speed and compact motor construction.

Additional information about propulsion units can be found in Bose (2008).

2.6.1 Azimuth Thruster

A standard azimuth thruster is a simple propulsion unit mounted directly on the hull for underwater operation, which can rotate 360º around the vertical axis.

The power input for the azimuth thruster is normally an electric motor located within the hull (Figure 2.15). Two types of azimuth thrusters are commercially available depending of the motor position: the Z-drive and the L-drive. In the former, the power input is received horizontally by a shaft line, as shown in Figure 2.14b. The power transmission as the change of the rotational speed and direction is made by two gearboxes, as shown in Figure 2.15. On the other hand, the motor shaft on the L-drive azimuth thruster is directly coupled to the vertical axis of the unit, requiring only one gearbox to change the rotational speed and direction of the propeller, as can be noticed in Figure 2.16. When compared, the Z-drive azimuth thruster presents greater mechanical losses than the L-drive one, with typical efficiencies about 95% compared to 97% for the L-drive unit (MULLER, 2008).

Propeller for azimuth thrusters are available with fixed (FPP) or controllable pitch-to-diameter ratio (CPP). In PSVs both are normally used within nozzle or open propellers. The FPP is mainly used with variable speed drives (electric motor driven by power converter), while the CPP is commonly used with combustion engines.

Z-drive azimuth thrusters are commercially available with power ratings up to 5000kW, propeller diameters as great as 3.9m, at rotational speeds of 1200, 900 and 720 rpm. The L-drive unit, meanwhile, is available at power ratings up to 5500kW, with propeller diameters below of 3.9m and rotational speed of 720, 600 (WARTSILA, 2013b).

Considering that the mass of the electric motor decreases with the speed increment, electric motors for Z-drive azimuth thrusters can be lighter and cheaper than motors for L-drive units. In fact, as pointed out by Muller (2008), the total cost of an L-drive azimuth thruster is 10% greater than a similar Z-drive unit. Furthermore, since the electric motor is not directly coupled to the Z-drive unit, its maintenance is easier compared with the L-drive thruster.

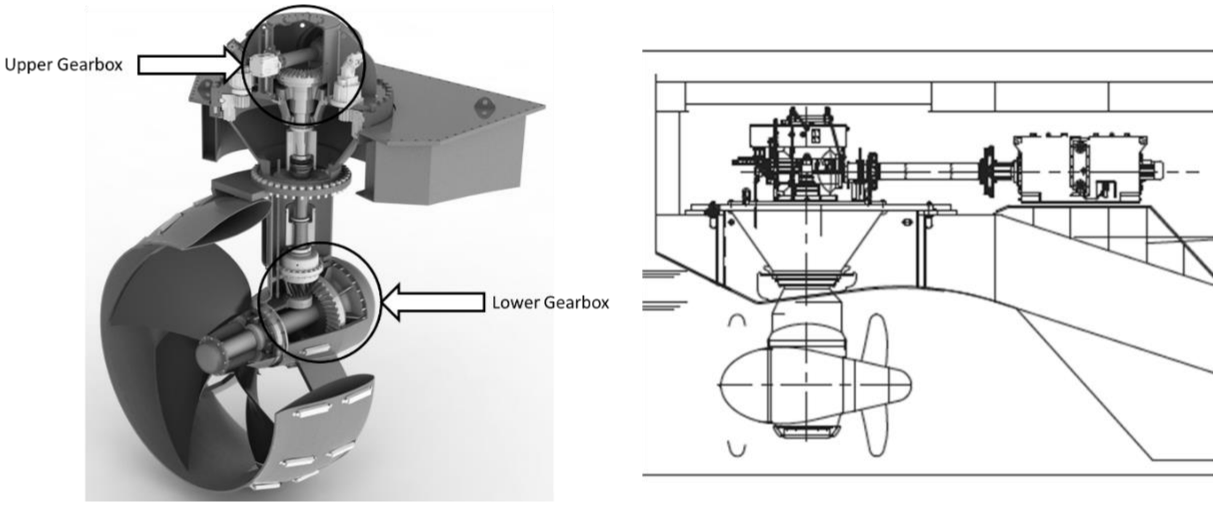


Figure 2.15 – Z-drive azimuth thrusters with gearbox detail (THRUST MASTER TEXAS, 2013).

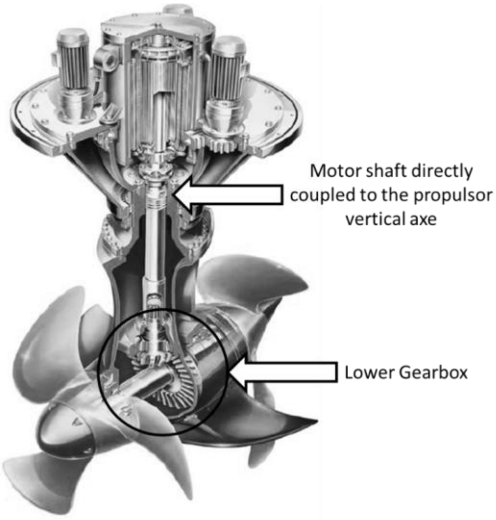


Figure 2.16 – L-drive azimuth thrusters with gearbox detail (SCHOTTEL, 2010).

3 PSV ELECTRIC PROPULSION ARRANGEMENT SELECTION METHODOLOGY

In previous works (WEISS, *et al.*, 2012; COPPE/UFRJ, IPT & USP, 2012, 2013), the first stages of the conceptual design of a PSV for operation in the pre-salt oil fields at Santos basin were performed, developing the basic hull form. Therefore, the following step is to define the propulsion arrangement taking into account that the use of electric propulsion systems in PSVs in Brazil is becoming a standard. Within this context, the present chapter describes a methodological proposal to determine the electric propulsion arrangement for the PSV conceptual design and performs its first steps. The final steps of the methodology are covered in Chapter 4.

3.1 PROBLEM DESCRIPTION AND PROPOSED METHODOLOGY

3.1.1 PSVs operational requirements in Santos Basin

The operations at the Santos Basin pre-salt area will be particularly complex owing to the long distance from shore, around 300km, and the rough weather conditions expected in the area. Hence, in order to transport a big amount of cargo and to overcome the enormous distance and the rough sea state, large PSVs are desired. From the logistic point of view, the most important parameters to develop the conceptual design are the deck useful area, the internal space for liquid storing and the service speed of the PSV. The desirable requirements for a PSV intended to operate at the pre-salt production fields at Santos basin are the following (WEISS, *et al.*, 2012):

- Service speed: 15knots
- Deadweight capacity: 4500DWT.
- Propulsion type: Diesel electric propulsion
- Dynamic positioning system capable of withstanding 4knots currents associated to swell.
- Dynamic positioning system class 2 (COPPE/UFRJ, IPT e USP, 2013).
- Low noise level produced by the side thrusters.

A research has been conducted by various institutions (Universidade Federal do Rio de Janeiro, Universidade de São Paulo and the Instituto de Pesquisas Tecnológicas) considering the previous requirements, in order to develop a conceptual design of a PSV to serve the pre-salt production fields at Santos Basin, attempting to maximize the machinery national content and the other components of the vessel

(COPPE/UFRJ, IPT e USP, 2012; COPPE/UFRJ, IPT e USP, 2013). The preliminary definition of hull form and particulars of the vessel was already proposed (WEISS, *et al.*, 2012; COPPE/UFRJ, IPT & USP, 2012, 2013) with its main parameters shown in Table 3.1.

Table 3.1 – Main Parameters of the Hull Form for the PSV Conceptual Design (COPPE/UFRJ, IPT, & USP, 2012, 2013).

Parameter	Value	Unit
Beam – B-	19.04	m
Draft Forward –T_F-	6.61	m
Draft Aft–T_A-	6.603	m
Length between perpendiculars – L_{PP}-	86,95	m
Length of waterline –L-	86,97	m
Block coefficient – C_B-	0.725	
Master section coefficient –C_M-	0.969	
Prismatic coefficient –C_P-	0.748	
Transverse bulb area –A_{BT}-	16.62	m^2
Waterplane coefficient –C_{WP}-	0.88899	
Longitudinal centre of buoyancy (+ forward) –L_{CB}-	+1.34	%
Height of the centre of the transverse bulb area -h_B-	2.3	m
Transom stern area –A_T-	9.56	m^2
Displacement -∇-	7932.68	m^3
Stern shape parameter –C_{stern}-	-10[25]	

3.1.2 Problem description and proposed solution

In order to complement the basic hull form previously detailed and complete the PSV conceptual design, the propulsion system must be determined. Considering the above, the present dissertation focuses in a methodology proposal to define the Diesel electric propulsion arrangement for the PSV, aiming to specify the equipment, so that national manufacturers can supply it. As discussed in Chapter 2, there are various alternatives for electric propulsion systems with important characteristics that can be applied to the PSV propulsion system; hence, in order to determine a suitable alternative, the Diesel electric propulsion system for the PSV will be selected after the evaluation of 4 arrangements:

1. Arrangement 1: Diesel electric propulsion system with induction motor as the main propulsion motor.

[25] The stern shape parameter is fixed as -10 taking in account the values recommended by Holtrop & Mennen (1982) and considering that the afterbody form of the vessel is a V-shaped section.

2. Arrangement 2: Diesel electric propulsion system with synchronous motor as the main propulsion motor.
3. Arrangement 3: it is the same as the arrangement 1 with a batteries bank connected to the main switchboards.
4. Arrangement 4: it is the same as the arrangement 2 with a batteries bank connected to the main switchboards.

Each of the 4 arrangements will be evaluated with two types of Diesel generator sets: high-speed Diesel generator set and medium-speed Diesel generator set. The arrangements are shown in Figure 3.1.

For the present dissertation, two additional arrangements were considered, both with variable speed Diesel generator sets and DC power transmission. Unfortunately, it was not possible to find clear and useful information about the performance of variable speed Diesel generator sets that would allow defining or specifying the arrangements; therefore, they were discarded and will be proposed for future work.

3.1.3 Proposed methodology

The methodological approach proposed in the present dissertation is shown in the schematic diagram in Figure 3.2.

The propulsion power estimation is the main input data to determine the electric propulsion arrangements for the design. The estimation will be made using the methodology proposed by Holtrop & Mennen (1982) and Holtrop (1984). The procedure requires as input data several parameters of the vessel such as the main dimensions, main coefficients, bulb data, etc. The main parameters of the conceptual design shown in Table 3.1 will be used as input for the power propulsion estimation. Furthermore, a characterization of similar PSVs will be made so as to be used as a guide to define some important issues of the propulsion power estimation.

With the propulsion power estimation as input, the electric propulsion arrangements can be defined. The definition consists in the detailed specifications of the electrical and mechanical equipment of each electric propulsion arrangement; the main parameters to be detailed are the voltage levels, rated power, electric frequency, efficiencies, mass[26], volume, estimated cost, etc. In order to perform the above, several equipment datasheets will be consulted and taken as reference to define the

[26] The mass is selected as criteria instead of the weight to correspond with the units of the payload of the PSV (deadweight) which is given in Tonnes (1 Tonne=1000kg). A Tonne is a mass unit.

equipment. Furthermore, the conclusions from the characterization of similar vessels will be also used to determine some details, as the rotational speed of the Diesel generator sets, voltage levels, etc. The arrangement must be selected meeting the regulations defined by the classification societies such as redundancy, reliability in the operation, exhaust gases emissions, etc.

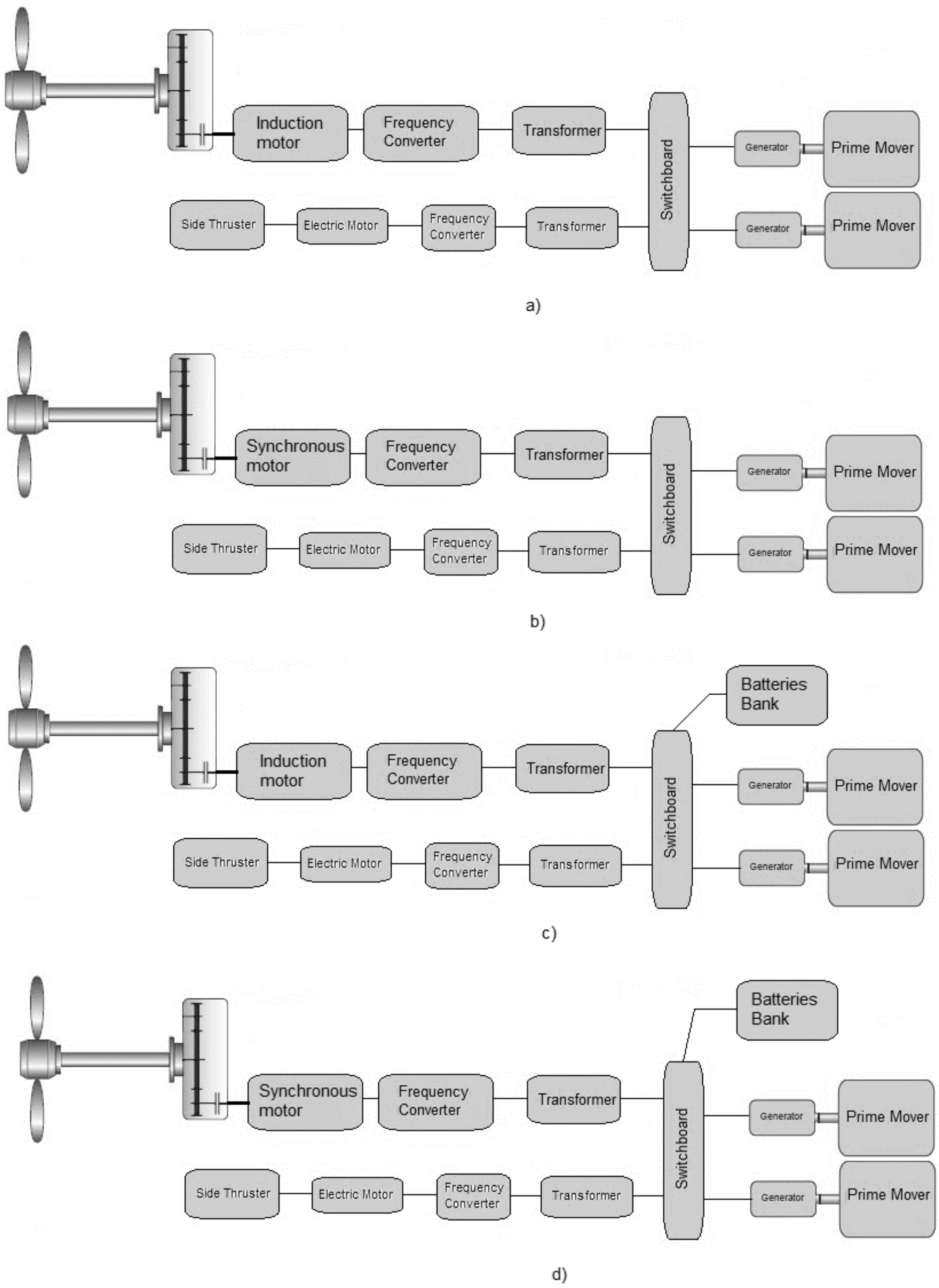


Figure 3.1 – Diesel Electric Propulsion Arrangements for Evaluation: a) Arrangement 1, b) Arrangement 2, c) Arrangement 3 and d) Arrangement 4.

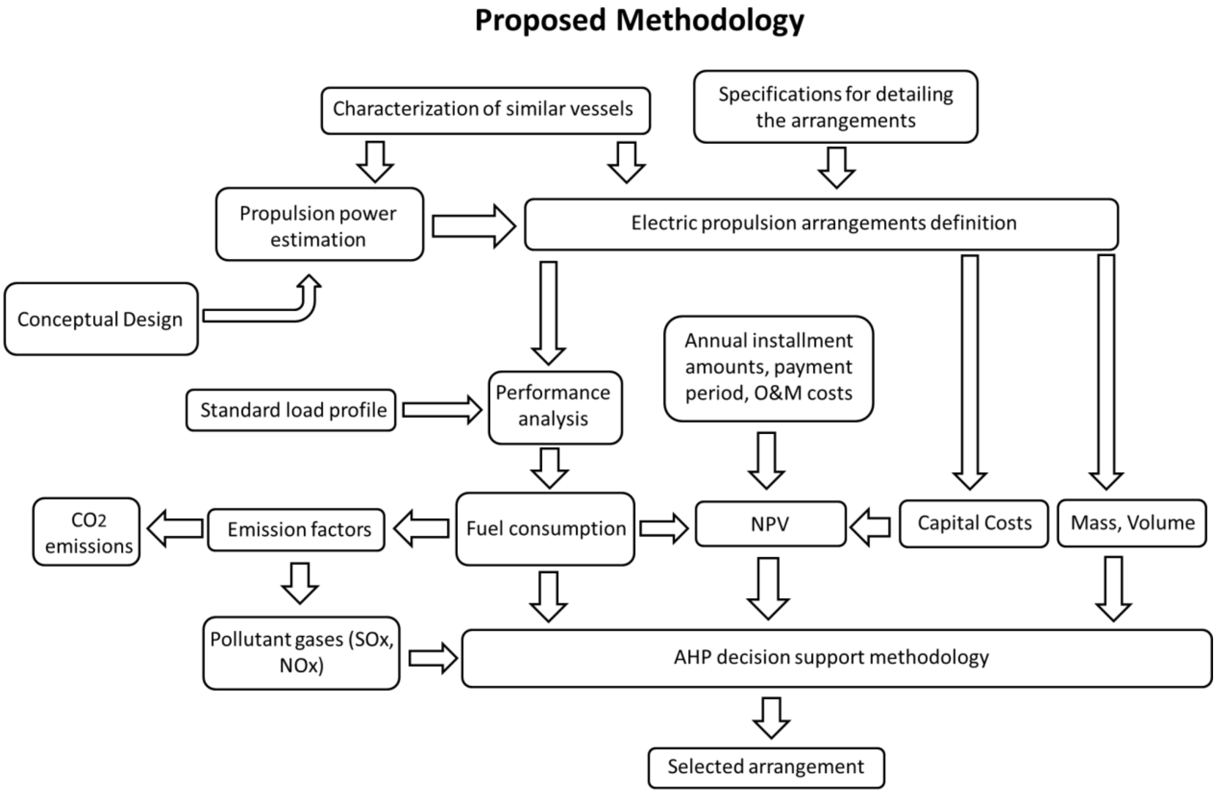


Figure 3.2 – Schematic Diagram of the Proposed Methodology.

The next stage is the performance analysis for each arrangement, which consists in determining the efficiency of the electric equipment, the total power provided by the generators and the Diesel engines, the loading of the Diesel engines and the number of Diesel generator sets in operation as a function of the load. In order to verify the aforementioned parameters numerically, a standard load profile will be defined and used as input. A standard load profile is the variation of the PSV electrical power requirements within a time range; in this case the time range comprehends a round-trip starting from port. From the analysis, the fuel consumption of the Diesel engine for each arrangement will be obtained by using the Diesel engine SFOC curves. Moreover, the most significant exhaust emissions (NOx, SOx and CO_2) will be approximated using emission factors, relating them to the fuel consumption.

The methodology of this dissertation continues with the calculation of a financial parameter, the net present value (NPV). To perform it, the capital costs, fuel consumption and O&M (Operation and Maintenance) expenses for each arrangement will be used as input data.

The last part of the methodology proposed is a comparison of the main parameters obtained for each arrangement: mass, volume, fuel consumption, exhaust gases emissions (NOx and SOx) and the NPV. The comparison will be made using the AHP as a support method to select the electric propulsion arrangement for the PSV.

The present chapter comprehends the first parts of the methodology: the estimation of the propulsion power and the definition of the four electric propulsion arrangements including their capital costs, mass and volume. Meanwhile, Chapter 4 details the performance analysis of the arrangements, fuel consumption, pollutant gases emissions, the NPV and the selection of the arrangement for the PSV.

3.2 CHARACTERIZATION OF SIMILAR VESSELS

In the conceptual stage of the design, it is desirable to have as much information as possible about similar vessels, with the objective of using it as a guide for possible solutions (GARBER, 2002). The similar vessels are ships with the same or almost the same characteristics as the ship under study, in this case PSVs with electric propulsion systems.

In this dissertation the characterization consists in the detailed description of the main propulsive characteristics of several electrically propelled PSVs. The description was done focusing in the engine generator sets and the type of fuel, the characteristics of the power transmission systems, the propulsion units and the dynamic positioning system arrangements.

The vessels considered for characterization are presented in Table 3.2 and were obtained from a PSVs database under rental agreement for an important oil production company. There are 32 electrically propelled PSVs currently operating in Brazil classified by their cargo capability and their operational speed. The main characteristics of each vessel were taken from the datasheets published by their respective ship-owners on the Internet; the datasheets are presented in this dissertation in Annex A.

The PSVs are normally classified by their deadweight capacity, measured in Tonnes (deadweight Tonnes, DWT). According to the literature, a PSV with a deadweight below of 3000DWT is considered to have a low capacity, whereas a PSV with deadweight equal or greater than 3000DWT is considered to have a high capacity (ARCOVERDE, 2013). Hence, from the 31 vessels in Table 3.2, 19 have a have a low capacity while the remaining 12 possess high capacity. Furthermore, the maximum speed of the high capacity PSVs tends to be higher than the other PSVs, with 13.45knots in average, whereas for the others the speed is 12.38knots in average.

Table 3.2 – List of Electrically Propelled PSVs for Characterization Detailing Their Deadweight and Maximum Speed.

No.	Ship Name	Cargo Capacity -DWT (Tonnes)	Maximum speed (knots)	No.	Ship Name	Cargo Capacity - DWT (Tonnes)	Maximum speed (knots)
1	LAB 150	1500	10,5[27]	**17**	TRIPLE PLAY	1686	12
2	LAB 151	1500	10,5*	**18**	ANNE CANDIES	2800*	12,5
3	LAB 152	1500	10,5*	**19**	KIMBERLY CANDIES	2800*	12,5
4	BOURBON LIBERTY 105	1509	12,5	**20**	SIEM SUPPLIER	3037	15,5
5	BOURBON LIBERTY 106	1509	12,5	**21**	BIGUÁ	3320	12
6	BOURBON LIBERTY 107	1509	12,5	**22**	FULMAR	3320	12
7	BOURBON LIBERTY 109	1509	12,5	**23**	PETREL	3320	12
8	BOURBON LIBERTY 119	1509	12,5	**24**	SAVEIROS FRAGATA	3320	12
9	BOURBON LIBERTY 120	1509	12,5	**25**	SAVEIROS PELICANO	3320	12
10	AMY CANDIES	1542	13	**26**	SKUA	3320	12,3
11	KERI CANDIES	1542	13	**27**	SKANDI CAPTAIN	3333	14,4
12	MARY FRANCIES CANDIES	1655	13	**28**	CELIA CANDIES	4036†	15,5
13	OLIVIA CANDIES	1655	13	**29**	TALHA - MAR	4393	12,7
14	DOUBLE EAGLE	1686	12	**30**	TAGAZ	4587	13
15	FIRST AND TEN	1686	12	**31**	ISLAND PATRIOT	4843	15,5
16	HAT TRICK	1686	12	**32**	KL BREVIKFJORD	5185	16

3.2.1 Engine Generator Sets

The generator set characterization was performed using the specifications given by the PSV datasheets, which details their model, reference number and/or power rating. The previous data was complemented with further details from the datasheets of each generator set. The main characteristics of the generator sets for each vessel were registered in Table 3.3.

From the data presented in Table 3.3, the following details about the Diesel generator sets in electrically propelled PSVs can be highlighted:

- The engines used as prime movers in the electrically propelled PSVs are prime rating Diesel engines, rotating at 1800rpm.

[27] Data not available directly from the ship-owner. Taken from the database of the author.

- The manufacturers inform that the high speed Diesel engines are fueled with #2 Diesel fuel, which is equivalent to DMA (MGO) in the ISO-F designation (VERMEIRE, 2007).
- The wound rotor synchronous generator is the alternator used by all the generator sets. The aforementioned statement was done considering the information about the exciter (permanent magnet exciter) and the voltage control (made by an automatic voltage regulator), which refers to typical specifications of wound rotor synchronous generators.
- Since the dominant rotational speed is 1800rpm, it can be deduced that the generated voltage has a frequency of 60Hz and each generator has 4 poles (refer to Table 2.3).
- Although water jacket to air-cooling with radiator is mentioned in most of the datasheets, for marine applications the water jacket exchanges heat with seawater as second coolant as discussed in the section 2.1.1.1. This cooling method is required due to limitations in the air flow of the engine room within the hull of PSVs.

3.2.2 Power Transmission

The power transmission characteristics as the voltage level and the frequency are detailed below. Concerning the frequency, it was already defined as 60Hz since all the generator sets rotates at 1800rpm. The voltage levels were taken from the PSV datasheets and registered in Table 3.4. It can be noticed that most of the PSV datasheets have no information about their voltage levels for transmission. From the data it can be deduced that the preferred voltage for transmission is low, at 480V or 690V three-phase.

Table 3.3 – Detailed Characteristics of the Diesel Generator Sets for the Electrically Propelled PSVs.

Ship Name	Rated power of main Diesel gensets (kW)	Rotational speed (rpm)	Type of rating	Fuel type	Alternator Type	Ship Name	Rated power of main Diesel gensets (kW)	Rotational speed (rpm)	Type of rating	Fuel type	Alternator Type
LAB 150	3x1360	1800	Prime	MGO	Wound rotor synchronous	**TRIPLE PLAY**	2x1240+1x450*	1800	Prime	MGO	Wound rotor synchronous
LAB 151	3x1360	1800	Prime	MGO	Wound rotor synchronous	**ANNE CANDIES**	4x1360	1800	Prime	MGO	Wound rotor synchronous
LAB 152	3x1360	1800	Prime	MGO	Wound rotor synchronous	**KIMBERLY CANDIES**	4x1360	1800	Prime	MGO	Wound rotor synchronous
BOURBON LIBERTY 105	2x1240+1x460*	1800	Prime	MGO	Wound rotor synchronous	**SIEM SUPPLIER**	2x1825+2x1360	1800	Prime	MGO	Wound rotor synchronous
BOURBON LIBERTY 106	2x1240+1x460*	1800	Prime	MGO	Wound rotor synchronous	**BIGUÁ**	4x1135*	1800	Prime	MGO	Wound rotor synchronous
BOURBON LIBERTY 107	2x1240+1x460*	1800	Prime	MGO	Wound rotor synchronous	**FULMAR**	4x1135*	1800	Prime	MGO	Wound rotor synchronous
BOURBON LIBERTY 109	2x1240+1x460*	1800	Prime	MGO	Wound rotor synchronous	**PETREL**	4x1135*	1800	Prime	MGO	Wound rotor synchronous
BOURBON LIBERTY 119	2x1240+1x460*	1800	Prime	MGO	Wound rotor synchronous	**SAVEIROS FRAGATA**	4x1135*	1800	Prime	MGO	Wound rotor synchronous
BOURBON LIBERTY 120	2x1240+1x460*	1800	Prime	MGO	Wound rotor synchronous	**SAVEIROS PELICANO**	4x1135*	1800	Prime	MGO	Wound rotor synchronous
AMY CANDIES	3x910	1800	Prime	MGO	Wound rotor synchronous	**SKUA**	4x1135*	1800	Prime	MGO	Wound rotor synchronous
KERI CANDIES	3x910	1800	Prime	MGO	Wound rotor synchronous	**SKANDI CAPTAIN**	4x1150*	1800	Prime	MGO	Wound rotor synchronous
MARY FRANCIES CANDIES	3x910	1800	Prime	MGO	Wound rotor synchronous	**CELIA CANDIES**	2x910+2x1360	1800	Prime	MGO	Wound rotor synchronous
OLIVIA CANDIES	3x910	1800	Prime	MGO	Wound rotor synchronous	**TALHA - MAR**	4x1360*	1800	Prime	MGO	Wound rotor synchronous
DOUBLE EAGLE	2x1240+1x450*	1800	Prime	MGO	Wound rotor synchronous	**TAGAZ**	4x1600*	1800	Prime	MGO	Wound rotor synchronous
FIRST AND TEN	2x1240+1x450*	1800	Prime	MGO	Wound rotor synchronous	**ISLAND PATRIOT**	4x1825*	1800	Prime	MGO	Wound rotor synchronous
HAT TRICK	2x1240+1x450*	1800	Prime	MGO	Wound rotor synchronous	**KL BREVIKFJORD**	4x2250*	1800	Prime	MGO	Wound rotor synchronous

* The rated power is taken from the diesel generator set datasheets and slightly differs from which it is informed in the vessel datasheets.

Table 3.4 – Characteristics of the Power Transmission in the Electrically Propelled PSVs.

Ship Name	Generated Voltage (V)	Ship Name	Generated Voltage (V)
LAB 150	690 - 3ϕ	**TRIPLE PLAY**	480 - 3ϕ
LAB 151	690 - 3ϕ	**ANNE CANDIES**	Not informed
LAB 152	690 - 3ϕ	**KIMBERLY CANDIES**	Not informed
BOURBON LIBERTY 105	Not informed	**SIEM SUPPLIER**	690 - 3ϕ
BOURBON LIBERTY 106	Not informed	**BIGUÁ**	690 - 3ϕ
BOURBON LIBERTY 107	Not informed	**FULMAR**	690 - 3ϕ
BOURBON LIBERTY 109	Not informed	**PETREL**	690 - 3ϕ
BOURBON LIBERTY 119	Not informed	**SAVEIROS FRAGATA**	690 - 3ϕ
BOURBON LIBERTY 120	Not informed	**SAVEIROS PELICANO**	690 - 3ϕ
AMY CANDIES	Not informed	**SKUA**	690 - 3ϕ
KERI CANDIES	Not informed	**SKANDI CAPTAIN**	690 - 3ϕ
MARY FRANCIES CANDIES	Not informed	**CELIA CANDIES**	Not informed
OLIVIA CANDIES	Not informed	**TALHA - MAR**	690 - 3ϕ
DOUBLE EAGLE	480 - 3ϕ	**TAGAZ**	690 - 3ϕ
FIRST AND TEN	480 - 3ϕ	**ISLAND PATRIOT**	450 - 3ϕ
HAT TRICK	480 - 3ϕ	**KL BREVIKFJORD**	Not informed

3.2.3 Propulsion Units

The main data of the propulsion units and their respective propulsion motors was taken directly from the PSV datasheets. The information is presented in Table 3.5. It should be observed that, since the diameter of the propulsors is not informed, their approximated values were obtained from the PSV drawings, measuring the diameter of the propulsor as a function of the draft. When the drawing was not available, the catalog of the propulsion unit was consulted to obtain its diameter.

From Table 3.5, the following characteristics can be detailed:

- All the vessels have at least two main propulsion units. For PSVs with low deadweight capacity (below 3000DWT) there is no definite preference between two or three main propulsion units; for deadweight above 3000DWT the PSVs are equipped with two main propulsion units.
- All the electrically propelled PSVs have installed azimuth thrusters as main propulsion units.
- There is no clear preference in terms of azimuth thrusters usage with open propeller or ducted propeller (FPP).
- The Z-drive azimuth thruster units are the preferred type of azimuth thrusters for PSVs with electric propulsion systems.
- There is no clear preference in terms of usage of azimuth thrusters with open propeller or ducted propeller.

Table 3.5 – Characteristics of the Main Propulsion Units for the Electrically Propelled PSVs.

Ship Name	Main propulsion power (kW)	Type of propulsion Unit	Propulsor diameter (as percentage of the draft)	Ship Name	Main propulsion power (kW)	Type of propulsion Unit	Propulsor diameter (as percentage of the draft)
LAB 150	2x1340	CPP, Azimuth	68%[*]	**TRIPLE PLAY**	3x843	Z-drive, Azimuth nozzle	48%
LAB 151	2x1340	CPP, Azimuth	68%[*]	**ANNE CANDIES**	Not informed	Z-drive, Azimuth nozzle	59%
LAB 152	2x1340	CPP, Azimuth	68%[*]	**KIMBERLY CANDIES**	Not informed	Z-drive, Azimuth nozzle	59%
BOURBON LIBERTY 105	3x843	L-drive, Azimuth	Not obtained	**SIEM SUPPLIER**	Not informed	Z-drive, Azimuth contrarrotating open propeller	Not obtained
BOURBON LIBERTY 106	3x843	L-drive, Azimuth	Not obtained	**BIGUÁ**	2x1500	Z-drive, Azimuth[†]	48%
BOURBON LIBERTY 107	3x843	L-drive, Azimuth	Not obtained	**FULMAR**	2x1500	Z-drive, Azimuth†	48%
BOURBON LIBERTY 109	3x843	L-drive, Azimuth	Not obtained	**PETREL**	2x1500	Z-drive, Azimuth†	48%
BOURBON LIBERTY 119	3x843	L-drive, Azimuth	Not obtained	**SAVEIROS FRAGATA**	2x1500	Z-drive, Azimuth†	48%
BOURBON LIBERTY 120	3x843	L-drive, Azimuth	Not obtained	**SAVEIROS PELICANO**	2x1500	Z-drive, Azimuth†	48%
AMY CANDIES	2x900	Z-drive, FPP, Azimuth open propeller	46%	**SKUA**	2x1500	Z-drive, Azimuth†	48%
KERI CANDIES	2x900	Z-drive, FPP, Azimuth open propeller	46%	**SKANDI CAPTAIN**	2x1470	Z-drive, Azimuth contrarrotating open propeller	36%
MARY FRANCIES CANDIES	2x900	Z-drive, FPP, Azimuth open propeller	46%	**CELIA CANDIES**	2x1800	CPP, Azimuth nozzle	Not obtained
OLIVIA CANDIES	2x900	Z-drive, FPP, Azimuth open propeller	46%	**TALHA - MAR**	2x2000	Z-drive, CPP, Azimuth	54%
DOUBLE EAGLE	3x843	Z-drive, Azimuth nozzle	48%	**TAGAZ**	2x2500	FPP, Azimuth	Not obtained
FIRST AND TEN	3x843	Z-drive, Azimuth nozzle	48%	**ISLAND PATRIOT**	2x2500	CPP, Azimuth	56%
HAT TRICK	3x843	Z-drive, Azimuth nozzle	48%	**KL BREVIKFJORD**	2x2200	Z-drive, FPP, Azimuth contrarrotating open propeller	61%

[*] The diameter was obtained from the specification sheet of Schottel rudderpropellers (SCHOTTEL, 2014a).
[†] Data taken from the specification datasheet of the Ulstein Aquamaster azimuth thrusters (ROLLS ROYCE, 2002).

- When compared to the design draft, the propulsor diameters (open propeller or propeller+nozzle) are within a range from 36% to 68% of the draft. Most of the diameters drop in the 46-48% range.
- It can be observed that the main propulsion power is not proportional to the deadweight capacity and the maximum speed, since some vessels have greater propulsion power than vessels with higher deadweight capacity and maximum speed. The different hull forms of the vessels produce non-linear behaviors in the hull resistance and the power demands for propulsion, which causes this non linearity between deadweight, speed and propulsion power.
- The power rating of individual propulsion motors does not exceed 2500kW.

3.2.4 Dynamic positioning system

The details about the dynamic positioning system classification and the side thrusters for position keeping were taken directly from the datasheets of the vessels and summarized in Table 3.6. The main features are highlighted below:

- The rated power of each side thruster does not exceed 883kW.
- There is the same preference between side thrusters with FPP propellers or CPP propellers.
- Most of the vessels are classified as class 2 dynamic positioning systems (IMO, 1994) which implies that they are equipped with 2 bow thrusters.
- Since the vessels possess azimuth thrusters as main propulsion units, they do not require stern thrusters for dynamic positioning.

3.2.5 Electric propulsion system mass

In the preliminary design of vessels, the mass of the propulsive installation must be considered in order to define the structure and the hull form. Since an accurate value for the propulsion system mass is not usually available at the preliminary stage, methods for estimating the mass value are required. In this context, Watson (1998), presented an expression for mass estimation of ship electric propulsion systems as a function of the power rating of all equipment for power generation; the expression is presented below:

$$M_{DEW} = 0.72(MCR)^{0.78} \tag{3.1}$$

Where, M_{DEW} is the mass of the Diesel electric propulsion installation in thousands of kg and MCR is the total maximum continuous rating in kW of all generating machinery. The formula is valid for all ship types.

Table 3.6 – Characteristics of the dynamic positioning system for the electrically propelled PSVs

Ship Name	Bow thrusters power (kW)	Stern thrusters	DP Class.	Ship Name	Bow thrusters power (kW)	Stern thrusters	DP Class.
LAB 150	1x522	No	DP-1	**TRIPLE PLAY**	2x560FPP	No	DP-2
LAB 151	1x522	No	DP-1	**ANNE CANDIES**	2x684CPP	No	DP-2
LAB 152	1x522	No	DP-1	**KIMBERLY CANDIES**	2x684CPP	No	DP-2
BOURBON LIBERTY 105	2x560	No	DP-2	**SIEM SUPPLIER**	1x883+1x883	No	DP-1
BOURBON LIBERTY 106	2x560	No	DP-2	**BIGUÁ**	2x588	No	DP-2
BOURBON LIBERTY 107	2x560	No	DP-2	**FULMAR**	2x588	No	DP-2
BOURBON LIBERTY 109	2x560	No	DP-2	**PETREL**	2x588	No	DP-2
BOURBON LIBERTY 119	2x560	No	DP-2	**SAVEIROS FRAGATA**	2x588	No	DP-2
BOURBON LIBERTY 120	2x560	No	DP-2	**SAVEIROS PELICANO**	2x588	No	DP-2
AMY CANDIES	1x440	No	DP-1	**SKUA**	2x588	No	DP-2
KERI CANDIES	1x440	No	DP-1	**SKANDI CAPTAIN**	2x800	No	DP-2
MARY FRANCIES CANDIES	1x440	No	DP-1	**CELIA CANDIES**	1x440+1x353	No	DP-2
OLIVIA CANDIES	1x440	No	DP-1	**TALHA - MAR**	2x588	No	DP-2
DOUBLE EAGLE	2x560FPP	No	DP-2	**TAGAZ**	2x745	No	DP-2
FIRST AND TEN	2x560FPP	No	DP-2	**ISLAND PATRIOT**	1x883CPP+1x883CPP	No	DP-2
HAT TRICK	2x560FPP	No	DP-2	**KL BREVIKFJORD**	2x880FPP+1x880FPP	No	DP-2

In the present dissertation, an additional expression for the mass estimation of electric propulsion arrangements in PSVs is proposed. The expression was obtained from a regression curve fitted to the mass values of the electric propulsion installations of the vessels in Table 3.2. The expression is:

$$M_{DE} = 3 \times 10^{-6} P_p^2 + 0.0119 P_p + 38.834 \quad (3.2)$$

Where M_{DE} is the mass of the electric propulsion arrangement in thousands of kg and P_p is the total installed power for propulsion (at the output of the propulsion motors) in kW. The R-squared factor of the equation was 0.823.

The mass values of the electric propulsion systems were obtained assuming that all the arrangements are the same as those ones shown in Figure 3.1a), with high speed Diesel generator sets. The mass of the individual components of the arrangements was acquired from datasheets and catalogs of different manufacturers (Siemens and ABB for induction motors, Rolls Royce and Schottel for thrusters, Siemens and ABB for VFDs, Caterpillar and Cummins for Diesel generator sets, EMG transformers for the VFD transformers).

The eq. (3.2) differs from the expression given by Watson in that the mass of the installation depends on the total power for propulsion instead of the total power of the generating equipment.

The expression can be used for design stages of electrically propelled PSVs, in which an estimation of the propulsive installation mass is required to obtain an acceptable hull form.

3.3 PROPULSION POWER ESTIMATION

3.3.1 Estimation of the PSV resistance

The vessel resistance estimation for the hull form defined in Table 3.1 was performed following the methodology proposed by Holtrop and Mennen (1982) and Holtrop (1984). The total resistance of the vessel was estimated for all the speed range (from 1 to 15knots with increasing steps of 1knot) and for two conditions: for laden voyage *i.e.* 100%∇ and partial load voyage *i.e.* 75%∇[31]. The resistance was obtained using an EXCEL® calculation sheet.

When in service, a ship is exposed to significant changes in the hull roughness due to fouling, marine life on the hull and variations in its shape, which can increase the total resistance of the vessel, as pointed out by Molland, Turnock and Hudson (2011) and Brinati (2011). In order to compensate the speed loss due to the additional resistance, the introduction of a resistance margin in the calculation process is recommended (MOLLAND, TURNOCK and HUDSON, 2011). Some authors suggest one from 15% to 25% (BRINATI, 2011); for the purposes of the present dissertation, it was considered as 15%. The resistance values including the resistance margin were plotted in Figure 3.3.

3.3.2 Hull-propeller interaction

It was seen in the characterization section that the electrically propelled PSVs are equipped with two propulsion units for main propulsion. The above is a consequence

[31] This condition implies that the length of waterline (Lwl), draft (D) and the hull form coefficients (block, prismatic, master section and waterplane) are modified from those defined in Table 3.1.

of the regulations settled by the IMO and the classification societies for class 2 dynamic positioning, which requires the electrical system of the vessel to be divided into two sections, including the electrical loads for main propulsion. Hence, taking the above observation as a guide, the PSV was considered equipped with two main propulsion systems, each one providing the half of the required thrust.

Regarding the type of propulsion unit, all the characterized PSVs have azimuth thrusters as main propulsion units. Considering the above and taking into account the advantage of thrust at 360°, which allows to eliminate the side thrusters at the stern, the azimuth thrusters were selected for the PSV as the main propulsion units.

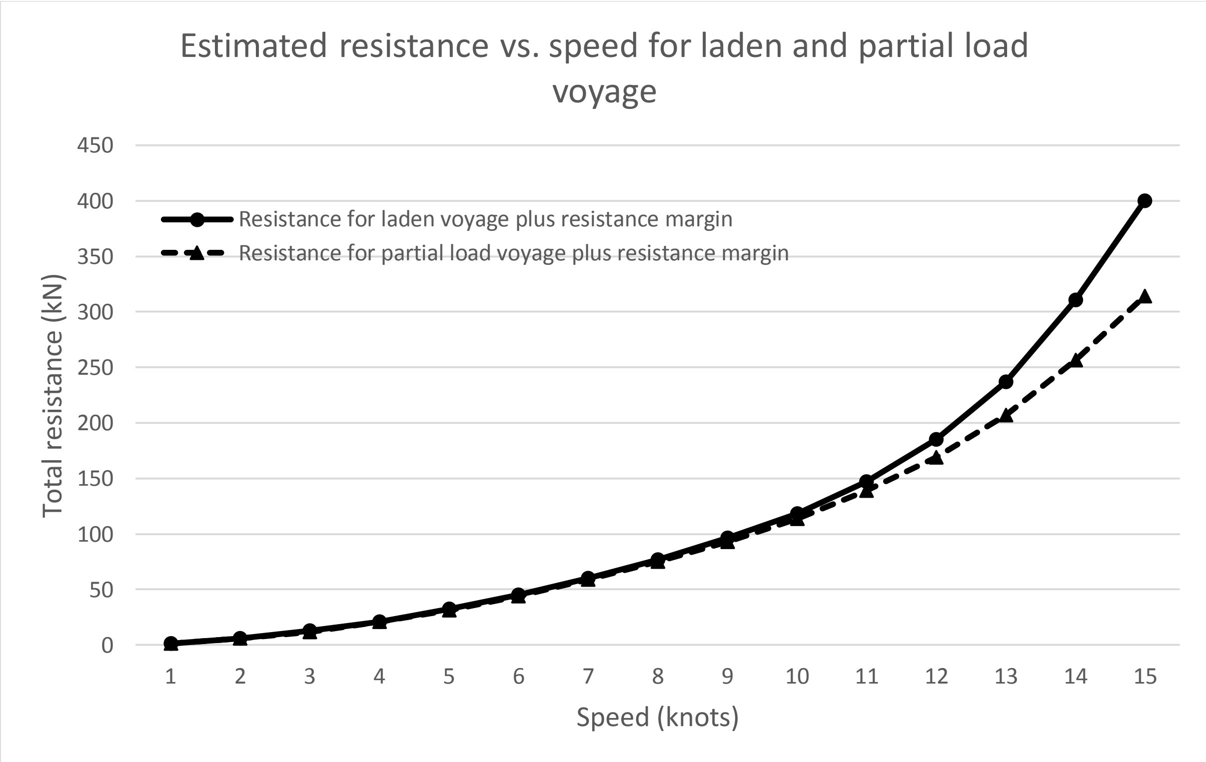


Figure 3.3 – Curves of the Total Ship Resistance vs. Speed for Laden Voyage and Partially Loaded Trip Including the Resistance Margin.

The propeller was selected for operation within a nozzle, considering that the ducted azimuth thruster produces 25% to 30% additional thrust than the azimuth thruster with open propeller (COPPE/UFRJ, IPT e USP, 2013). The 19A nozzle was chosen because it was developed for situations with high loading (COPPE/UFRJ, IPT e USP, 2013) and is the most used nozzle design (BOSE, 2008). The Ka propeller series were developed to be used along with 19A nozzle; a commonly used propeller, the Ka 4.70, was considered for the propulsion system (4 blades and expanded area ratio equal to 0.7). From the two alternatives, FPP or CPP propellers, the FPP was selected taking into account the lower complexity when compared to the CPP (ADNANES, 2003; ARCOVERDE, 2013).

Regarding the propeller diameter, it is recommended to select one as large as possible, in order to have the highest open water efficiency (BRINATI, 2011). The maximum diameter is normally limited within 60% to 70% of the design draft (BRINATI, 2011). In the present design, the diameter was fixed at 65% of the draft, considering the previous limit and taking into account that in Table 3.5, some electrically propelled PSVs have similar diameters equivalent to 68% of the draft. However, it should be noticed that, since the propeller is within a nozzle, the fixed diameter corresponds to the nozzle, since the diameter of the propeller is smaller. Consulting drawings of various commercial ducted azimuth thrusters (WARTSILA, 2013d), it was observed that the nozzle diameter is 24% greater than the propeller diameter. Hence, taking the above as a guide, in this dissertation it was considered that the typical diameter of the nozzles is equal to 1.24 times the propeller diameter.

Considering the aforementioned statement, the propeller diameter is:

$$D = \frac{\left(0.65\left(\frac{T_F+T_A}{2}\right)\right)}{1.24} = \frac{0.65\times 6.605m}{1.24} = 3.46m \tag{3.3}$$

Where D is the propeller diameter, the term 0.65 correspond to the condition of the diameter already settled (65% of the draft), T_F is the draft forward and T_A is the draft aft, the term 1.24 corresponds to the diameter of the nozzle compared to the propeller diameter.

Several commercial azimuth thrusters were consulted from various manufacturers (Schottel, Brunvoll, Wartsila, Rolls Royce) in order to find one model meeting with the diameter requisites. The commercial model with the closest characteristics has a propeller diameter equal to 3.4m (WARTSILA, 2013c; SCHOTTEL, 2014a; BRUNVOLL, 2012; ROLLS ROYCE, 2012) and is offered in L-drive or the Z-drive options.

It should be noticed that the manufacturers do not specify the nozzle design and the propeller type of their azimuth thrusters. However, it will be considered that any manufacturer can provide an azimuth thruster with 19A nozzle and Ka 4.70 propeller within the nozzle.

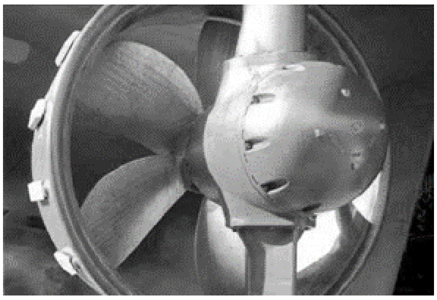
As a next step, the systematic series of the Ka 4.70 propeller in the 19A nozzle, published in Bose (2008), are used along with the propulsion coefficients proposed in

Holtrop and Mennen (1982) and Holtrop (1984) for twin screw vessels, to obtain the thrust, torque, rotational speed and required input power for the propeller. Since the propeller is FPP, the pitch to diameter ratio value is obtained from a range of proposed values within 0.6 and 1.4, varying them and selecting the one with the highest open water efficiency. The input data are the resistance values for laden voyage and partially loaded trip including the resistance margin (Figure 3.3). The pitch to diameter ratio with the best open water efficiency was 1.2 and the maximum power request (corresponding to laden voyage at 15knots) is 2663kW for each azimuth thruster or 5326kW for the two units.

Regarding the selection of the type of drive for the azimuth thruster, *i.e.* Z-drive option or L-drive option, the former presents a lower efficiency than the latter, 95% versus 97%. Moreover, the space occupied by the L-drive is smaller than the Z-drive option. Nevertheless, after consulting the models offered by manufacturers, most of them offer azimuth thrusters with allowable rotational speeds up to 1000rpm in the Z-drive or L-drive option; whereas Wartsila offers units with allowable rotational speed of 1200rpm in Z-drive option and 900rpm in L-drive option. Taking into account that an electric motor with a higher rotational speed is desirable owing to its low mass (the mass increases as the rotational speed decreases) and cost, the Z-drive option is a reasonable choice. Besides, bearing in mind that the motor in the Z-drive thruster is not integrated to the thruster, its maintenance is easier, since the motor can be disengaged from the thruster easily instead of dismounting all the structure as in the case of the L-drive thruster. For the present design, low weight of the thruster, low capital costs and ease of maintenance are more desirable conditions than high transmission efficiency and low space occupation; hence, the Z-drive thruster is selected as the propulsion unit. In Figure 3.4 the datasheet of the azimuth thrusters offered by Wartsila is presented, highlighting the selected model.

The mass of the propulsion unit is also an important parameter; however, the catalog of Wartsila does not inform the mass of the azimuth thruster. Another manufacturer, Schottel, published the main features of a similar azimuth thruster (SCHOTTEL, 2014a), with a diameter of 3.4m and Z-drive power input with 1000rpm of input speed. It is known that the mass of two similar azimuth thruster units vary between manufacturers owing to the materials, the mechanisms, the procedures, etc. Nonetheless, since the azimuth thrusters are similar, it will be assumed that the mass of the Wartsila azimuth thruster selected is in the order of magnitude similar to the

Schottel thruster one. Therefore, the 53000kg of the Schottel thruster will be taken as reference.



Wärtsilä Modular Thrusters for over 2000 kW

Thruster type			1510	2500	2510	3500	5000
Maximum allowable power	kW		2300	3200	3500	5500	7000
Maximum allowable input speed	rpm	Z-drive	1200	1200	1200	900	900
Maximum allowable input speed	rpm	L-drive	1000	900	900	750	750
Propeller diameter in nozzle	mm	Maximum	2900	3200	3400	3800	4400
Propeller diameter in nozzle	mm	Standard	2700	3000	3200	3600	4200

Figure 3.4 – Wartsila Steerable Modular Thrusters Catalog (WARTSILA, 2013c).

With the transmission efficiency already determined, the input power required by the azimuth thrusters was obtained. In the calculation process, it was considered that each propulsion unit provides thrust to one half of the vessel; however, owing to the non-linearity of the propulsion coefficients, the resistance was divided by two and the input power was calculated under this condition. The results for each azimuth thruster are presented in Figure 3.5. An analysis made to the curves of Figure 3.5 shows that the input power for the azimuth thruster is approximately proportional to the cube of the rotational speed of the propeller or the speed of the vessel between 1 and 13knots.

Vessel power requirements significantly increase in rough sea weather, in part because of wave action and, in part because of wind resistance. A ship required to transit at a constant speed needs a sufficient power margin to maintain the service speed even for strong weather conditions at the sea (MOLLAND, HUDSON and TURNOCK, 2011). A PSV intended to operate at Santos Basin will be exposed to roughly weather conditions ($H_{1/3}$=2.01m, T_M=5.1, Head sea, incidence=180° at 15 knots) classified as 5 in the Beaufort scale (COPPE/UFRJ, IPT e USP, 2012; MET OFFICE, 2013). Since the vessel is expected to have scheduled services, the speed will be required to be constant while in transit, which implies that a power margin should be considered. The effects of the sea weather over the speed in cargo vessels were studied by several authors (AERTSSEN, 1975; TOWNSIN and KWON, 1983; TOWNSIN, *et al.*, 1993; KWON, 2008), which proposed various methodologies to determine how the sea weather reduces the speed and which is the power margin required to avoid this from happening. The most important methodologies were proposed by Aertssen (1975) and Kwon (2008) as a result of the statistical analysis of several containerships, VLCC and bulk carriers; the former methodology can be applied in containerships with L_{PP}>146m and C_b between 0.588 to 0.675; while the latter can be applied to containerships, bulk carriers and VLCC with C_b from 0.55 to 0.85 in steps of 0.05 and with Froude number from 0.05 to 0.3. Since the PSV, here defined, significantly differs from containerships, and as its block coefficient does not drop in the categories for which the methodologies are applicable (see Table 3.1), the speed loss and power margin cannot be estimated. Therefore, it will be set following the recommendation stated by Brinati (2011); a power margin of 10% will be considered. Thus, the maximum power requirement (corresponding to laden voyage at 15knots) will be increased by the power margin to define the rated power of the motor for main propulsion, hence the result is:

Power required for laden voyage at 15knots= 2663kW

Power margin=10%

Maximum input power to the azimuth thruster=2929kW

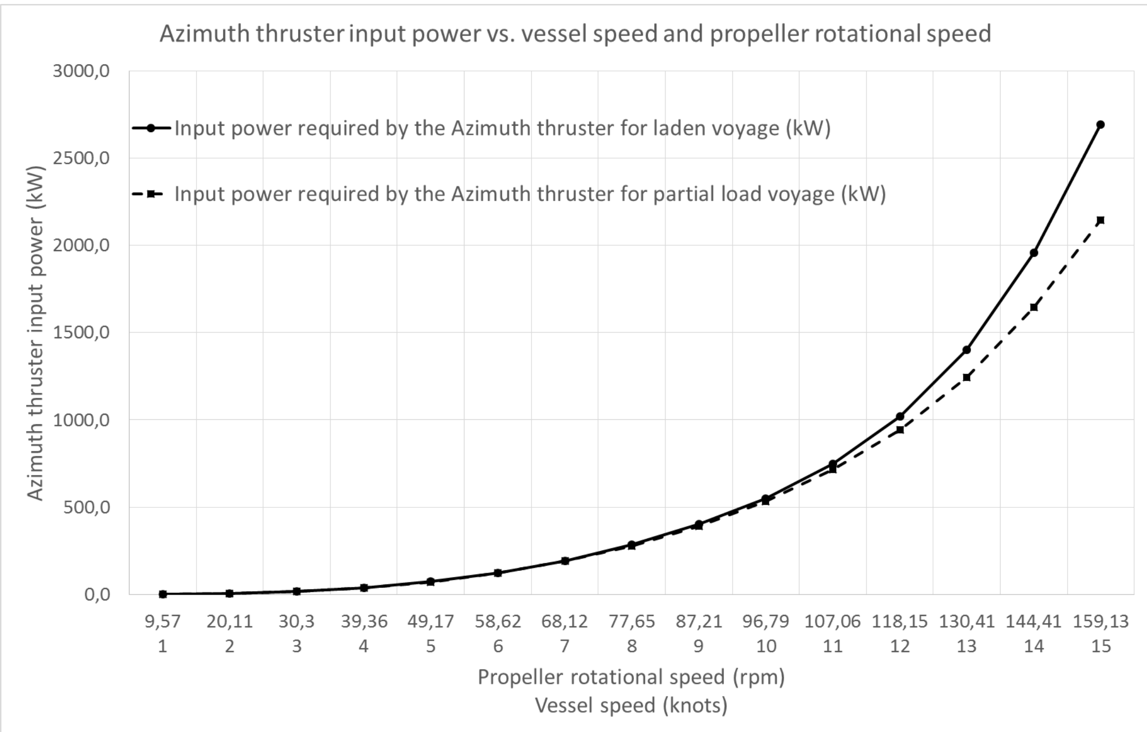


Figure 3.5 – Azimuth Thruster Input Power vs. Vessel Speed and Propeller Rotational Speed.

Each electric propulsion motor must deliver at least 2929kW to each azimuth thruster at the input. It can be noticed that the azimuth thruster selected (Figure 3.4) has a rated input power greater than the required one, thus, it is suitable for the mandatory power level.

Since the rated input speed of the azimuth thruster is 1200rpm and the propeller required rotational speed is 159rpm, the proposed reduction ratio of the Z-drive azimuth thruster is 7,3.

3.4 SPECIFICATIONS FOR THE ELECTRIC PROPULSION SYSTEM

The electric propulsion arrangements for the PSV have to meet some requirements settled by the classification societies and the IMO. Furthermore, for defining the electrical equipment for each arrangement, some additional considerations will be established as design conditions.

The following part of this document will discuss the most important specifications for the electric propulsion arrangements.

3.4.1 Exhaust gases emissions

Taking into account that shipping is a significant source of air pollution and a contributing factor to global climate change (CORBETT and KOEHLER, 2003; IMO, 2010; IMO, 2004), the IMO settled regulations for the prevention of air pollution from ships (MARPOL 73/78 Annex VI), which are mandatory for every ship constructed after 2005. Since the present dissertation is intended to define the propulsion system for a PSV aiming to operate at Santos Basin in the following years, the MARPOL 73/78 Annex VI conditions must be fulfilled.

The MARPOL 73/78 Annex VI mainly restricts the NOx and SOx emissions released by ships. Regarding the NOx emissions, the restrictions were divided in Tiers, each Tier with different date for entering into force (IMO, 2004); currently, the Tier II has been effective since 2011, limiting the emissions of NOx according to the rotational speed of the marine Diesel engines as shown in Figure 3.6. In accordance to the figure, a Diesel generator set operating at 1800rpm can release a maximum of 7,8g/kWh of NOx, while for a Diesel engine operating at 900rpm there is a limit of 9,2g/kWh.

Regarding the SOx emissions, the MARPOL 73/78 Annex VI regulates the sulfur content of marine fuels. The maximum sulfur content allowable for any fuel oil used on board ships shall not exceed 3.5% after January 1st, 2012 (IMO, 2004).

3.4.2 Dynamic positioning system

As discussed in Section 3.1.1, the vessel is required to have a dynamic positioning system classified as class 2. According to the IMO (1994), for a class 2 dynamic positioning system, “a loss of position is not to occur in the event of a single fault in any active component or system”; the single failure criteria include:

- Any active component or system (generators, thrusters, switchboards, etc.)
- Any normally static components (cables)

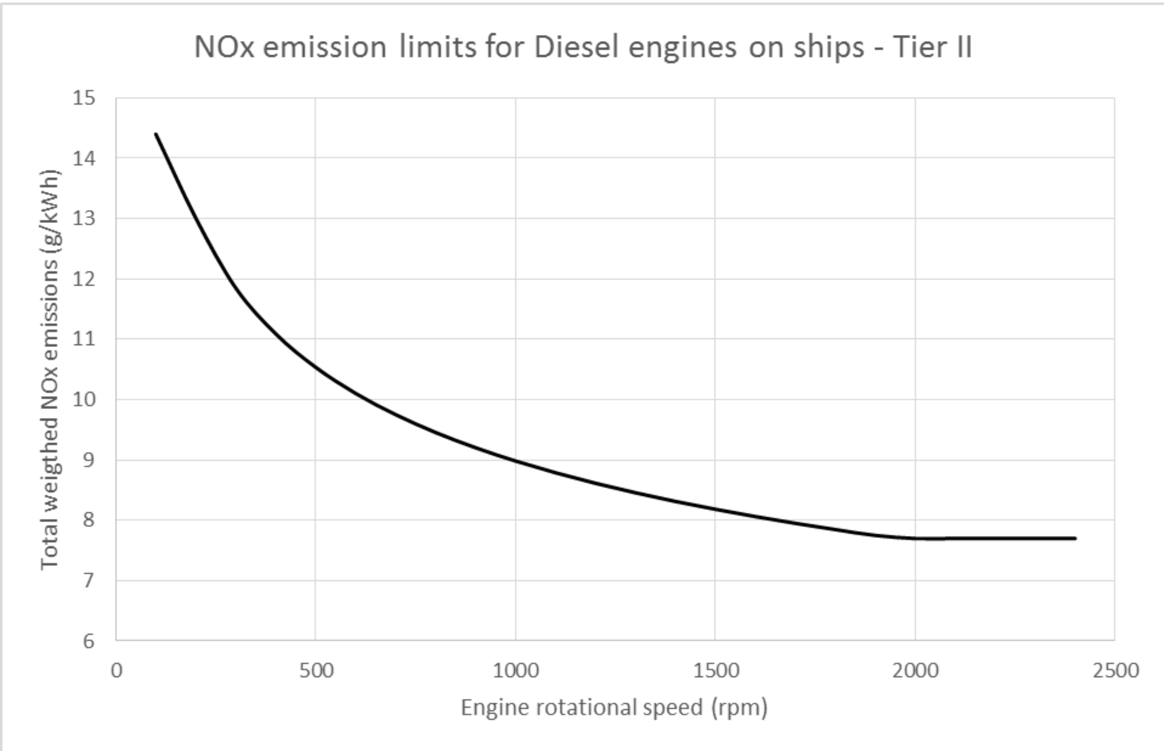


Figure 3.6 – NOx Emissions Limits for Diesel Engines on Ships Covered by Tier II (IMO, 2004).

In order to meet the single failure criteria for a class 2 DP system, redundancy of all active components is required. The above implies the following(IMO, 1994):

- The power system should be divisible into two or more systems such that in the event of failure of one system, at least the other system will remain in operation. The power system may be run as one during operation, but should be arranged by bus-tie breakers to separate automatically in case of failures, including overloading and short-circuits.
- The thruster system should be connected to the power system in such a way that adequate thrust in longitudinal and lateral directions can be provided

with even after failure of one of the constituent power systems and the thrusters connected to that system.

The abovementioned requisites implies that all the electric propulsion arrangements must be split into two sections, which can operate as one unit with breakers protecting one system from the other. Furthermore, the thrusters intended to operate as side thrusters for dynamic positioning must be doubled along with their associated equipment.

The classification societies have been emitting regulations to complement those ones published by the IMO for offshore support vessels with class 2 DP system; the most important conditions with applicability in electric propulsion arrangements are the following (ABS, 2011, 2013):

- **Condition 1 -** The number and capacity of generating sets is to be sufficient under normal seagoing conditions with any one generator as a reserve to carry those electrical loads for essential services and for minimum comfortable conditions of habitability (ABS, 2013 p. 480).
- **Condition 2 -** Where the electrical power is normally supplied by more than one generator set simultaneously in parallel operation, the system is to be so arranged that in the event of the loss of any one of the generators in service, the electrical supply to equipment necessary for propulsion and steering and to ensure the safety of the vessel will be maintained by the remaining generators in service (ABS, 2013 p. 483).
- **Condition 3 –** Generators and their distribution systems are to be sized and arranged such that in the event of any section of bus bar being lost for any reason, sufficient power is to remain available to supply the essential ship service loads, the critical operational loads and to maintain the vessel position within the stipulated operating envelope under the specified maximum environmental conditions (ABS, 2011 p. 488).
- **Condition 4 –** For vessels with an integrated electric propulsion system, under normal sea-going conditions, when one generator is out of service, the remaining generator capacity is to be sufficient to carry all of the loads for vessel services and the propulsion loads to provide for a speed of not less than 7knots or one half of the design speed, whichever is the lesser (ABS, 2013 p. 572).

Analyzing the conditions, it should be noticed that conditions 1 and 2 are particular cases of condition 4. Hence, if the condition 4 is fulfilled, the condition 1 and 2 are too.

3.4.3 Additional considerations

Further specifications about various issues are also discussed.

- The vessel will be supposed to transit in laden voyage with 100% of its design displacement and the return trip to port partially loaded at 75% of its design displacement.
- Changes in the hull state or shape during the lifetime of the vessel, caused by fouling and roughness, will be disregarded.
- As far as possible, all the electrical equipment must be water-cooled (condition settled taking in account the limits for ventilation).
- The variable frequency drives are supposed to meet the harmonic production limits settled by ABS (2006).

3.5 ELECTRIC PROPULSION ARRANGEMENT SIZING

The definition of the electric propulsion arrangements for evaluation is the next step of the proposed methodology. The four arrangements will be detailed taking into account the components discussed in chapter 2, the conclusions of the characterization and the design conditions settled in Section 3.3.

From the characterization, it was observed that the rated voltages of the electric propulsion system are 690V and 480V. Taking into account that the current level is inversely proportional to the voltage for a constant load, a high rated voltage for the system is desirable. Considering that 690V is higher than 480V, it is selected as the rated voltage of the system. The electrical frequency is fixed at 60Hz.

3.5.1 Arrangement 1 definition

The arrangement 1 was described in Section 3.4.1. In this section, the main parameters of each component of the arrangement: rated power, voltage, frequency, efficiency, power factor, mass and volume are to be defined. First, the induction motor is detailed taking as reference the power and rotational speed defined for the azimuth thruster. Afterwards, the VFDs for the propulsion motors are specified including the transformer. Furthermore, the electric motors, the VFD and the transformer for the dynamic positioning system are also defined taking as input the power ratings defined in COPPE/UFRJ, IPT & USP (2013). The typical auxiliary loads are taken from the literature. Finally, the switchboards and the Diesel generator sets are defined.

3.5.1.1 Main Induction motor

The main specifications to size and select the induction motor are summarized in Table 3.7. The rated power, rotational speed and torque were obtained from the hull-propeller integration, while the cooling method was taken from the design conditions.

Table 3.7 – Main Specifications for the Selection of Each Main Propulsion Motor.

Parameter	Value
Rated power output (kW)	≥2940
Rotational speed (rpm)	≤1200
Rated voltage (V)	690V
Cooling	IC71W

Several catalogs of commercial induction motors were consulted from various manufacturers (ABB, Siemens, WEG, General Electric, Baldor, Leroy Somer, etc.) in order to find an induction motor meeting the previous requirements. Unfortunately, there is limited information available about commercial induction motors detailing the power level, voltage magnitude and rotational speed required. According to the websites of the manufacturers, induction motors with the specifications indicated in Table 3.7 are tailor made, *i.e.* manufactured upon request, since they are not as commercial as low power induction motors. Considering the lack of information, it was considered that a manufacturer might build, under request, an induction motor meeting the requisites of Table 3.7. Furthermore, since the main parameters as the rated speed, power factor, efficiency, mass, volume, etc. are required to size the other equipment of the arrangement; the parameters of two similar induction motors from WEG, one of 2940kW and other of 2500kW (See Annex B and Annex C) were taken as references[32]. The first motor has a rated power of 2940kW at 3.4kV with IC81W cooling and 6 poles; the rated power, torque, efficiency, power factor and rotational speed were taken as a reference for the propulsion motor and are shown in Table 3.8. The datasheet with the information of the 2940kW induction motor and its dimensional drawing is presented in Annex B.

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[32] Since the 2940kW is air cooled, its mass and volume is different from a water cooled motor. The 2500kW motor is considered only to take its mass and volume as reference for sizing the arrangement.

Regarding to the other induction motor, its rated power is 2500kW at 690V with IC71W cooling and 6 poles; the power rating is ≈13% greater than the required. Nevertheless, its mass and volume are considered to be in the order of magnitude similar to the induction motor required. In Annex C, the specification sheet and the dimensional drawings are shown.

The reference characteristics of the induction motor are presented in Table 3.8. It is assumed that a manufacturer can build the motor with the parameters in the order of magnitude as those presented in Table 3.8.

Table 3.8 – Characteristics of the Induction Motor Selected as Main Propulsion Motor.

Parameter	Value	Parameter	Value
Rated Power (kW)	2940	Rated power factor	0,86
Rated Voltage (V)	690	Rated torque (kN.m)	23,55
Rated Frequency (Hz)	60	Mass (for reference) (kg)	12118
Rated rotational speed (rpm)	1192	Volume (for reference) (m^3)	5,12
Rated efficiency	96,9%	Cooling	IC71W
Protection index	IP54[33]	Maximum rotational speed (rpm)	1200

Regarding to the cost, in Appendix A, Section A.1, an analysis of induction motor prices is performed. The analysis uses pricing information from Siemens, about air-to-water cooled induction motors at 2300V, to give a regression curve for estimating the cost of the induction motor as a function of its rated power. The function, presented in the Eq. A.1, will be applied in this section using as input the rated power registered in Table 3.8. Since the result will give the approximated cost for an induction motor with different characteristics from those required here, the value will give an idea of the possible motor cost for the electric propulsion arrangement. Applying the Eq. A.1 gives:

$$IM_{cost} = -64{,}423\ (2{,}940MW)^3 + 437{,}4(2{,}940MW)^2 - 848{,}21 \times 2{,}940MW + 678{,}57 = US\$328.410 \quad (3.4)$$

Hence, the reference cost for each of the two induction motors at the United States is US$328.410,00; the costs in Brazil might be different.

3.5.1.2 Variable frequency drive for main induction motors

The VFD for the propulsion motor is sized to provide the rated power of the motor at the rated power factor. A VFD is defined by the active power and the output current

[33] According to IEC IP protection code, IP 54 corresponds to an electrical equipment protected against dust and splashing of water. (IEC, 2001).

demanded by the motor. The active power supplied by the VFD is defined by the rated power of the motor increased by its efficiency:

$$VFD_{AP} = \frac{P_m}{\eta_m} = \frac{2940kW}{0.966} = 3043kW \quad (3.5)$$

Where VFD_{AP} is the active power of the VFD, P_m is the motor rated power and η_m is the rated efficiency of the motor.

The current that the VFD must supply will compensate the active and reactive power required by the motor, including the losses; the required rated current of the converter is, therefore:

$$VFD_{RC} = \frac{P_m}{\eta_m \times P.F._m \times V_r \times \sqrt{3}} = \frac{3043kW}{0.87 \times 690V \times \sqrt{3}} = 2926A \quad (3.6)$$

Where VFD_{RC} is the rated current of the VFD, $P.F._m$ is the rated power factor of the motor and V_r is the rated voltage.

Various manufacturers were consulted for VFDs commercial catalogs, as ABB, Siemens, WEG, Schneider Electric, among others. Considering the defined characteristics of the propulsion motor, the Siemens catalog shows commercial options that can be used along with the induction motor (SIEMENS, 2011b). In the catalog, the VFDs offered are divided into modules: the line connection module, the basic line module (AC/DC converter) and the motor module (corresponding to the inverter section) as shown in Figure 3.7.

The motor module is the inverter section, which provides power and varies the frequency for the motor. The highest power rating offered by a motor module unit is 1200kW with a rated current of 1270A; however, it is possible to connect up to 4 motor modules in parallel of the same ratings to supply one motor (SIEMENS, 2011b). From the catalog, the combination of motor modules in parallel to provide at least 3043kW is three units of 1200kW, totalizing 3600kW; the catalog section of the selected motor modules are presented in Annex D. In Table 3.9, the main characteristics of the motor modules are presented.

The basic line module is a 12-pulse, three-phase diode bridge rectifier, which transforms the AC input to DC for the motor module. The power rating of the basic line module will be defined by the maximum power that will be demanded from the motor module increasing the losses. The minimum power rating of the basic line module is:

$$BL_{RP} = \frac{VFD_{AP}}{\eta_{motor\ module}} = \frac{3043kW}{0.985} = 3089{,}3kW \quad (3.7)$$

Where BL_{RP} is the minimum power rating of the basic line module and $\eta_{motor\ module}$ is the efficiency of the motor module.

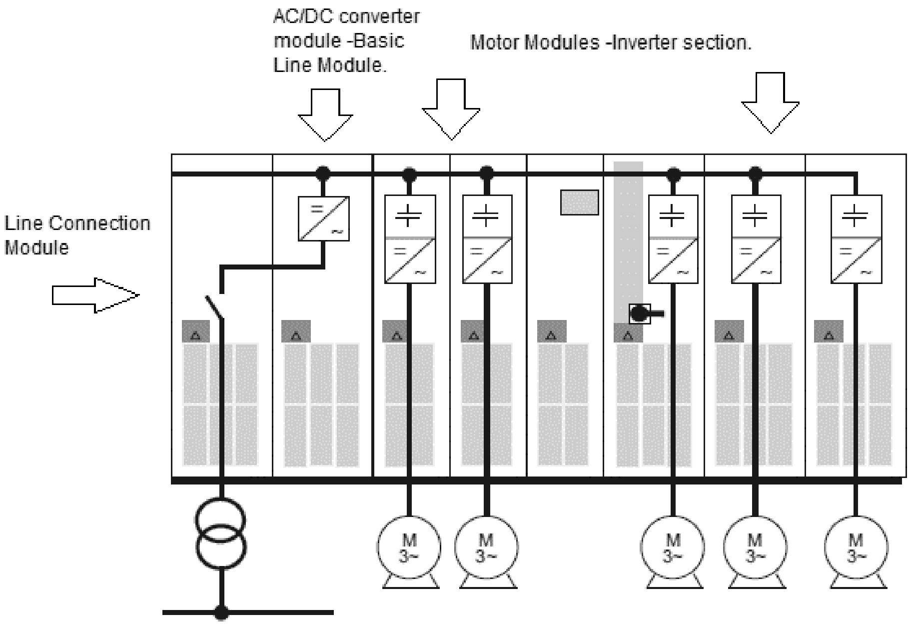

Figure 3.7 – VFD Offered by the Manufacturer Catalog Detailing the Modules in Which is Divided (SIEMENS, 2011b).

Table 3.9 – Specifications of the Motor Module (Inverter Section) of the VFD for the Propulsion Motor.

Parameter	Value	Parameter	Value
Total rated output power (kW)	3600	Approximated Total Mass (kg)	2100
Output frequency range (Hz)	0-600	Approximated volume (m^3)	3,17
Total rated current (A)	3810	Cooling	Water
Rated output voltage (V)	690	Protection Index	IP54[34]
Rated efficiency	0,985		

From the catalog, the maximum rated power of one module is 1500kW, but up to 4 units can be connected in parallel. In order to supply the power obtained in the Eq. 3.7, three units of 1100kW will be connected in parallel, totalizing 3300kW. The main specifications of the basic line modules are presented in Table 3.10.

[34] The standard protection index is IP20; however, the case is available in IP54 under requirement.

Table 3.10 - Specifications of the Basic Line Module (AC/DC Converter Section) of the VFD for the Propulsion Motor.

Parameter	Value	Parameter	Value
Total rated output power (kW)	3300	Approximated Total Mass (kg)	1440
DC output voltage (V)	1035	Approximated volume (m³)	2,38
Total rated output current in DC (A)	4200	Cooling	Water
Rated Input current in AC (A)	3540	Protection Index	IP54
Rated efficiency	0,99	Rated input voltage (V)	690
Pulse operation	12-pulse	Rated input power factor	0,96

The basic line module is required to be connected to the electrical network of the vessel through a line connection module. The line connection module is defined by the input voltage and the input current; the input voltage is 690V while the input current will be defined from the power output of the basic line module (Eq. 3.7), increased by its efficiency and considering its power factor:

$$BL_{RC} = \frac{BL_{RP}}{\sqrt{3} \times P.F_{RP}.\times \eta_{RC} \times V_r} = \frac{3089.3kW}{\sqrt{3} \times 0.96 \times 0.995 \times 690V} = 2706A \quad (3.8)$$

Where BL_{RC} is the rated current of the line connection module, V_r is 690V, $P.F._{RC}$ is the power factor of the basic line module and η_{RC} is the efficiency of the connection module.

From the available units in the catalog, 2 units of 1462A connected in parallel are selected. The two units will receive the input power form a three winding transformer for a 12-pulse operation, each receiving three phase power from one of the secondary windings of the transformer. The main specifications of the line connection modules are presented in Table 3.11.

Table 3.11 - Specifications of the Line Connection Module of the VFD for the Propulsion Motor.

Parameter	Value	Parameter	Value
Rated current (A)	2924	Approximated Total Mass (kg)	720
Rated voltage (V)	690	Approximated volume (m³)	1,32
Rated efficiency	0,9995	Cooling	Air
Protection Index	IP54		

The summarized characteristics of the complete VFD as a single unit are presented in Table 3.12.

Table 3.12 – Summarized Input and Output Specifications of the VFD for the Propulsion Motor.

Parameter	Value	Parameter	Value
Rated input current (A)	2924	Approximated total Mass (kg)	4260
Rated input voltage (V)	690	Approximated total volume (m³)	6,86
Rated output power (kW)	3600	Pulse operation	12-pulse
Rated output current (A)	3810	Protection Index	IP54
Output frequency range (Hz)	0-600	Cooling	Air-Water
Rated output voltage (V)	690	Rated efficiency	0,975
Input power factor	0,96	Ambient temperature	45°

Regarding the cost of the VFD unit, the Eq. A.2 presented in Appendix A, Section A.2, will be taken to obtain a reference value for the VFD. Since the VFDs under study in the abovementioned appendix possess different characteristics than the one defined in Table 3.12, the cost obtained by the equation will give an idea of the price order for similar equipment.

$$VFDcost = 208{,}9(3600kW) - 2185{,}5 = US\$749.854 \quad (3.9)$$

Therefore, the reference cost for each VFD unit in the United States is US$749.854,00; the cost in Brazil could vary.

3.5.1.3 Frequency converter transformer

The transformer for the frequency converter is sized to supply the rated power of the propulsion motor including the losses of the frequency converter. Besides, it must support the power factor of the VFD. The power rating of the three winding transformer was obtained using the result of Eq. 3.5 increasing the VFD losses and the power factor:

$$Trafo_{PR} = \frac{VFD_{AP}}{\eta_{VFD} \times P.F._{VFD}} = \frac{3043kW}{0.975 \times 0.96} = 3251kVA \quad (3.10)$$

Where $Trafo_{PR}$ is the power rating of the transformer, η_{VFD} is the efficiency of the VFD and $P.F._{VFD}$ is the rated power factor of the VFD.

The three winding transformer receives 690V at the primary winding and delivers 690V at the secondaries to supply the 12-pulse rectifier of the abovementioned VFD. As described in the Chapter 2, the required cooling method is the FAFW and the transformer is required to be of the dry type.

Unfortunately, after consulting various manufacturers (Schneider, ABB, Siemens, WEG), a catalog of power converter transformers with the required specifications was not available for consulting the commercial characteristics. However, there is a catalog, which presents the characteristics of transformers for 12-pulse rectifiers with power ratings from 73kVA to 1600kVA at 50/60Hz; the transformers are of the dry type, with protection index IP00 and with normal air-cooling (EMG TRANSFORMERS, 2013).

This catalog can be used to estimate a reference value for the mass, volume and efficiency of the required transformer, although the specifications are different.

In order to perform the abovementioned values, the regression curves of the mass and the volume of the transformers in the catalog were obtained as presented in Appendix B. The regression curves (or trend-lines) give various expressions, which permit the estimation of a reference value for the mass and the volume using the power rating of the transformer as input. The values can provide an idea of the dimensions and the mass of the required transformer taking into account that the cooling method is different. Hence, for purposes of the present dissertation the mass and volume values obtained from the trend-lines are assumed as reference values for the transformer. The catalog is shown in Annex E while the trend-lines for estimation of mass and volume are presented in the Appendix B.

The results give an approximately mass of 6660kg for the transformer while 2,68m^3 for the volume (See Appendix B).

The efficiency of the three winding transformer is estimated using Eq. 2.1 The equation requires the no-load losses and the load losses to obtain the efficiency. Since a catalog for the transformer is not available, the required data for efficiency calculation was taken from the catalog shown in Annex E, assuming that two parallel units of 1600kVA are sufficient to replace one transformer of 3251kVA. The total power rating is 3200kVA, 51kVA lower than the transformer required in the application; therefore, the result is considered as acceptable. The estimated efficiency for the transformer is:

$$\eta = \left(1 - \frac{P_{NL}+P_{LL}}{S \times P.F.}\right) = \left(1 - \frac{9.2kW+36.8kW}{3200kVA \times 0.96.}\right) = 0.985 \quad (3.11)$$

Due to the parallel operation, the no load losses P_{NL}=9.2kW and the load losses P_{LL}=36.8kW are the double of the informed value in the catalog for the 1600kVA transformer. The load power factor is the power factor of the VFD. The efficiency is assumed as constant for all the load range and independent from the harmonic content of the voltage and current.

The main characteristics of the three winding transformer for each VFD as previously estimated are shown in Table 3.13.

Table 3.13 – Estimated Specifications of the Three Winding Transformer for VFD.

Parameter	Value	Parameter	Value
Total rated output power (kVA)	3251	Approximated Total Mass (kg)	6617
Output frequency (Hz)	60	Approximated volume (m³)	2,68
Primary Voltage (V)	690	Cooling	FAFW
Secondaries Voltage (V)	690	Protection Index	IP54
Type	Dry type	Transformer for 12-pulse converter	
Rated efficiency	0,985		

In Appendix A, Section A.3, the cost analysis of dry type distribution transformers for substations was conducted. The transformers present significant differences with the rectifier transformers herein defined; however, in the aforementioned appendix, it was discussed that the cost of two units can give an idea of the cost of one rectifier transformer, since they can operate in parallel as rectifier transformer to supply a VFD. The reference cost for the rectifier transformer is defined by Eq. A.3:

$$Trafo_{cost} = 2\left(9{,}4821 \times \left(\frac{3251kVA}{2}\right) + 12029\right) = US\$54.884 \quad (3.12)$$

Thus, the reference cost for each rectifier transformer in the United States is estimated to be US$27.442,00; the price must be examined for Brazil.

3.5.1.4 Side thrusters for the dynamic positioning system

To maintain the position at sea while is in dynamic positioning mode, the vessel is required to withstand forces and moment due to current, wind, local waves and to swell. The determination of these forces and moments is shown in COPPE/UFRJ, IPT & USP (2013) considering the environmental conditions indicated in Tables 3 and 4 of the cited reference. The recommended configuration is shown in Figure 3.8. It may be noticed that azimuth thrusters make unnecessary any additional stern thrusters and there are two bow thrusters to meet IMO DP class 2.

To provide the required force at the bow, two side thrusters driven by motors of minimum 830kW each are required. The electric motors selected are of the induction type, which is the most suitable option for the application taking into account the power rating discussed in Section 2.5.1. Various manufacturers were consulted and several catalogs are available with commercial alternatives; for instance, WEG offers an induction motor suitable for the characteristics of the PSV. The motor is specially designed for operation as a side thruster motor in dynamic positioning systems with a power rating of 880kW. The main features of the motor are presented in Table 3.14, while the complete datasheet from the manufacturer is shown in Annex F

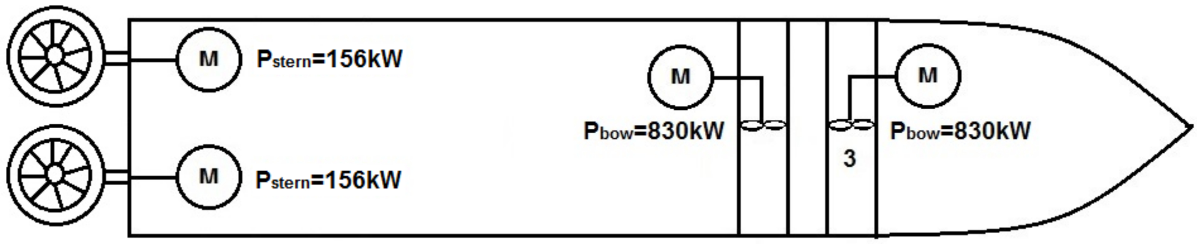

Figure 3.8 – Required Power for Position Keeping at Dynamic Positioning.

Table 3.14 – Main Specifications of the Induction Motors for the Bow Thrusters.

Parameter	Value	Parameter	Value
Rated power (kW)	880	Cooling	IC71W
Rated frequency (Hz)	60	Protection Index	IP55
Rated voltage (V)	690	Approximated Total Mass (kg)	6533
Rated rotational speed (rpm)	1195	Approximated volume (m³)	2,57
Pole number	6	Rated efficiency	0,965
Power factor	0,83		

Using the same analysis made for the main propulsion motor, the reference cost for the induction motor for dynamic positioning is defined by the Eq. A.1:

$$IM_{cost} = -64{,}423\ (0{,}88MW)^3 + 437{,}4(0{,}88MW)^2 - 848{,}21 \times 0{,}88MW + 678{,}57 = US\$226.965 \quad (3.13)$$

The cost is a reference for the United States, for Brazil it could be different.

In order to define an approximated value for bow thruster mass, several catalogs of various manufacturers of side thrusters were consulted (Voith, Wartsila, Schottel, ZF, Scana, Brunvoll, Rolls Royce). From the catalogs, the most suitable diameter for a propeller to withstand a power input of 830kW at a rotational speed close to 1200rpm is 1.75m for the Wartsila CTF175M (WARTSILA, 2014), 1.99m for the Schottel STT 4 (SCHOTTEL, 2014b) or 1.85m for the Rolls Royce TTFP 2000 (ROLLS ROYCE, 2012). The mass is 5900kg for the CTF175M and the TTFP 2000, while for the STT 4 is 9400kg.

Since the accurate details of the bow thrusters are not defined already for the conceptual design, the mass of each bow thruster will be assumed as 5900kg for purposes of mass comparison.

The required power and current rating of the VFD for the bow thruster motor is obtained from the rated power of the motor increased by the efficiency and the power factor:

$$VFD_{AP} = \frac{P_m}{\eta_m} = \frac{880kW}{0.965} = 911kW \tag{3.14}$$

$$VFD_{RC} = \frac{P_m}{\eta_m \times P.F._m \times V_m \times \sqrt{3}} = \frac{911kW}{\sqrt{3} \times 690V \times 0.83} = 918{,}4A \tag{3.15}$$

WEG offers a VFD suitable for usage with its induction motor. The VFD includes a passive filter for high harmonic distortion and high reliability as it can be seen in Annex I. The VFD is also divided in modules, as the VFD for the main propulsion motor; however, the unit will be analyzed as a single equipment. The main features of the VFD are shown in Table 3.15.

Table 3.15 – Summarized Specifications of the VFD for the Side Thrusters.

Parameter	**Value**	**Parameter**	**Value**
Rated input current (A)	770	Approximated total Mass (kg)	2800
Rated input voltage (V)	690	Approximated total volume (m³)	4,48
Rated output power (kW)	1000	Pulse operation	6-pulse
Rated output current (A)	920	Protection Index	IP44
Output frequency range (Hz)	0-600	Cooling	Water
Rated output voltage (V)	690	Rated efficiency	0,998
Input power factor	0,96		

In the manufacturer datasheet the currents, input power factor, rated efficiency and pulse operation are not clearly defined. The rated output current was obtained from Eq. 3.15 and supposing that the VFD is designed for exclusive use along with the motor. The efficiency of the drive was obtained from the power losses (1,5kW); the input current was obtained from the active power of the VFD divided by its efficiency and by its voltage. The rated power factor is neither informed nor indicated in the datasheet; therefore, it is considered the same as the power factor for similar VFDs. The pulse operation is not clearly indicated in the datasheet, but since the VFD operates with a passive filter, which can be bypassed when required, this allows the VFD to operate directly from the network; hence, it is supposed that the VFD is 6-pulse operation.

Regarding the cost, Eq. A.2 can give a reference value for the VFD as previously discussed:

$$VFDcost = 208{,}9 \times 1000kW - 2185{,}5 = US\$206.714 \quad (3.16)$$

With the cost referenced to the United States, for Brazil it could require some verification.

3.5.1.5 Auxiliary and hotel loads

A PSV continuously requires energy to supply the hotel loads (accommodations for the crew and the passengers) and the auxiliary loads (pumps, compressor, navigation equipment, security equipment, etc.). The auxiliary and hotel loads must be defined in order to determine the power demand that the Diesel generator sets will supply and to size the main switchboards. Unfortunately, the complete list of auxiliary and hotel loads for an electrically propelled PSV with 4500DWT is not available; however, Arcoverde (2013) presents a detailed electrical load balance for a typical mechanically propelled PSV which will be taken as a reference for calculation purposes. In order to be in accordance with an electrically propelled PSV, the load balance was modified, suppressing the elements related to the mechanical propulsion system and changing the power ratings of the thrusters for the dynamic positioning system. The electrical load balance used in this dissertation is presented in Annex G; the total auxiliary and hotel loads for each type of operation are presented in the Table 3.16; the apparent power required by the loads was obtained supposing a power factor of 0.85 lagging.

Table 3.16 – Auxiliary and Hotel Loads for an Electrically Propelled PSV.

Transit-Normal	Transit-Essential	Dynamic Positioning	Port/Stand by
1046,9kW	684kW	1261,9kW	725,2kW
1232kVA	804kVA	1484,6kVA	853,2kVA

3.5.1.6 Electrical demands

The electrical demands for each type of operation will be defined to size the main switchboards and the Diesel generator sets. Taking into account the auxiliary and the propulsion loads, the expected electrical demand of the vessel for each type of operation is presented in Table 3.17. The propulsion loads were obtained including the efficiencies of each element and the power factor at the input of the VFDs. Besides, they include the power margin and the losses of the components. For DP operation, the power requirement from the propulsion unit was obtained considering that the two bow thrusters are operating at the same time at rated power, while two azimuth thrusters are providing thrust, each one at the required power as indicated in Figure 3.8. The electrical demands in the table are supposed as measured at the output of the switchboard, it is, include the losses of the equipment and power factor.

Table 3.17 – Total Electrical Loads for Each Type of Operation.

	Laden Voyage	Partially loaded trip	Dynamic Positioning	Port/Stand By
Propulsion	6557kVA@F.P. =0,96	5277kVA@F.P. =0,96	2230,6kVA @F.P. =0,96	-----
Auxiliary	1232kVA@F.P. =0,85	1232kVA@F.P. =0,85	1484,6kVA @F.P. =0,85	853, 2kVA@F.P. =0,85
Total	7751kVA@F.P. =0,95	5494kVA@F.P. =0,945	3781,9kVA @F.P. =0,92	853kVA@F.P. =0,85

For calculation purposes, the power factor of the propulsion loads were considered as inductive, disregarding the effects produced by the harmonic components in the current from the VFD.

The maximum demand is, therefore, the corresponding to laden voyage, 7751kVA at power factor of 0.95

3.5.1.7 Main switchboards

The main switchboard must be sized following the recommendations of the classification societies for OSVs with class 2 dynamic positioning system (ABS, 2013 p. 250, 483). The classification societies require that where the main source of electrical power is necessary for propulsion of the vessel, the main bus bar is to be subdivided into at least two parts, which are normally to be connected by circuit breakers or other approved means. Besides, they require that, so far as it is practicable, the connection of generator sets and other duplicated equipment is to be equally divided between parts. The above implies that the main switchboard (which includes one bus bar) must be divided; for purposes of the present application it will be separated into two sections, each one containing the duplicated equipment (main propulsion loads, dynamic positioning loads and the generator sets). The auxiliary loads will also be divided into two sections, disregarding the redundancy required for the essential services. Using the maximum load request and considering that the rated voltage of the system is 690V, the rated current of each switchboard is:

$$Switchboard_{RC} = \frac{Total\ electrical\ demand}{2\times\sqrt{3}\times V_{rated}} = \frac{7751kVA}{2\times\sqrt{3}\times 690V} = 3242A \quad (3.17)$$

From a catalog (ABB, 2012b), the switchboard with the closest current rating is 4000A, which will be selected for the application.

The mass and dimensions of the switchboard depend not only on the external case and the internal busbars, but also on the number of circuits and the circuit breakers used. Since these details are out of scope in this dissertation, representative dimensions of a switchboard will be taken from a catalog (ABB, 2012b) for the rated current specified; the catalog does not provide mass estimations; however, from previous experiences of the author, the mass of each switchboard will be assumed as 700kg, including busbars, meter equipment, and circuit breakers. The efficiency will be considered as 99.5% for all the load range.

The characteristics of each switchboard are presented in Table 3.18.

Table 3.18 – Main Switchboard Specifications.

Rated current (A)	Rated voltage (V)	Estimated mass (kg)	Width (m)	Height (m)	Depth (m)	Efficiency
4000	690	700	2,4	2,2	1,6	0,995

So as to define an accurate cost for each of the main switchboards, a detailed design is required indicating the circuits, type of construction, breakers, meters, etc. Nonetheless, since the detailed design is not available, an estimated cost for each main switchboard will be settled from previous experiences of the author in switchboard design and installation. An approximated value for each switchboard including high power breakers, meters, distribution circuits, bus bars and for a high resistance material can be set as US$32.000,00.

3.5.1.8 Diesel generator sets

The final element for sizing is the Diesel generator set. The definition of the number and the power rating of the units is made taking into account that the propulsion system of the PSV follows the concept of integrated electric propulsion. The number of units is an important detail, since it determines the power rating of each unit and the redundancy of the system. According to the specifications for offshore support vessels with class 2 dynamic positioning systems, each section of the main switchboard is required to have the same generator set units. It was seen in Section 3.2.1 that the similar PSVs, with high deadweight capacity, are equipped with 4 generator set units; thus, using this data as a guide, the number of generator sets for the electric propulsion arrangements defined in this dissertation is established as four, each one with the same power rating.

The maximum power demand is expected when the vessel is in laden voyage. It is increased by the losses in the switchboard and divided by the number of Diesel generator sets to obtain the minimum rated power for each unit:

$$G_{PRkVA} = \frac{Maximum\ power\ demand}{\eta_{switchboard} \times 4} = \frac{7751kVA}{0.995 \times 4} = 1947.48kVA \quad (3.18)$$

Where G_{PRkVA} is the power rating of the generator sets in kVA.

Since the total power factor $(P.F._{load})$ is 0.95 (See Table 3.17), the power rating in kW is:

$$G_{PRkW} = G_{PRkVA} \times P.F._{load} = 1947.48kVA \times 0.95 = 1850.11kW \quad (3.19)$$

Therefore, each of the four Diesel generator sets is required to have a rated power at least of 1850kW and 1947kVA at 690V.

As mentioned before, the Diesel generator sets considered for sizing are of the high and medium speed type. The sizing of the Diesel gensets must follow the recommendations settled by the classification societies presented in Section 3.4.2.

- High speed Diesel generator sets

The high speed Diesel generator set was selected after a comparison between three units with similar power ratings and same rotational speeds, but made by different manufacturers. The selection criteria included the mass of the equipment, the specific fuel oil consumption, the NOx emissions and its closeness to the power rating required. It should be noticed that, since the electrical load of the vessel is expected to vary in time, the high speed Diesel genset must be of the prime rating type, as defined in Chapter 2.

The characteristics of the three units evaluated are presented in the table below.

Table 3.19 – Three High Speed Diesel Gensets Evaluated for Arrangement 1.

Manufacturer	Cummins	Caterpillar	MTU
Model	DQLC	3516C-HD	2045-XC6DT2
Power rating (kW)	2275	2250	2045
Rotational speed (rpm)	1800	1800	1800
SFOC (g/kWh)	195,04	208,54	202
Mass (kg)	21408	21214	16994
NOx emissions (g/kWh)	9,38	0,61	7,29

Among them, the most reasonable choice was the MTU genset, because its power is close to what is required (1850kW) and it also presents the lowest mass. Besides, it meets the MARPOL 73/78 Annex VI for Tier II conditions regarding to NOx emissions. Its main characteristics are shown in Table 3.20.

Table 3.20 – Main Characteristics of the High Speed Diesel Generator Set for Arrangement 1.

Rating Type	**Prime rating**
Fuel System	MGO
Engine rated power (kW)	2280
Generator rated output (kVA)	2556
Cooling	Cooling water system with heat exchanger
SFOC (g/kWh) for 50% rated load*	209
SFOC (g/kWh) for 75% rated load*	200
SFOC (g/kWh) for 100% rated load*	202
Rated efficiency @ P.F.=0,9	96,75%
Output Voltage (V)	690,0
Unit Volume (m^3)	45,39

The evaluation of the conditions settled by the classification societies is required.

The first, second and fourth conditions are evaluated within the same analysis. These condition establishes that with a generator set out of service, the remaining ones must supply all the normal loads of the vessel and guarantee a transit speed of 7knots or one half of the design speed, the lowest one; nonetheless, to show that a higher speed can be achieved, for the present case the speed is supposed as 14knots. The power balance is shown in the left column of Figure 3.9; it can be seen that even with one generator set out of service, the vessel can supply the normal auxiliary/hotel loads and transit at 14knots, still remaining more than 850kW of available power. Therefore, it can be deduced that the conditions 1, 2 and 4 are fulfilled.

The third condition indicates that, if one of the main switchboards stops working, the remaining generator sets and distribution systems must provide the sufficient power to supply the essential loads and to maintain the position of the vessel within the design specifications. Therefore, if one switchboard is out of service, two of the generator sets, one bow thruster and one azimuth thruster, will also be lost. In this case, the essential loads in DP mode, both the remaining bow and azimuth thruster, must be fed to maintain the position. The electric motor of the remaining bow thruster is supposed to provide the maximum required power *i.e.* 830kW, whereas the electric motor of the remaining azimuth thruster is supposed to supply 156kW. The total power for thrusting is consequently 986kW, which increased by the losses of the equipment gives 1118,7kW at the output of the generator sets. The auxiliary loads are considered as the normal ones for dynamic positioning, 1261.9kW. The power balance for the third condition is presented in the right column of Figure 3.9. It can be seen that, even in the mentioned conditions, a power margin of more than 1600kW is still available. Therefore, the third condition is fulfilled as well.

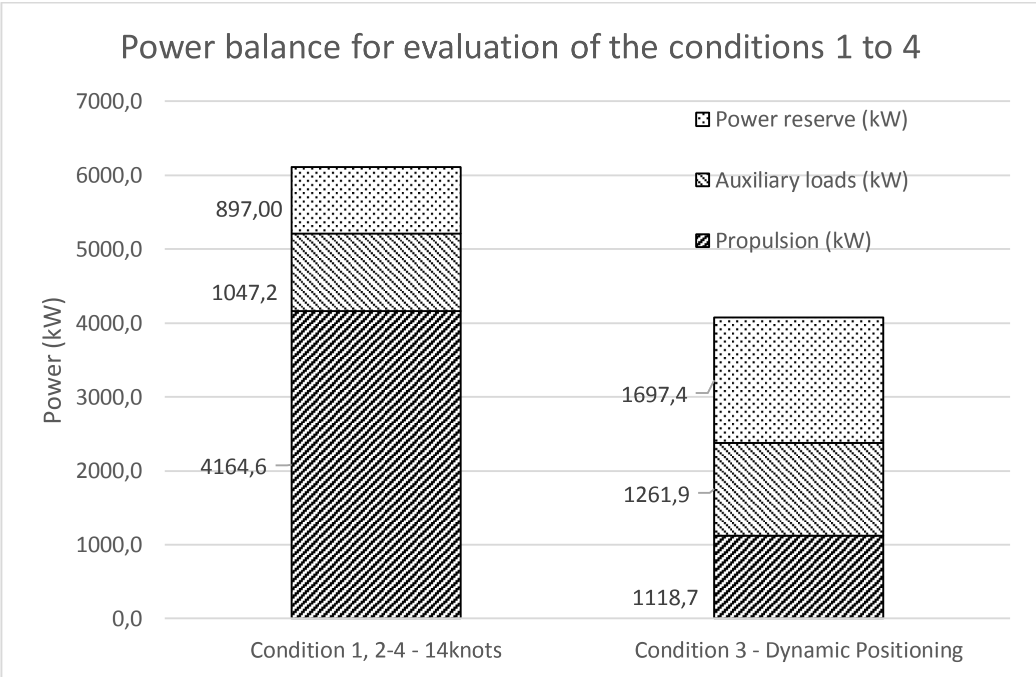

Figure 3.9 – Power Balance for Evaluation of Conditions 1 to 4 for the high speed gensets.

In conclusion, the high-speed Diesel generator sets selected are suitable to supply the electric demand required by the vessel.

Regarding the cost of the high-speed Diesel generator sets, in Appendix A Section A.4 a cost analysis of several high-speed Diesel generator sets was made resulting in a regression function, which allows to estimate an approximate price for the high-speed Diesel generator set selected here. Since the generator sets, object of this study, are fan cooled, the cost obtained from the regression function (Eq. A.4) gives a reference price for each generator set unit. Substituting the power rating in Eq. A.4:

$$hsgenset_{cost} = 295{,}67 \times 2045kW - 57785 = US\$546.860 \quad (3.20)$$

Hence, the reference cost of each high-speed Diesel generator set for the United States is estimated at US$546.860. The cost for Brazil could require some verification.

- Medium speed Diesel generator sets

The medium speed Diesel generator sets are commercially available mostly at rotational speeds of 720 and 900rpm for 60Hz power production. Since the mass of the synchronous generator significantly increases with the reduction of the rotational speed for the same power rating, it is desirable to select the highest rotational speed; therefore, the selected units for the electric propulsion system have a rotational speed of 900rpm.

Three different Diesel generator sets from different manufacturers, *i.e.* MAN, Wartsila and Rolls Royce, are evaluated as shown in Table 3.21 the selection criteria is the same as for the high speed Diesel genset.

Table 3.21 – Three Medium Speed Diesel Gensets Evaluated for Arrangement 1.

Manufacturer	MAN Diesel & Turbo	Wartsila	Rolls Royce
Model	9L21/31	2100W8L26	C25:33L8A
Power rating (kW)	1915	2100	2457
Rotational speed (rpm)	900	900	900
SFOC (g/kWh)	189	188	182
Mass (kg)	36500	39200	40000
NOx emissions (g/kWh)	9	9	Not informed

Between the alternatives, a suitable choice is the MAN genset, because it presents the lowest mass and the closest power rating to that required (1850kW). Furthermore, it meets the MARPOL 73/78 Annex VI for Tier II conditions. The main features of the Diesel generator set are presented in Table 3.22.

Table 3.22 - Main Characteristics of the Medium Speed Diesel Generator Set for Arrangement 1.

Fuel System	MGO, MDO or HFO
Engine rated power (kW)	1980
Generator rated output (kVA)	2394
Cooling	Cooling water system
SFOC (g/kWh) for 25% rated load	207,0
SFOC (g/kWh) for 50% rated load	193,0
SFOC (g/kWh) for 75% rated load	189,0
SFOC (g/kWh) for 85% rated load	189,0
SFOC (g/kWh) for 100% rated load	192,0
Alternator power rating (kVA)	1915
Rated efficiency @ P.F.=0,9	96,75%
Output Voltage (V)	690,0
Unit Volume (m3)	37,1

In Figure 3.10, the power balance obtained to assess of the conditions settled by the classification societies is shown.

The condition 1, 2 and 4 is evaluated considering the same assumptions as before, the vessel is in load voyage at 14knots and the power request by the auxiliary/hotel loads is 1047kW. The power balance presented in Figure 3.10, left column indicates that there is more than 500kW of power reserve, hence, the generator sets meet with the conditions 1, 2 and 4.

Regarding to the condition 3, it is evaluated under the same assumptions as described before. The power balance shown in Figure 3.10, right column points out that more than 1400kW are available as power reserve when a bus bar is lost and the vessel is in dynamic positioning mode. Therefore, the condition 3 is fulfilled.

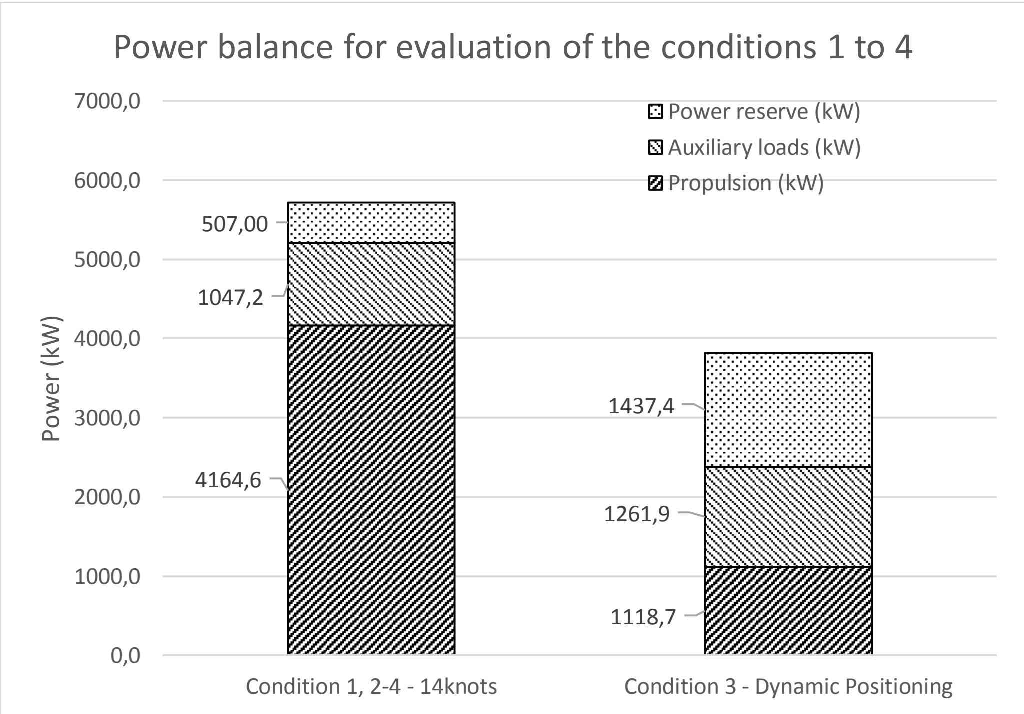

Figure 3.10 - Power Balance for Evaluation of Conditions 1 to 4 for the medium speed gensets.

Dedes, Hudson and Turnock (2012) estimate a typical cost factor for medium speed Diesel generator sets at 350$/kW; hence, the estimated cost of each medium speed Diesel genset is:

$$msgenset_{cost} = \frac{350\$}{kW} \times 1915kW = US\$670.250 \quad (3.21)$$

The cost is a reference for the United States.

The complete schematic of the arrangement 1, with details of the components, is shown in the Figure 3.11.

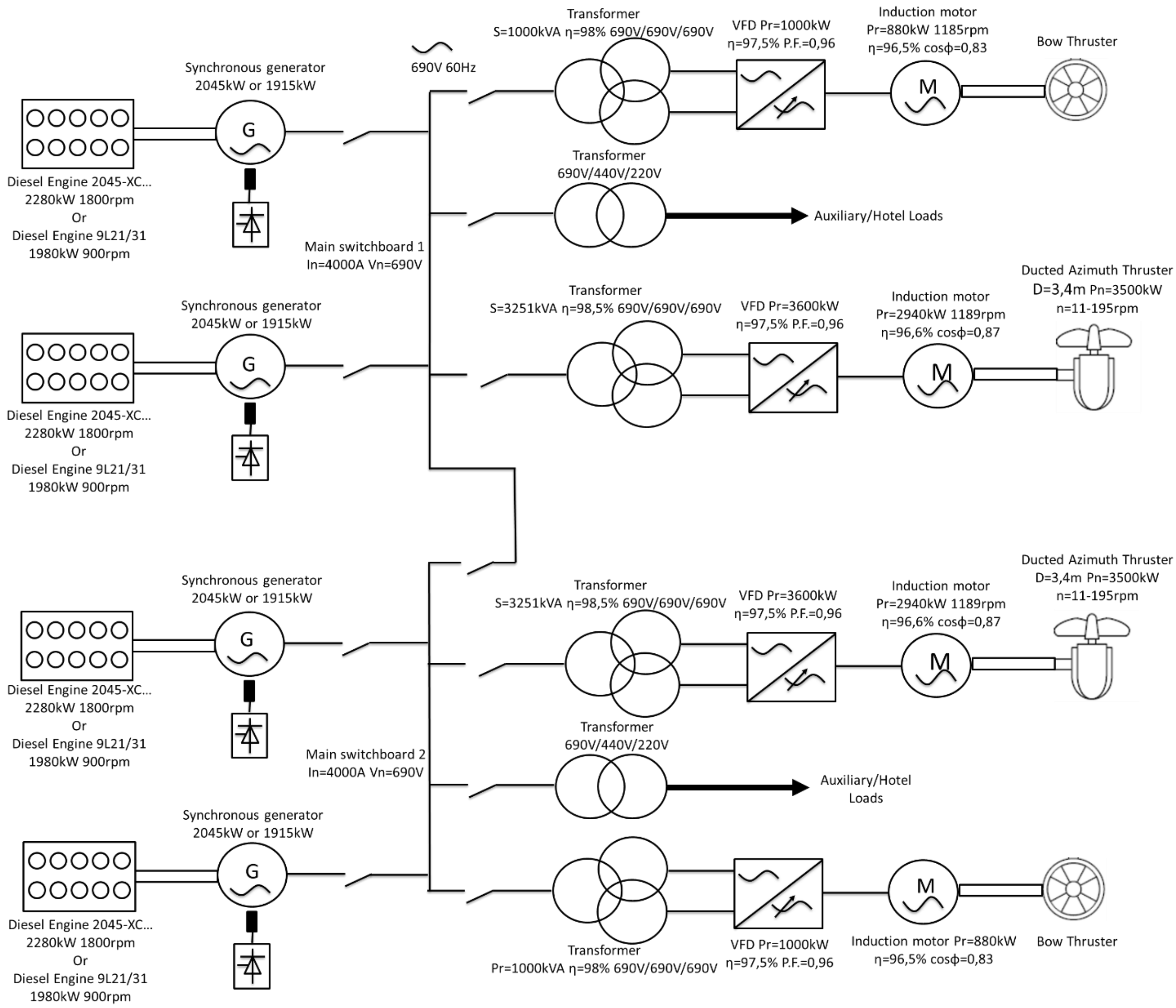

Figure 3.11 – Complete Schematic of Arrangement 1.

- Alternator for high and medium speed Diesel generator sets

The efficiency of the generator varies as a function of the load power factor and the power demand required, as it was discussed in Chapter 2. The efficiency curves of the alternators for high and medium speed generator set types will be assumed the same as the one presented in Figure 2.6. Since the load is expected to have a global power factor between 0.85 and 0.95 (see Table 3.17), the power factor will vary around 0.9; hence, the alternator efficiency curve for a power factor equal to 0.9 will be selected as the reference curve. The efficiency as a function of the load for a power factor of

0.9 is presented in Table 3.23. The data was obtained from the curve in Figure 2.6 for a power factor of 0.9.

Table 3.23 – Generator Efficiencies as a Function of the Load for a Power Factor of 0.9.

Load	**0,25**	**0,3**	**0,4**	**0,5**	**0,6**	**0,7**	**0,8**	**0,9**	**1**	**1,1**
Efficiency	95,4%	95,9%	96,55%	96,85%	96,9%	96,95%	96,9%	96,8%	96,75%	96,6%

3.5.1.9 Estimated mass, volume and reference cost

For arrangement 1, the total mass is estimated in hundreds of kg and takes into account the individual contributions of each component in Figure 3.11 (excluding the mass of the auxiliary loads and their transformers, since they are unknown). During the estimation of the volume and capital costs, the main azimuth thrusters and the side thrusters were not considered. Regarding the volume, since the propulsion units are not within the hull of the vessel, they do not account for the volume of the installation. About the cost of the units, this last was not considered because there was no information available corresponding to the cost of the propulsion units.

In Table 3.24, the mass, occupied volume and reference capital costs for the arrangement 1 are presented for both, high and medium speed Diesel generator sets.

Table 3.24 – Estimated Mass, Volume and Reference Capital Costs for Arrangement 1.

	Mass (thousands of kg)	**Volume (m3)**	**Reference Capital Cost (US$)**
Azimuth thrusters	53,0	----	----
Main induction motors	24,2	10,2	$ 656.820
VFDs for main induction motor	8,5	13,7	$ 1.499.708
VFD transformers	13,2	5,4	$ 109.768
Side thrusters	11,8	----	----
Side thruster induction motors	13,1	5,1	$ 453.930,00
VFDs for side thruster motor	5,6	9,0	$ 413.428,00
Main switchboards	1,4	4,8	$ 62.984,00
High speed Diesel generator sets	68,0	181,6	$ 2.187.440,00
Medium speed Diesel generator sets	146,0	148,4	$ 2.681.000,00
Total for high speed genset	**198,8**	**229,8**	**$ 5.384.078,00**
Total for medium speed genset	**276,9**	**196,6**	**$ 5.877.638,00**

3.5.2 Arrangement 2 definition

In arrangement 2, described in the Section 3.1.3, the synchronous motor is the main propulsion motor instead of the induction one.

As discussed in Chapter 2, in electric propulsion applications, the synchronous motor is restricted for vessels that require high power demands for propulsion at high torque. However, regarding the recommendations of the manufacturer shown in Figure 2.11 and taking into account that the maximum power demand expected for propulsion is 5858kW (2929kW for each propulsion unit) at 1200rpm (6poles), the synchronous motor is a valid option for propulsion which deserves to be evaluated.

The sizing process follows the same procedure as in arrangement 1 and uses some parameters already calculated in the previous sizing process.

3.5.2.1 Synchronous motor

The synchronous motors are normally manufactured under request for specific applications; therefore, commercial catalogs of this type of equipment are not available for consulting. However, taking into account the information about the synchronous motors in Section 1.1.1 and the general specifications of the AC machines, it is possible to estimate the main parameters of the motor. Moreover, since a synchronous motor is exactly equal to a synchronous generator (CHAPMAN, 2005), some characteristics of the synchronous generators, available in the catalogs, can be assumed as the same for a similar synchronous motor.

Using the main characteristics of the propulsion motor of arrangement 1 as a guide, it is assumed that a manufacturer can produce a synchronous motor meeting the following specifications:

- The power rating of the motor is considered the same as the induction motor one in arrangement 1, 2940kW.
- The rated power factor is considered as unitary.
- The rated voltage is 690V, 60Hz, three-phase.
- The rated rotational speed is 1200rpm.
- The motor is required to be totally enclosed, with protection index IP54.
- The available cooling method offered by the manufacturers for synchronous motors is the air-to-water heat exchanger, IC81W (ABB, 2005). This cooling process is selected as the cooling method for the synchronous motor.
- Since synchronous motors and generators have the same characteristics, the rated efficiency is taken as 97.2%, as shown in Figure 2.7 for a power factor equal to 1 and for rated load.

- Taking into account that the mass of a synchronous motor is nearly equal to the mass of a similar induction motor, as discussed in Table 2.6, the mass of the synchronous motor is supposed as approximately equal to the mass of an induction motor with 2940kW, IC81W cooling and with 6 poles. The mass of an induction motor with the abovementioned characteristics is 10300kg as informed in the dimensional drawings in Annex B.

Table 3.25 summarizes the main specifications of the synchronous motors for propulsion.

Table 3.25 – Main Specifications of the Synchronous Motor for Main Propulsion.

Parameter	Value	Parameter	Value
Rated Power (kW)	2940	Rated power factor	1
Rated Voltage (V)	690	Rated torque (kN.m)	23,61
Rated Frequency (Hz)	60	Mass (kg)	6850
Rated rotational speed (rpm)	1200	Volume (m^3)	8,1
Rated efficiency	97,2%	Cooling	IC81W
Protection index	IP54	Maximum rotational speed (rpm)	1200

Considering that the cost of a synchronous motor is 25% higher than the cost of a similar induction motor as indicated in Table 2.6, thus, the reference cost estimated for the main propulsion motor in the arrangement 1 (Eq. 3.4) is increased 25% and taken as the reference cost for the main synchronous motor.

$$SM_{cost} = US\$328.410 \times 1.25 = US\$410.512 \quad (3.22)$$

The reference cost for the synchronous motor in the United States is US$410.512,00. For Brazil the cost could be different.

3.5.2.2 Variable frequency drive

As done for arrangement 1, the variable frequency drive is sized for the rated power of the synchronous motor.

$$VFD_{AP} = \frac{P_m}{\eta_m} = \frac{2940kW}{0.972} = 3024kW \quad (3.23)$$

Since the synchronous motor does not require reactive power, the VFD will supply the current for the active power. The minimum rated current for the VFD is:

$$VFD_{RC} = \frac{P_m}{\eta_m \times P.F._m \times V_m \times \sqrt{3}} = \frac{3024kW}{1 \times 690V \times \sqrt{3}} = 2530A \quad (3.24)$$

The VFD, which meets the requirement of power and current, is the same as the one of arrangement 1; therefore, all the specifications and characteristics presented in Table 3.9 to Table 3.12 are the same. The estimated cost is the same as the one of the main VFD for arrangement 1, U$749.854.

3.5.2.3 Frequency converter transformer

Following the same procedure of the arrangement 1, the power rating of the frequency converter transformer for the arrangement 2 is defined by the following equation.

$$Trafo_{PR} = \frac{VFD_{AP}}{\eta_{VFD} \times P.F._{VFD}} = \frac{3024kW}{0.975 \times 0.96} = 3230kVA \tag{3.25}$$

The required power rating of the transformer is 3230kVA. The conditions of the transformer described in the arrangement 1 are assumed as the same for the present arrangement. Therefore, the mass and volume of the transformer are estimated using the regression curves in the Appendix B, resulting in 6617kg of mass and 2,68m^3 of volume. The efficiency is taken as the same one calculated in Eq. 3.11. The main parameters of the transformer are shown in Table 3.26.

Table 3.26 - Estimated Specifications of the Three Winding Transformer for the VFD.

Parameter	Value	Parameter	Value
Total rated output power (kVA)	3230	Approximated Total Mass (kg)	6617
Output frequency (Hz)	60	Approximated volume (m^3)	2,68
Primary Voltage (V)	690	Cooling	FAFW
Secondaries Voltage (V)	690	Protection Index	IP54
Type	Dry type	Transformer for 12-pulse converter	
Rated efficiency	0,985		

The reference cost for the transformer is obtained using the Eq. A.3:

$$Trafo_{cost} = 2\left(9{,}4821 \times \left(\frac{3230kVA}{2}\right) + 12029\right) = US\$54.685 \tag{3.26}$$

The cost is a reference for the United States.

3.5.2.4 Dynamic positioning and auxiliary loads

The specifications of the side thrusters, motors and VFDs for the dynamic positioning system remain the same as the ones presented in Section 3.5.1.4. The auxiliary loads for each type of operation also remains the same as informed in Section 3.5.1.5.

3.5.2.5 *Electrical demands*

The electrical demands are presented in Table 3.27. The auxiliary and propulsion loads for DP remain exactly identical as the ones presented in Table 3.17. The propulsion loads were obtained including the losses of each component. In the case of laden and partial load trip, the propulsion load includes also the power margin. The power factor of the VFD is considered inductive disregarding the effects of the harmonic components.

Table 3.27 - Total Electrical Loads for Each Type of Operation.

	Laden Voyage	Partial load voyage	Dynamic Positioning	Port/Stand By
Propulsion	6537kVA@F.P. =0,96	5262kVA@F.P. =0,96	2230,6kVA @F.P. =0,96	-----
Auxiliary	1232kVA@F.P. =0,85	1232kVA@F.P. =0,85	1484,6kVA @F.P. =0,85	853, 2kVA@F.P. =0,85
Total	7732kVA@F.P. =0,95	6457kVA@F.P. =0,94	3781,9kVA @F.P. =0,926	853kVA@F.P. =0,85

It can be noticed that the total electrical demands for laden and ballast voyage are lower than the electrical demands of arrangement 1.

3.5.2.6 *Main switchboards*

The main switchboards are sized considering the same specifications described in Section 3.2.4. The rated current required for the switchboard is:

$$Switchboard_{RC} = \frac{Total\ electrical\ demand}{2\times\sqrt{3}\times V_{rated}} = \frac{7732kVA}{2\times\sqrt{3}\times 690V} = 3234A \quad (3.27)$$

From the ABB catalog (ABB, 2012b) the commercial unit with the closest current rating is 4000A, the same of the arrangement 1. Thus, the parameters of the main switchboard are the shown in Table 3.18. The cost of the main switchboard is the same one of arrangement 1.

3.5.2.7 *Diesel generator sets*

The number of Diesel generating units will be also taken as four. The maximum power demand is expected when the vessel is in laden voyage; this load demand is increased by the losses in the switchboard and divided by the number of Diesel generator sets units to obtain the minimum rated power for each unit:

$$G_{PRkVA} = \frac{Maximum\ power\ demand}{\eta_{switchboard}\times 4} = \frac{7732kVA}{0.995\times 4} = 1942.7kVA \quad (3.28)$$

Since the total power factor was 0.95 (See Table 3.27), the power rating in kW is:

$$G_{PRkW} = G_{PRkVA} \times P.F._{load} = 1942.7kVA \times 0.94 = 1845.5kW \quad (3.29)$$

Therefore, each of the four Diesel generator sets are required to have a rated power at least of 1846kW and 1943kVA at 690V. It can be noticed that, as a consequence of the higher efficiency of the synchronous motor, the required power for the generator sets is slightly lower than it is for arrangement 1.

High and medium speed Diesel generator sets will also be selected for arrangement 2 following the conditions established by the classification societies.

- High speed Diesel generator sets

In Table 3.28, the main characteristics of the three units considered are presented below.

Table 3.28 - Three High Speed Diesel Gensets Evaluated for Arrangement 2

Manufacturer	Cummins	Caterpillar	MTU
Model	DQLC	3516C-HD	2045-XC6DT2
Power rating (kW)	2275	2250	2045
Rotational speed (rpm)	1800	1800	1800
SFOC (g/kWh)	195,04	208,54	202
Mass (kg)	21408	21214	16994
NOx emissions (g/kWh)	9,38	0,61	7,29

Again, the MTU genset is a reasonable selection considering its low mass, power rating and because it meets the limits settled in MARPOL 73/78 Annex VI Tier II. Since the MTU genset is the same generator set of arrangement 1, the main parameters are already presented in Table 3.20.

Using the results of the evaluation of the conditions performed in the arrangement 1 and, considering that the electrical demands of the arrangement 2 are slightly lower than the ones of in the arrangement 1, it can be deduced that the 4 MTU generator sets meets with the classification societies conditions. Therefore the Diesel generator sets are selected.

Since the high-speed Diesel generator sets are the same of the arrangement 1, the costs are the same as informed in Eq. 3.20.

- Medium speed Diesel generator sets

The three generator set units for evaluation are presented in .

Comparing the characteristics of the three generator sets, the most suitable option is, again, the MAN genset, since it has the lowest mass and the closest power rating to the one required (1846kW). Moreover, it meets the restrictions related to the NOx emissions settled by MARPOL 73/78 Annex VI, tier II. Its main characteristics were already presented in Table 3.22.

Table 3.29 - Three Medium Speed Diesel Gensets Evaluated for Arrangement 2

Manufacturer	MAN Diesel & Turbo	Wartsila	Rolls Royce
Model	9L21/31	2100W8L26	C25:33L8A
Power rating (kW)	1915	2100	2457
Rotational speed (rpm)	900	900	900
SFOC (g/kWh)	189	188	182
Mass (kg)	36500	39200	40000
NOx emissions (g/kWh)	9	9	Not informed

Considering that the power request for propulsion in the arrangement 2 is lower than the arrangement 1, and taking into account that the conditions assessment for the medium speed Diesel gensets in arrangement 1 have approved the selection of the MAN 9L21/31 gensets. Thus, the MAN 9L21/31 gensets selected for the arrangement 2 are also supposed to meet with the conditions, for this reason the evaluation will not be made.

The cost of the medium speed Diesel generator sets are obtained using the factor of 350$/kW as suggested by Dedes, Hudson and Turnock (2012):

$$msgenset_{cost} = \frac{350\$}{kW} \times 1800kW = US\$630.000 \quad (3.30)$$

- Alternator of both Diesel generator sets

The efficiency of the generator as a function of the load is supposed the same as the values presented in Table 3.23.

3.5.2.8 Estimated mass, volume and reference cost

The estimated mass, occupied volume and reference capital costs are shown.in Table 3.30.

The complete schematic of the arrangement is shown in Figure 3.12.

Table 3.30 - Estimated Mass, Volume and Reference Capital Costs for Arrangement 2.

	Mass (thousands of kg)	Volume (m3)	Reference Capital Cost (US$)
Azimuth thrusters	53,0	----	----
Main synchronous motors	13,7	16,2	$ 821.024
VFDs for main synchronous motor	8,5	13,7	$ 1.499.708
VFD transformers	13,2	5,4	$ 109.370
Side thrusters	11,8	----	----
Side thruster induction motors	13,1	5,1	$ 453.930,00
VFDs for side thruster motor	5,6	9,0	$ 413.428,00
Main switchboards	1,4	4,8	$ 62.984,00
High speed Diesel generator sets	68,0	181,6	$ 2.187.440,00
Medium speed Diesel generator sets	146,0	148,4	$ 2.681.000,00
Total for high speed genset	**188,3**	**235,7**	**$ 5.547.884,00**
Total for medium speed genset	**266,3**	**202,6**	**$ 6.041.444,00**

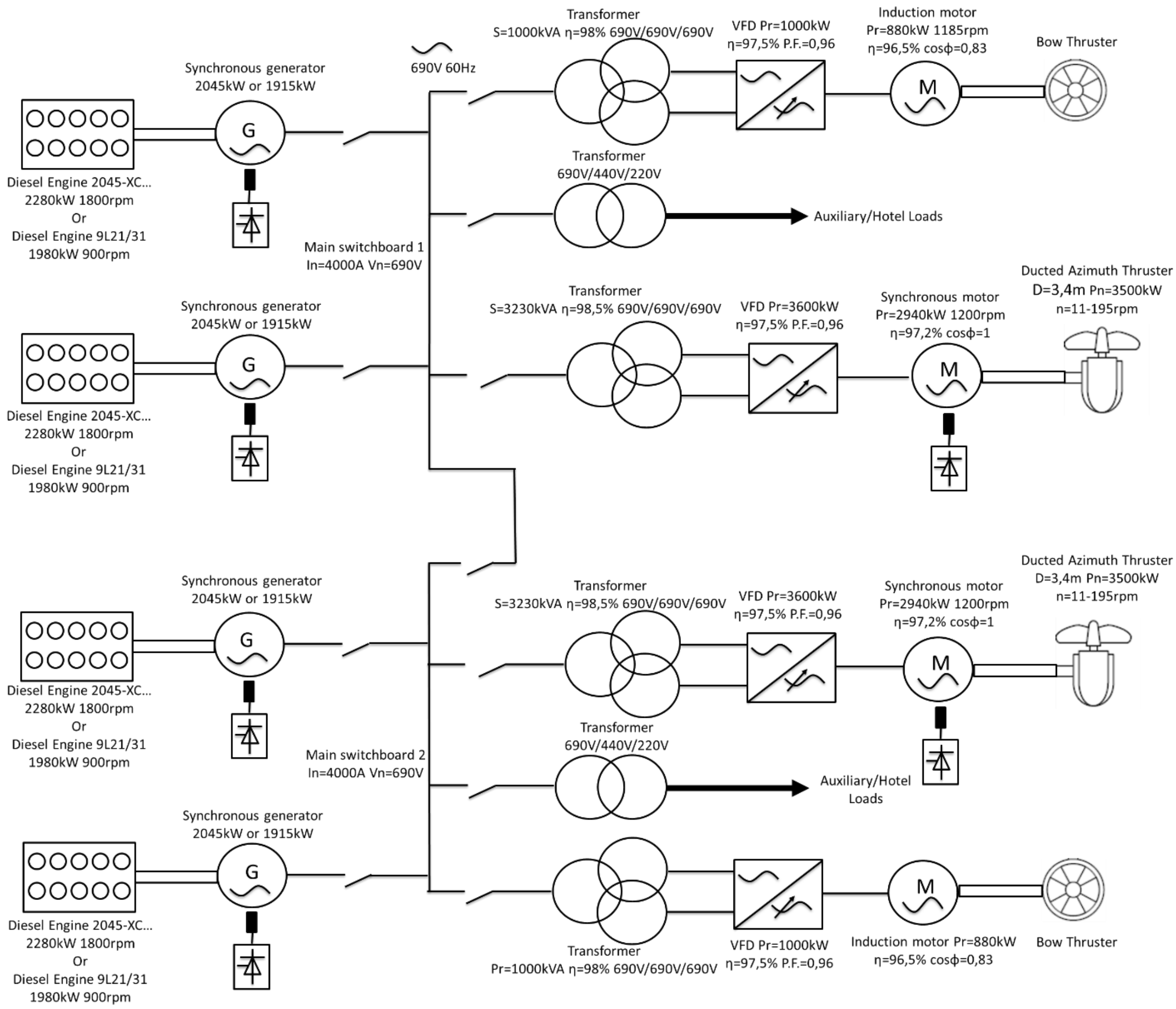

Figure 3.12 - Complete Schematic of Arrangement 2.

3.5.3 Arrangements 3 and 4 definition

Since arrangements 3 and 4 possess the same structure as arrangement 1 and 2 respectively, most components of the arrangements were already sized. The remaining components pending for sizing are the batteries bank and the AC/DC converter, which are the main focus of the present section.

For both arrangements, the batteries bank are implemented with the objective of compensating the lack or excess of power in order to keep the Diesel engines of the generator sets loaded at their optimum operational point. Furthermore, they are also sized to supply the required power while the vessel is in port. The sizing process will be considered the same for both arrangements.

It should be mentioned that for the present arrangements, the supercapacitors were considered as energy storage technology. The various advantages of the supercapacitors over the batteries make them a desirable solution for energy storage in ship electric propulsion systems. The main advantage is the possibility of load compensation with high power density. Nevertheless, one of the requirements for the design, as will be discussed below, is that the storage technology must supply the power demand when the vessel is in port operation and maintain the engines loaded at their optimum operational point, which requires a high energy density. In this context the batteries possess a higher energy density than supercapacitors, so they are the most suitable storage technology for the design.

3.5.3.1 Batteries bank

As mentioned before, the batteries bank will be sized for loading compensation of the Diesel engines and supplying the power required by the vessel when it is in port operation. The sizing process must cover the aforementioned objectives. Considering the first criterion, since the optimum operational point of the Diesel engines is particular for each engine, the batteries bank should be sized for each generator set in arrangements 1 and 2. In contrast, if the batteries bank is sized to meet the power demand for port operation, it can also be used for loading compensation for all the Diesel engines; besides, the sizing results in a simpler procedure. Taking this into account, the batteries bank will be sized to supply the energy required by the vessel for port operational mode.

In this dissertation, the total storage capacity of the batteries will be sized to supply the auxiliary power demand for port/stand by operation for 20 hours, the estimated average time in which the vessel stays in port (MURTA and SUZANO, 2013). The required storage capacity is, therefore:

$$estrg = Power\ demand \times total\ time = 725.2kW \times 20h = 14504kWh \quad (3.31)$$

Where $estrg$ is the total energy storage.

Taking into account the information about batteries presented in Chapter 2 and the type of batteries in Table 2.4, the Lithium ion and the ZEBRA batteries will be considered for evaluation. These batteries present the highest efficiencies and energy densities, and higher recharge cycles when compared to other types of batteries.

The energy density of the Lithium ion batteries will be assumed as 260Wh/l (260kWh/m^3) (BROUSSELY and ARCHDALE, 2004), and their specific energy as 150Wh/kg (DEDES, TURNOCK and HUDSON, 2010); their cost is presented in the Table 2.4, which is \$90/kg. The ZEBRA battery has an energy density of 180Wh/l (180kWh/m^3) (MANZONI, METZGER and CRUGNOLA, 2008), a specific energy of 115Wh/kg and a cost of \$12.7/kg. For the required energy storage capacity, the mass, volume and cost of the batteries are the ones presented in Table 3.31.

Table 3.31 – Characteristics of the Batteries Evaluated for Arrangement 3.

Battery Type	Lithium ion	ZEBRA	Difference
Mass (kg)	96693	126122	30%
Volume (m^3)	55,8	80,6	44%
Cost	\$ 8.702.400,00	\$ 1.601.746,09	-82%

Taking as a reference the characteristics of the Lithium ion batteries, it can be seen that the ZEBRA batteries are 30% heavier, occupy 44% more space but are 82% cheaper. Considering that the cost is more important than the mass and the volume, the ZEBRA batteries are a reasonable option.

The charge or discharge rate of the batteries bank is considered limited by the rated current of the AC/DC converter.

In order to meet with the redundancy requirements settled by the IMO for vessels with class 2 DP systems, the batteries bank are supposed to be divided in two sections, each one connected to one main switchboard section.

3.5.3.2 AC/DC converter for the batteries bank

The batteries bank will receive/supply power through two AC/DC converter units, each one connected to one main switchboard section. In order to size the power converters, the voltage rating of the batteries bank must be defined first.

The individual cells of the ZEBRA batteries have a rated voltage of 2.58V; according to Manzoni, Metzger and Crugnola (2008), the cells can be arranged such that, theorethically, any voltage level can be reached. For purposes of the present dissertation, it is assumed that a manufacturer can produce a batteries bank with the storage capacity required at a voltage level close to $1035V_{DC}$. An arrangement of 401 cells gives approximately $1034V_{DC}$ for the batteries bank. It should be noticed that $1035V_{DC}$ was selected as the rated voltage to match the highest rated voltage level for AC/DC converters offered in the commercial catalog of power converters (SIEMENS, 2011b). In the same catalog, the AC voltage input for the power converter is 690V, which is the rated voltage of the system.

Each of the AC/DC bi-directional converters is sized to supply the maximum instantaneously power request expected from the auxiliary loads of the vessel, which is 1261.9kW (the active power requested by the auxiliary loads in Table 3.27). The commercial unit with the closest power rating is 1400kW for the Siemens catalog of power converters (SIEMENS, 2011b).

The main characteristics of the AC/DC converter for the batteries bank are shown in Table 3.32; the complete catalog section of the converter is presented in the Annex H.

Table 3.32 – Main Characteristics of the AC/DC Converter for the Batteries Bank.

Parameter	Value	Parameter	Value
Rated input current (A_{DC})	1270	Approximated total Mass (kg)	1360
Rated output current (A_{DC})	1422	Approximated total volume (m^3)	1,85
Rated input voltage (V_{AC})	690	Active rectifier	---------
Rated output voltage (V_{DC})	1035	Protection Index	IP54
Input frequency (Hz)	60	Cooling	Air-Water
Rated power (kW)	1400	Rated efficiency	0,975
Input power factor	1		

The maximum discharge rate for the batteries is limited to the rated current of the two AC/DC converters, which is $2844A_{DC}$ or 2844A/h.

The active AC/DC bi-directional converter has the same arrangement of an inverter section of a complete 6-pulse VFD unit. Furthermore, both the AC/DC and the VFD unit have almost the same behavior, with a similar control scheme and switching devices. Considering the above, it will be assumed that the active rectifier with bi-directional power flow is equivalent to a VFD unit for cost estimation purposes. The Eq. A.2 from Appendix A will be used to estimate the reference cost for each power converter:

$$VFDcost = 208{,}9(1400kW) - 2185{,}5 = US\$290.274 \quad (3.32)$$

According to this, the reference cost for each AC/DC active converter for the batteries bank is US$290.274.

With the batteries bank and the AC/DC power converter already sized, the electric system of the arrangements 3 and 4 are presented in Figure 3.13 and the Figure 3.14, respectively.

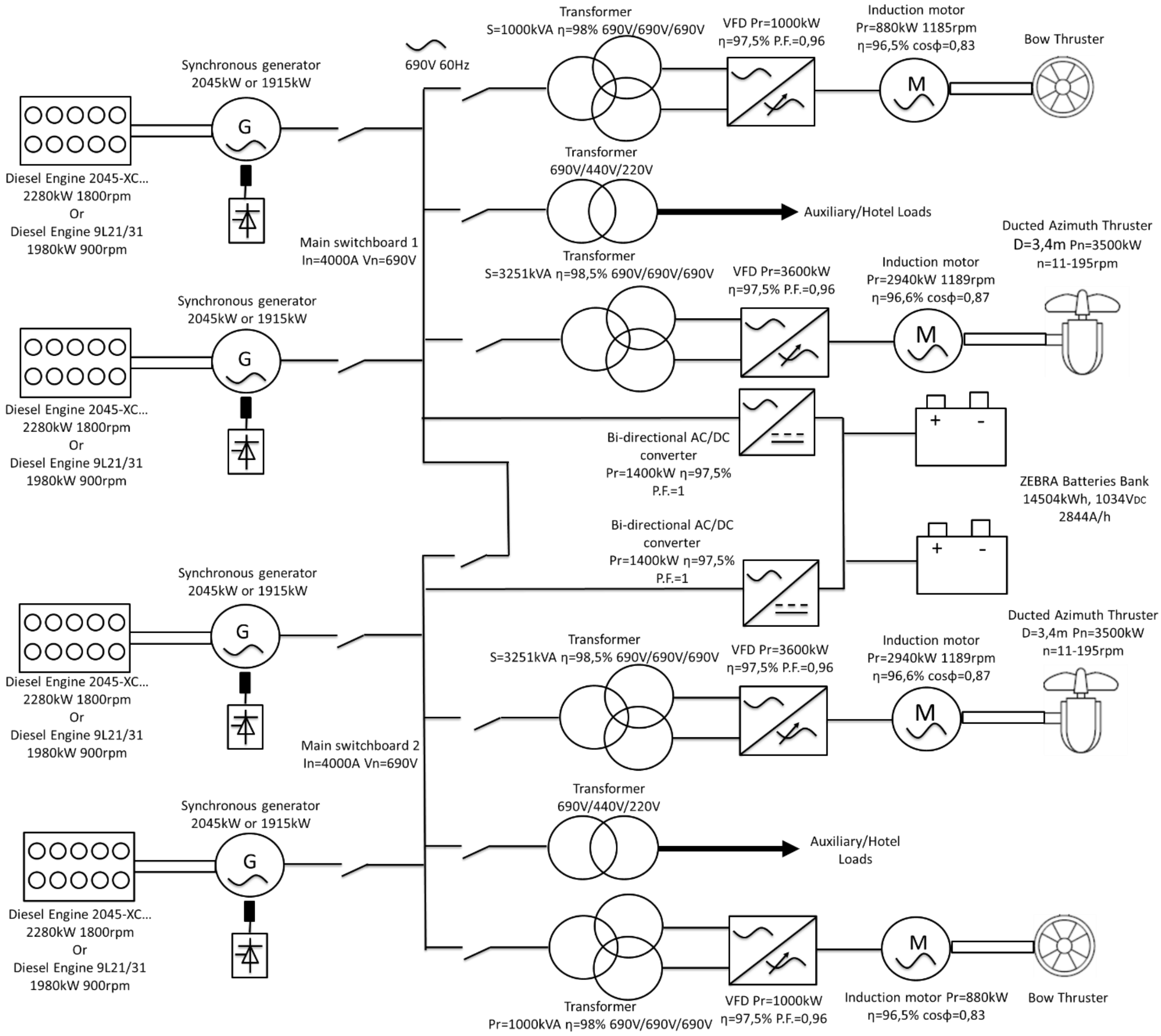

Figure 3.13 - Complete Schematic of the Arrangement 3.

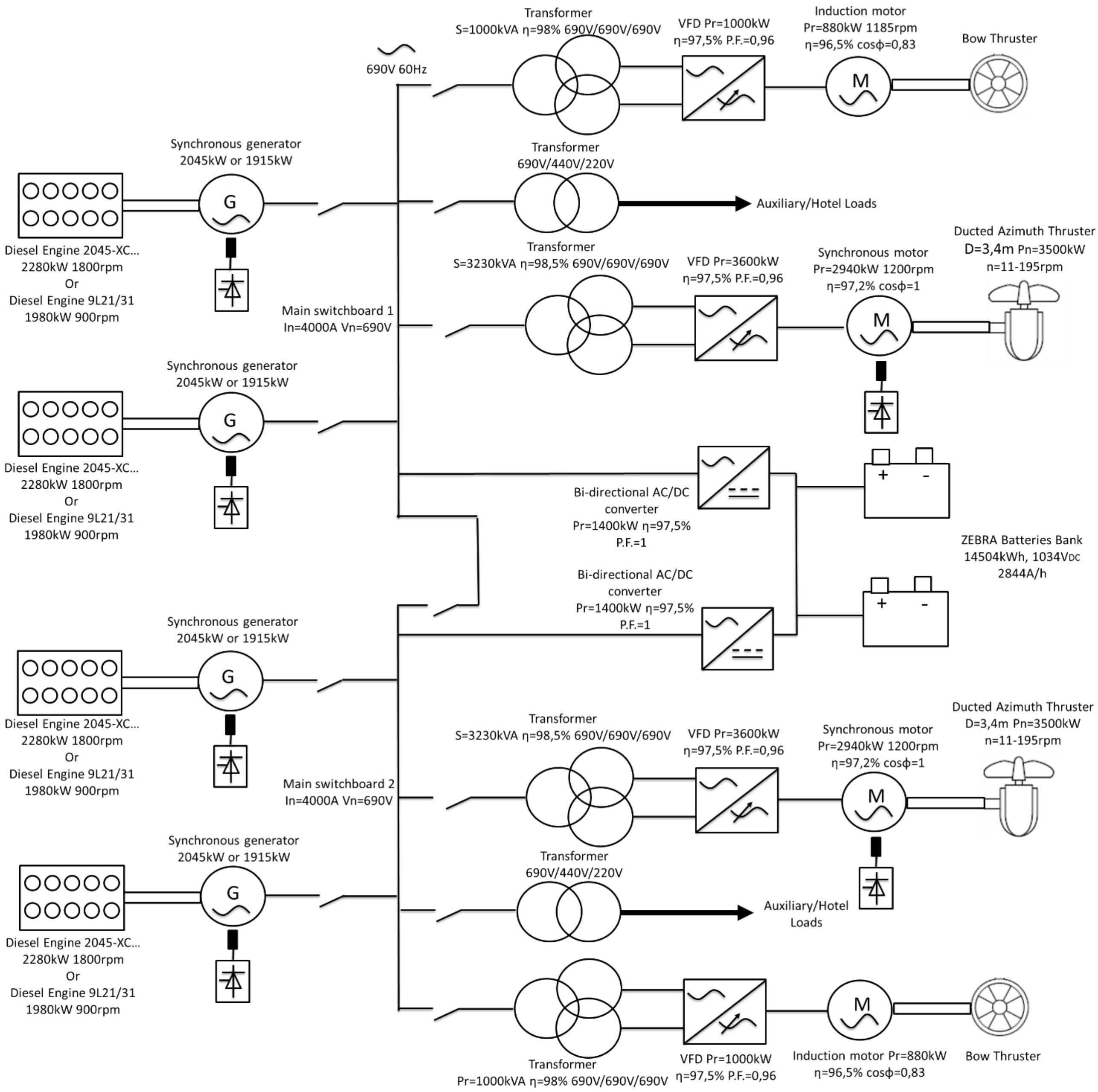

Figure 3.14 - Complete Schematic of the Arrangement 4.

3.5.3.3 Estimated mass, volume and reference cost

The mass, volume and cost presented in arrangements 1 and 2 are the same for arrangements 3 and 4 with the batteries bank contributions and the active rectifiers. The parameters for arrangement 3 and 4 are presented in Table 3.33 and Table 3.34 respectively.

Table 3.33 - Estimated Mass, Volume and Reference Capital Costs for the Arrangement 3.

	Mass (thousands of kg)	Volume (m3)	Reference Capital Cost (US$)
Azimuth thrusters	53,0	----	----
Main induction motors	24,2	10,2	$ 656.820
VFDs for main induction motor	8,5	13,7	$ 1.499.708
VFD transformers	13,2	5,4	$ 109.768
Side thrusters	11,8	----	----
Side thruster induction motors	13,1	5,1	$ 453.930,00
VFDs for side thruster motor	5,6	9,0	$ 413.428,00
Main switchboards	1,4	4,8	$ 62.984,00
High speed Diesel generator sets	68,0	181,6	$ 2.187.440,00
Medium speed Diesel generator sets	146,0	148,4	$ 2.681.000,00
Batteries bank	126,1	80,6	$ 1.601.746,00
AC/DC power converter	2,72	3,7	$ 580.548,00
Total for high speed genset	**327,7**	**314,1**	**$ 7.566.372,00**
Total for medium speed genset	**405,7**	**280,9**	**$ 8.059.932,00**

Table 3.34 - Estimated Mass, Volume and Reference Capital Costs for the Arrangement 4.

	Mass (thousands of kg)	Volume (m3)	Reference Capital Cost (US$)
Azimuth thrusters	53,0	----	----
Main synchronous motors	13,7	16,2	$ 821.024
VFDs for main synchronous motor	13,7	13,7	$ 1.499.708
VFD transformers	13,2	5,4	$ 109.370
Side thrusters	11,8	----	----
Side thruster induction motors	13,1	5,1	$ 453.930,00
VFDs for side thruster motor	5,6	9,0	$ 413.428,00
Main switchboards	1,4	4,8	$ 62.984,00
High speed Diesel generator sets	68,0	181,6	$ 2.187.440,00
Medium speed Diesel generator sets	146,0	148,4	$ 2.681.000,00
Batteries bank	126,1	80,6	$ 1.601.746,00
AC/DC power converter	2,72	3,7	$ 580.548,00
Total for high speed genset	**322,3**	**320,0**	**$ 7.730.178,00**
Total for medium speed genset	**400,3**	**286,9**	**$ 8.223.738,00**

3.6 MASS, VOLUME AND CAPITAL COSTS COMPARISON

In this sub-section, the mass, volume and capital costs of the arrangements are analyzed. The mass and the volume for all the arrangements are presented in Figure 3.15. Moreover, the estimated mass of the electric propulsion systems as defined by Eq. 3.1 and 3.2 is also shown for comparison and validation purposes. The capital costs are plotted in Figure 3.16.

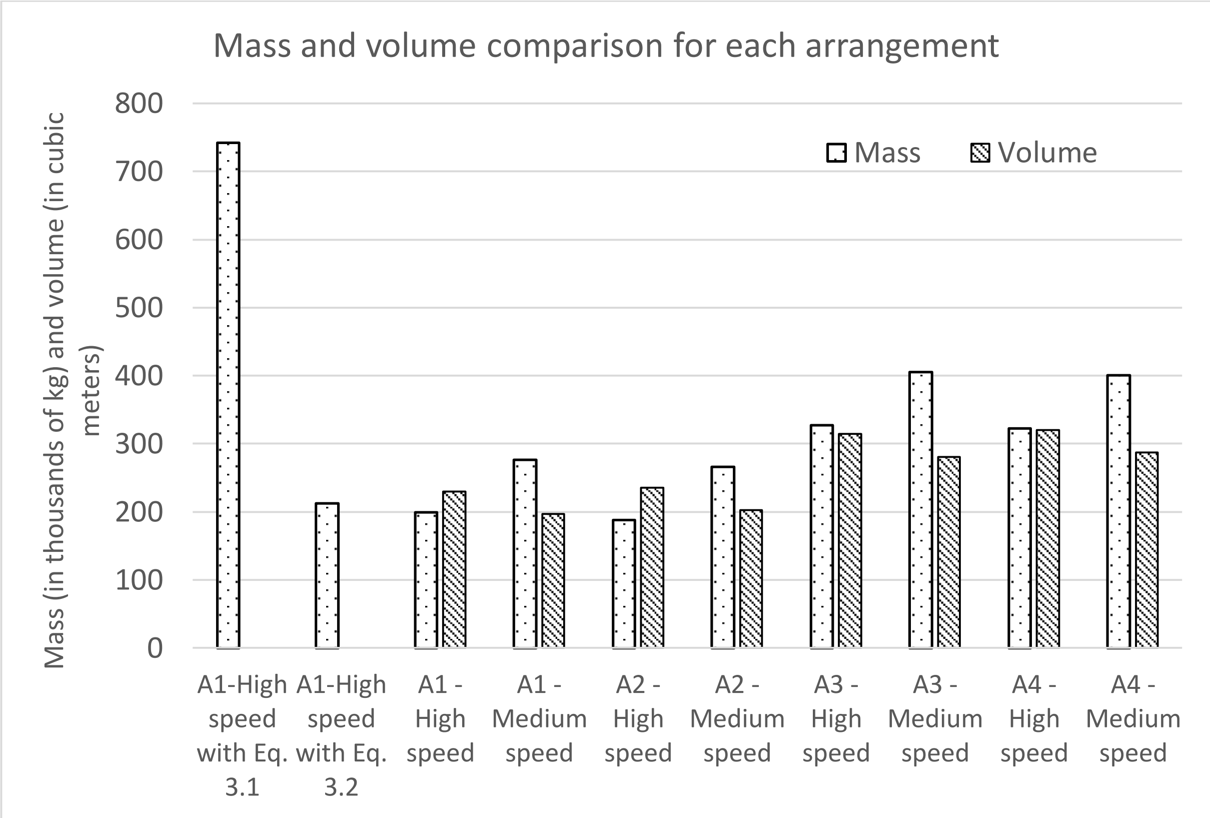

Figure 3.15 – Mass and Volume for Each Arrangement.

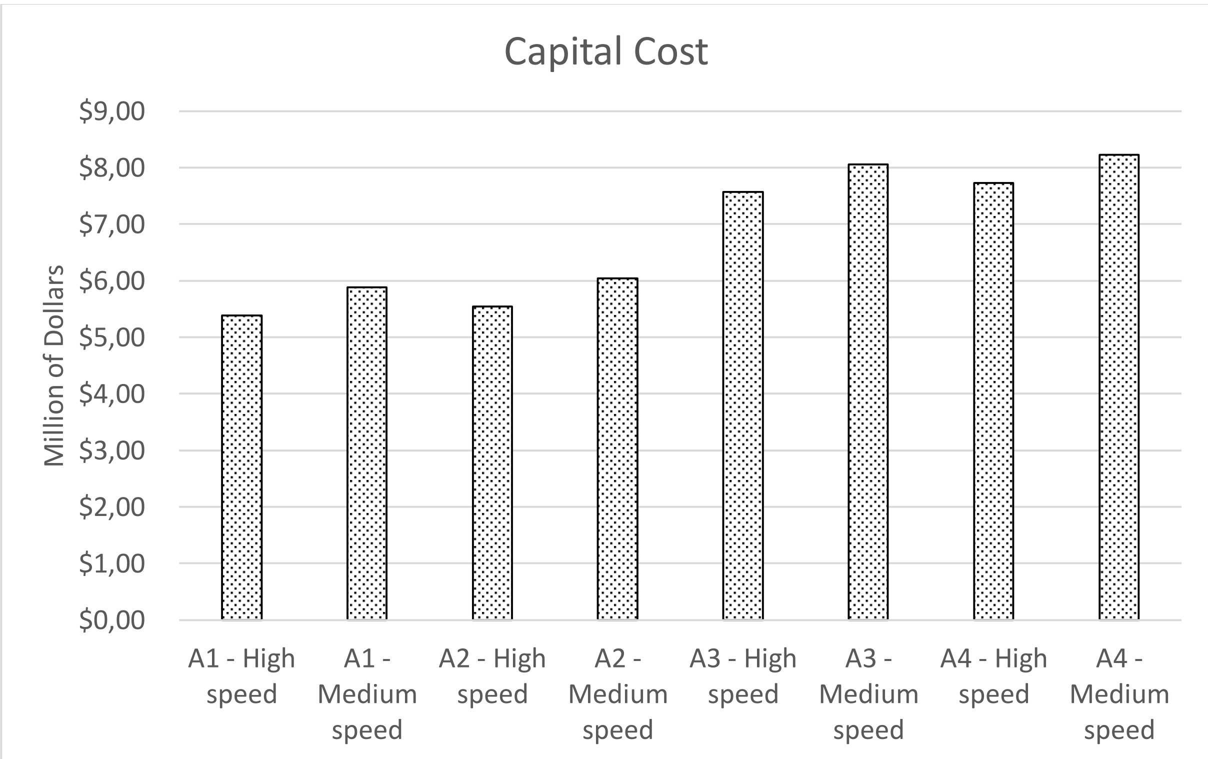

Figure 3.16 – Capital Cost for Each Arrangement.

From the figures, the following analysis can be performed:

- The estimated mass obtained with the formula proposed by Watson (1998) in Eq. 3.1 differs significantly from the result gotten by Eq. 3.2 and from the mass of arrangement 1 with high speed genset. The difference between the result of Eq. 3.1 and the other values exceeds the 500 thousands of kg; the reason for this difference is that the formula of Eq. 3.1 was developed from information gathered more than 35 years ago, when power electronics and electric machinery was not as developed as it is now.
- The mass obtained with Eq. 3.2 is 11% greater than the estimated mass of arrangement 1 (21000kg higher). Hence, the formula can give a reasonable estimation of the mass for a conventional electric propulsion installation for PSVs.
- The additional mass of the batteries in arrangements 3 and 4, when compared to arrangements 1 and 2, is around 128.8Tonnes.
- The mass of the arrangements with medium speed Diesel gensets is approximately 1.45 times the mass of the same arrangement with high speed Diesel generator sets; it counts for approximately 80.000kg of additional mass. The above implies that the vessel would transport 80.000kg less payload with medium speed gensets than with high speed gensets (if the deadweight of the vessel is maintained constant).
- The mass of arrangements 2 and 4, when compared to arrangements 1 and 3 respectively, is lower. This is caused by the lower mass of the air-to-water cooled synchronous motor when compared to the water-to-water cooled induction motor.
- The additional volume of the arrangements with medium speed gensets and batteries also reduces the payload that can be transported. However, its effect is not considered as big as the additional mass since the volume represents space occupied, which could be optimized for the same deadweight.
- The arrangements with batteries bank present the highest volumes, with arrangement 4 being the one with the highest volume.
- For arrangements 1 and 3, the volume difference between the installation with high speed genset and medium speed genset is less than 1%.

- For arrangements 2 and 4, the volume difference between the installation with high speed genset and medium speed genset is higher than 31%.
- The observed tendency for the capital costs presents a higher value for the arrangements with batteries when compared to the arrangements without them.
- The alternatives with medium speed generator sets present higher capital costs than the same alternatives with high speed generator sets.
- The difference between the capital costs of arrangements 3 and 4, with medium speed Diesel generator sets is less than 0.1%.
- The lowest capital cost corresponds to the arrangement 1 with high speed Generator sets.

4 ELECTRIC PROPULSION ARRANGEMENT SELECTION

The present chapter intends to develop the remaining stages of the methodological proposal presented in Figure 3.2. To start, the standard load profile is defined so as to execute the performance analysis for each arrangement, which is focused on determining the efficiency of the system and the SFOC for the Diesel generator sets for varying loads. Next, the fuel consumption and the pollutant gasses released by the Diesel engines (NOx, SOx and CO_2) for the standard load profile are estimated. Afterwards, the NPV is obtained for each arrangement, taking into account some conditions. Finally, the main characteristics of each arrangement, *i.e.* mass, volume, fuel consumption, pollutant gasses emissions (NOx and SOx) and the NPV are compared using the AHP methodology. The final result of this comparison is the selection of the electric propulsion arrangement for the PSV.

4.1 STANDARD LOAD PROFILE ESTIMATION

4.1.1 Operational profile

The platform supply vessel is distinguished from other cargo ships by its particular operational profile, which is divided in transit, port, stand by and dynamic positioning (ABB, 2007). The transit operation is divided, in turn, in laden voyage (loaded voyage from port to oilfields) and partial load voyage (transit condition without useful load). When a PSV is required for service, the usual procedure begins with a service request and then it goes to port for loading; after being loaded, the vessel transits in laden voyage to the oilfields; later, the vessel goes into dynamic positioning (DP) operation delivering cargo to the platforms and receiving waste material from them at sea. While the vessel is in the oilfields, it is required to transit between platforms. When the vessel finishes supporting the platforms, it returns to the continent without useful load (this type of transit is called partial load voyage). Finally, the vessel is kept anchored waiting in standby mode to start another service.

The operational profile of a PSV working at Santos Basin will be estimated to define the load profile and to calculate the fuel consumption and the exhaust gases emissions.

The Santos Basin is located to the south of the Campos Basin and covers the sea area in the front of the south coast of Rio de Janeiro, passing through São Paulo and Parana coasts, until the north coast of Santa Catarina, as shown in Figure 4.1. Currently, the main oil production activities at Santos Basin are concentrated in the Tupi field, at a distance of 290km from the coast. Considering the distance, and taking into account that the required service speed for the PSVs is 15knots (27,78km/h) (MURTA and SUZANO, 2013), it can be deduced that each voyage to or from the oilfields will take approximately 10.5 hours, disregarding weather effects. Moreover, the PSV is supposed to take approximately 15 hours supporting each platform (MURTA and SUZANO, 2013), serving 3 to 6 platforms per service (MEDEIROS, 2010). The time employed loading at port is approximately 20h (MURTA and SUZANO, 2013), while the total time at standby, waiting to enter the port is considered to be 24 hours (ABB, 2007; MEDEIROS, 2010). The operational profile is, therefore, summarized in Figure 4.2, which will be assumed as a typical operational profile for reference purposes in subsequent calculations.

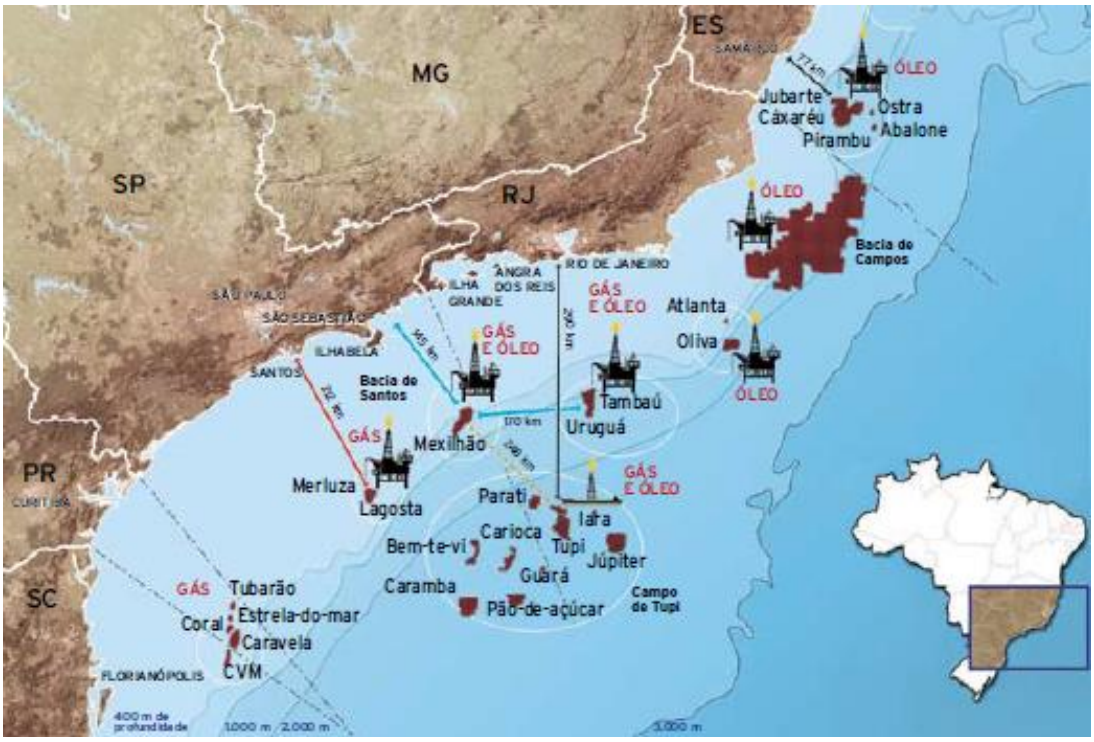

Figure 4.1 –Santos Basin and Tupi Field (DE OLIVEIRA, 2008).

4.1.2 Standard load profile

A reference load profile is defined in order to estimate the fuel consumption and the pollutant gasses emissions of the arrangements for the PSV conceptual design. To perform the above, the operational profile is taken as a reference to approximate the electrical demands per type of operation and for a complete service (round trip).

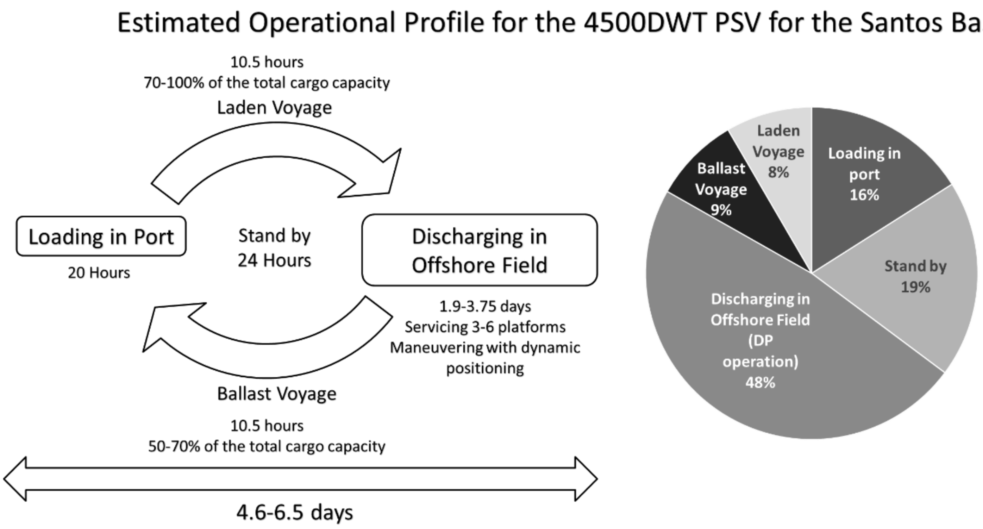

Figure 4.2– Estimated Operational Profile of a PSV Operating at Santos Basin.

The load profile estimation is developed for a round trip starting from port. The following conditions are considered:

- In the Diesel generator sets, the torque provided by the engine is proportional to the active power demand (in kW); the reactive power demand (in kVAR) produced by the inductive loads does not have any influence over the torque delivered by the engine if the global power factor is kept above 0.8. Thus, it is assumed that the global power factor of the vessel loads is greater than 0.8 for all the time range; hence, the reactive and apparent power demands (in kVAR and kVA, respectively) are disregarded taking into account only the active power demand (in kW).
- In laden voyage, the vessel is fully loaded (corresponding to 100% of the design draft). Furthermore, the speed of the vessel is supposed to vary between 14 to 15knots to represent the speed variations due to sea state.
- While the vessel is in transit from the oilfields to the port, it is assumed that it is loaded at 75% of its design capacity. In this mode of operation, the speed of the vessel is supposed to vary between 14 to 15knots.
- Taking into account the operational requisites for a vessel with class 2 DP system, at least two Diesel generator sets must be in operation while the vessel is in Dynamic Positioning mode. Each one of the Diesel generator sets must be connected to a different busbar.

- In stand by operation near the port, the vessel is supposed to maintain its position at sea while being anchored without using the dynamic positioning system.
- The offshore stand by operation is included within the dynamic positioning load profile.
- The load profile is defined in hourly time samples.

4.1.2.1 Port operation

In port, the electrical demands of the vessel are associated only to the auxiliary and the hotel loads. Since all the loads do not operate simultaneously, the demand is expected to vary in time. Hence, the power demand from the hotel and the auxiliary loads is varied randomly between 180kW and 725.2kW. The highest limit was taken from Table 3.16 while the lowest limit was arbitrarily settled at this value supposing that the power demand of a PSV in port cannot be lower. The time range of the samples is 20h, which is the time for port operation as established in Section 4.1.1.

In Figure 4.3, the load profile for port operation is plotted detailing the power samples.

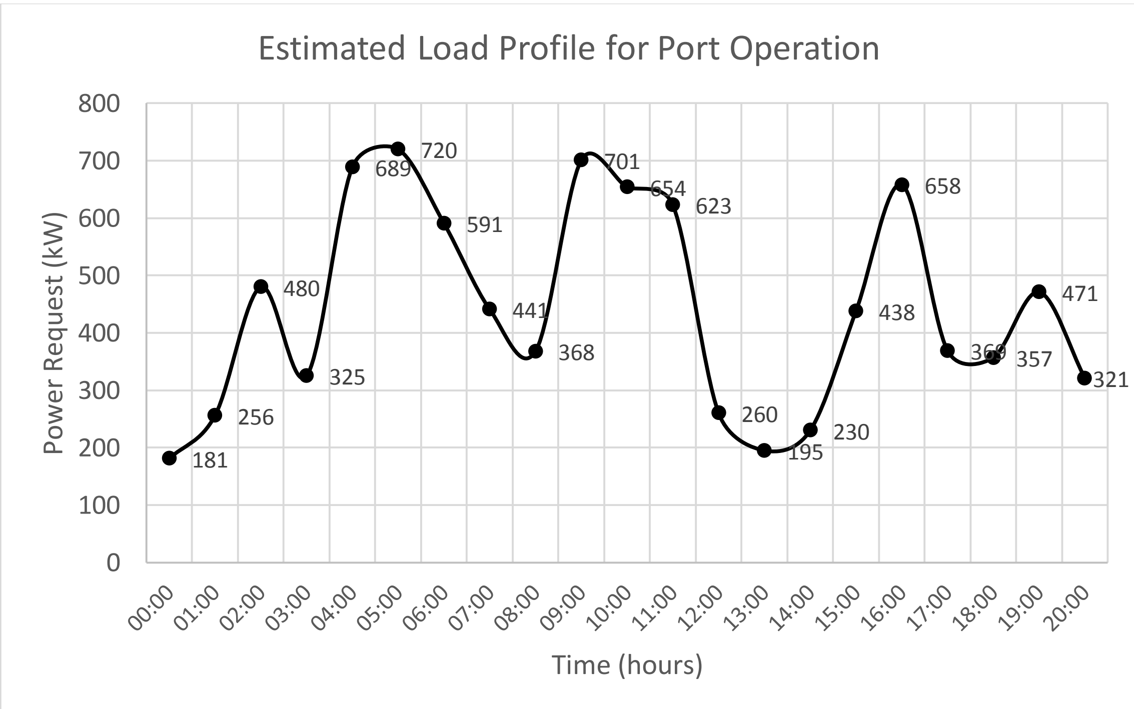

Figure 4.3 – Estimated Load Profile for Port Operation.

4.1.2.2 Laden voyage

The power demand from the auxiliary/hotel loads in laden voyage is defined in samples within a power range as it was made for port operation; the highest limit is 1046.9kW (from Table 3.16) while the minimum limit is settled at 230kW. The power samples of the auxiliary and hotel electrical demands are shown in Figure 4.5.

Regarding the propulsion loads, vessel speed samples are defined as primary data to calculate the power demands for propulsion. They are established by a random variation of speed values between 14 and 15knots as shown in Figure 4.4.

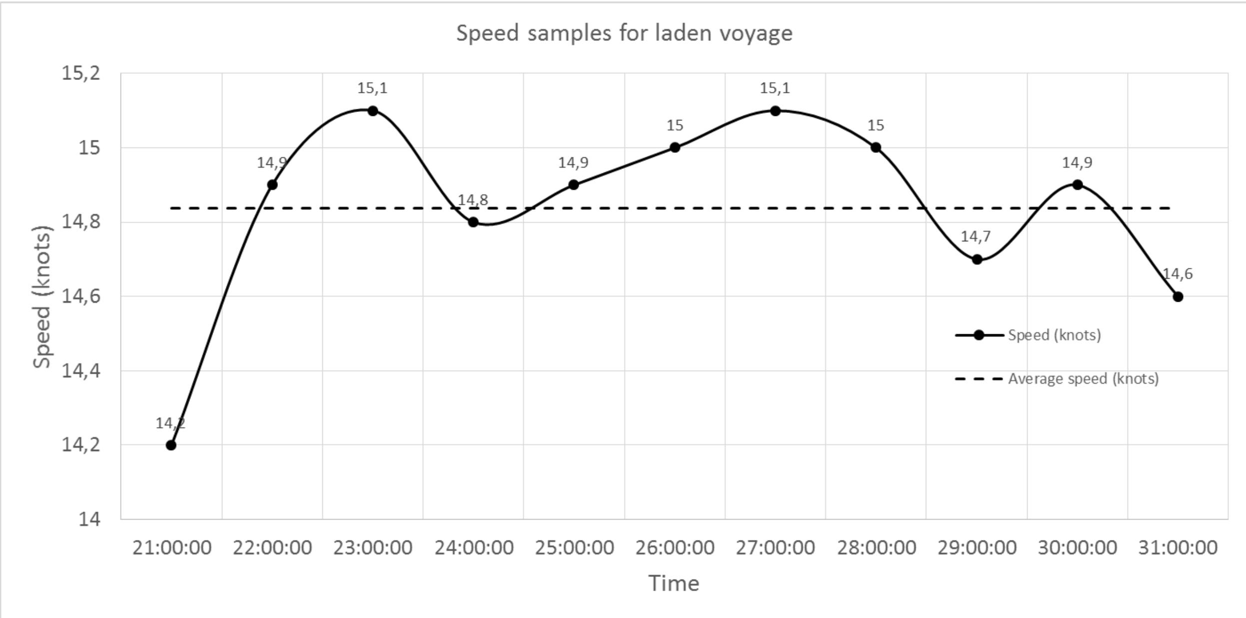

Figure 4.4 – Vessel Speed Samples for Laden Voyage.

The corresponding power required by the azimuth thrusters to thrust the vessel at the speed samples of Figure 4.4 was obtained through Figure 3.5. The corresponding propulsion power demands for the speed samples of Figure 4.4 are shown in Figure 4.5, along with the auxiliary/hotel power demands.

4.1.2.3 Dynamic positioning load profile

The electrical demands in dynamic positioning are from main propulsion units, side thrusters and, hotel and auxiliary loads. The maximum expected power demand from the auxiliary/hotel loads is 1261.9kW (Table 3.16) and the minimum power request is assumed to be 280kW. The propulsion loads for dynamic positioning are divided into two groups: the main propulsion loads (corresponding to the azimuth thrusters) and the side thruster loads. As discussed in Section 3.5.1.4, the maximum expected power request from the azimuth thrusters in DP mode is 156kW; on the other hand, the maximum expected demand from the side thrusters is 830kW. The minimum power request from both propulsion groups is fixed at zero. The power samples were randomized as it was made for the previous load profiles.

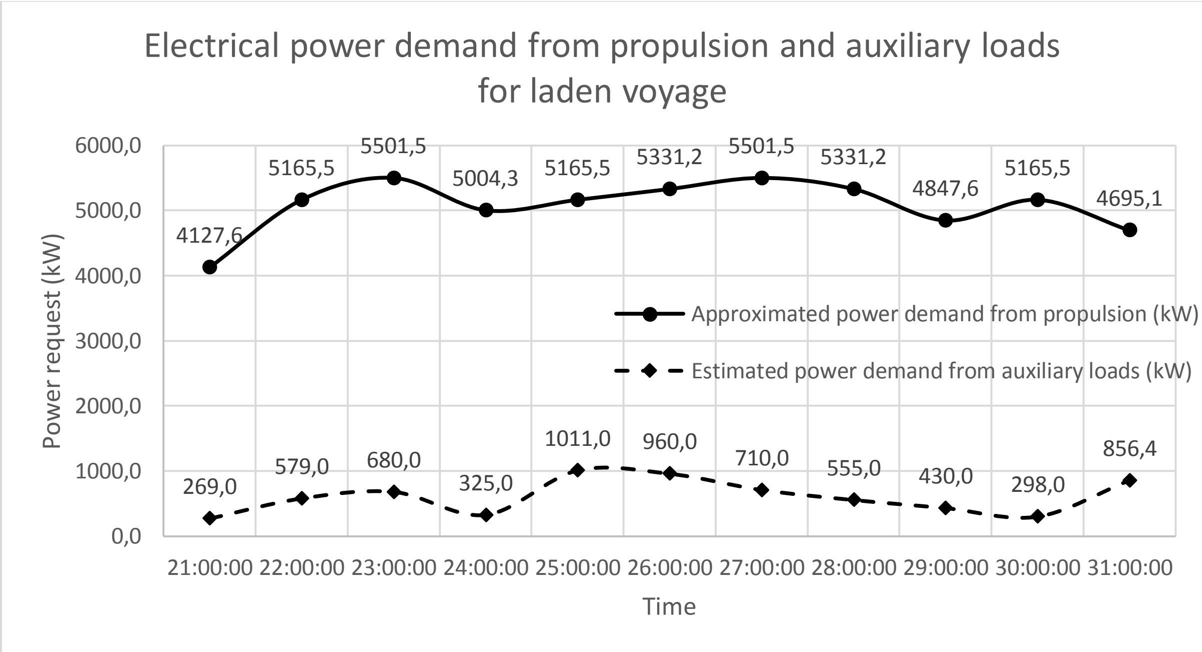

Figure 4.5 - Estimated Load Profile for Laden Voyage.

The load profile for the dynamic positioning operation was defined assuming that the vessel serves 3 platforms and spends 15hours with each one; therefore, the total time of operation is 45 hours.

The power samples are registered in Figure 4.6.

4.1.2.4 Partial load voyage

The auxiliary/hotel demands are defined exactly as it was made for laden voyage, with the highest limit as 1046.9kW (Table 3.16) and the lowest one as 230kW.

The speed samples for partial load voyage were varied randomly between 14 and a little above 15knots; the samples are shown in Figure 4.7. The power demands from the azimuth thrusters to thrust the vessel at the corresponding speed in the samples were obtained from Figure 3.5.

The total power demands are shown in Figure 4.8.

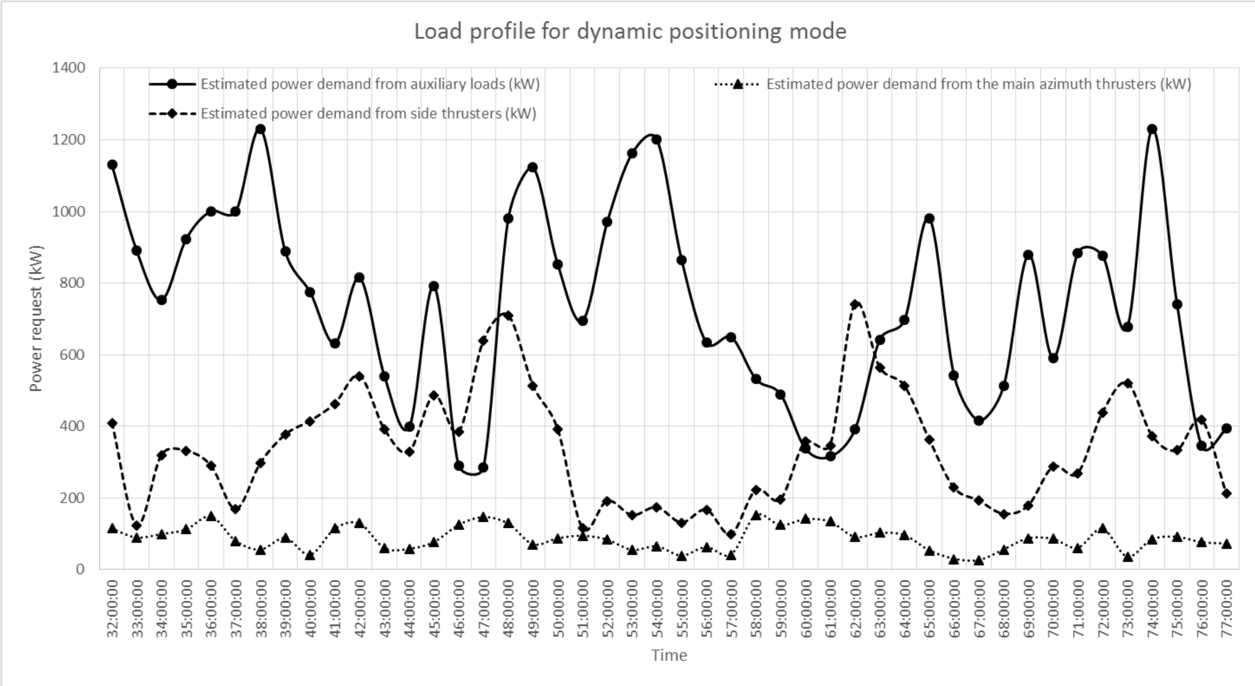

Figure 4.6 – Load Profile for Dynamic Positioning Mode.

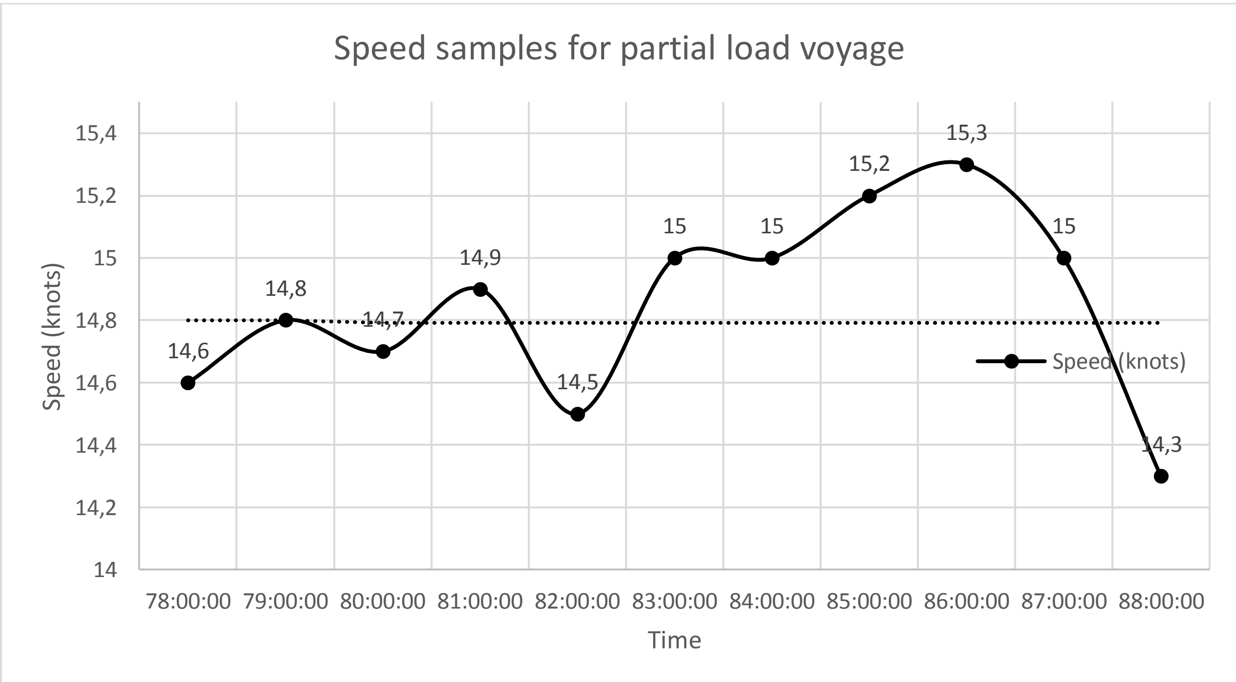

Figure 4.7 – Speed samples for partial load voyage.

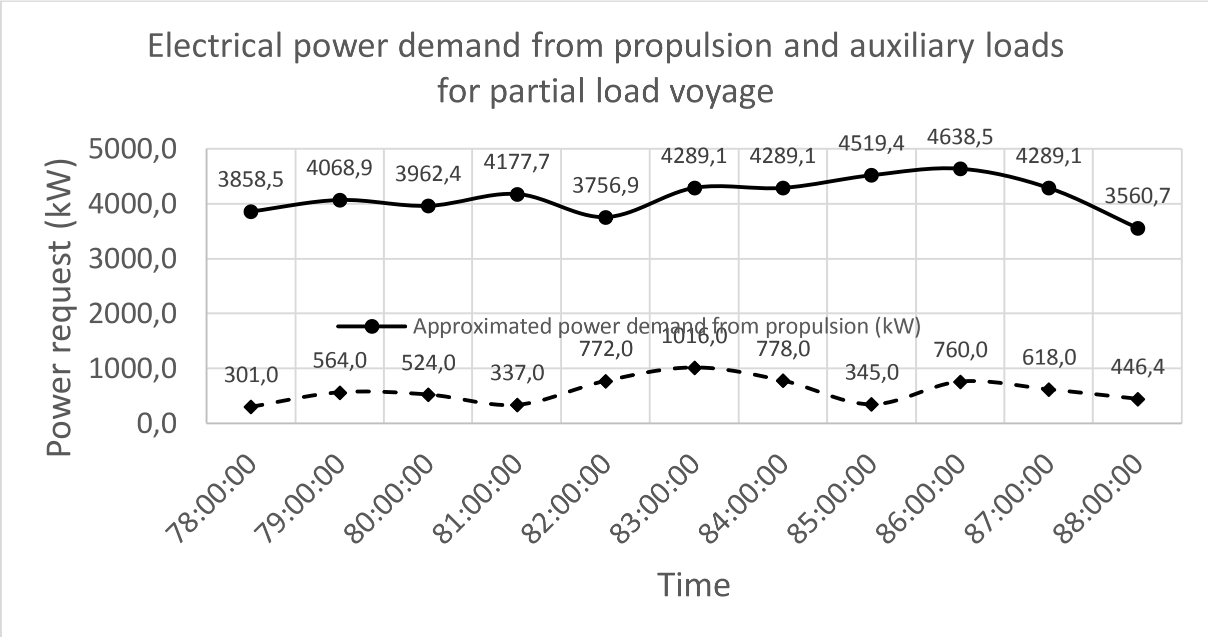

Figure 4.8 – Load profile for partial load voyage

4.1.2.5 Stand by

The load profile for the stand by operation mode is defined exactly as it was done for the port operation. Hence, the propulsion power demands are zero and the auxiliary/hotel power demand varies between 180kW and 725.2kW (Table 3.16); the time range of the samples is 24h, the time settled in section 4.1.1 for stand by operation.

In Figure 4.9 the values of the load profile are plotted.

4.1.2.6 Standard load profile

The standard load profile is the combination of the load samples for each operation type for the entire time range, which is equivalent to a round trip. The standard load profile versus the total accumulated time of the service is plotted in Figure 4.10. It should be noticed that the power request by the main propulsion system, the thrusters for the DP operation and the auxiliary/hotel loads are plotted separately. In the figure, the regions marked as 1, 2, 3, 4 and 5 are, respectively: port operation, laden voyage, dynamic positioning operation, partial load voyage and stand by operation. The accumulated time of the service is 4.7 days (113 hours). The complete data of the standard load profile is presented in Appendix C.

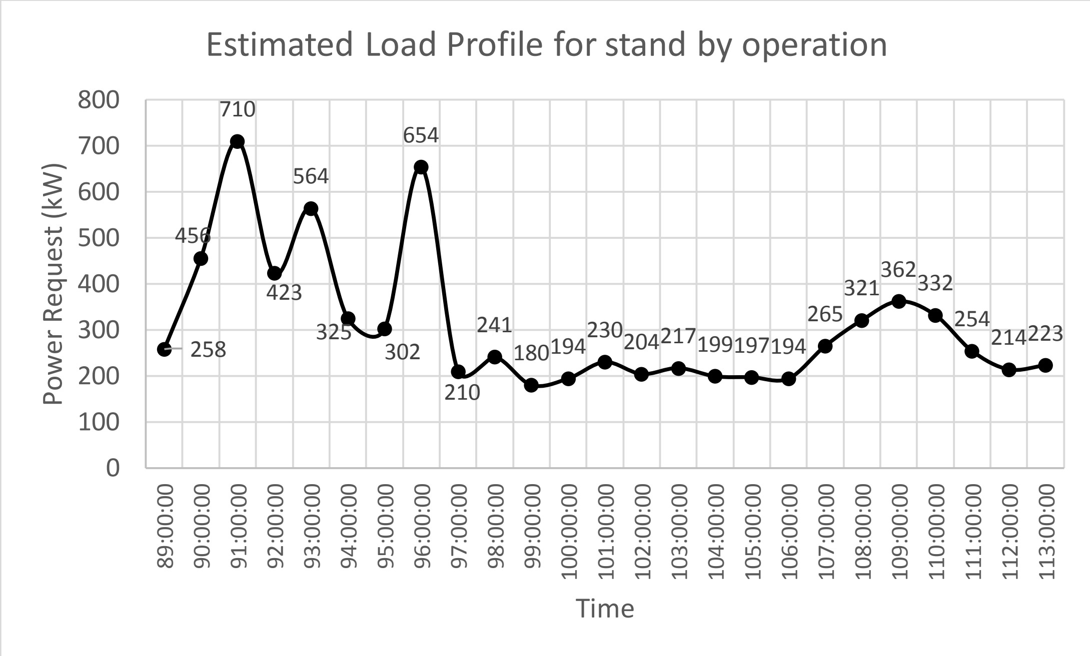

Figure 4.9 – Load Profile for Standby Operation.

4.2 PERFORMANCE ANALYSIS, FUEL CONSUMPTION AND EXHAUST GASES ESTIMATION

The fuel consumption and the estimated pollutant gases released by each arrangement will be approximated for the standard load profile, by analyzing the performance of the electrical and mechanical equipment. The procedure is schematized in Figure 4.11 in which the power flux is in the inverse direction. The standard load profile is the input of the process; the power demands from the main propulsion system and the side thrusters are assumed as measured at the shaft of the motors. Meanwhile, the power demands corresponding to the auxiliary/hotel loads are supposed to be measured at the switchboard. In this context the Diesel engines provide all the power; the mass of fuel required to produce the demanded power in each sample is defined by:

$$Fuel\ consumption = \int_{t_1}^{t_2} h\, SFOC_n\, Engpow_n\, dt \qquad (4.1)$$

Where h is the number of Diesel engines in operation, $SFOC_n$ is the specific fuel consumption of the engine for the corresponding power delivered, $Engpow_n$ is the power delivered by the Diesel engines in kW, $t_{1,2}$ are the time limits between samples and the sub index n is the number of the sample. The fuel consumption is given in grams.

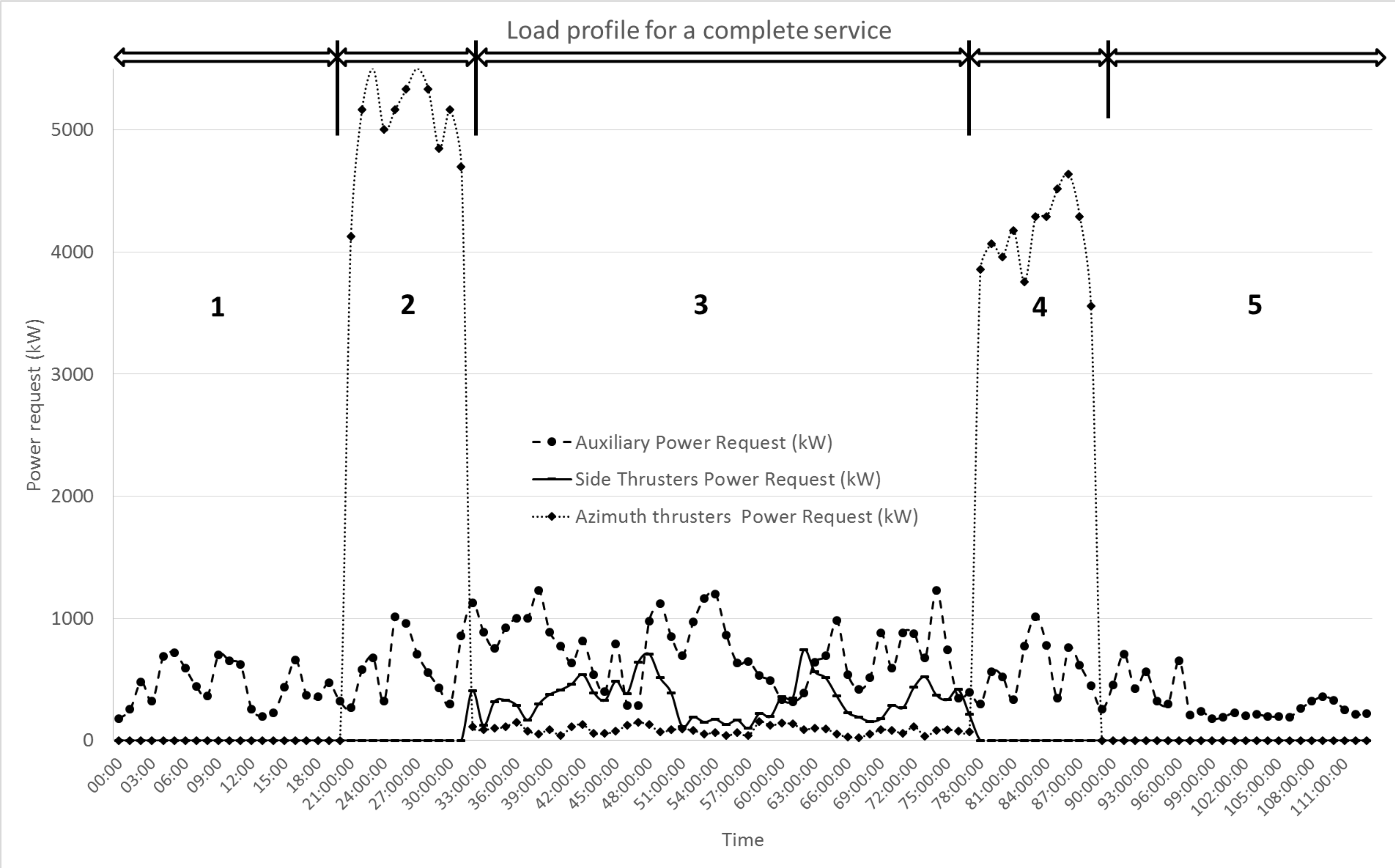

Figure 4.10 – Standard Load Profile for a Complete Service.

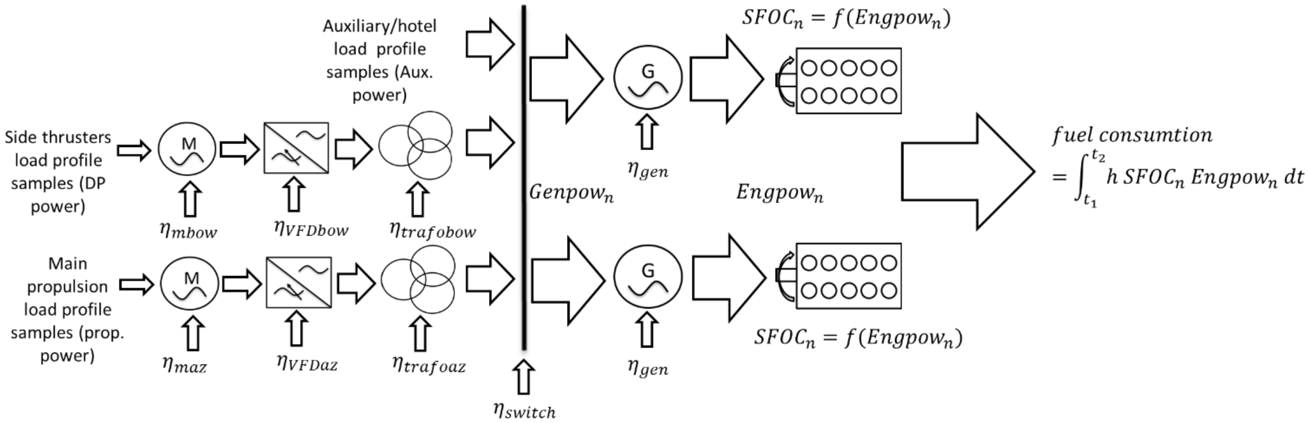

Figure 4.11 – Schematic Diagram for Obtaining the Fuel Consumption.

The SFOC depends on the loading of the motor, hence, it is a function of the power delivered by the engine. The SFOC function can be represented by the following expression:

$$SFOC = f\left(\frac{Engpow_n}{engine\ rated\ power}\right) \tag{4.2}$$

In order to estimate an expression for the SFOC, each manufacturer gives SFOC values measured at partial loads (usually at 25, 50, 75 and 100% of the MCR), which can be used to perform a regression curve.

$Engpow_n$ represents the power that is delivered by the engines at each period of time and is defined as:

$$Engpow_n = \frac{1}{\eta_{switch}\eta_{gen}}\left(\frac{Prop.power_n}{\eta_{maz}\eta_{VFDaz}\eta_{trafoaz}} + \frac{DP\ power_n}{\eta_{mbow}\eta_{VFDbow}} + Aux.power_n\right) \tag{4.3}$$

Where, $Prop.power_n$ is the power sample corresponding to the main propulsion load profile; $DP\ power_n$ is the power sample corresponding to the load profile of the side thrusters; $Aux.power_n$ are the power samples of the auxiliary/hotel loads; $\eta_{maz}, \eta_{VFDaz}, \eta_{trafoaz}$ are the efficiencies of the motor, VFD and transformer for the main propulsion system; $\eta_{mbow}, \eta_{VFDbow}$ are the efficiencies of the motor, VFD and transformer for the bow thrusters; whereas η_{switch} and η_{gen} are the efficiencies of the switchboards and generators.

Since the alternator efficiency for all the generator set units is the same (Table 3.23) a regression curve fitted to the data of Table 3.23 was made to obtain a function for approximating its efficiency for all loads. The best fitted curve is:

$$\eta_{gen} = 0{,}1208genload_n^3 - 0{,}2888genload_n^2 + 0{,}2203genload_n + 0{,}915 \quad (4.4)$$

Where, $genload_n$ is the loading of the generator sets as a percentage of the rated power:

$$genload_n = \frac{Genpow_n}{h \cdot generator\ rated\ power} \quad (4.5)$$

In which $Genpow_n$ is:

$$Genpow_n = \frac{1}{\eta_{switch}}\left(\frac{Prop.power_n}{\eta_{maz}\eta_{VFDaz}\eta_{trafoaz}} + \frac{DP\ power_n}{\eta_{mbow}\eta_{VFDbow}} + Aux.power_n\right) \quad (4.6)$$

The fuel consumption can be obtained using Eq. 4.2 and 4.3 by substituting the efficiencies of the motors, VFDs, transformers, switchboards and generators; the SFOC curves must be obtained for each Diesel engine.

On the other hand, the exhaust emissions from Diesel engines that will be estimated are the Nitrous Oxides (NO_X), Sulphur Oxides (SO_X) and Carbon Dioxide (CO_2), which are the most studied emissions from ships in the literature (CISNEROS, 2012; CORBETT and KOEHLER, 2003). The exhaust gases can be obtained applying power based factors (in g/kWh) or fuel based factors (kg/tonne of fuel burned) (DEDES, HUDSON and TURNOCK, 2010). In the case of the NOx emissions, they are specific for each motor and are usually defined using power based factors (in g/kWh) depending on the energy delivered by the engine. The NOx mass released to the environment can be approximated by:

$$NO_X = (ef_{NOx}) \int_{t_1}^{t_2} h\, Engpow_n\, dt \quad (4.7)$$

Where, ef_{NOx} is the NOx power emission factor given in g/kWh, NO_X is the total mass of NOx released in g.

The SOx and CO_2 emissions are defined using fuel based factors, thus, they depend on the mass of fuel burned. Regarding the SOx emissions, they also depend on the sulfur content in the fuel. The SOx and CO_2 masses released to the environment are defined as following:

$$SO_X = (ef_{SOx}) fuel\ consumption \quad (4.8)$$

$$ef_{SOx} = 20 \times \%sulfur\ content \quad (4.9)$$

$$CO_2 = \left(ef_{CO_2}\right) fuel\ consumption \qquad (4.10)$$

Where, $\%sulfur\ content$ is the sulfur content of the fuel as a percentage of the total mass or volume, ef_{SOx} is the SOx fuel emission factor in kg per 1000kg of fuel burned, ef_{CO_2} is the CO_2 fuel emission factor in kg per 1000kg of fuel burned. The SOx and CO_2 mass is given in kg.

The fuel consumption and the exhaust emissions will be obtained for each arrangement assuming the following:

- It is assumed that the high speed Diesel engines burn MGO while the medium speed Diesel engines are supposed to burn HFO.
- The sulfur content of the MGO is settled as the maximum admissible: 1.5% (VERMEIRE, 2007).
- The sulfur content of the HFO is settled as the maximum permitted by the MARPOL 73/78 Annex VI, 3.5% (IMO, 2004).
- The CO_2 emission factor is 3190kg per each 1000kg of fuel burned, disregarding the engine type and the fuel type.
- Variations in the reference SFOC values of the Diesel engines are disregarded.
- The global power factor is considered as 0.9.
- It is supposed that the vessel possesses a power managing system which divides the power demand between the generator sets in operation. It is assumed that each generator has the same load.

The estimation of the fuel consumption and exhaust gases will be made for each arrangement.

The performance analysis will be focused on the generated power $Genpow_n$ defined by Eq. 4.6, the loading of the Diesel engines and the number of Diesel generator sets in operation.

4.2.1 Arrangement 1

The SFOC curves and emission factors for both high and medium speed gensets, are defined first.

- High speed Diesel generator set

The SFOC of the high speed Diesel generator set is approximated to a regression curve fitted to the data of Table 3.20; the regression curve is defined by:

$$SFOC_{high1n} = 88englo ad_{high1n}^{2} - 146englo ad_{high1n} + 260 \quad (4.11)$$

Where $engload_n$ is the loading of the Diesel engine as a percentage of its rated power, for this engine it is 2280kW, the loading is defined by:

$$engload_{high1n} = \frac{Engpow_n}{2280kW} \quad (4.12)$$

Regarding the exhaust gases, the NOx emission factor of the high speed Diesel engine is 7,29 g/kWh (Table 3.19).

- Medium speed Diesel generator set

The SFOC of the medium speed Diesel engine is approximated by a curve fitted to the values shown in Table 3.22. The SFOC function is fitted to a third degree polynomial with a R-squared factor equal to 0.9994:

$$SFOC_{medium1n} = -22{,}266engload_{medium1n}^{3} + 110{,}18engload_{medium1n}^{2} - 128{,}56engload_{medium1n} + 232{,}59 \quad (4.13)$$

Where engload is defined by Eq. 4.14 with the engine rated power equal to 1980kW:

$$engload_{medium1n} = \frac{Engpow_n}{1980kW} \quad (4.14)$$

The NOx emission factor of the medium speed Diesel engine is 9g/kWh (see Table 3.21).

4.2.1.1 Port operation

In port operation the total power provided by the Diesel engines is defined by a simplified form of Eq. 4.3, in which the power for propulsion and DP is zero, hence, the power given by the engines is:

$$Engpow_n = \frac{1}{\eta_{switch}\eta_{gen}}\left(Aux.power_n\right) \quad (4.15)$$

Where the generator efficiency is defined by Eq. 4.4,, 4.5, and 4.6; in port operation Eq. 4.6 becomes:

$$Genpow_n = \frac{1}{\eta_{switch}}\left(Aux.power_n\right) \tag{4.16}$$

The generated power and the loading of the high and medium speed Diesel engines are defined by Eq. 4.15, 4.16, 4.12, and 4.14, respectively. They are plotted in Figure 4.12. The figure shows the total generated power, the number of Diesel generator sets operating (for high and medium speed) and their corresponding loading.

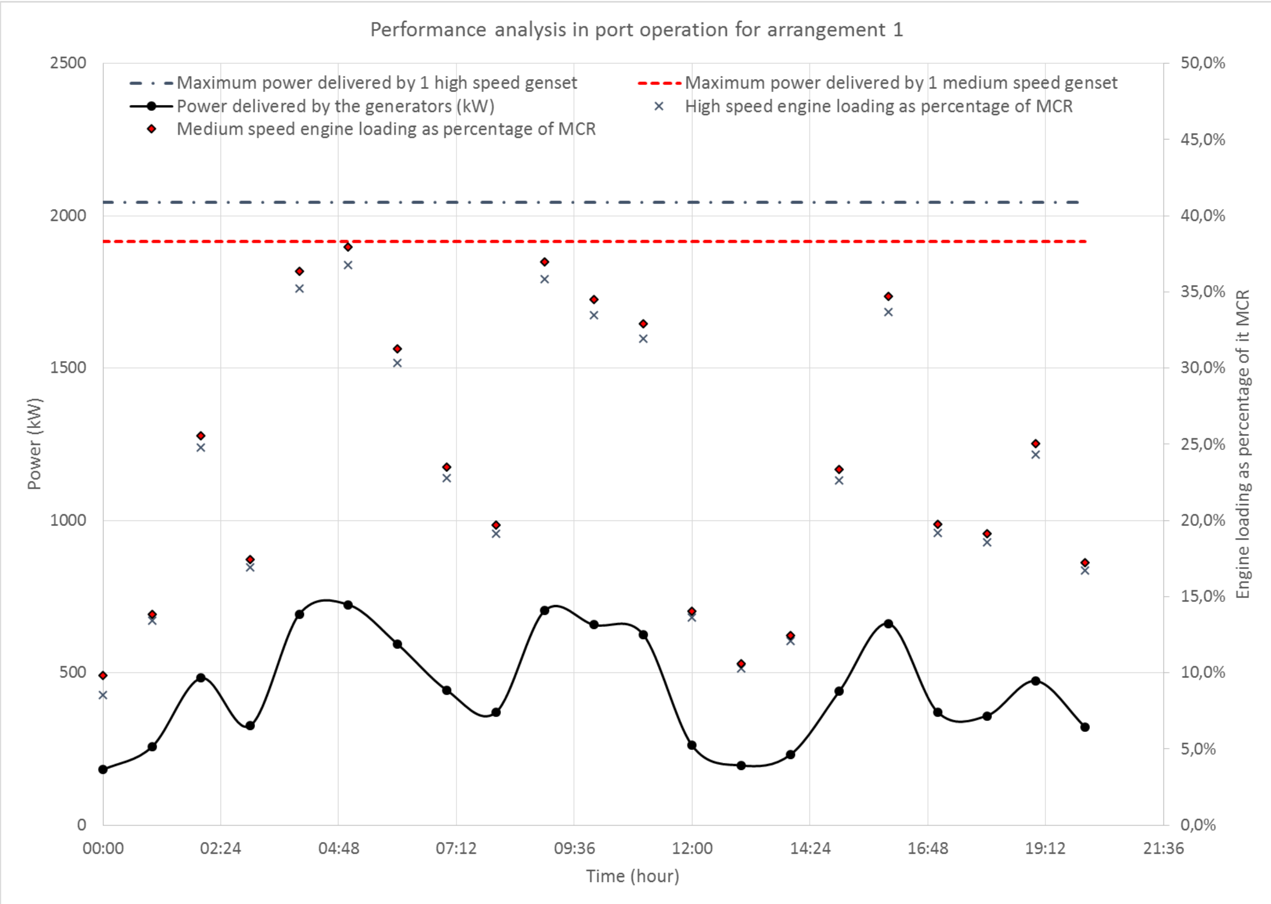

Figure 4.12 – Generated Power for Port Operation Detailing the Number of Diesel Generator Sets in Operation and Their Corresponding Loading.

It should be noticed that only one Diesel generator set of each type was required to supply the demand. Furthermore, the loading of the Diesel engines is low, varying within a range from 10% to around 40%; the loading samples are highly scattered for the time range.

The fuel consumed by the high and medium speed Diesel engines and their respective exhaust emissions were obtained using Eq. 4.11 to 4.15 for the SFOC functions of high and medium speed Diesel engines, Eq. 4.7 to 4.10 for the exhaust gases. The fuel consumption and the exhaust gases released are shown in Table 4.1.

Table 4.1 – Fuel Consumption and Exhaust Gases Released in Port Operation for Arrangement 1.

Port Operation				
	Fuel consumption (kg)	NOx emissions (kg)	SOx emissions (kg)	CO_2 emissions (kg)
High speed generator set (MGO)	2215,2	69,8	66,5	7066,6
Medium speed generator set (HFO)	1973,2	86,0	138,1	6294,4

4.2.1.2 Laden voyage

In laden voyage the power produced by the engines is defined by a simplified form of Eq. 4.3 in which the dynamic positioning power is zero:

$$Engpow_n = \frac{1}{\eta_{switch}\eta_{gen}}\left(\frac{Prop.power_n}{\eta_{maz}\eta_{VFDaz}\eta_{trafoaz}} + Aux.power_n\right) \tag{4.17}$$

The efficiencies for the main propulsion system are 0.966 for the motor (see Table 3.8), 0.975 for the VFD (see Table 3.12) and 0.985 for the converter transformer (see Table 3.13). The generated power is also defined by a simplified form of Eq. 4.6:

$$Genpow_n = \frac{1}{\eta_{switch}}\left(\frac{Prop.power_n}{\eta_{maz}\eta_{VFDaz}\eta_{trafoaz}} + Aux.power_n\right) \tag{4.18}$$

The loading of the engines is defined by Eq. 4.12 and 4.14. In Figure 4.13 the total power provided by the generators, the number of Diesel generator sets in operation and their loading are plotted.

From the figure it can be noticed that 3 to 4 Diesel generator sets are required. Besides, the loading of both type of Diesel engines is within a range from 70% to almost 100%.

The fuel consumption was obtained using Eq. 4.3 and from 4.11 to 4.14; whereas Eq. 4.7 to 4.10 for the exhaust gases. The number of Diesel engines in operation for each power sample was shown in Figure 4.13. The results are presented in Table 4.2.

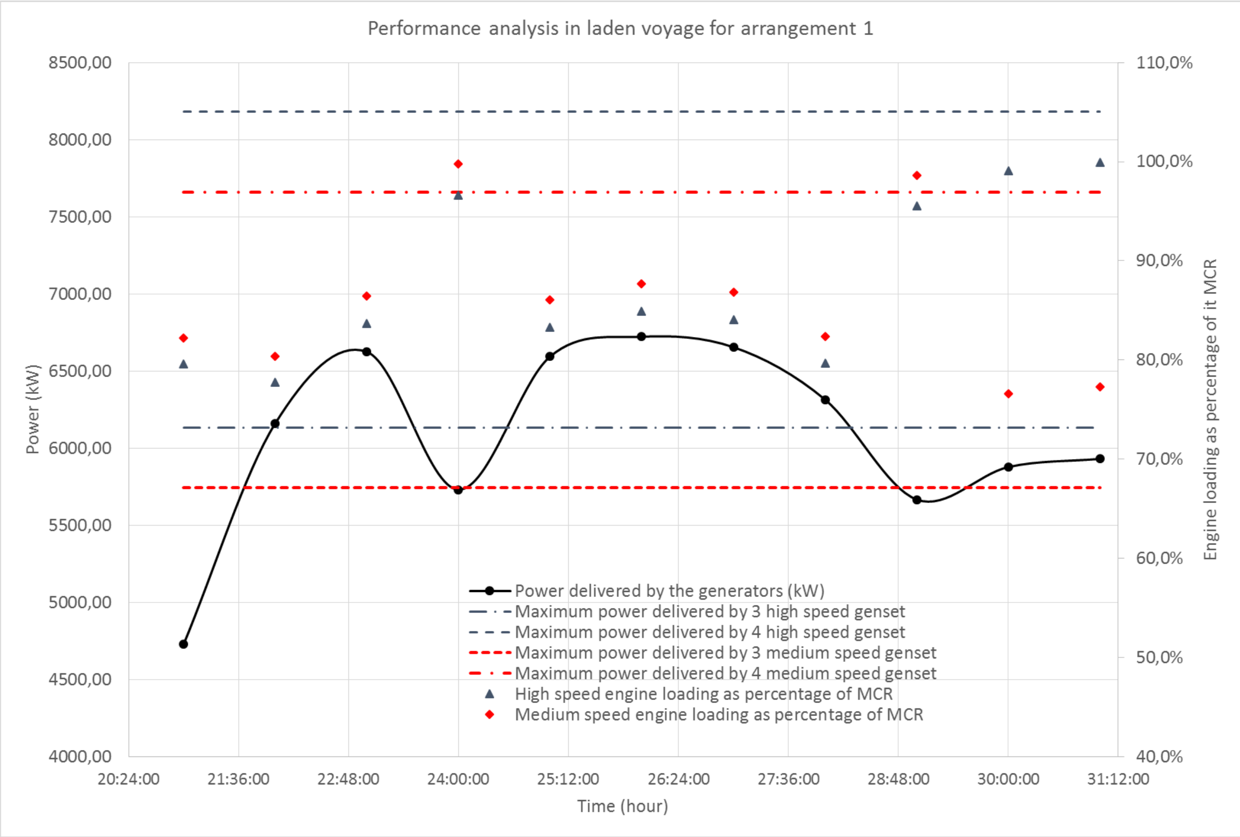

Figure 4.13 - Generated Power for Laden Voyage Detailing the Number of Diesel Generator Sets in Operation and Their Corresponding Loading.

Table 4.2 - Fuel Consumption and Exhaust Gases Released in Laden Voyage for Arrangement 1

Laden voyage				
	Fuel consumption (kg)	NOx emissions (kg)	SOx emissions (kg)	CO_2 emissions (kg)
High speed generator set (MGO)	13268,3	483,6	398,1	42326,0
Medium speed generator set (HFO)	12583,7	597,1	880,9	40142,1

4.2.1.3 Dynamic positioning

In dynamic positioning the maximum power request from the main azimuth thrusters, as defined in the load profile, is 156kW; assuming that this power is provided by one of the two main induction motors, this value is equivalent to 5% of the motor rated power. As it was discussed in Section 2.5.1, the efficiency of the induction motor significantly drops when the load is below 20% of the rated power; hence, if 156kW is the maximum power delivered by one of the induction motors, it can be deduced that the efficiency will be low. Unfortunately, it was not possible to obtain the accurate efficiencies of the motors for low loadings; instead of this, it will be assumed an efficiency of 85% for all the shaft loads below 156kW, taking as a guide the typical efficiency curves of the induction motor for partial loads presented in the U.S. department of energy (2008). Furthermore, the efficiency of the VFD is also affected by low loads; since it is not possible to obtain the approximated values for the VFD efficiency (because the rotational speed of the azimuth thrusters is not known), the efficiency of the VFD for the main propulsion motors will be fixed at 90%, which corresponds to the value of the typical VFD efficiency for a load equal to 10% of the rated load at 50% of the rated frequency (see Figure 2.10).

The efficiency of the VFD transformer will be maintained unchanged at 98.5% for all the load range.

For the side thrusters, the efficiencies will be considered as constant for all the load range and equal to those presented in Section 3.5.3.4. For the induction motor the efficiency is 96.5% and for the VFD converter it is 99.8%.

The power provided by the engines is defined by Eq. 4.3, while the power generated is defined by Eq. 4.6. The loading of the Diesel engines is obtained by Eq. 4.12 and 4.14.

The total power generated and the loading of the Diesel engines for dynamic positioning operation are shown in Figure 4.14.

From the figure, it should be noticed that one Diesel generator set (in the high and medium speed range) is sufficient for providing power to supply the power demand for Dynamic Positioning. However, since at least two generating units are required to be in operation, the loading of their Diesel engines is significantly low, between 18% and 50%.

The fuel consumption is obtained using Eq. 4.1 along with Eq. 4.6 and from 4.11 to 4.14 for the SFOC definition using the efficiencies already informed. The exhaust gases are obtained by means of Eq. 4.7 to 4.10. The summarized results are presented in .

Table 4.3 - Fuel Consumption and Exhaust Gases Released in Dynamic Positioning for Arrangement 1

Dynamic Positioning				
	Fuel consumption (kg)	NOx emissions (kg)	SOx emissions (kg)	CO_2 emissions (kg)
High speed generator set (MGO)	13688,1	443,1	410,6	43665,1
Medium speed generator set (HFO)	12228,5	546,2	856,0	39008,9

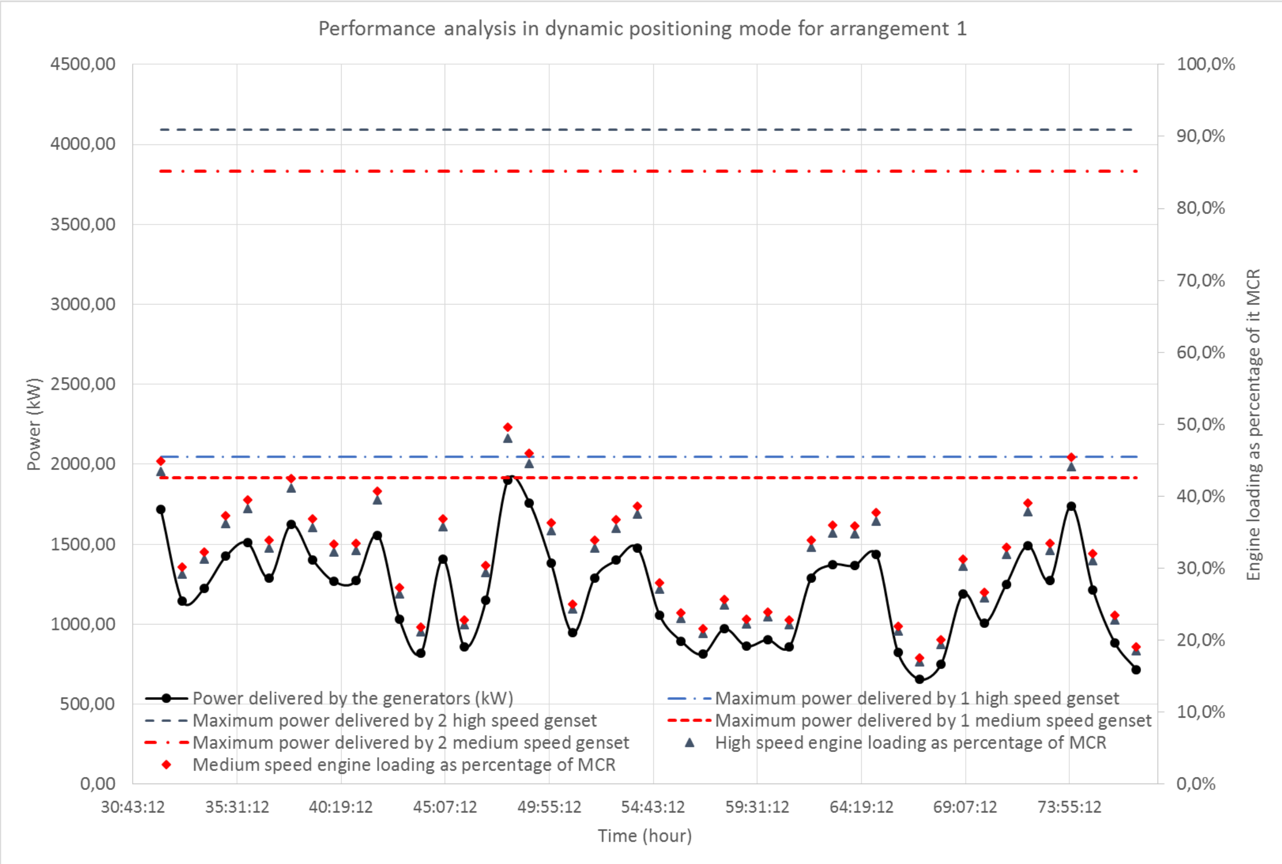

Figure 4.14 - Generated Power for Dynamic Positioning Detailing the Number of Diesel Generator Sets in Operation and Their Corresponding Loading.

4.2.1.4 Partial load voyage

The same equations for the laden voyage are used. The generated power, the Diesel engines loading and the number of the Diesel generator sets in operation are presented in Figure 4.15.

It can be noticed that, for most of the time, only 3 generator sets are required. The loading of the engines is almost the same, varying between 70% and 98%.

The fuel consumption and the exhaust gases emissions are obtained using the same equations applied for laden voyage, Table 4.4 summarizes the fuel consumed and the exhaust gases released.

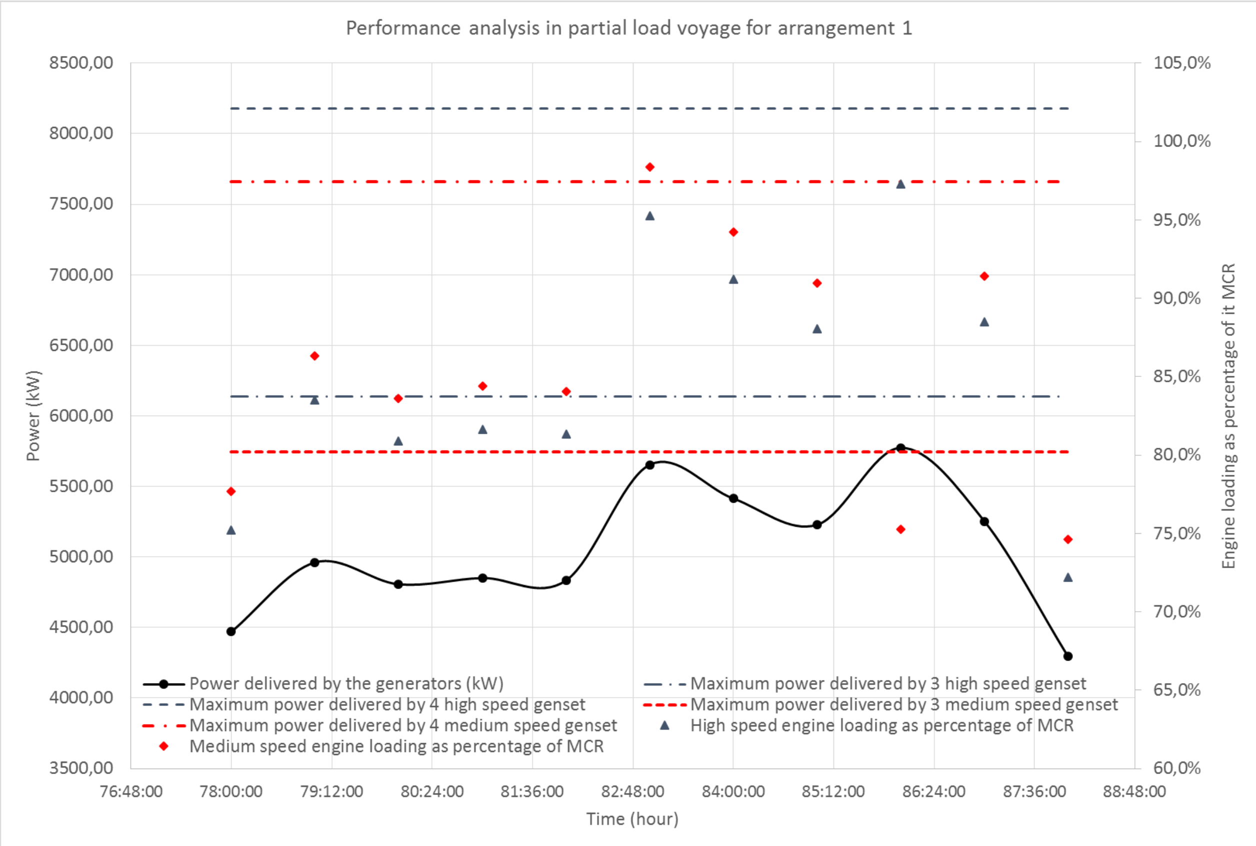

Figure 4.15 - Generated Power for Partial Load Voyage Detailing the Number of Diesel Generator Sets in Operation and Their Corresponding Loading.

Table 4.4 - Fuel Consumption and Exhaust Gases Released in Partial Load Voyage for Arrangement 1

Partial load voyage				
	Fuel consumption (kg)	NOx emissions (kg)	SOx emissions (kg)	CO_2 emissions (kg)
High speed generator set (MGO)	11113,2	404,8	333,4	35451,3
Medium speed generator set (HFO)	10534,5	499,8	737,4	33604,9

4.2.1.5 Stand by operation

In stand by operation mode, the same equations and assumptions made for port operation are applied. The generated power, the number of Diesel generator sets in operation and their respective loading are shown in Figure 4.16.

No more than 1 generator set is needed to supply the required power demand for standby mode. Furthermore, the Diesel engines loading is significantly low, below 40% for all time samples.

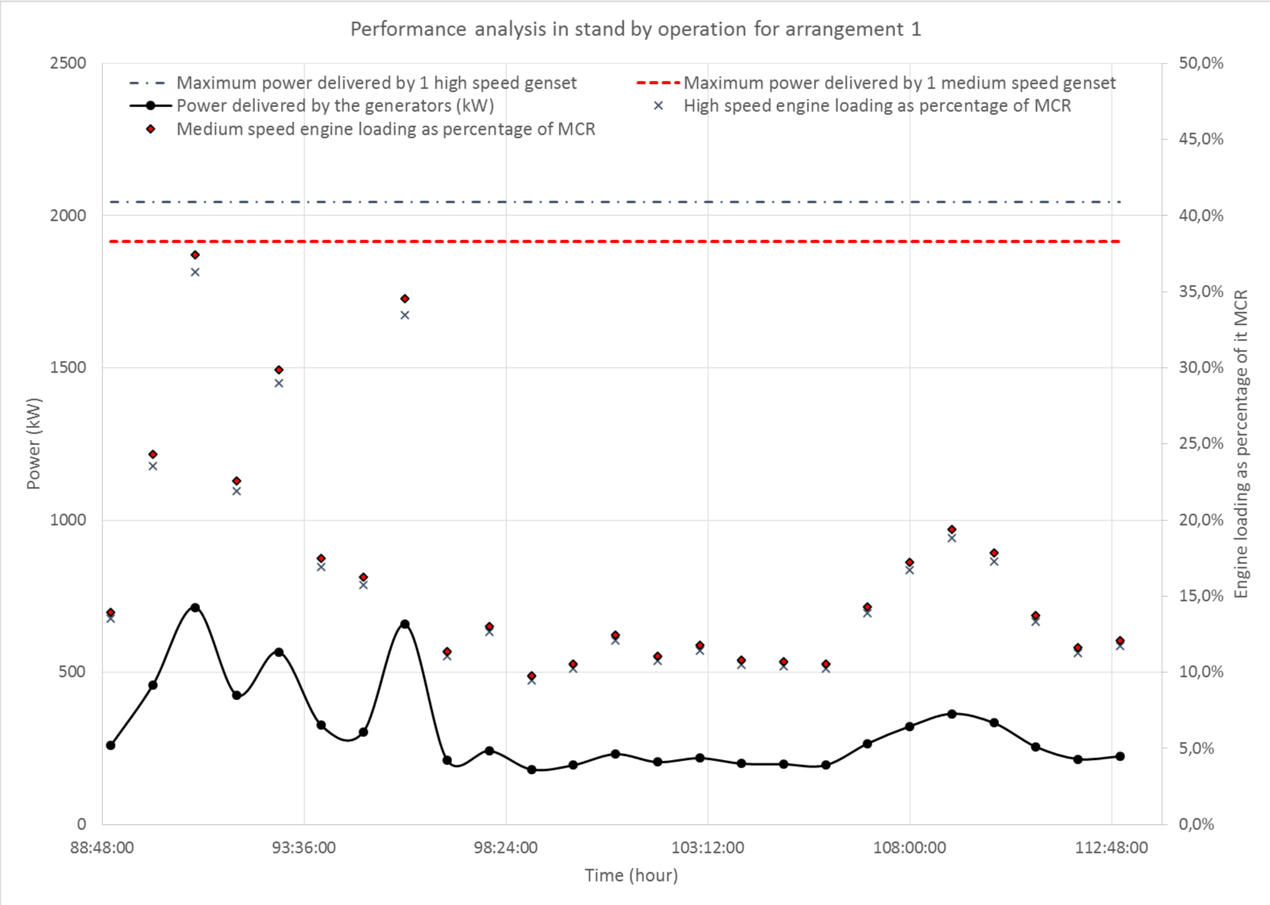

Figure 4.16 - Generated Power for Standby Mode, Detailing the Number of Diesel Generator Sets in Operation and Their Corresponding Loading.

The estimation of the fuel consumption and exhaust gases was made using the same procedure as for port operation. Table 4.5 shows the summarized fuel consumption and exhaust gases for stand by operation.

Table 4.5 - Fuel Consumption and Exhaust Gases Released in Stand by Operation for Arrangement 1

Stand by operation				
	Fuel consumption (kg)	NOx emissions (kg)	SOx emissions (kg)	CO2 emissions (kg)
High speed generator set (MGO)	2473,7	75,2	74,2	7890,9
Medium speed generator set (HFO)	2200,7	92,8	154,1	7020,3

4.2.1.6 Average engine loading, total fuel consumption and exhaust gases emissions

The average loading of the Diesel engines for this arrangement was estimated in 37% for the high speed ones and 37.4% for the medium speed ones. The total fuel consumption and exhaust emissions for each operation type and each type of Diesel generator set are presented in Table 4.6.

Table 4.6 – Fuel Consumption and Exhaust Gases Released by Arrangement 1.

		Fuel consumption (kg)	NOx emissions (kg)	SOx emissions (kg)	CO2 emissions (kg)
Port Operation	High speed generator set (MGO)	2215,2	69,8	66,5	7066,6
	Medium speed generator set (HFO)	1973,2	86,0	138,1	6294,4
Laden voyage	High speed generator set (MGO)	13268,3	483,6	398,1	42326,0
	Medium speed generator set (HFO)	12583,7	597,1	880,9	40142,1
Dynamic positioning	High speed generator set (MGO)	13688,1	443,1	410,6	43665,1
	Medium speed generator set (HFO)	12228,5	546,2	856,0	39008,9
Partial load voyage	High speed generator set (MGO)	11114,6	404,8	333,4	35455,4
	Medium speed generator set (HFO)	10535,7	499,9	737,5	33608,8
Stand by	High speed generator set (MGO)	2473,7	75,2	74,2	7890,9
	Medium speed generator set (HFO)	2200,7	92,8	154,1	7020,3
TOTAL	High speed generator set (MGO)	42759,9	1476,5	1282,8	136404,1
	Medium speed generator set (HFO)	39521,8	1821,9	2766,5	126074,5

From the table, the following observations can be highlighted:

- The fuel consumption of the high speed generator set is approximately 7% higher than for the medium speed generator sets. This is a consequence of the lower SFOC values of the medium speed Diesel engines when compared to the high speed ones. Furthermore, since the CO_2 emissions depend only on the amount of fuel burned, the same proportion between high speed and medium speed is maintained.
- Because of the high NOx emission factors for medium speed Diesel engines, the NOx emissions are 23% higher for this engine when compared to the high speed ones.
- The SOx emissions for medium speed Diesel engines are more than the double when compared to the high speed ones.

4.2.2 Arrangement 2

Since the Diesel generator sets for the arrangement 2 are the same of the arrangement 1, the SFOC curves defined from Eq. 4.11 to 4.14 are used to determine the fuel consumption of the Diesel engines. The emission factors are also the same as defined before.

4.2.2.1 Port operation

The same equations applied for port operation in arrangement 1 for the power provided by the Diesel engines and the generated power are applied here. The high speed Diesel engine loading is defined by Eq. 4.12, while the medium speed Diesel engine loading is defined by Eq. 4.20. In Figure 4.17, the generated power, engines loading and number of Diesel generator sets in operation are presented.

From the figure it can be noticed that one Diesel generator set is enough to supply the power demand from the auxiliary loads; the engines are loaded between 10% and 40% of their rated MCR. Besides, when making a comparison between the engines, the loading of the medium speed Diesel engines is slightly superior than it is for the high speed ones.

The fuel consumed by the high and medium speed Diesel engines and their respective exhaust emissions were obtained using the SFOC definitions in Eq. 4.11, 4.12, 4.13, 4.14 and from Eq. 4.7 to 4.10. In Table 4.7 the results are shown.

Table 4.7 - Fuel Consumption and Exhaust Gases Released in Port Operation for Arrangement 2.

Port Operation				
	Fuel consumption (kg)	NOx emissions (kg)	SOx emissions (kg)	CO2 emissions (kg)
High speed generator set (MGO)	2215,2	69,8	66,5	7066,6
Medium speed generator set (HFO)	1973,2	86,0	138,1	6294,4

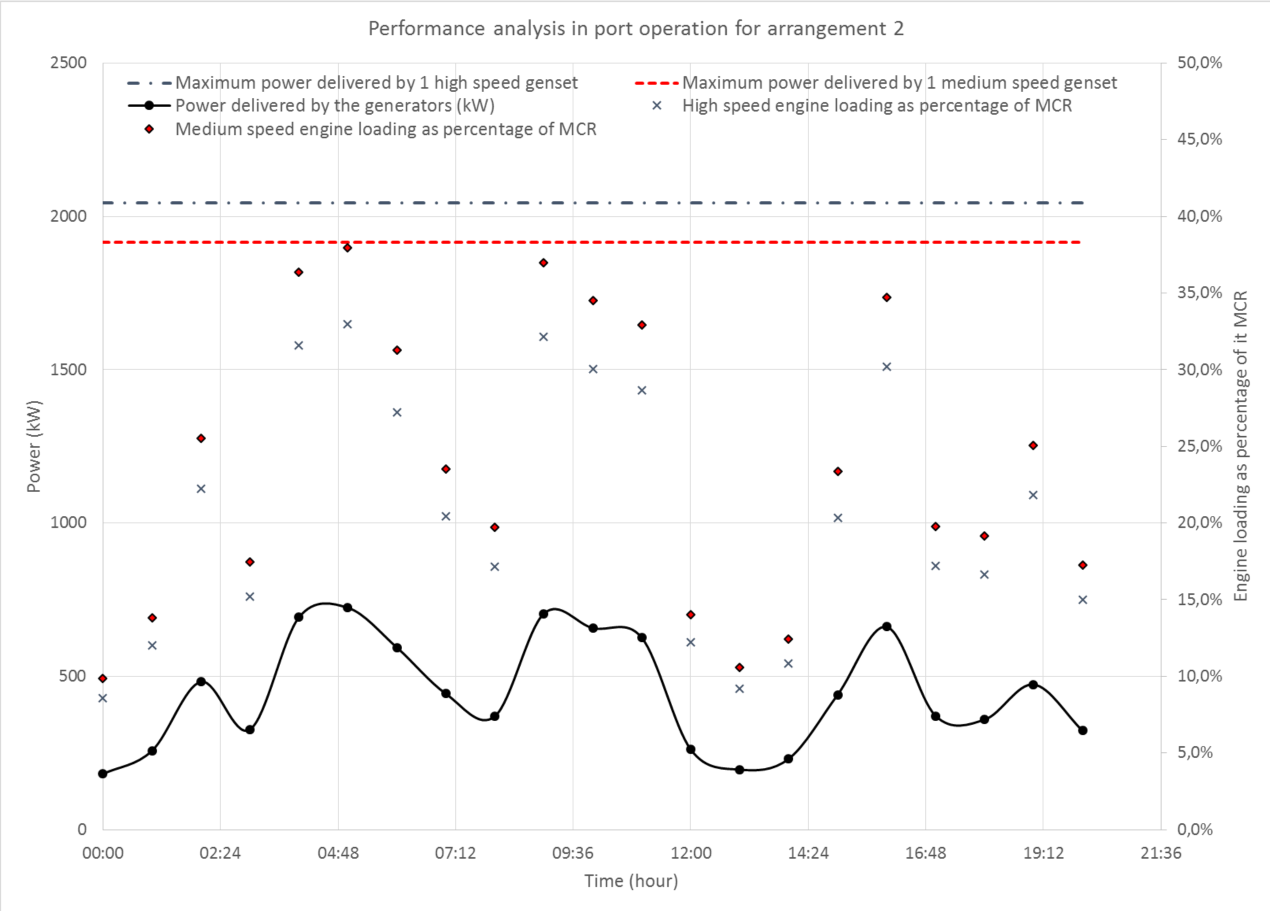

Figure 4.17 - Generated Power for Port Operation in Arrangement 2, Detailing the Number of Diesel Generator Sets in Operation and Their Corresponding Loading.

4.2.2.2 *Laden voyage*

The same equations applied in laden and partial load voyage in arrangement 1 for the generated power and the power produced by the engine are used here. The high speed Diesel engine loading is defined by Eq. 4.12 and for the medium speed Diesel engine by Eq. 4.14. In Figure 4.18, the total power generated, number of generator sets in operation and each engine loading are plotted.

From the figure it can be noticed that for most of the time, 4 Diesel generating sets are required to be in service; additionally, the power rating of the medium speed Diesel generator sets is lower when compared to the high speed ones, thus their loading is higher. For the medium speed Diesel engines the loading is between 76% and 97%, while for the high speed ones it is between 72% and 91%.

The fuel consumption is determined using the same equations as those in port operation for arrangement 2. In Table 4.8 the summarized results are presented.

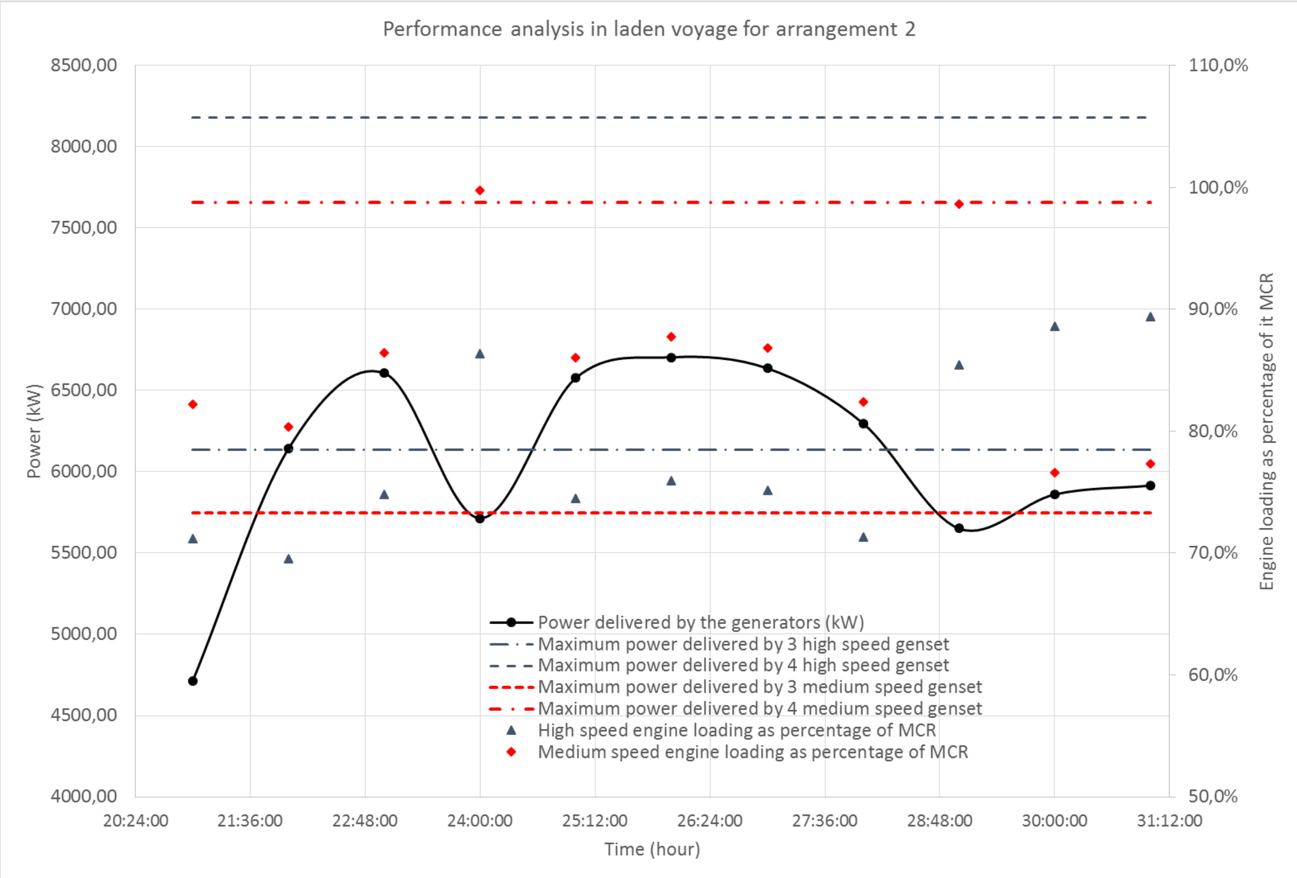

Figure 4.18 - Generated Power for Laden Voyage in Arrangement 2 Detailing the Number of Diesel Generator Sets in Operation and Their Corresponding Loading.

Table 4.8 - Fuel Consumption and Exhaust Gases Released in Laden Voyage for Arrangement 2

Laden voyage				
	Fuel consumption (kg)	NOx emissions (kg)	SOx emissions (kg)	CO2 emissions (kg)
High speed generator set (MGO)	13285,9	481,9	398,6	42382,0
Medium speed generator set (HFO)	12506,3	595,3	875,4	39895,2

4.2.2.3 Dynamic positioning

Eq. 4.3, for the power produced by the Diesel engines, and Eq. 4.6, for the generated power, are used for DP operation. Regarding the efficiencies of the main propulsion system, the synchronous motor efficiency varies as a function of the shaft load. Assuming that a single synchronous motor is operating to provide the required thrust for DP, the maximum expected power from the motor is 156kW, hence, the loading of the motor is approximately 5.3%. The efficiency for this loading is not available in the literature; thus, it will be assumed that the efficiency of the synchronous motor is exactly the same as the one considered for the main induction motors in arrangement 1 *i.e.*, 85%. The VFD efficiency will be also supposed as 90% while 98.5% for the transformer. The efficiencies for side thrusters are the same as those of arrangement 1.

The generated power is plotted in Figure 4.19. Additionally, the loading of the Diesel generator sets, defined by Eq. 4.12 and 4.14 is plotted in the figure.

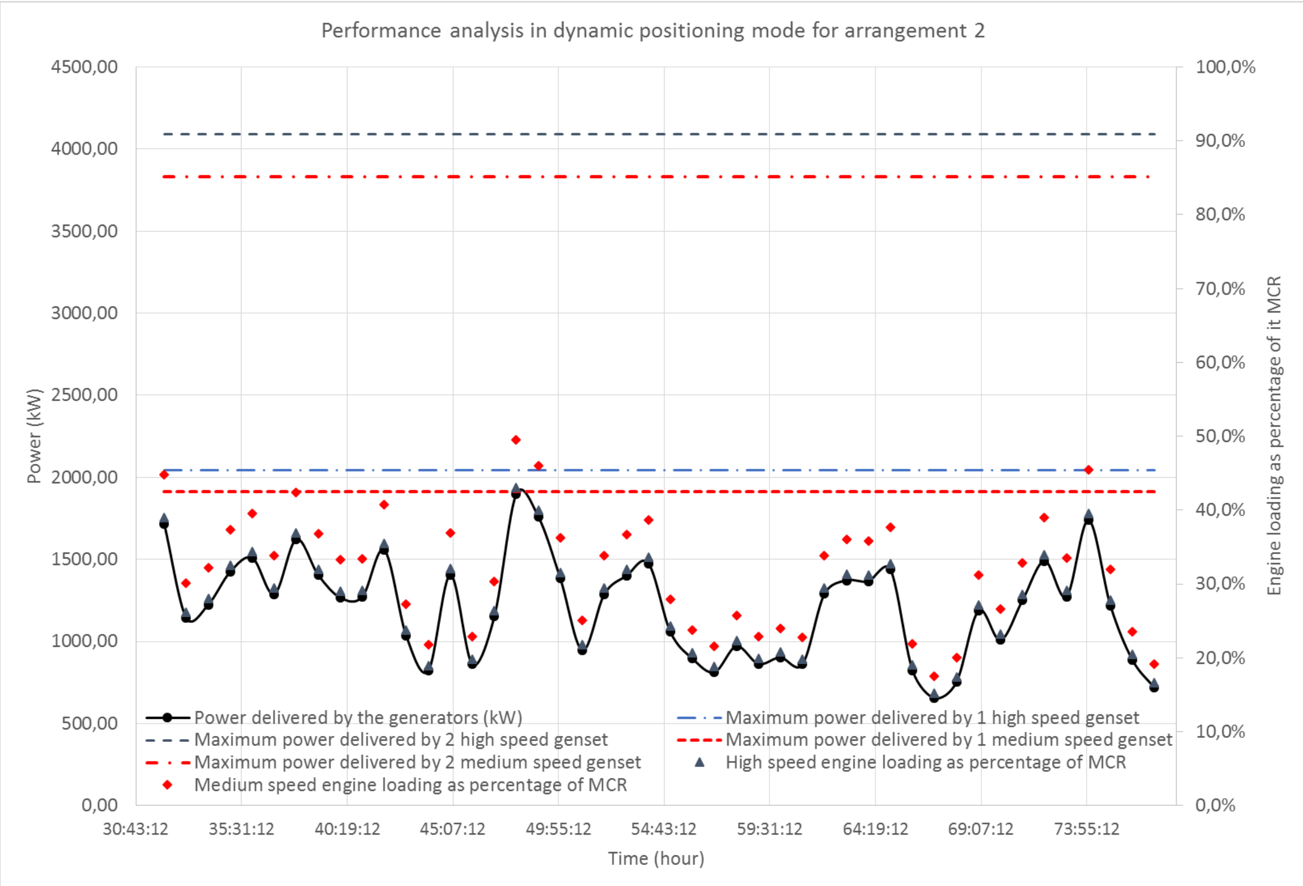

Figure 4.19 - Generated Power for Dynamic Positioning in Arrangement 2 Detailing the Number of Diesel Generator Sets in Operation and Their Corresponding Loading.

Similar to the arrangement 1, it can be observed that 1 Diesel generator set can provide the sufficient power to supply the power demand in Dynamic Positioning mode. The total power demand is split in two Diesel generator sets, hence, the loading of each Diesel engine is maintained low, between 15% and 50% for the two types of Diesel generator sets.

The fuel consumption and the exhaust gases released are shown in Table 4.9.

Table 4.9 - Fuel Consumption and Exhaust Gases Released in Dynamic Positioning for Arrangement 2

Dynamic Positioning				
	Fuel consumption (kg)	NOx emissions (kg)	SOx emissions (kg)	CO2 emissions (kg)
High speed generator set (MGO)	13686,4	443,0	410,6	43659,5
Medium speed generator set (HFO)	12226,9	546,1	855,9	39003,8

4.2.2.4 Partial load voyage

The same equations used for laden voyage are applied here. The generated power, loading of the Diesel engines and number of Diesel generator sets in operation are shown in Figure 4.20.

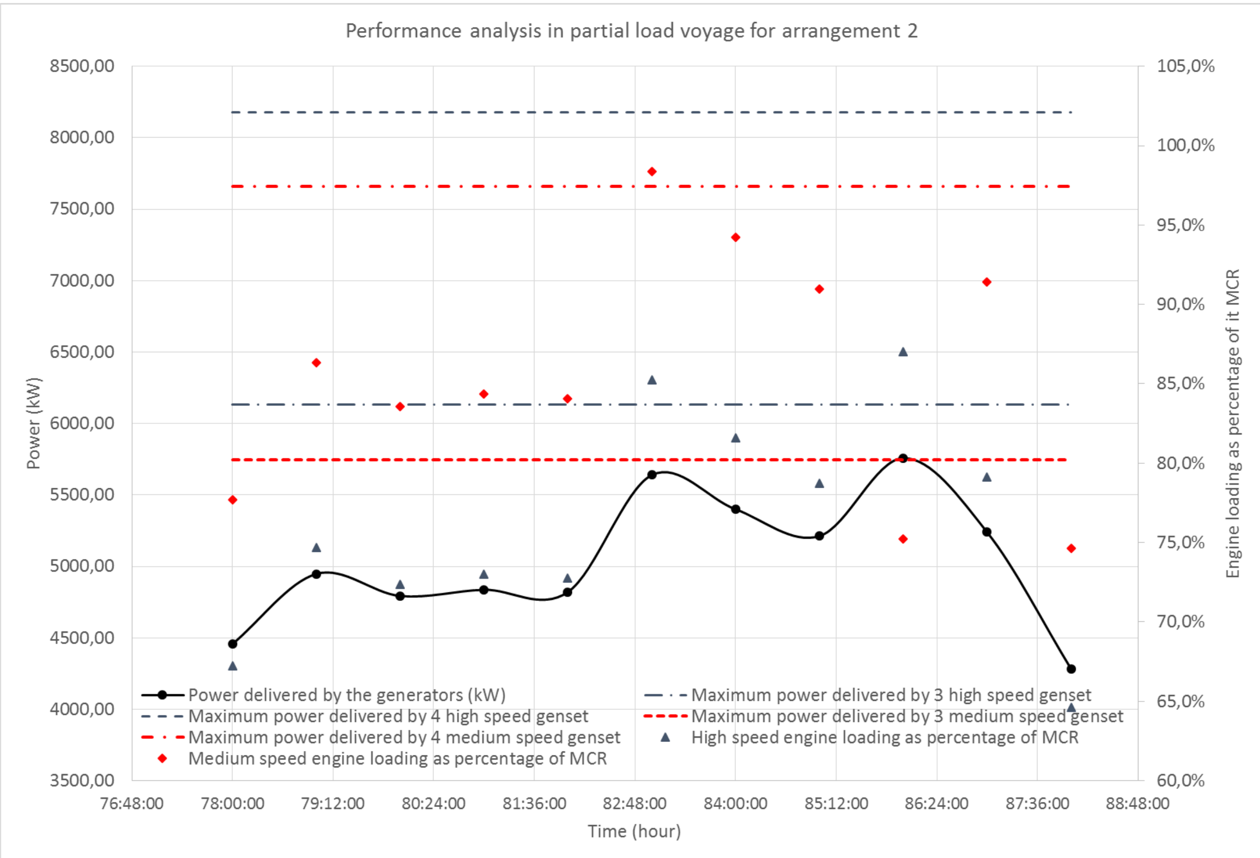

Figure 4.20 - Generated Power for Partial Load Voyage in Arrangement 2, Detailing the Number of Diesel Generator Sets in Operation and Their Corresponding Loading.

It can be seen that most of the time 3 generator sets are in operation. The loading of the medium speed Diesel engines is significantly higher than the loading of the high speed ones, almost 5%. The loading of the Diesel generator sets ranges between 73% and more than 98%.

The fuel consumption and the exhaust gases emitted are calculated using the same equations as for laden voyage. Table 4.10 presents the results.

Table 4.10 - Fuel Consumption and Exhaust Gases Released in Partial Load Voyage for Arrangement 2.

Partial load voyage				
	Fuel consumption (kg)	NOx emissions (kg)	SOx emissions (kg)	CO2 emissions (kg)
High speed generator set (MGO)	11111,7	403,5	333,4	35446,5
Medium speed generator set (HFO)	10487,6	498,4	734,1	33455,5

4.2.2.5 Stand by operation

The generated power, number of Diesel generating sets and their respective loading are shown in Figure 4.21. The data was obtained using the same equations applied in port operation.

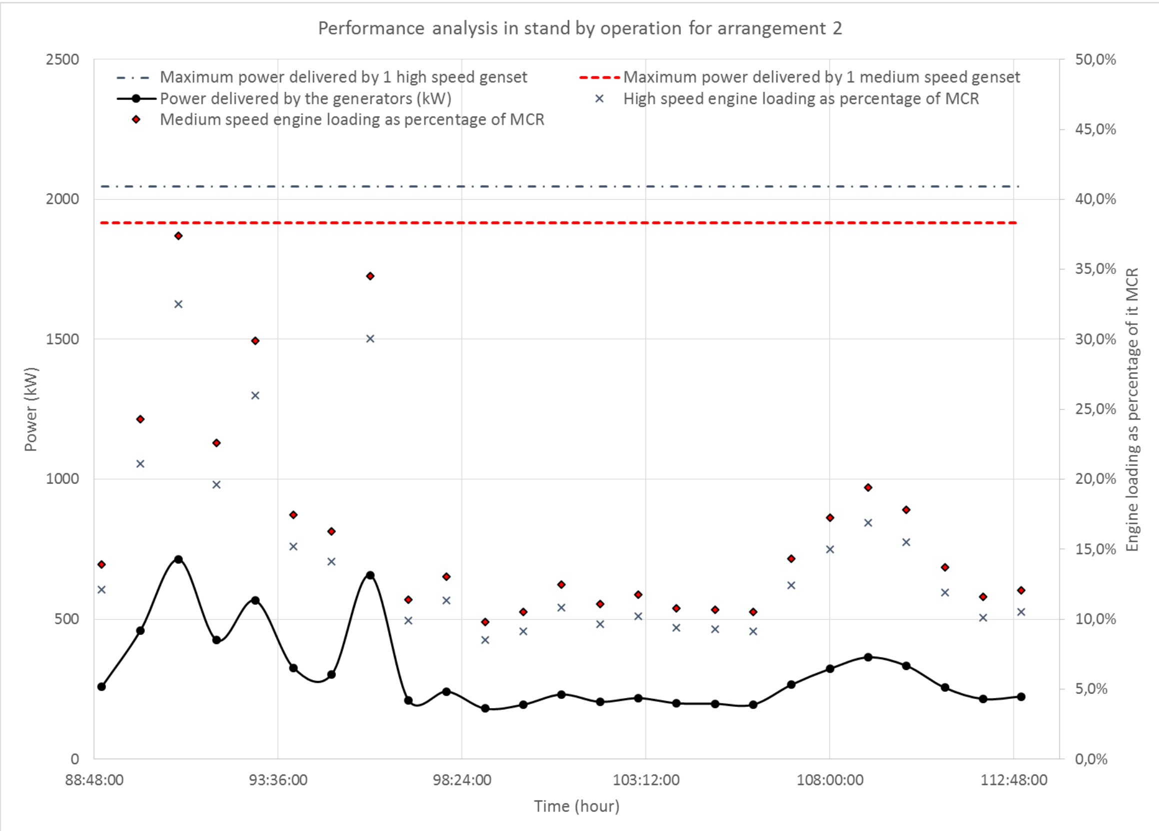

Figure 4.21 - Generated Power for Standby Mode in Arrangement 2 Detailing the Number of Diesel Generator Sets in Operation and Their Corresponding Loading.

From the figure, the same performance seen in port operation is presented. One Diesel generator set is supplying the demanded load while being under loaded, below 40% of its MCR.

The fuel consumption and exhaust gases released are shown in Table 4.11.

Table 4.11 - Fuel Consumption and Exhaust Gases Released in stand by Operation for Arrangement 2.

Stand by operation				
	Fuel consumption (kg)	NOx emissions (kg)	SOx emissions (kg)	CO2 emissions (kg)
High speed generator set (MGO)	2472,2	75,2	74,2	7886,2
Medium speed generator set (HFO)	2199,4	92,7	154,0	7016,1

4.2.2.6 Average engine loading, total fuel consumption and exhaust gases emissions

For this arrangement the average loading of the Diesel engines was 33% for the high speed engines and 37.4% for the medium speed ones. The fuel consumption and exhaust gases emissions for arrangement 2 are presented in Table 4.12, divided into operation type and generator set type.

From the table some details can be highlighted:

- The fuel consumption of the high speed Diesel generator set is approximately 8% higher than for the medium speed one. The difference between the fuel consumption of the high speed generator set and that of the medium speed one is more than 3tonnes.
- The NOx emissions for the medium speed engine remain 23% higher than those for the high speed one.
- As deduced in arrangement 1, the SOx emissions for medium speed gensets are more than the double of the high speed gensets.
- The CO_2 emissions are 8% lower for the medium speed gensets when compared to the high speed ones.

4.2.3 Arrangement 3

In this arrangement, since its structure is the same as arrangement 1, the same equations are applied. The efficiency of the ZEBRA batteries is reported as 100% (see Table 2.4), while the efficiency of the bidirectional AC/DC power converter is reported as 97.5% (see Table 3.32).

Table 4.12 - Fuel Consumption and Exhaust Gases Released by Arrangement 2

		Fuel consumption (kg)	NOx emissions (kg)	SOx emissions (kg)	CO2 emissions (kg)
Port Operation	High speed generator set (MGO)	2215,2	69,8	66,5	7066,6
	Medium speed generator set (HFO)	1973,2	86,0	138,1	6294,4
Laden voyage	High speed generator set (MGO)	13232,2	482,2	397,0	42210,6
	Medium speed generator set (HFO)	12546,7	595,4	878,3	40024,0
Dynamic positioning	High speed generator set (MGO)	13686,4	443,0	410,6	43659,5
	Medium speed generator set (HFO)	12226,9	546,1	855,9	39003,8
Partial load voyage	High speed generator set (MGO)	11085,5	403,7	332,6	35362,6
	Medium speed generator set (HFO)	10505,5	498,5	735,4	33512,5
Stand by	High speed generator set (MGO)	2472,2	75,2	74,2	7886,2
	Medium speed generator set (HFO)	2199,4	92,7	154,0	7016,1
TOTAL	High speed generator set (MGO)	42691,4	1473,9	1280,7	136185,5
	Medium speed generator set (HFO)	39451,6	1818,8	2761,6	125850,7

The performance analysis for arrangement 3 was done for all the operational modes and summarized in one figure for each type of Diesel generator set. In Figure 4.22 and Figure 4.23 the performance analysis is shown for the complete standard load profile for both high speed Diesel generator sets and medium speed ones respectively. In contrast with the graphs in arrangements 1 and 2, the figures detail the power at the input of the switchboard (consisting in the power provided by the batteries and the Diesel generator sets to supply the total power demand) and the total power delivered by the generator sets; the difference between these values is the energy provided/demanded from the batteries bank, which is represented by the colored areas in Figure 4.22 and Figure 4.23; a yellow colored area indicates that the battery is providing energy to compensate the power demand, whereas the green colored area indicates that the battery is storing energy (taking the excess of energy from the generator sets). It is assumed that the batteries bank is totally charged at the beginning of the service.

In the analysis performance of arrangements 1 and 2 was noticed that in port, dynamic positioning and stand by operational modes the Diesel engines in operation are loaded under 50% of their rated power. According to the analysis made to the Diesel engines in section 2.1.1, a Diesel engine consumes more fuel per kWh generated when is underloaded than when is loaded at their optimum operational point (between 75%-90% of its rated power). Therefore, so as to reduce the fuel consumed by the Diesel engines, the energy compensation of the batteries bank is focused for when the vessel is in port operation, dynamic positioning mode and stand by operation. When the vessel is in laden or partial load voyage the batteries are mainly receiving power.

It should be noticed that in some time periods, the generator sets are not providing power, which is supplied by the batteries. When the generator sets are in service, their loading is maintained almost constant and close to the maximum power that they can provide; whereas the batteries bank is compensating the difference with the demanded power. This loading of the generator sets was selected to match the optimum operational point of the Diesel engines. For the high speed Diesel engines selected (MTU), the lowest SFOC is at 75% of their MCR, which was settled as the loading target. For the medium speed ones (MAN), the lowest SFOC is within a range from 75% to 90% of MCR, thus, the loading target was settled at 85%. The black dots in the figures indicate the engine loading; it can be seen that the loading is not constant and varies around the loading target for each type of engine. The available energy from the batteries at the beginning and at the end of the round trip is indicated. It is important to observe that the stored energy does not reach the rated level as it did in the beginning; this is because the power management system is supposed to maintain a balance between the stored energy meant for keeping the engines loaded at their optimum operational point and for supplying all the power required in port, DP and stand by operation; hence, the stored energy at the end of the round trip can be different from that at the beginning.

For this arrangement it is supposed that the energy of the batteries bank is regulated by a power managing system in order to maintain the engines loaded close to their optimum operational point. It is assumed that the system maintains the batteries charged at the end of the round trip with an energy level close to the rated energy capacity of the batteries. Furthermore, it is assumed that the system controls the charge and discharge current of the batteries.

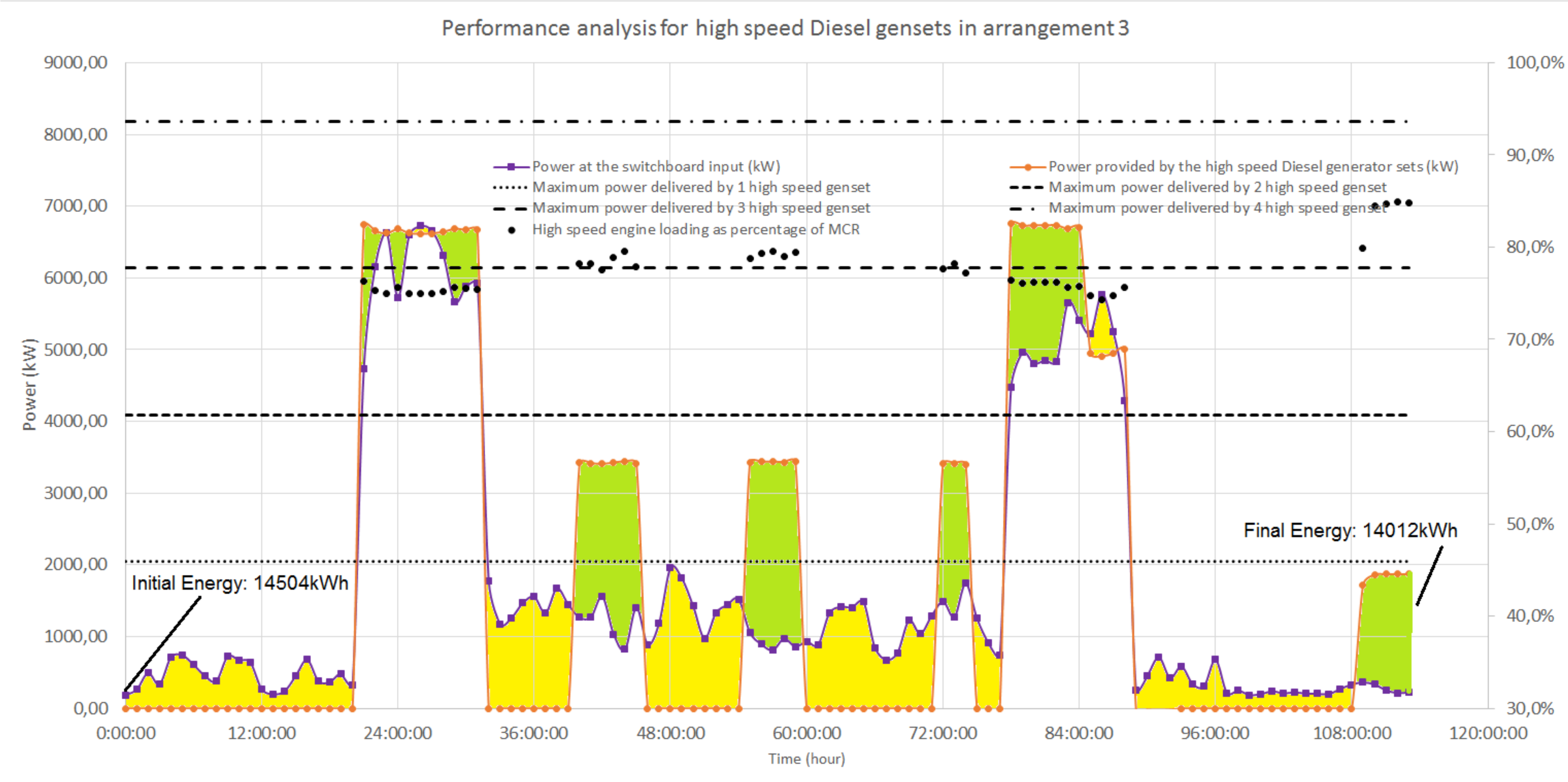

Figure 4.22 – Performance Analysis for High Speed Diesel Generator Sets in Arrangement 3 Detailing the Engines Loading, the Power Provided by the Generator Sets, the Power at the Switchboard Input, the Energy Delivered by the Batteries Bank (Yellow Colored Areas) and the Energy Stored by the Batteries Bank (Green Colored Areas).

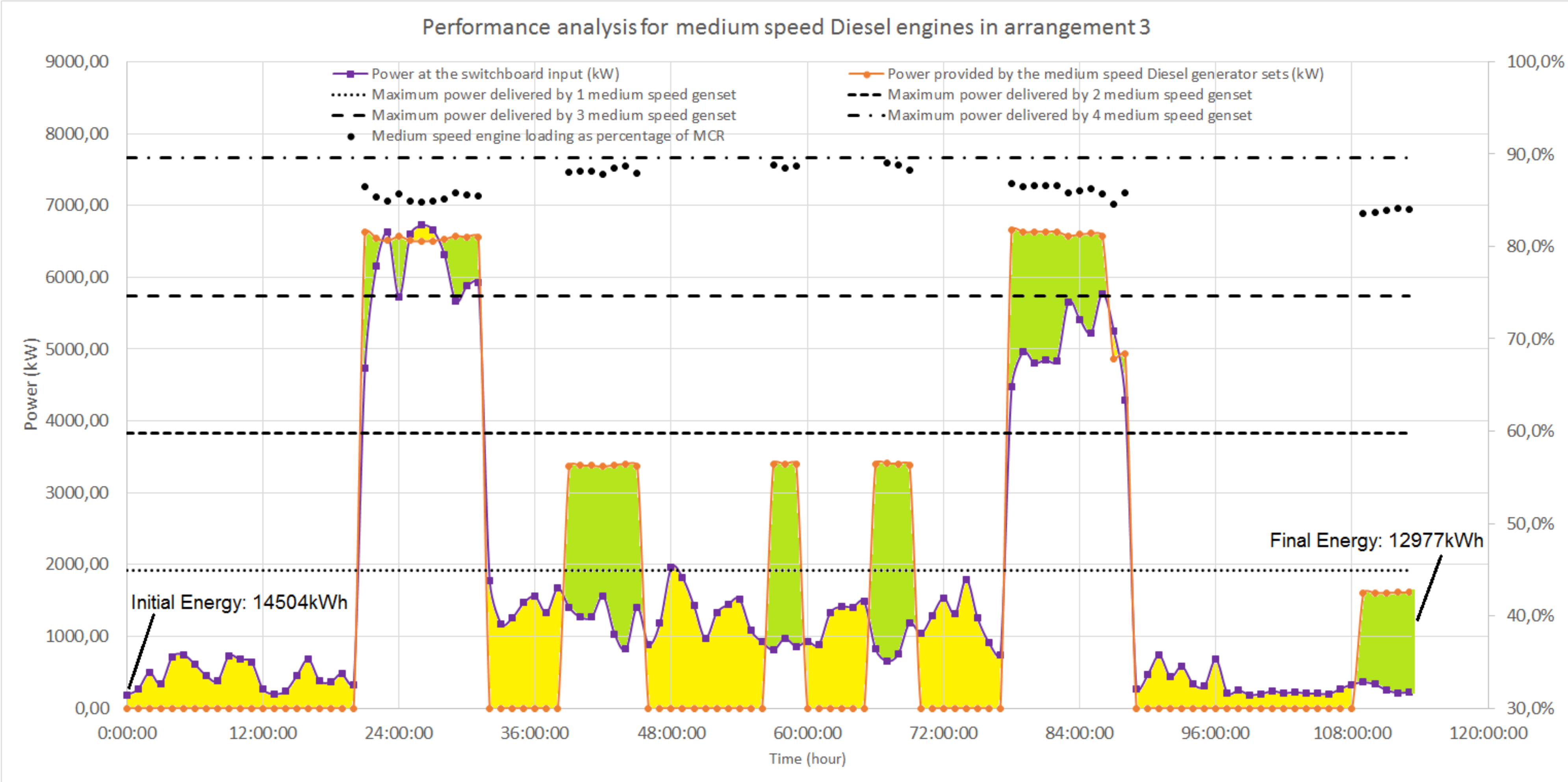

Figure 4.23 - Performance Analysis for Medium Speed Diesel Generator Sets in Arrangement 3 Detailing the Engines Loading, the Power Provided by the Generator Sets, the Power at the Switchboard Input, the Energy Delivered by the Batteries Bank (Yellow Colored Areas) and the Energy Stored by the Batteries Bank (Green Colored Areas).

Additionally, when the batteries are delivering power in DP mode, it is supposed that no one Diesel generator set is in operation. Since the batteries bank is divided in two sections, each one connected to one main busbar section, the arrangement of this system meets with the redundancy requisites for vessels with class 2 DP systems. When the batteries are receiving energy in DP mode, at least two Diesel generator sets must be operating.

The average loading of the Diesel engines for the arrangement is 94.4% for the high speed Diesel engines and 86% for the medium speed ones.

The fuel consumption and the exhaust gases emissions for this arrangement were approximated using the same eq. as in the previous arrangements and registered in Table 4.13.

Table 4.13 - Fuel Consumption and Exhaust Gases Released by Arrangement 3.

		Fuel consumption (kg)	NOx emissions (kg)	SOx emissions (kg)	CO_2 emissions (kg)
Port Operation	High speed generator set (MGO)	0,0	0,0	0,0	0,0
	Medium speed generator set (HFO)	0,0	0,0	0,0	0,0
Laden Voyage	High speed generator set (MGO)	14427,5	526,0	432,8	46023,8
	Medium speed generator set (HFO)	13438,3	638,9	940,7	42868,0
Dynamic Positioning	High speed generator set (MGO)	8939,3	325,4	268,2	28516,5
	Medium speed generator set (HFO)	8305,6	409,9	581,4	26494,8
Partial load Voyage	High speed generator set (MGO)	13285,7	484,5	398,6	42381,5
	Medium speed generator set (HFO)	13084,8	621,8	915,9	41740,5
Stand by	High speed generator set (MGO)	1712,0	62,4	51,4	5461,2
	Medium speed generator set (HFO)	1412,6	67,2	98,9	4506,3
TOTAL	High speed generator set (MGO)	38364,6	1398,3	1150,9	122383,1
	Medium speed generator set (HFO)	36241,3	1737,8	2536,9	115609,7

From table the following characteristics can be highlighted:

- Since the batteries are providing energy in port operational mode to supply all the power demand, the fuel consumption and the emitted gases are equal to zero.
- The difference between the gases emitted by the high and medium speed engines is maintained the same way as in the previous arrangements.
- The implementation of the batteries bank kept the average loading of the Diesel engines close to their optimum operational point.

4.2.4 Arrangement 4

The performance analysis for this arrangement was done exactly as in arrangement 3, detailing the loading of the engines, the energy provided/demanded from the batteries, the number of generator sets in operation and the total power provided by the generator sets. In Figure 4.24 and Figure 4.25 the performance of the Diesel generator sets is shown.

One more time, when the vessel is in port, no generator set is in operation, as well as in some time periods for dynamic positioning mode and stand by operation; in these moments the power is provided by the batteries bank, which starts the service with a stored energy of 14504kWh. When the Diesel generator sets are running, their output power is kept constant and close to the rated power to match the loading of the Diesel engines with their optimum operational point. Since the Diesel generator sets are the same as for the arrangement 3, their loading set point sets was settled exactly as for the arrangement 3.

In similar way to the arrangement 3, the energy compensation is focused for the time periods in which the loading is low (port, DP and stand by). When the vessel is in DP and the batteries bank is not delivering energy, at least two Diesel generator sets are maintained in operation.

In the figures, the black dots show a slightly variation between the estimated loading of the Diesel engines and the target loading. As explained in arrangement 3, the final charge of the batteries is different from that in the beginning due to the balance between load compensation and energy storage for port operation.

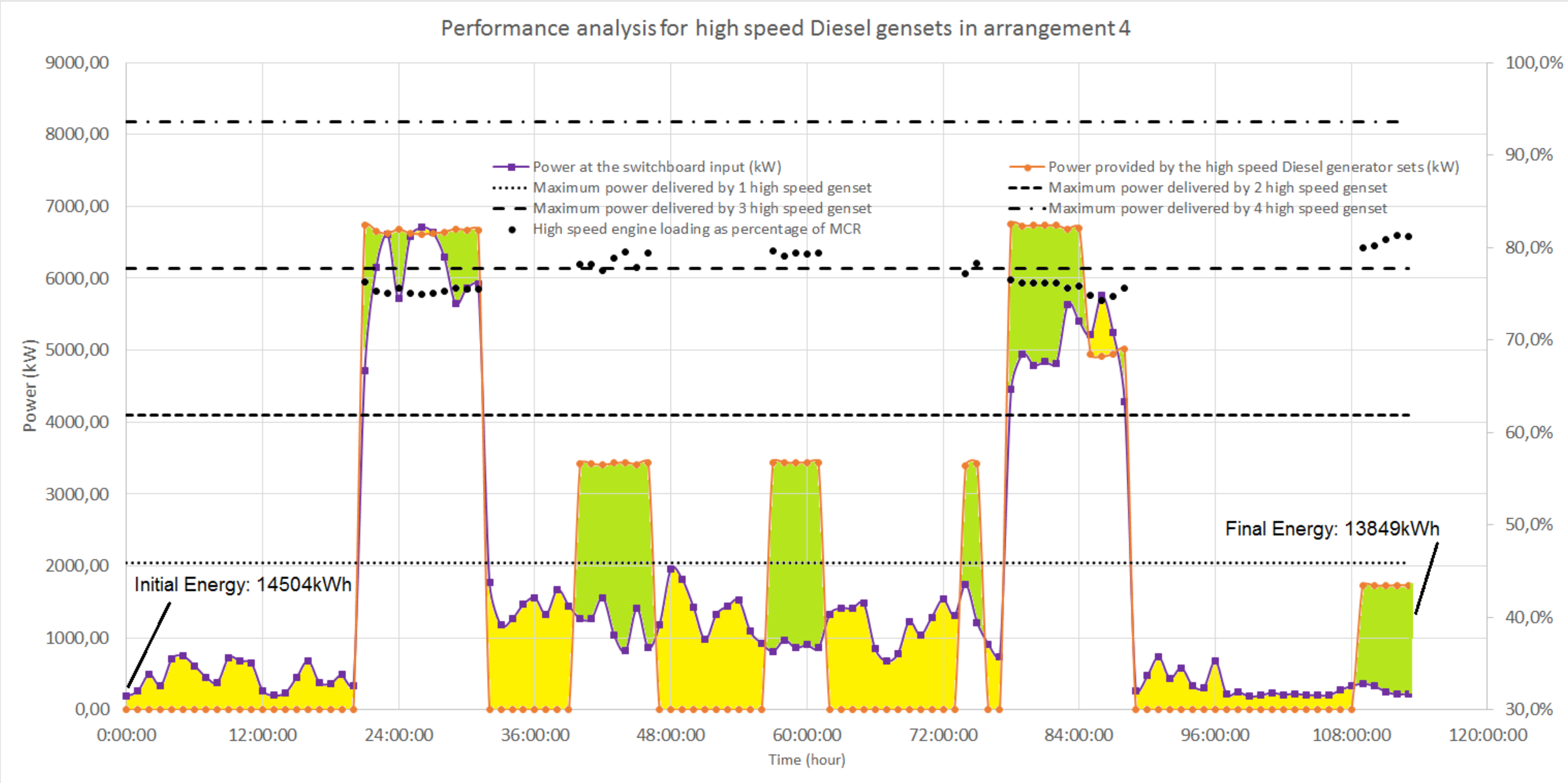

Figure 4.24 – Performance Analysis for High Speed Diesel Generator Sets in Arrangement 4 Detailing the Engines Loading, the Power Provided by the Generator Sets, the Power at the Switchboard Input, the Energy Delivered by the Batteries Bank (Yellow Colored Areas) and the Energy Stored by the Batteries Bank (Green Colored Areas).

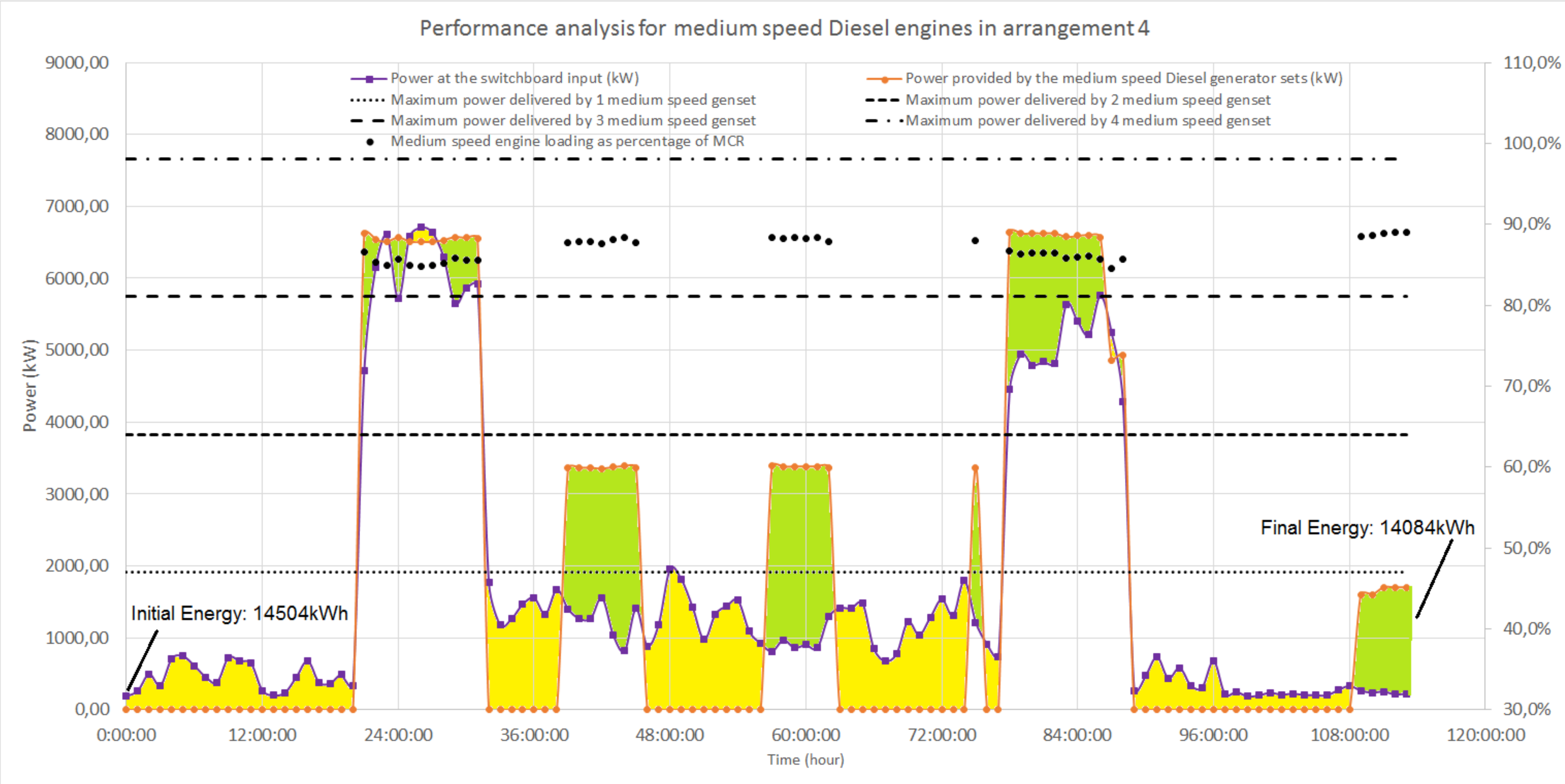

Figure 4.25 - Performance Analysis for Medium Speed Diesel Generator Sets in Arrangement 4 Detailing the Engines Loading, the Power Provided by the Generator Sets, the Power at the Switchboard Input, the Energy Delivered by the Batteries Bank (Yellow Colored Areas) and the Energy Stored by the Batteries Bank (Green Colored Areas).

It is also assumed that the energy and power of the batteries bank is regulated by a power managing system. The average loading of the Diesel engines is 77.2% for the high speed units and 87.9% for the medium speed units. The fuel consumption and the exhaust gases emissions are shown in Table 4.14.

Table 4.14 - Fuel Consumption and Exhaust Gases Released by Arrangement 4.

		Fuel consumption (kg)	NOx emissions (kg)	SOx emissions (kg)	CO_2 emissions (kg)
Port Operation	High speed generator set (MGO)	0,0	0,0	0,0	0,0
	Medium speed generator set (HFO)	0,0	0,0	0,0	0,0
Laden Voyage	High speed generator set (MGO)	14429,6	526,1	432,9	46030,4
	Medium speed generator set (HFO)	13440,7	639,0	940,8	42875,9
Dynamic Positioning	High speed generator set (MGO)	8949,2	326,8	268,5	28548,1
	Medium speed generator set (HFO)	8267,4	392,4	578,7	26373,2
Partial load Voyage	High speed generator set (MGO)	13287,4	484,5	398,6	42386,9
	Medium speed generator set (HFO)	13072,3	621,2	915,1	41700,7
Stand by	High speed generator set (MGO)	1650,2	60,3	49,5	5264,3
	Medium speed generator set (HFO)	1501,3	71,2	105,1	4789,3
TOTAL	High speed generator set (MGO)	38316,5	1397,8	1149,5	122229,7
	Medium speed generator set (HFO)	36281,8	1723,8	2539,7	115739,0

4.2.5 Results summary

With the fuel consumption and the exhaust gases emissions already estimated for each arrangement, the next step is to compare the results. The fuel consumption for each arrangement and for both types of generator sets is presented in Figure 4.26. Additionally, the estimated fuel consumption of a similar vessel is shown for reference purposes. The vessel is the the Edda Fram with its main characteristics described as follows (See Annex J):

- Length b. p.: 77.4m
- Breadth: 19.2m

- Depth: 8m
- Draft: 6.5m
- Deadweight: 4100t
- Max speed: 15.5knots
- Diesel electric propulsion 2xvoith propellers 2800kW each
- 4 Mitsubishi generators of 1920kW, 1800rpm each burning MGO/MDO.
- Dynamic positioning system class 2 (DYNPOS-AUTR)

Its fuel consumption was obtained using the following performance data as informed by the ship-owner:

- Fuel consumption at max speed: 28000kg/day.
- Fuel consumption in dynamic positioning: 5000kg/day.
- Fuel consumption in port: 1000kg/day
- stand by: 4000kg/day

The previous consumption rates are averaged and their values are not guaranteed by the ship-owner, because the conditions and the hypothesis considered for the measurement may be different for each operation type and service. Nevertheless, for reference purposes, the fuel rates are considered as acceptable figures that can give an idea of the magnitude order of the fuel consumed by a real vessel.

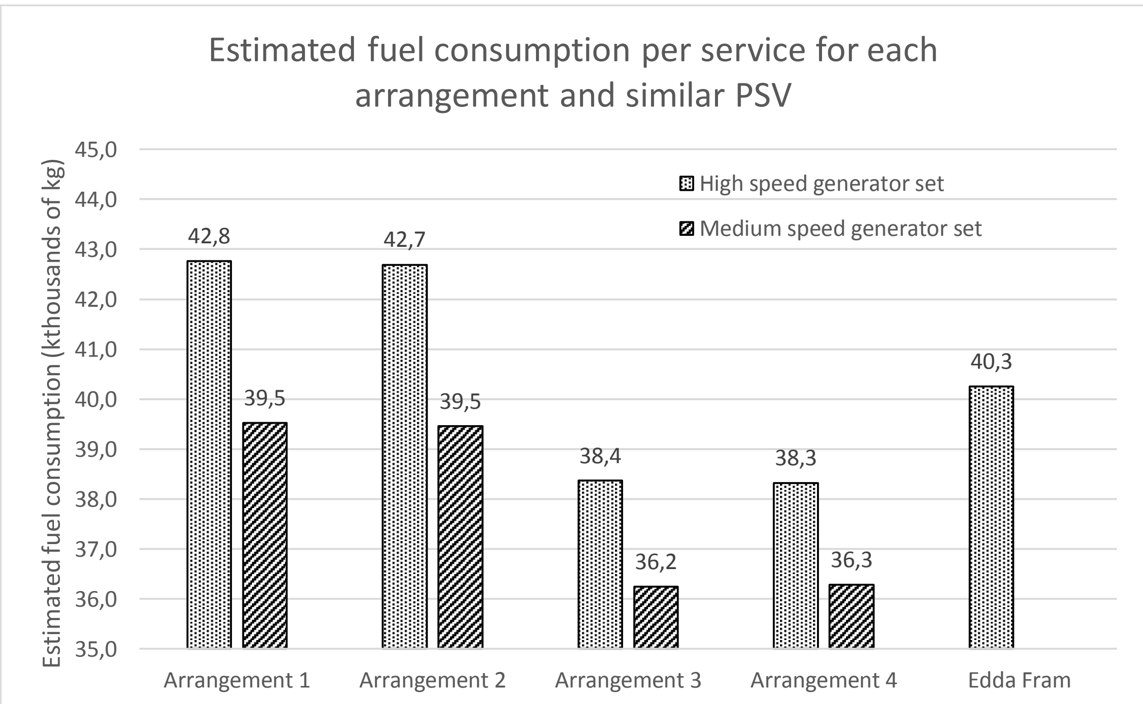

Figure 4.26 – Estimated Fuel Consumption per Service for Each Arrangement and for a Similar PSV.

The NOx and SOx emissions for each arrangement are compared within the same graph in Figure 4.27. Moreover, the CO_2 is also compared in Figure 4.28. The data used for the comparison are the total results for each arrangement as they were presented in Tables 4.6, 4.12, 4.13 and 4.14.

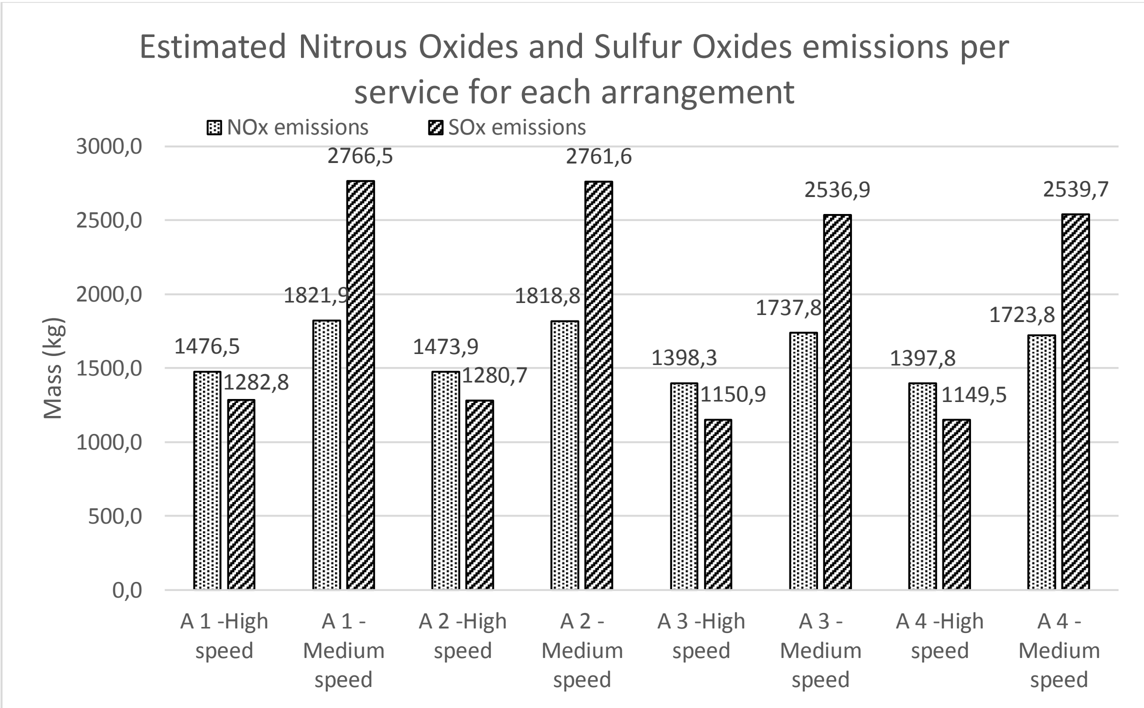

Figure 4.27 - Estimated NOx and SOx Emissions per Service for Each Arrangement.

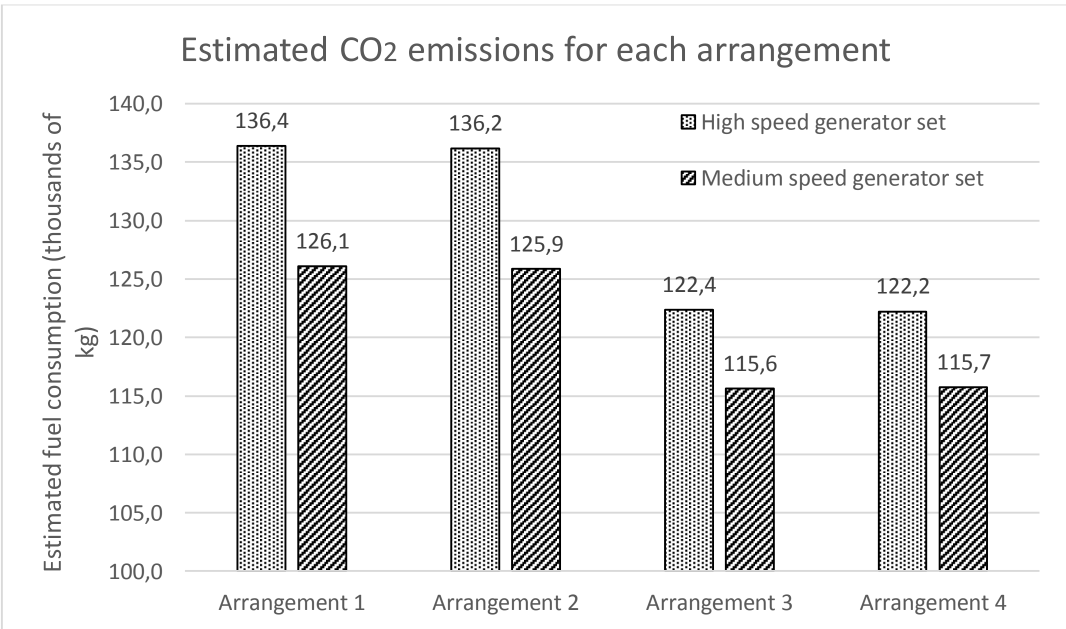

Figure 4.28 – Estimated CO_2 Emissions per Service for Each Arrangement.

The following analysis can be made from the figures:

- The estimated fuel consumption for the arrangements is within a reasonable value when compared to the fuel consumption of a similar vessel taken as a reference. Therefore, it can be considered that the estimated load and operational profile represent in a reasonable way the load variation of a real vessel with similar characteristics.
- Owing to the low SFOC, the fuel consumed by the medium speed generator sets is significantly lower than that consumed by the high speed ones. The differences are within a range from 5.5% (2000kg) to 8.3% (3300kg).
- The potential reduction in fuel consumption of the arrangements with medium speed gensets, compared to the high speed ones, implies a reduction in the stored fuel in the vessel, freeing up space for payload transport. Nevertheless, the amount of payload that could be transported by the reduction of fuel consumption would not be higher than 3300kg, which does not compensate the additional 80.000kg of mass of the medium speed gensets.
- The loading of the Diesel engines is of significant importance in the magnitude of the fuel consumption. The arrangements in which the Diesel engines were loaded close to their optimum operational point, presented lower fuel consumption than the arrangements that were not loaded at this point.
- The influence of the batteries in the reduction of the fuel consumption is more important for the high speed Diesel units than for the medium speed ones. The differences between arrangements 1-2 and arrangements 3-4 showed that for the high speed Diesel engines the fuel reduction was up to 4400kg, while for the medium speed ones was about 3300kg.
- Although the batteries present a potential fuel reduction that can reach up to 4400kg per service (for the same type of generator set), their additional mass (approximately 129.000kg) reduces significantly the payload that can be transported. The fuel reduction would not compensate the amount of payload that is not transported.
- Regarding the CO_2 and SO_x emissions, since fuel based factors were used for their estimation, they are directly proportional to the fuel burned. Their behavior is exactly the same as the fuel consumption maintaining the proportions. In the case of SOx emissions, they are also dependent of the fuel

type, the sulfur content MGO is lower than the sulfur content of the HFO, hence, medium speed Diesel engines releases more SOx than the high speed ones.

- With respect to the NOx emissions, owing to the power based factors used, they are related to the energy given by the Diesel engines; the NOx values are neither influenced by the loading of the Diesel engines nor the reduction of the fuel consumption. Therefore, the difference of NOx emissions between arrangements for the same type of Diesel generator units was not higher than 30kg and was not significantly influenced by the batteries bank.
- Taking into account the effects of the batteries bank over the loading of the Diesel engines, it is a good alternative to reduce the fuel consumption of the vessels. As a consequence, the CO_2 and SO_x released to the environment can also be reduced by its implementation.
- The lowest fuel consumption corresponded to arrangement 3, while the highest one corresponded to arrangement 1.

4.3 ECONOMIC EVALUATION

The economic analysis of the arrangements will be performed by using the net present value (NPV), which is one of the most used tools for financial assessment of projects (SNAME, 2004). The NPV uses the cash flow as input, which is the sum of the incomes and outgoings of a project in its entire lifetime. Therefore, for the present economic analysis the cash flow must be defined first considering the following conditions:

- The total lifetime of the vessel is 20 years.
- It is assumed that the displacement of the vessel is constant for all the alternatives. So the deadweight of the vessel depends on the mass of each arrangement.
- In accordance with the previous condition, the economic effects of the arrangements over the payload should be considered. For this, a further analysis from the logistic point of view is required, which is out of scope for the present dissertation. Consequently, for the purposes of this dissertation the effects of the arrangements in vessel logistic operations are ignored.
- The economic influence of the potential fuel reductions on the payload of the vessel is ignored.

- The economic study will be performed disregarding the cost of the workforce.
- For obtaining the cash flow the outgoings and the incomes must be defined. The time periods for the cash flow were settled annually as recommended by the Society of Naval Architects and Marine Engineers [SNAME] (SNAME, 2004).

The first outgoing corresponds to the investment. It was assumed that the funding of the investment for each arrangement (corresponding to the capital costs) was achieved by a fixed interest rate bank loan. Every installment amount for paying the loan per year is given by (DEDES, HUDSON and TURNOCK, 2012):

$$A_{Lt} = L_t \frac{R_L}{1-(1+R_L)^{-N_L}} \tag{4.19}$$

Where R_L is the interest rate, L_t is the loan amount,and N_L is the loan payback period. For the present analysis it was considered that the bank rate is 8% and the payback period is 10 years.

The next expense corresponds to the costs associated to fuel consumption. The fuel consumption of the arrangements for each service was discussed in Section 4.2.5; it was assumed that a PSV could perform around 6 services per month, which implies 72 services in average per year. Furthermore, on February 2nd 2014 the marine bunker fuels price was 1002.5$/Tonne for MGO and 593.5$/Tonne for the HFO defined for Houston, United States (PETROMEDIA, 2014). According to these values, the fuel expenses in the first year are:

$$fexp_1 = SY \times fuel\,consumption \times fcost \tag{4.20}$$

Where $fexp_1$ is the fuel expenses for the first year, SY is the number of services per year, $fuel\,consumption$ is the fuel consumption for each arrangement as obtained in section 4.2, and $fcost$ is the fuel cost.

For the following years, the expenses associated to fuel must be obtained by a forecast of the fuel prices. Nevertheless, price forecasts for bunker fuels are difficult to develop. After consulting various websites specialized in bunker fuel prices, there was no information about price forecasts available for free consulting. Hence, the MGO and HFO annually variations were settled at a reasonable value in accordance with the behavior of the prices in the recent years (PETROMEDIA, 2014): 5% and 8%, respectively. Considering the variations, the fuel expenses for the remaining years are defined by:

$$fexp_i = fexp_{i-1}(1 + \%fvar) \tag{4.21}$$

Where the sub-index i indicates the year and $\%fvar$ represents the variation in the fuel price per year.

The last outgoing corresponds to the operation and maintenance costs (O&M). For the arrangements, the maintenance costs were only considered for the Diesel generator sets. As presented in Chapter 2, the maintenance costs are 0.01$/kWh for the high speed Diesel generator sets, whereas 0.005$/kWh for the medium speed ones (KOZLOWSKI, 2002). The batteries bank is maintenance free (LINDEN e REDDY, 2002) and other electrical equipment requires minimum maintenance; therefore, they are not considered. The maintenance expenses for the first year are:

$$mexp_1 = SY \times mfactor \int_{t_1}^{t_2} h\, Engpow_n\, dt \tag{4.22}$$

Where $mexp_1$ is the maintenance expenses for the first year and, $mfactor$ is the cost of maintenance as a function of the Diesel engine in $/kWh. It can be noticed that the energy delivered by the Diesel generator sets must be taken into account.

For the following years the maintenance expenses are defined by the following expression assuming a variation of 3%:

$$mexp_i = mexp_{i-1}(1 + \%mvar) \tag{4.23}$$

Where the sub-index i indicates the year and $\%mvar$ represents the variation in the maintenance price per year for each engine type.

The incomes of the project (considering the finished PSV, the complete project) require a complex study in which several conditions must be taken into account, including projections about oil production, logistics, situation of the market, etc. Since a study of that magnitude is out of scope for the present dissertation, no incomes associated to the PSV operation were considered for the cash flow. Furthermore, potential incomes from the arrangements components sale at the end of its lifetime are also ignored. In spite of not considering the incomes for the project, it is assumed that the incomes of the vessel are the same for any of the electric propulsion arrangements considered.

The cash flow for arrangements 1, 2, 3 and 4 are plotted in Figure 4.29, Figure 4.30, Figure 4.31 and Figure 4.32, respectively. The horizontal axis represents the years.

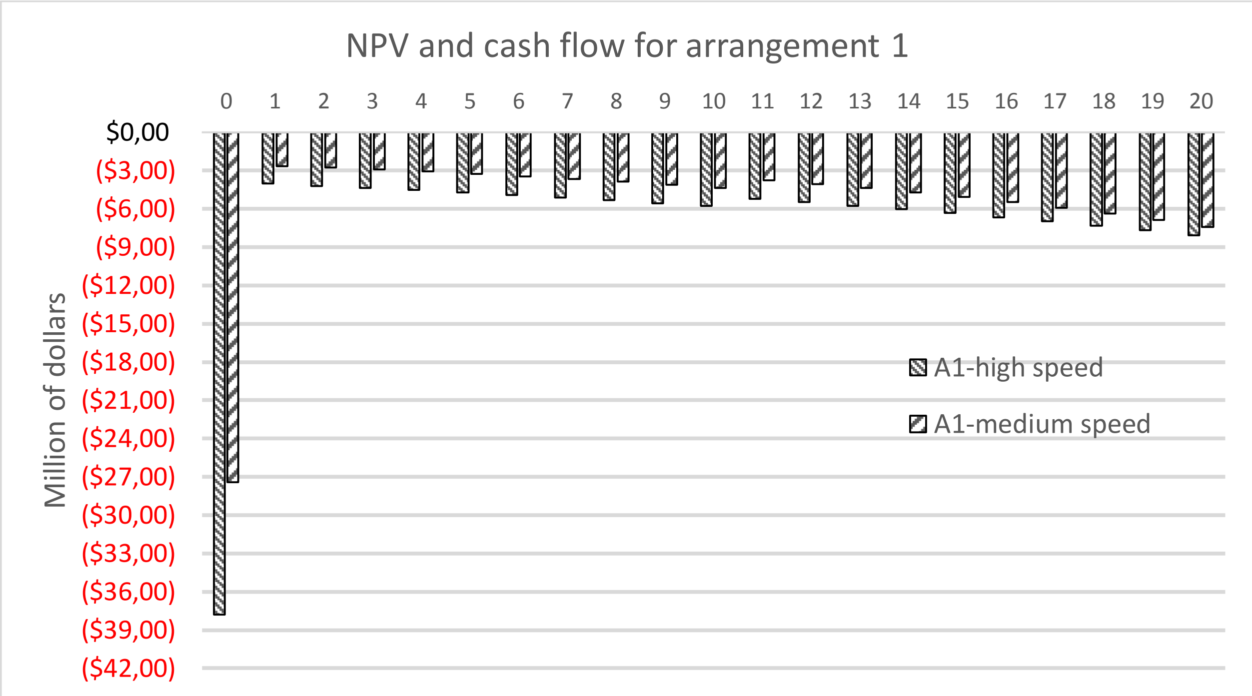

Figure 4.29 – Cash Flow and NPV for Arrangement 1.

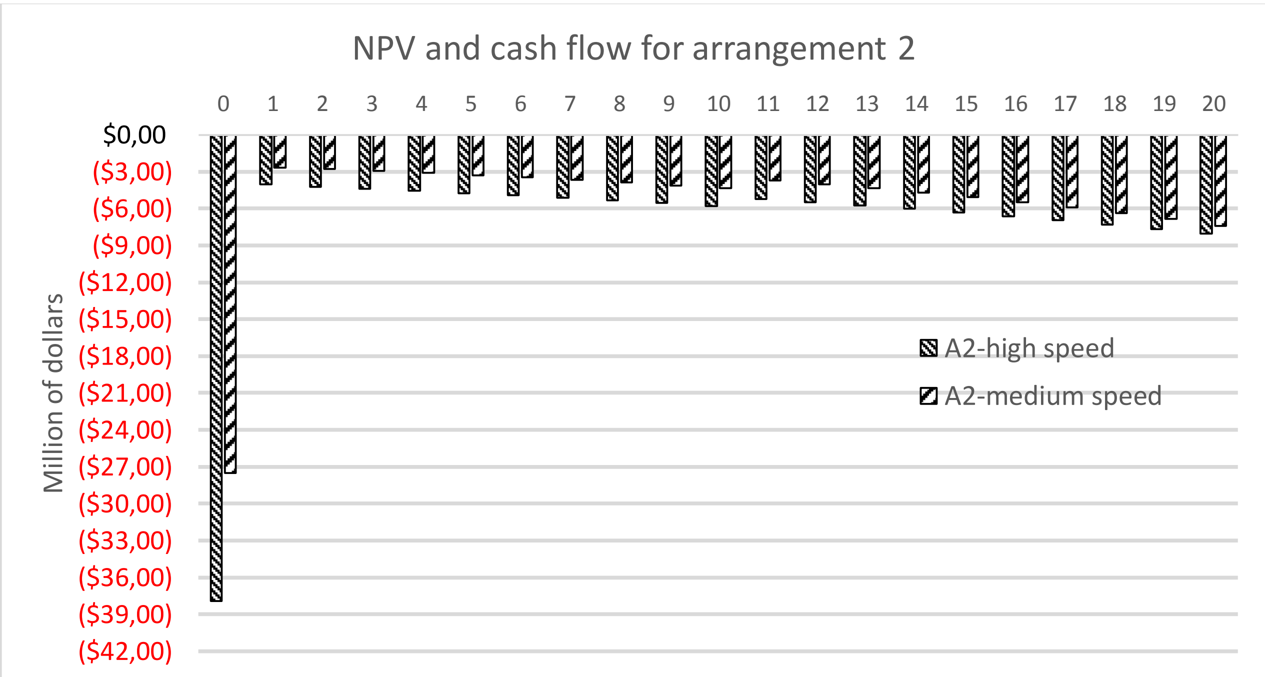

Figure 4.30 - Cash Flow and NPV for Arrangement 2.

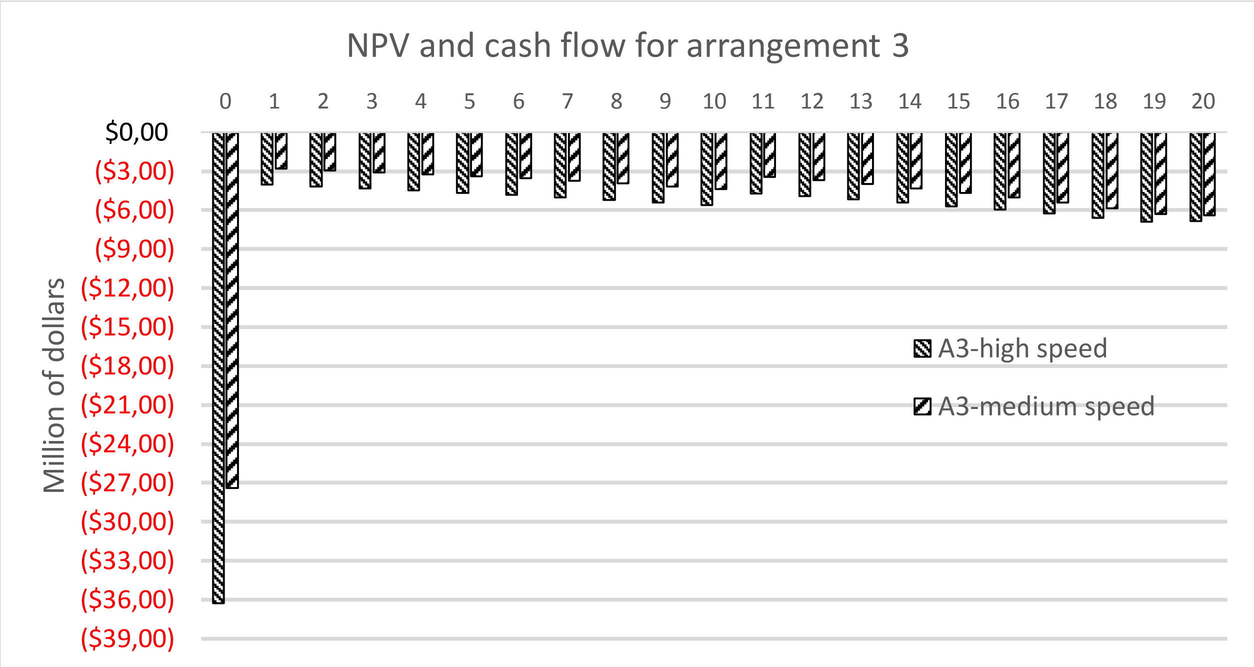

Figure 4.31 - Cash Flow and NPV for Arrangement 3.

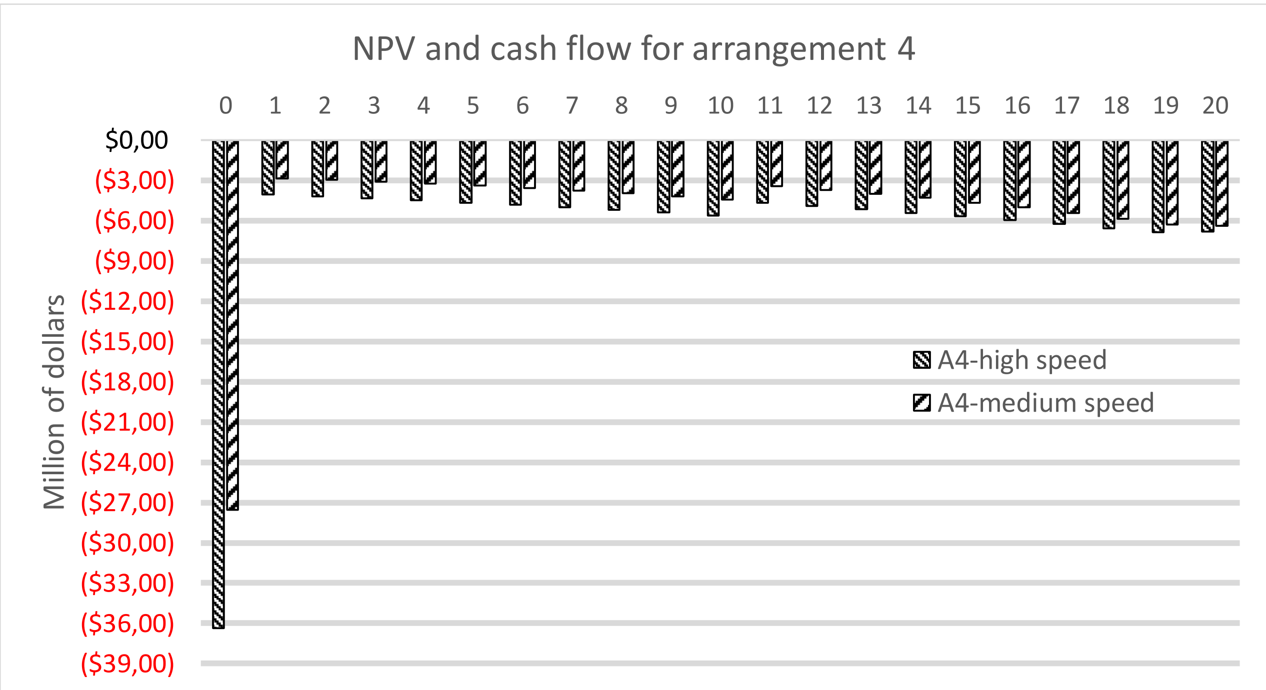

Figure 4.32 - Cash Flow and NPV for Arrangement 4.

The NPV is defined by the following expression:

$$NPV(k, N) = \sum_{t=0}^{N} \frac{R_t}{(1+k)^t} \quad (4.24)$$

Where $NPV(k, N)$ is the net present value, k is the discount rate, N is the total number of periods, t is the period of time, and R_t is the cash flow for the period t.

Since the cash flow and the periods for the cash flow were already defined, the only parameter needed is the discount rate. The NPV for the arrangements was obtained for various discount rates, from 6% to 12% in steps of 2%; a sensitivity analysis was performed with these values. It was observed that if the interest rate increases 2%, the NPV of the arrangements becomes 15% less negative (since the cash flow is negative, then, the NPV is negative too). The previous behavior is within what is expected for the NPV; therefore, if an interest rate is increased, the net value is reduced (in this case the total outgoings are diminished with the increase of the discount rate). The discount rate is determined by the market and the particular interests of the investors; however, for the purposes of this dissertation, the rate is fixed at 12%.

The NPV at year zero for arrangements 1, 2, 3 and 4 is also presented in Figure 4.29, Figure 4.30, Figure 4.31 and Figure 4.32, respectively. Furthermore, in Figure 4.33 the NPV for each of the arrangements is presented for comparison purposes.

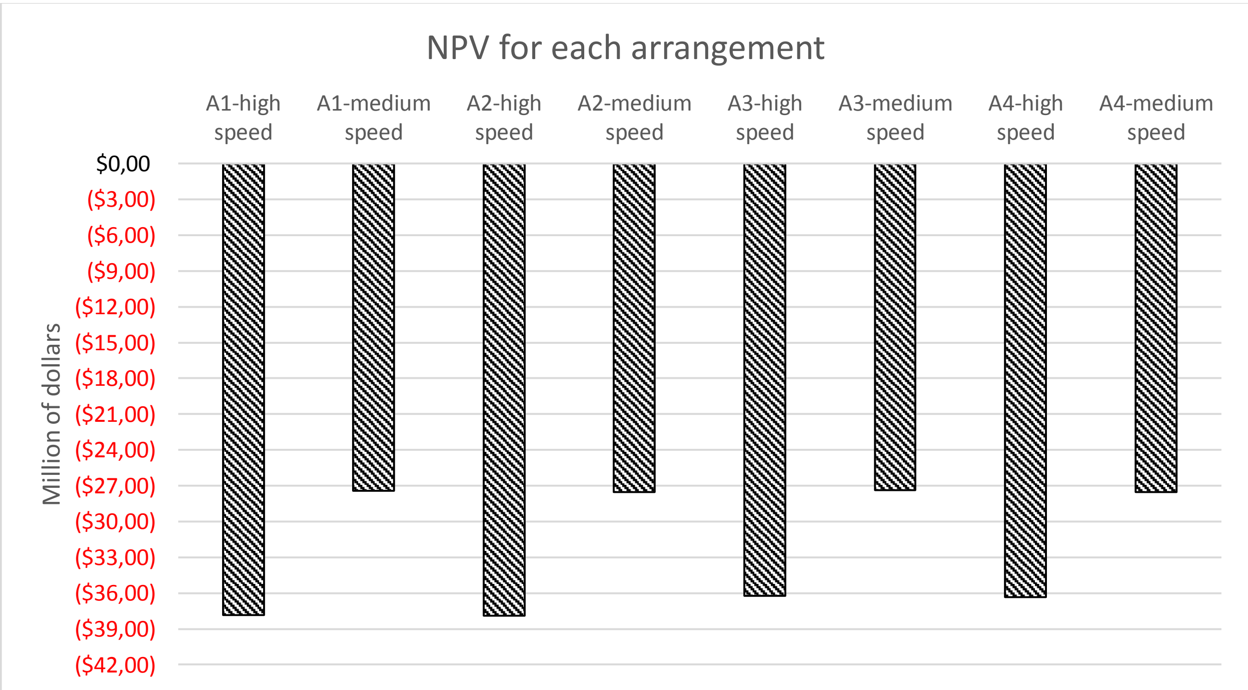

Figure 4.33 – NPV for each of the Arrangements.

The following analysis can be performed from the figures:

- The cash flow and NPV are negative. Therefore, the less negative the values, the better from an economic point of view.

- The cash flow for each arrangement becomes more negative as the periods increase. It should be noticed that after the 10^{th} year, the cash flow is slightly reduced, because the installment amounts for paying the bank loan end in the 10^{th} year.
- The NPV between alternatives with the same type of generator sets varies less than 4% (less than US$ 2million). For any of the alternatives, the NPV difference between high and medium speed generator set varies 38.4% (approximately US$ 9million).
- The cash flow for the arrangements with batteries becomes lower than the cash flow for arrangements 1 and 2 as the periods increase. The above occurs due to lower fuel expenses.

4.4 ELECTRIC PROPULSION ARRANGEMENT SELECTION USING THE AHP METHODOLOGY

The final step of this methodology is the selection of the arrangement or arrangements that best fit the following criteria: low fuel consumption, exhaust gases emissions, mass, volume, and high NPV. The decision is taken through the usage of the AHP methodology, which is briefly described in Appendix D.

In order to carry out the AHP methodology, the first step is defining the problem, which in this case means selecting the electric propulsion arrangement for the conceptual design of the PSV. Afterwards, the decision hierarchy has to be structured from the top with the goal of the decision, to the lowest level (the solution alternatives) passing through the intermediate levels (criteria or sub-criteria). Herein, the problem structure is shown in Figure 4.34.

As shown in the figure, the criteria for selecting the electric propulsion arrangement are the parameters related to the size and mass of the installation, the net present value and the exhaust gases. The mass, volume and amount of fuel consumed are sub-criteria grouped within the criteria defined as the ones related to the size and mass of the arrangements. The NOx and SOx emissions are included within the exhaust gases criteria. The remaining parameters defined before for each arrangement i.e., capital costs and CO_2 emissions, are not considered as criteria or sub-criteria within the AHP methodology. The former is already included within the NPV criteria, while the latter is directly proportional to the fuel consumption, which is already defined as sub-criteria. Hence, both were disregarded.

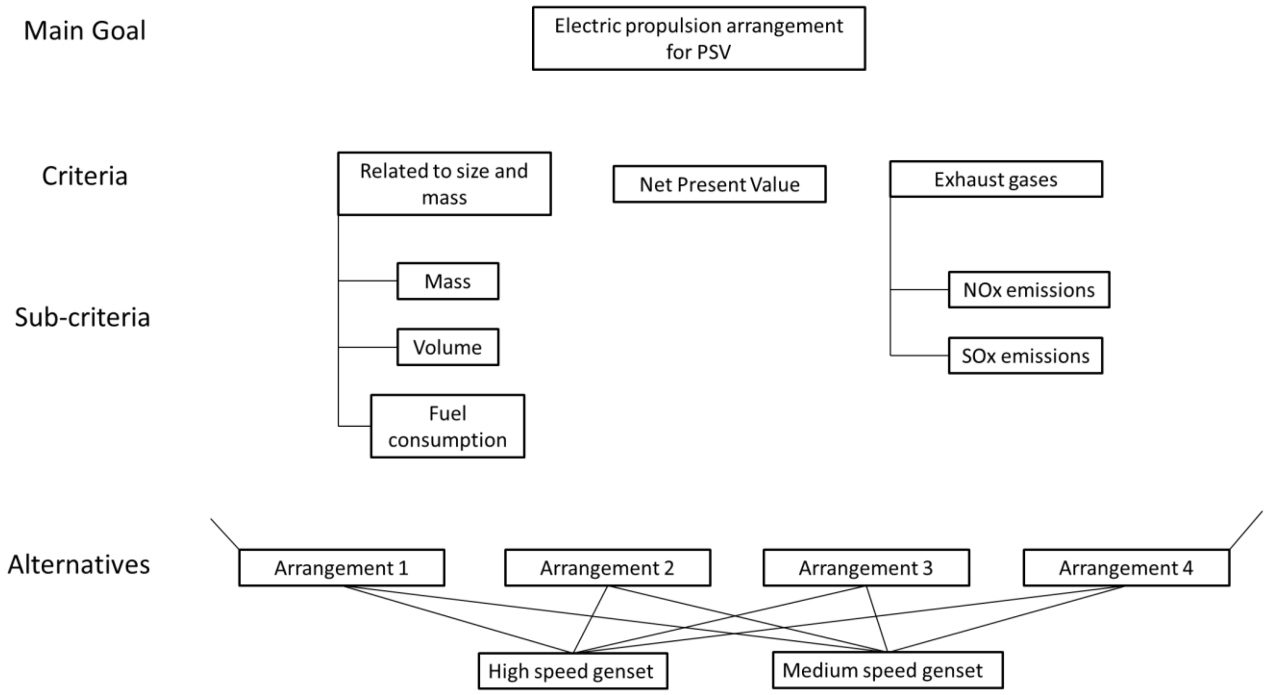

Figure 4.34 - Problem Structure According to the AHP Methodology.

The following step of the methodology, as defined by Saaty (1980), is the construction of a set of pairwise comparison matrices. Each element in an upper level is used to compare the elements in the level immediately below with respect to it. In these matrices, the compared elements are the criteria or sub-criteria, depending on the level. For the structure proposed here, three matrices are necessary to develop the methodology: the first one to compare the criteria, the second one to compare the sub-criteria correspondent to the size and mass, and the third and last one for the exhaust gases. The importance of one criterion when compared to another one is defined subjectively, since it depends on the evaluator and how this person uses the preference values shown in Table D.1 in Appendix D. With the compared criteria, a criteria matrix is formed, which contains all the preference values of one criterion when compared to the others.

In order to determine the influence of setting different preference values on the final decision, two scenarios with different levels of importance between the criteria are defined. In the first scenario, the main criteria matrix is developed giving priority to the financial component (NPV and the payload, represented by the mass and the volume). A second scenario gives priority to the exhaust emissions over the NPV, mass and volume. The levels of importance between the criteria for both scenarios is schematized in Figure 4.35 for the first one and Figure 4.36 for the second one.

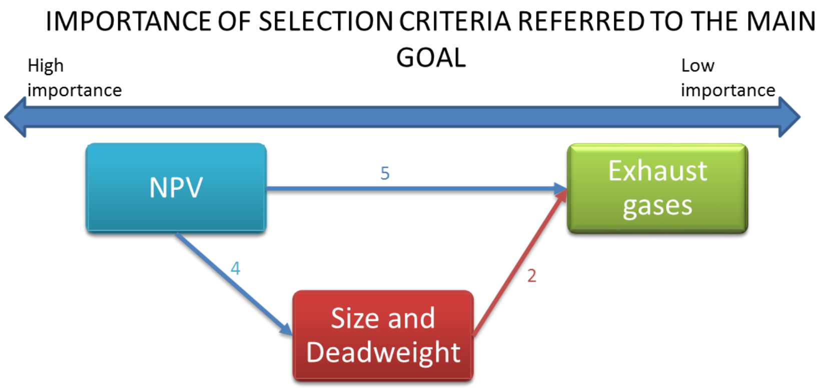

Figure 4.35 – Importance Levels of the Main Criteria for Scenario 1.

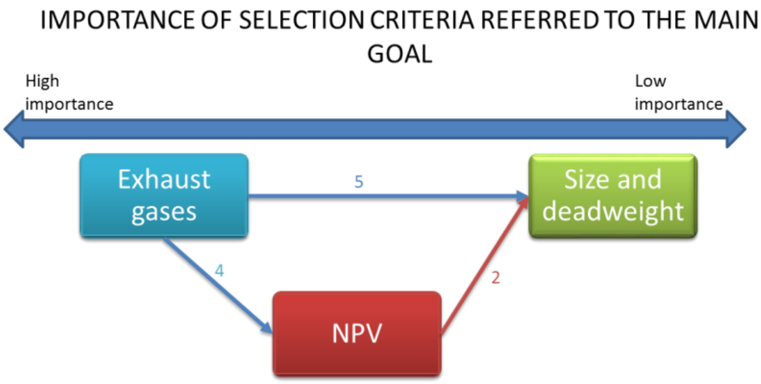

Figure 4.36 - Importance Levels of the Main Criteria for Scenario 2.

The importance of the sub-criteria for all scenarios is schematized in Figure 4.37.

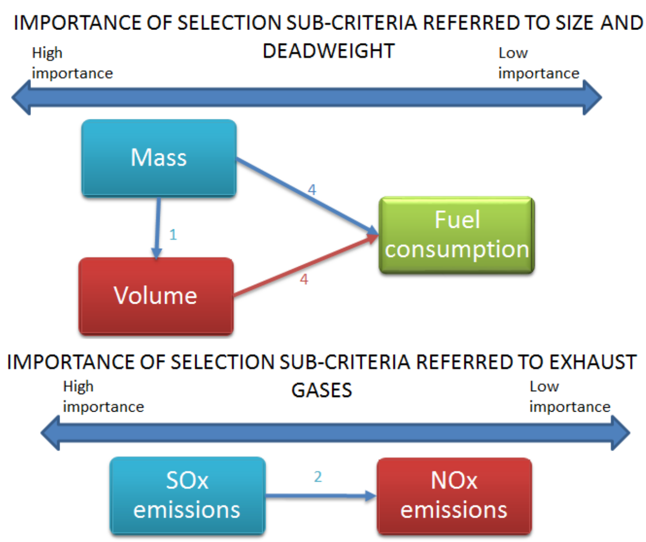

Figure 4.37 – Importance Levels of the Sub-Criteria for All Scenarios.

In the present analysis the NPV was settled as the most important parameter in Scenario 1, because the financial component is the most significant factor to be taken into account in almost every project. In this case, since the NPV indicates the expenses of the arrangements during the project lifetime, it is better for the ship-owner when the expenses are the lowest ones possible. The criterion associated to the mass and volume of the arrangements was settled as more important than the exhaust gases, since they influence the payload. An arrangement with low mass and volume can transport more payloads per service, which impact the economics of the vessel.

Scenario 2 gives more priority to the environment than economics, since the pollutant gases released to the environment is a more important criterion than the NPV. The mass and volume becomes the least important criteria.

Regarding those sub-criteria related to the size and mass, both the volume and mass of the arrangement are considered to have the same importance, considering that the vessel is limited to weight and space. Both the mass and the volume of the arrangement are considered more important than the amount of fuel required per service, since it does not have a significant effect on the payload as the mass and volume do. In the exhaust gases sub-criteria, SOx is considered to be more important than NOx because the former has a larger effect over the human health than the NOx (MEDEIROS, 2010).

The criteria matrices for Scenarios 1 and 2 are shown in Tables 4.15 and 4.16, whereas the sub-criteria matrices for size and mass and for exhaust gases are shown in Tables 4.17 and 4.18.

Table 4.15 – Main Criteria Matrix for Scenario 1[35]

Main Criteria Matrix With Respect to the Main Goal – Scenario 1				
	C1	**C2**	**C3**	**Criteria Importance**
C1-Size and mass	1	1/4	2	0,20
C2-NPV	4	1	5	0,68
C3-Exhaust gases	1/2	1/5	1	0,12

With the criteria and sub-criteria matrices already defined, it is possible to determine the importance levels between the alternatives, when applying the AHP methodology. The complete matrices for Scenario 1 and Scenario 2 are presented in Table 4.19 and Table 4.20 respectively. The arrangement values for each parameter (mass, volume, etc.) were normalized according to the methodology for quantitatively data (see

[35] Consistency index: 0.03

GARBER, 2002; PEREIRA, 2007; MORATELLY, 2010; SAATY, 1980) and placed in the correspondent space.

Table 4.16 – Main Criteria Matrix for Scenario 2[36]

Main Criteria Matrix With Respect to the Main Goal – Scenario 2				
	C1	**C2**	**C3**	**Criteria Importance**
C1-Size and mass	1	1/2	1/5	0,12
C2-NPV	2	1	1/4	0,20
C3-Exhaust gases	5	4	1	0,68

Table 4.17 – Sub-Criteria Matrix for Size and Mass Criterion[37]

Sub-Criteria Matrix With Respect to Size and Mass Criterion				
	C1	**C2**	**C3**	**Criteria Importance**
C1-Mass	1	1	5	0,45
C2-Volume	1	1	5	0,45
C3-Fuel Consumption	1/5	1/5	1	0,09

Table 4.18 – Sub-Criteria Matrix for Exhaust Gases Criterion

	C1	**C2**	**Criteria Importance**
C1-SOx	1	2	0,67
C2-NOx	1/2	1	0,33

The overall priority is obtained by the multiplication of the normalized value of each sub-criteria by the weigh of the sub-criteria (for example, in the Scenario 1- arrangement 1, the normalized value of the mass is multiplied by 0.45), afterwards, it is necessary to add this result to the remaining results of the grouped sub-criteria (the mass is multiplied by 0.45 added to the volume, which is multiplied by 0.45, and to the fuel consumption, also multiplied by 0.09), the total sum is then multiplied by the weigh of the main criterion which is added to the results of the remaining sub-criteria and main criteria. The complete procedure for calculation is shown in Appendix D.

The preference for Scenario 1 is given to arrangement 1 and arrangement 2, both with medium speed Diesel generator sets; each one with an importance level of 13.59% and 13.56%, respectively. The preference for Scenario 2 is given to arrangements 3 and 4 with high speed Diesel gensets, with 14.84% and 14.83%, respectively. Nevertheless, arrangements 1 and 2 with high speed gensets have a high preference as well.

[36] Consistency index: 0.03
[37] Consistency index: 0.00009

Table 4.19 – AHP Methodology for Scenario 1

Criteria	**Size and Mass**			**NPV**	**Exhaust gases**		**Overall Priority**
	0,20141				**0,11795**		
Sub-Criteria	Mass	Volume	Fuel Consumption	**0,68064**	SOx	NOx	
	0,45455	0,45455	0,09091		0,66667	0,33333	
Arrangement 1 - High speed Genset	0,174	0,136	0,114	0,108	0,162	0,134	0,1222
Arrangement 1 - Medium speed Genset	0,125	0,159	0,124	0,143	0,075	0,109	**0,1359**
Arrangement 2 - High speed Genset	0,184	0,133	0,114	0,104	0,162	0,135	0,1197
Arrangement 2 - Medium speed Genset	0,130	0,154	0,124	0,143	0,075	0,109	**0,1356**
Arrangement 3 - High speed Genset	0,106	0,100	0,127	0,108	0,181	0,142	0,1146
Arrangement 3 - Medium speed Genset	0,086	0,111	0,135	0,143	0,082	0,114	0,1290
Arrangement 4 - High speed Genset	0,108	0,098	0,127	0,108	0,181	0,142	0,1144
Arrangement 4 - Medium speed Genset	0,087	0,109	0,135	0,143	0,082	0,115	0,1284

Table 4.20 – AHP Methodology for Scenario 2

Criteria	**Size and Mass**			**NPV**	**Exhaust gases**		**Overall Priority**
	0,11795				**0,68064**		
Sub-Criteria	Mass	Volume	Fuel Consumption	**0,20141**	SOx	NOx	
	0,45455	0,45455	0,09091		0,66667	0,33333	
Arrangement 1 - High speed Genset	0,174	0,136	0,114	0,108	0,162	0,134	**0,1437**
Arrangement 1 - Medium speed Genset	0,125	0,159	0,124	0,143	0,075	0,109	0,1042
Arrangement 2 - High speed Genset	0,184	0,133	0,114	0,104	0,162	0,135	**0,1433**
Arrangement 2 - Medium speed Genset	0,130	0,154	0,124	0,143	0,075	0,109	0,1042
Arrangement 3 - High speed Genset	0,106	0,100	0,127	0,108	0,181	0,142	**0,1483**
Arrangement 3 - Medium speed Genset	0,086	0,111	0,135	0,143	0,082	0,114	0,1040
Arrangement 4 - High speed Genset	0,108	0,098	0,127	0,108	0,181	0,142	**0,1484**
Arrangement 4 - Medium speed Genset	0,087	0,109	0,135	0,143	0,082	0,115	0,1039

From the Scenario 1 results, it can be deduced that the NPV had an important influence on them, since the NPV for the arrangements with medium speed Diesel generator sets is significantly lower than for those arrangements with high speed ones. This leads to the conclusion that arrangements 1 and 2 with medium speed gensets are the best option. When the priority is given to the environmental criterion, the high speed Diesel generator sets are a better option than the medium speed ones, the highest priority is for arrangements 4 and 3 with high speed units, closely followed by arrangements 1 and 2 with high speed units.

These results have indicated that the selection of the Diesel electric installation for the PSV depends on the evaluator. It was seen that from the economic point of view, arrangements with medium speed generator sets are the best option, whereas from the environmental point of view, arrangements with high-speed generator sets are seen as a suitable alternative.

5 CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

As the oil production moves away from shore, the demand for electric propelled PSVs increases. In this sense, one of the main contributions of the present work was a methodology proposal to define the electric propulsion systems for PSVs. The methodology was applied to the conceptual design of a PSV for the pre-salt fields at Santos Basin considering not only the conventional electric propulsion arrangements but also the implementation of batteries bank as a relatively new alternative for electric propulsion systems in PSVs.

During the analysis, the batteries influence in the reduction of the fuel consumption was demonstrated. In fact, it was seen that the batteries kept the Diesel engines loaded at their optimum operational point, burning less fuel per unit of energy delivered when compared to the conventional electric propulsion arrangements. In this context, the batteries stand as an important alternative to reduce the impact of the exhaust emissions by decreasing the fuel burned and, consequently, the CO_2 and SO_X emissions. Nevertheless, when evaluated from an economic point of view, the batteries presented several disadvantages over the conventional electric propulsion systems: higher mass, volume and capital costs limiting their current implementation in PSVs.

On the other hand, the AHP methodology was seen as a subjective procedure in the definition of the preferences for the selection criteria. Two scenarios were evaluated with different results. The first scenario, with priority for financial component, resulted in the arrangements 2 and 1 with medium speed generator sets as the best options for the design. While the scenario 2, which gave priority to the exhaust gases, resulted in the arrangements 3 and 4 as the best options.

Regarding the exhaust emissions, the approach used in the present work was the use of fuel-based factors for the estimation of the SOx and CO_2 emissions, while for the NOx emissions the estimation was made using power based factors. Consequently, the NOx emissions were slightly affected by the reduction of the fuel consumption. With respect to the CO_2 and SOx emissions, they are strongly dependent on the amount of fuel burned, since the fuel-based factor is related to the fuel consumption.

Concerning the economic analysis, the use of the NPV allowed the estimation of the economic impact of the arrangements operation, indicating the total expenses for the vessel lifetime.

The standard load profile and the operational analysis were presented as the main input data of the methodology. Their correct determination or estimation is important for subsequent stages of the methodology, leading to different results when varied.

The expression developed by the author for the estimation of the electric propulsion system mass as a function of the power for propulsion presented reasonable results and is considered acceptable for the early stages of the project, in which the knowledge of the approximated value of the propulsive installation mass is important.

5.2 RECOMMENDATIONS

The standard load profile, alongside the hull-propeller integration and the arrangement definition, is one of the main inputs of the proposed methodology. In the present dissertation, the standard load profile was estimated and arbitrarily settled using as a guide the load inventory from literature. In this respect, the present work could be more accurate using real data from the electrical loads of a PSV, measured at shorter time intervals and directly from the switchboards.

The operational profile was estimated taking into account ideal conditions (calm weather); nevertheless, the weather conditions at sea can be rough. Hence, it is also necessary to measure a real operational profile, considering the influence of the weather on the operational profile.

In this dissertation, two additional alternatives were considered for evaluation, both with DC electric transmission and variable speed Diesel generator sets as power source; nevertheless, not enough information was found to define these arrangements. Therefore, for future work, it is recommended to establish or assure the support of various manufacturers in early stages of the methodology, in order to provide the necessary information about the required equipment. This detail is highly important in the study and definition of electric propulsion systems.

A further study to assess the effects of the mass, volume and fuel consumption of the electric propulsion installations over the payload transport and their economic consequences is proposed as future work. In this context, the batteries bank presents itself as a suitable option, which deserves to be evaluated considering its effect on fuel consumption and exhaust emissions.

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APPENDIX A – COST TREND-LINES OF EQUIPMENT FOR ELECTRIC PROPULSION SYSTEMS

The present section is intended to perform a cost analysis for electric equipment that could be used in electric propulsion systems. The purpose of the analysis is to provide reference cost factors or trend-lines for each equipment considered, based in pricing lists of similar equipment available in the web. The equipment under consideration are: induction motors, variable frequency converters, transformers and high speed Diesel generator sets.

A.1 INDUCTION MOTORS

The induction motor is the most common used electrical machine in industry. Is available in rated powers from Watts up to hundreds of MW. Several manufacturers in many countries produce this type of machines in power ratings below hundreds of kW; while few ones built motors in the high power range, in which the demand is lower and the exigencies are greater. In electric propulsion systems, the rated power of the propulsion motors (for main propulsion and dynamic positioning) often exceeds 100kW, especially in vessels with high requirements. Due to the power rating, the motors are not commercial and are produced under request for the particular application. Hence, pricing lists or cost estimation for induction motors in the high power range are difficult to obtain.

For the PSV conceptual design, the exact cost of the induction motor for the arrangements 1 and 3 is not available for consulting; so as to better assess the electric propulsion arrangements and to have a better selection criterion, a function to estimate a reference cost of the induction motor is developed. The function takes as reference the Siemens pricing list for NEMA induction motors available in the internet (SIEMENS, 2013b). After searching and consulting manufacturers of high power induction motors (ABB, Siemens, WEG, Leroy Somer, etc.), the pricing list of Siemens induction motors was founded. Nevertheless, the motors listed do not meet with the specifications required for the electric propulsion systems. Considering the above and in order to have a reference function for cost estimation, the prices of the induction motors in the previous list are used to obtain a reference cost trend-line. The characteristics of the induction motors of the list are the following:

- Motor type: squirrel cage induction motor
- Rated voltage and frequency: 2300V at 60Hz

- Pole number: 6
- Cooling type: air-to-water cooling, IC81W.
- Protection index: IP54
- Insulation: class F
- Temperatures: 40°C ambient temperature with 80°C rise by resistance.

The prices for various power ratings are shown in Table A.1

Table A.1 – Induction Motor Reference Prices (SIEMENS, 2013b).

Rated power (HP)	Rated power (kW)	Cost (Thousands of US$)
1000	1340	$ 172,33
1250	1676	$ 188,00
1500	2011	$ 199,02
1750	2346	$ 282,14
2000	2681	$ 308,39
2250	3016	$ 321,25
2500	3351	$ 327,68

Testing with various regression curves fitted to the data of Table A.1, the best fitted regression function is a third order polynomial with an R-squared value of 0.969:

$$IM\_cost = -64{,}423\ (IM\_rated\ power)^3 + 437{,}4(IM\_rated\ power)^2 - 848{,}21 IM\_rated\ power + 678{,}57 \quad \text{(A.1)}$$

IM_cost is the estimated cost of the induction motor in thousands of dollars, while the $IM\_rated\ power$ power is the rated power of the induction motor in MW.

A.2 VARIABLE FREQUENCY CONVERTER

The VFDs are mostly used along with induction or synchronous motors for applications in which rotational speed variation is required. As well as induction motors, high power VFDs are not as commercial as low power VFDs. Hence, high power units are also produced under request, and normally for exclusive use with a particular motor. Several manufacturers of VFDs were consulted (Siemens, ABB, Allen Bradley, Leroy Sommer, WEG, etc.) looking for pricing lists of VFDs with similar specifications to that required in the arrangements, *i.e.* with high power, water cooling, module connection, etc. Only one pricing list was founded (ABB, 2008b); the document provides the price of several VFDs from 0.75 to 3000HP with the following main characteristics:

- Input voltage: 208/220/230/240/380/400/415/440/460/480/500/525/575/600/690V.
- Input frequency: 48 to 63Hz
- Fundamental power factor: 0.98
- Output frequency: 0 to 300Hz
- Efficiency: 98%
- Ambient temperature: 40°C
- Cooling method: internal fan (air cooled)
- 12-pulse input
- Cabinet VFD.

The main difference between this VFD and that taken as reference for the electric propulsion arrangements, is the cooling method (water vs. air) and the impossibility of connect individual modules to increase the power rating. The prices for the VFD units with rated input voltage of 690V and rated output voltage of 690V are shown in Table A.2.

Table A.2 – VFD Reference Prices (ABB, 2008b).

Rated power (HP)	Rated power (kW)	Price (US$)
600	447,6	$ 91.011,00
750	559,5	$ 113.969,00
900	671,4	$ 137.035,00
1000	746	$ 153.347,00
1250	932,5	$ 195.077,00
1500	1119	$ 234.353,00
1850	1380,1	$ 287.693,00
2000	1492	$ 305.705,00
2400	1790,4	$ 370.246,00
2750	2051,5	$ 424.909,00
3000	2238	$ 467.756,00

The best fitted regression curve to the prices in the table is a linear function with an R-squared factor equal to 0.9997:

$$VFDcost = 208{,}9VFDrated\ power - 2185{,}5 \quad (A.2)$$

Where $VFDcost$ is the estimated cost of the VFD in dollars and $VFDrated\ power$ is the rated power of the VFD in kW.

A.3 TRANSFORMER FOR THE VFD CONVERTER

The transformers are used at the input of VFDs for phase-shifting and reduction of harmonic components. In these functions, they are exposed to high temperature rises and important losses. In order to avoid damage or excessive heating, the transformers intended to be used along with VFDs have to be designed with this particular purpose.

Rectifier transformers (transformers for special use with power converters) are normally produced under request for a certain application, since they are not as commercially as conventional transformers. After consult the transformer offer of various manufacturers (ABB, Schneider, Siemens, etc.), no detailed information about this type of transformers was founded, especially regarding to the price.

It is possible to use conventional transformers to supply a VFD (for example a 12-pulse VFD can be supplied by two conventional transformers in parallel, one with the secondary connected in Y whereas the secondary of the other transformer connected in delta), by reducing the maximum power that it can supply to avoid failures due to excessive temperature rise. In this respect, information about conventional transformers is more accessible, in several literature and manufacturer websites within the range of a few kW to hundreds of MW. In fact, a particular document was found with important cost information about conventional transformers. In Nochumson (2002) a cost characterization of distribution transformers for substations in the power rating of 500kVA to 2500kVA was performed, presenting a cost comparison between mineral oil and dry type transformers with primary voltage of 15kV and secondary voltage of 480/277V, three phase, 60Hz. The costs obtained by Nochumson (2002) will be used as a guide to have an idea of the order of magnitude of the rectifier transformer price.

The characteristics of the transformer used for cost reference are the following:

- Transformer type: Dry type transformer, polyester.
- Cooling method: Forced air cooling
- Temperatures: ambient temperature 45°C – 150°C rise
- Insulation: Class H – 220°C
- Use: Indoor use
- Protection index: IP00
- Primary winding rated voltage: 15kV
- Secondary winding rated voltage: 480/277V
- BIL:15kV

The main differences between this type of transformer and the rectifier transformer for the arrangements is in the rated voltages.

For the cost estimation, since the VFDs for main propulsion are of the 12-pulse type, it is supposed that two conventional transformers in parallel can replace one rectifier transformer; each of the conventional transformers with half of the rated power of the rectifier transformer.

The reference prices of each individual transformer are shown in Table A.3.

Table A.3 – Transformer Reference Prices (NOCHUMSON, 2002).

KVA	Cost
500	$ 15.900,00
750	$ 20.000,00
1000	$ 22.000,00
1500	$ 26.000,00
2000	$ 30.500,00
2500	$ 36.000,00

The best fitted regression curve for the data of the table is a linear function with an R-squared factor equal to 0.9921:

$$Trafo\_cost = 2(9{,}4821 trafo\_rated\ power + 12029) \qquad (A.3)$$

Where $Trafo\_cost$ is the cost of the transformer in dollars and $trafo\_rated\ power$ power is the power rating of the conventional transformer (half of the power rating of the rectifier transformer) in kVA; the number two multiplying Eq. A.3 is the cost of the two transformers operating in parallel.

A.4 HIGH SPEED DIESEL GENERATOR SET

Pricing lists of high speed Diesel generator sets were consulted from manufacturer websites (Cummins, MTU and Caterpillar) and distributors. From these, one distributor provides detailed cost information in its site (GENERATOR JOE, 2014), publishing a price list of several high speed gensets (1800rpm) from various manufacturers: Perkins, MTU, Iveco, Mitsubishi, Volvo and Jhon Deere with power ratings within 200kW to 2000kW. Most gensets meet with the emission limits settled in the Tier 3 by the EPA (United States Environmental Protection Agency). Tier 3 limits the NOx emissions to 4g/kWh (CUMMINS, 2007), hence, if an engine meets with EPA Tier 3, meets also with MARPOL Tier II (with a limit of 7.8g/kWh for 1800rpm Diesel engine).

The characteristics of the high speed Diesel generator sets from the pricing list are the following:

- Rotational speed: 1800rpm (60Hz)
- Cooling method: Water jacket cooled by fan
- Enclosure: Open type without enclosure
- Meet with EPA Tier 3 (also meets with MARPOL Tier II)
- Voltage output: low voltage, exact value under request up to 690V, 3-phase

The main difference between the generator sets of the list with that required for the electric propulsion arrangement is in the cooling method, for the arrangements the required cooling method is water jacket cooled by sea water.

In Table A.4 the price list is shown. A regression curve fitted to the data in the table is performed, the best fitted expression is a linear function with an R-squared factor equal to 0.951:

$$genset\_cost = 295{,}67 genset\_rated\ power - 57785 \quad \text{(A.4)}$$

In where $genset\_cost$ is the estimated cost of each generator set unit in dollars and $genset\_rated\ power$ is the rated power of the generator set in kW.

Table A.4 – High Speed Generator Set Reference Prices (GENERATOR JOE, 2014).

Manufacturer	Electric output power (kW)	Rotational speed	TIER Accomplishment	Price
Cummins	200	1800	3	$ 38.740,00
Perkins	250	1800	3	$ 39.395,00
Iveco	255	1800	3	$ 69.215,00
Perkins	275	1800	3	$ 39.395,00
Perkins	300	1800	3	$ 45.990,00
Perkins	350	1800	3	$ 45.990,00
Perkins	400	1800	3	$ 47.795,00
Perkins	450	1800	3	$ 53.380,00
Perkins	500	1800	3	$ 53.530,00
Perkins	550	1800	3	$ 56.590,00
Perkins	600	1800	3	$ 85.340,00
Mitsubishi	800	1800	3	$ 154.930,00
Mitsubishi	1000	1800	3	$ 255.615,00
Mitsubishi	1250	1800	3	$ 300.590,00
MTU	1250	1800	3	$ 322.200,00
Mitsubishi	1500	1800	3	$ 390.780,00
Mitsubishi	1600	1800	3	$ 376.220,00
Cummins	2000	1800	3	$ 646.130,00
Mitsubishi	2000	1800	3	$ 472.065,00

APPENDIX B – VFD TRANSFORMER REGRESSION LINES

In the present section, the trend-lines for estimation of the mass and the volume of the VFD transformer will be presented. Moreover, the mass and the volume of the VFD transformers for the arrangements 1, 2, 3 and 4 will be obtained.

The regression curves were constructed with the data of the rectifier transformer catalog presented in the Annex D (EMG TRANSFORMERS, 2013). The technical data of the transformers is presented in Table B.1.

Table B.1 – Technical Data of Rectifier Transformers.

Technical Data	
Primary Voltage (V)	690
Secondaries Voltage (V)	690
Frequency (Hz)	50/60
Short Circuit Voltage	4%
Protection Index	IP00
Cooling	Normal Air
Ambient Temperature	-5 to 40°C

B.1 MASS TREND-LINE

The mass of the transformers as a function of the power rating is presented in Table B.2.

Table B.2 – Mass of the Power Converter Transformers as a Function of the Power Rating

Power rating (kVA)	**73**	**90**	**120**	**145**	**175**	**210**	**260**
Mass (kg)	310	330	390	490	520	570	670
Power rating (kVA)	315	390	480	610	770	1000	1600
Mass (kg)	750	910	1140	1380	1500	2400	3300

The data in the table is plotted in Figure B.1. Various regression lines were obtained using the Excel® trend-line tool; the best fitted regression line is the shown in Eq. (B.1):

$$Transformer\ Mass = 2{,}0005 \cdot power\ rating + 155{,}76 \quad (B.1)$$

Where: $Transformer\ Mass$ is given kg and the $power\ rating$ is given in kVA.

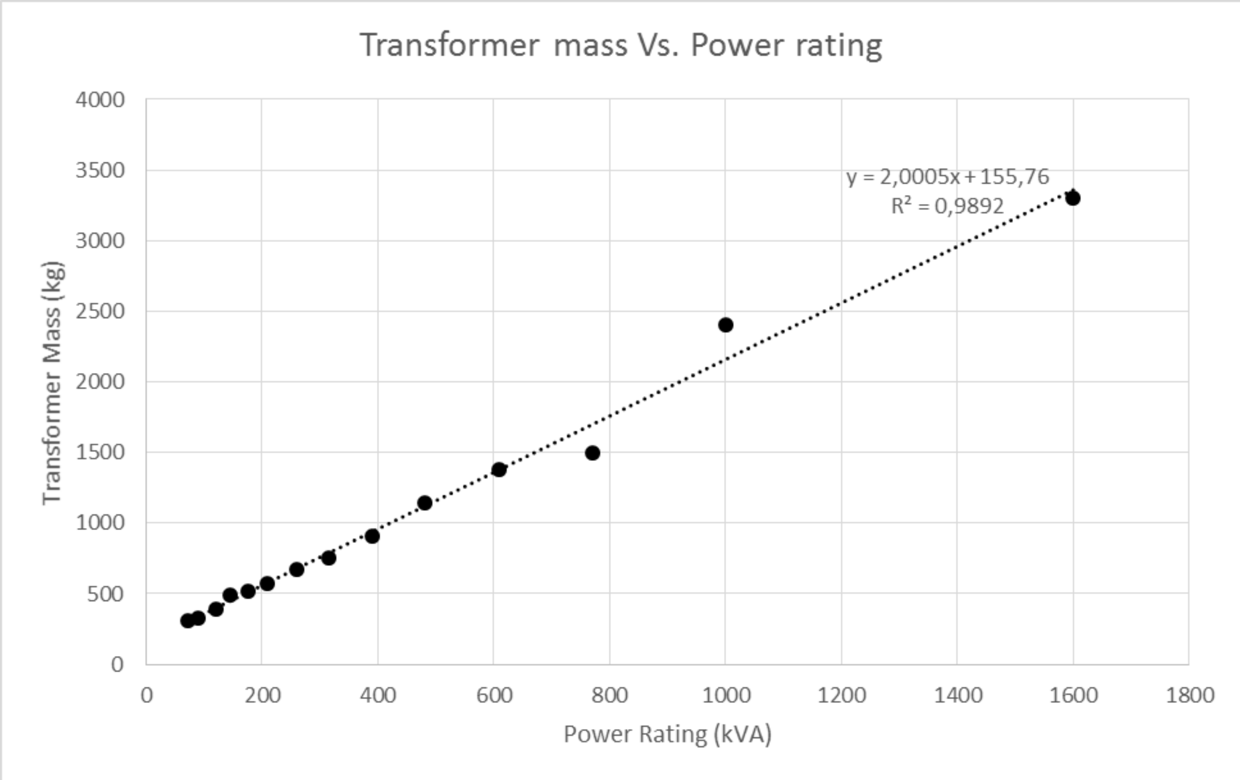


Figure B.1 – Data Points in Table B.1 and Fitted Regression Line.

B.2 REGRESSION LINES FOR THE DIMENSIONS

The dimensions of power converter transformer as a function of the power rating are presented in Table B.3.

Table B.3 – Transformer Dimensions as a Function of Power Rating

Power rating (kVA)	**73**	**90**	**120**	**145**	**175**	**210**	**260**
Length (m)	0,73	0,73	0,75	0,88	0,8	0,84	0,8
Width (m)	0,37	0,44	0,48	0,45	0,5	0,52	0,59
Height (m)	0,52	0,52	0,56	0,6	0,65	0,65	0,72
Power rating (kVA)	315	390	480	610	770	1000	1600
Length (m)	0,8	0,85	0,97	0,97	0,97	1,25	1,25
Width (m)	0,62	0,54	0,56	0,7	0,8	0,76	0,86
Height (m)	0,8	0,9	1	1	1	1,57	1,6

The above table is plotted in Figure B.2, also showing the regression lines. The best fitted regression line for the length is shown in Eq. B.2, for the width is Eq. B.3 and for the height is Eq. B.4.

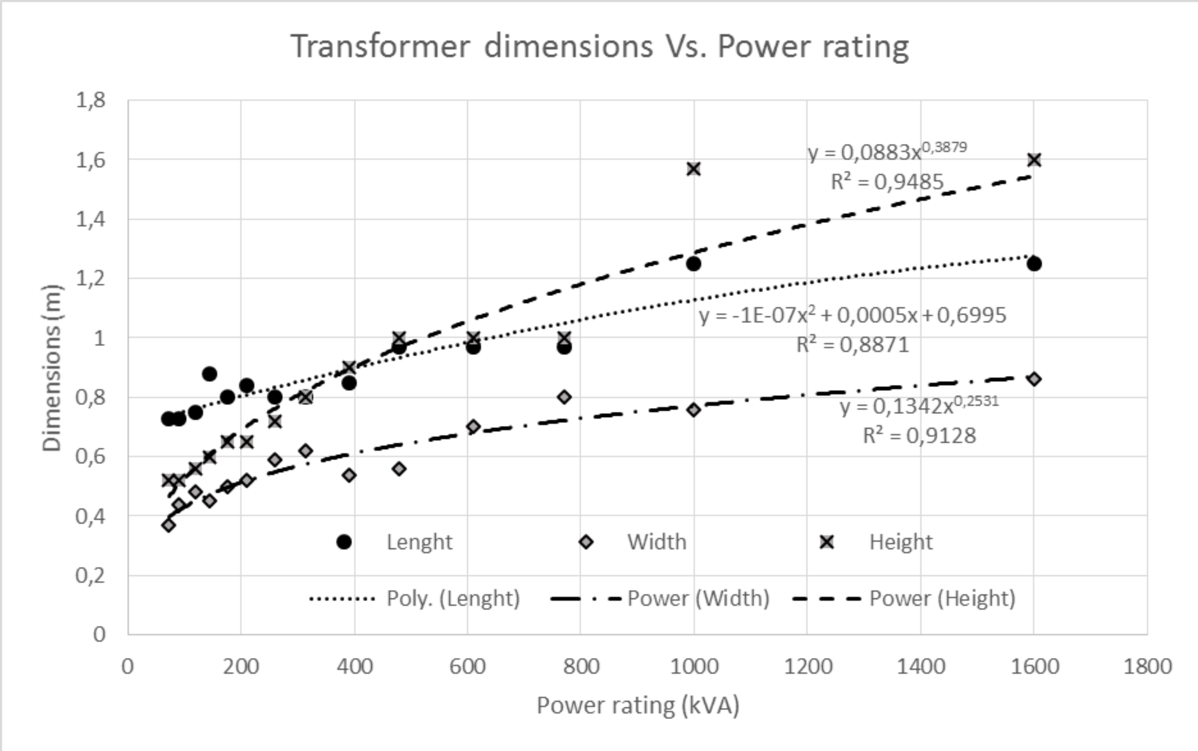


Figure B.2 – Data Points for the Dimensions and Fitted regression lines.

$$length = -1 \times 10^{-7} power\ rating^2 + 0.0005 power\ rating + 0.6995 \quad \text{(B.2)}$$

$$Width = 0.1342 power\ rating^{0.2531} \quad \text{(B.3)}$$

$$Height = 0.0883 power\ rating^{0.3879} \quad \text{(B.4)}$$

Where: $length$, $Width$ and $Height$ are given in m and $power\ rating$ is given in kVA.

B.3 MASS AND VOLUME FOR THE MAIN PROPULSION VFD TRANSFORMERS IN THE ARRANGEMENTS 1 AND 3

In arrangements 1 and 3, the transformer for the VFD of the main propulsion motor is required to have a power rating of 3251kVA. Using Eq. B.1, the mass of the transformer is estimated to be:

$$Transformer\ Mass = 2{,}0005 \cdot power\ rating + 155{,}76 = 6659{,}4 \approx 6660kg \quad \text{(B.5)}$$

The volume is obtained using Eq. B.2 to B.4 and multiplying their results:

$$length = -1 \times 10^{-7} power\ rating^2 + 0.0005 power\ rating + 0.6995 \approx 1{,}27m \quad \text{(B.6)}$$

$$Width = 0.1342 power\ rating^{0.2531} \approx 1{,}04m \quad \text{(B.7)}$$

$$Height = 0.0883 power\ rating^{0.3879} \approx 2{,}03m \quad \text{(B.8)}$$

$$Volume = 1{,}27m \times 1{,}04m \times 2{,}03m \approx 2{,}68m^3 \quad \text{(B.9)}$$

B.4 MASS AND VOLUME FOR THE VFD TRANSFORMERS IN THE ARRANGEMENTS 2 AND 4

In arrangements 2 and 4 the VFD transformer for the main propulsion motor is required to have a power rating of 3230kVA. Using Eq. B.1, the mass of the transformer is:

$$Transformer\ Mass = 2{,}0005 \cdot power\ rating + 155{,}76 = \approx 6617kg \quad \text{(B.10)}$$

The volume is obtained using Eq. B.2 to B.4 and multiplying their results:

$$length = -1 \times 10^{-7} power\ rating^2 + 0.0005 power\ rating + 0.6995 \approx 1{,}27m \quad \text{(B.11)}$$

$$Width = 0.1342 power\ rating^{0.2531} \approx 1{,}04m \quad \text{(B.12)}$$

$$Height = 0.0883 power\ rating^{0.3879} \approx 2{,}03m \quad \text{(B.13)}$$

$$Volume = 1{,}27m \times 1{,}04m \times 2{,}03m \approx 2{,}68m^3 \quad \text{(B.14)}$$

APPENDIX C – STANDARD LOAD PROFILE

C.1 PORT OPERATIONAL MODE

Table C.1 – Power Samples of the Load Profile for Port Operation.

Port load profile					
Sample Time (hour)	**Power Request (kW)**	**Sample Time (hour)**	**Power Request (kW)**	**Sample Time (hour)**	**Power Request (kW)**
00:00	181	07:00	441	14:00	230
01:00	256	08:00	368	15:00	438
02:00	480	09:00	701	16:00	658
03:00	325	10:00	654	17:00	369
04:00	689	11:00	623	18:00	357
05:00	720	12:00	260	19:00	471
06:00	591	13:00	195	20:00	321

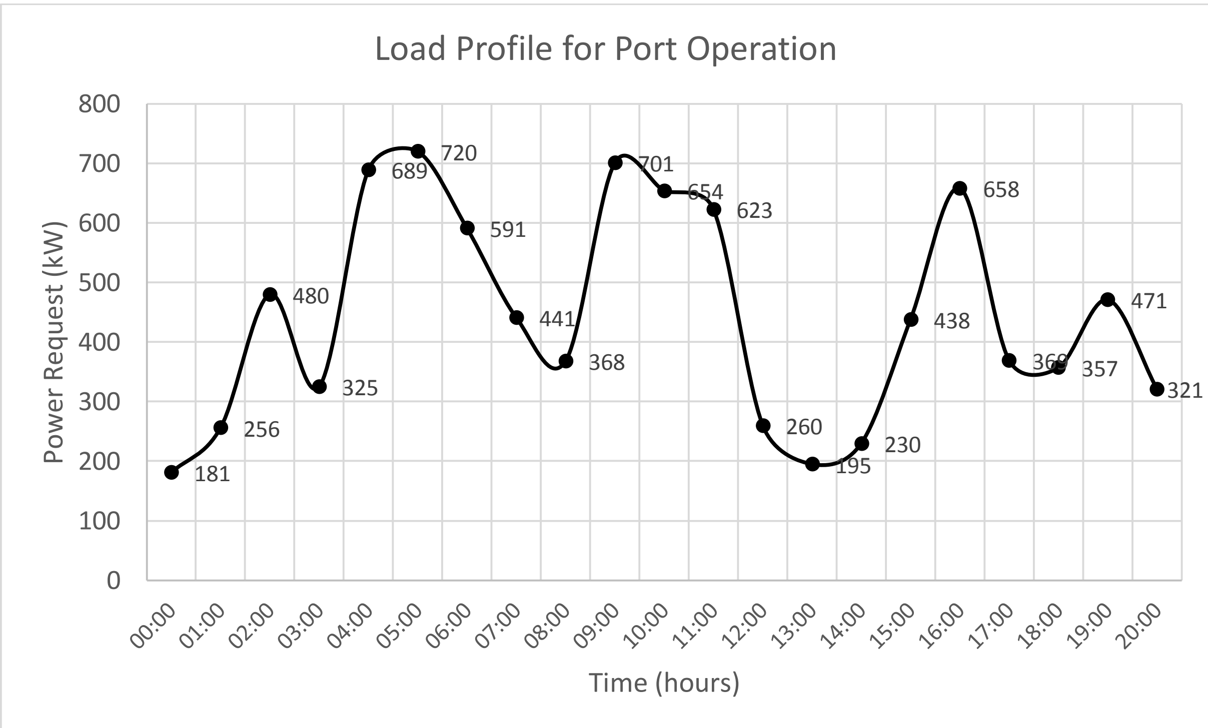


Figure C.1 – Power Demand for Port Operation

C.2 LADEN VOYAGE

Table C.2 – Speed and Power Samples for the Load Profile in Laden Voyage.

Laden voyage load profile				
Sample Time (hour)	**Speed (knots)**	**Approximate distance traveled (km)**	**Approximated power demand from propulsion (kW)**	**Estimated power demand from auxiliary loads (kW)**
21:00:00	14,2	26,30	3817,3	269,0
22:00:00	14,9	53,25	4843,4	579,0
23:00:00	15,1	81,03	5177,9	680,0
24:00:00	14,8	108,71	4683,4	325,0
25:00:00	14,9	136,21	4843,4	1011,0
26:00:00	15	163,90	5008,3	960,0
27:00:00	15,1	191,77	5177,9	710,0
28:00:00	15	219,65	5008,3	555,0
29:00:00	14,7	247,15	4527,9	430,0
30:00:00	14,9	274,56	4843,4	298,0
31:00:00	14,6	301,88	4377,0	856,4

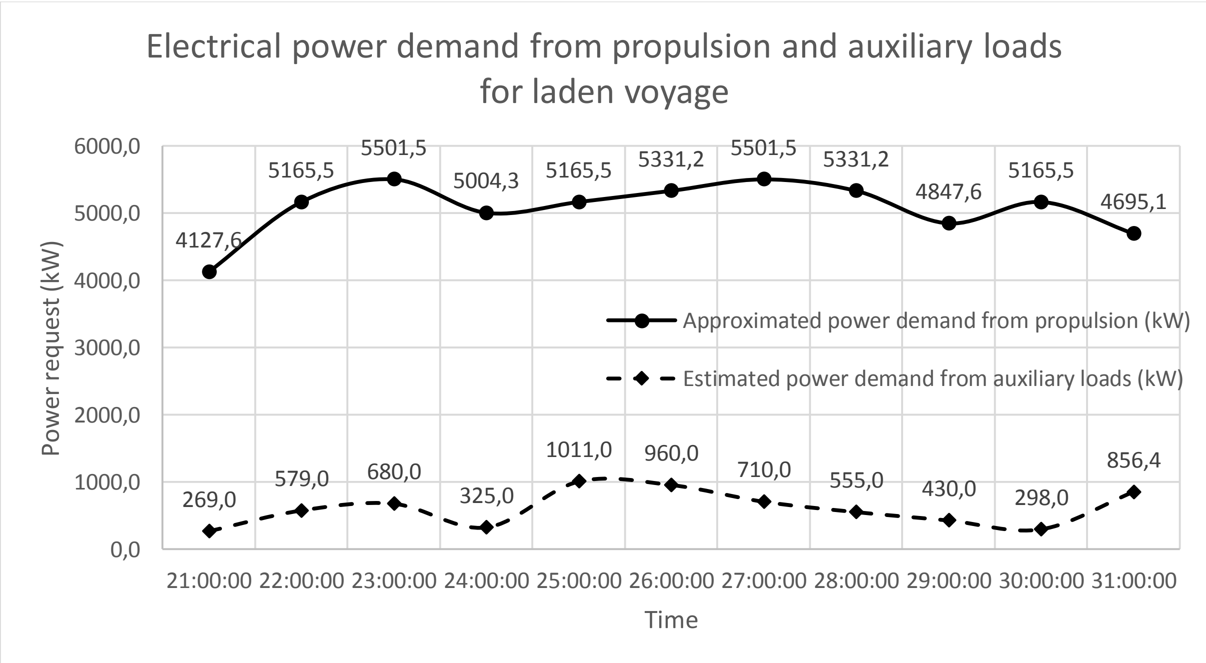


Figure C.2 – Power Demand for Laden Voyage.

C.3 DYNAMIC POSITIONING

Table C.3 – Power Samples for Dynamic Positioning Operational Mode.

Dynamic positioning load profile				
Number of platforms	**Sample time (hour)**	**Estimated power demand from auxiliary loads (kW)**	**Estimated power demand from the main azimuth thrusters (kW)**	**Estimated power demand from side thrusters (kW)**
1	32:00:00	1130	115	410
	33:00:00	890	90	123
	34:00:00	753,2	100	320
	35:00:00	923,6	113	331
	36:00:00	1001,2	150	290
	37:00:00	1000,3	80	169
	38:00:00	1230	56	298
	39:00:00	887,6	89	377
	40:00:00	775,2	41	415
	41:00:00	632,3	115	463
	42:00:00	815	130	541
	43:00:00	541	60	392
	44:00:00	398,6	58	329
	45:00:00	791	77	487
	46:00:00	290	126	384
	47:00:00	286	148	639
2	48:00:00	980	130	710
	49:00:00	1123	71	514
	50:00:00	852	88	392
	51:00:00	695	95	116
	52:00:00	971	84	192
	53:00:00	1162	55	152
	54:00:00	1201	65	174
	55:00:00	865	39	131,3
	56:00:00	634	63	167
	57:00:00	650	42	99
	58:00:00	532	153	222
	59:00:00	489	125	196,5
	60:00:00	338	142	358
	61:00:00	316	135	347
	62:00:00	392	92	741
3	63:00:00	642	103	565
	64:00:00	698	97	513
	65:00:00	981	54	364
	66:00:00	542	30	229
	67:00:00	416,3	26	193
	68:00:00	512,3	56	156
	69:00:00	879,3	88	178,6

	70:00:00	591,2	86	287
	71:00:00	884,2	61	269
	72:00:00	875,6	115	438
	73:00:00	678,3	36	521
	74:00:00	1230,3	85	374
	75:00:00	742	92	333
	76:00:00	345	77	418
	77:00:00	395	73	213

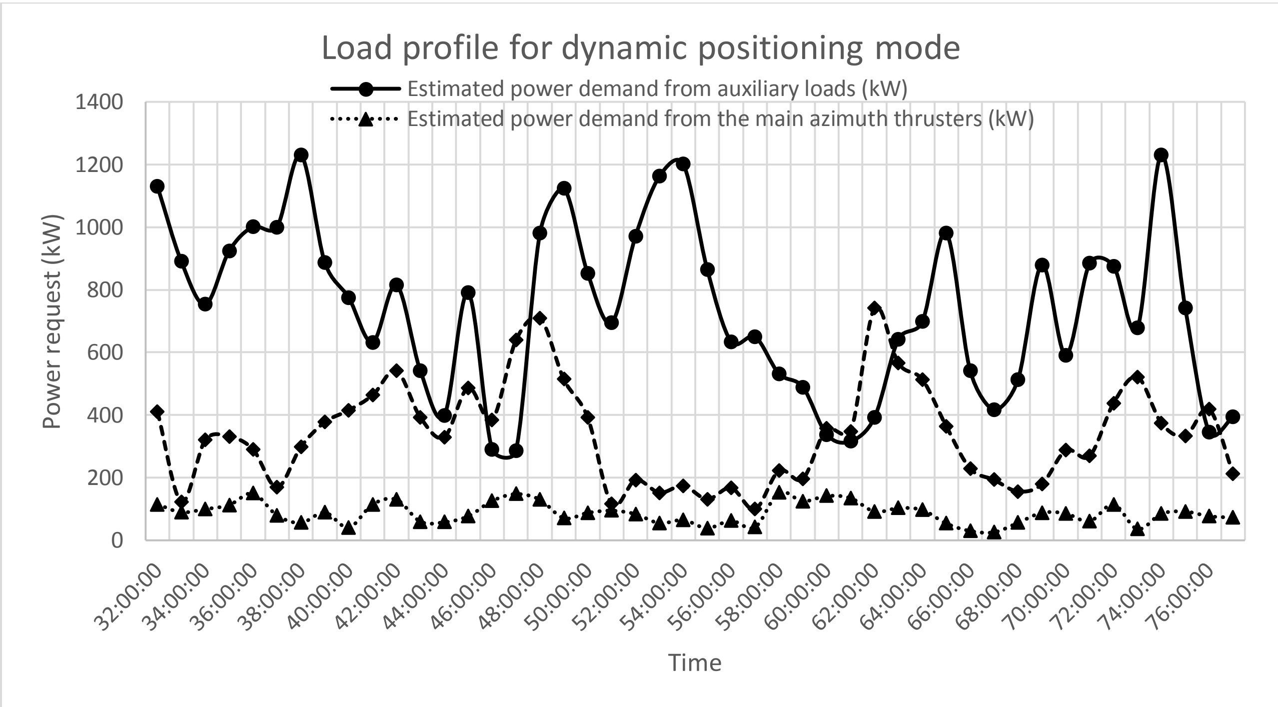


Figure C.3 – Power Demands for Dynamic Positioning Mode.

C.4 PARTIAL LOAD VOYAGE

Table C.4 – Speed and Power samples for Partial Load Voyage.

Load profile for partial load voyage					
Sample Time (hour)	**Speed (knots)**	**Approximate distance traveled (km)**	**Average speed (knots)**	**Approximated power demand from propulsion (kW)**	**Estimated power demand from auxiliary loads (kW)**
78:00:00	14,6	27,04	14,8	3765,0	301,0
79:00:00	14,8	54,26	14,8	3989,7	564,0
80:00:00	14,7	81,58	14,8	3875,9	524,0
81:00:00	14,9	108,99	14,8	4106,4	337,0
82:00:00	14,5	136,21	14,8	3657,0	772,0
83:00:00	15	163,53	14,8	4226,1	1016,0
84:00:00	15	191,31	14,8	4226,1	778,0

85:00:00	15,2	219,28	14,8	4474,6	345,0
86:00:00	15,3	247,52	14,8	4603,5	760,0
87:00:00	15	275,58	14,8	4226,1	618,0
88:00:00	14,3	302,71	14,8	3449,2	446,4

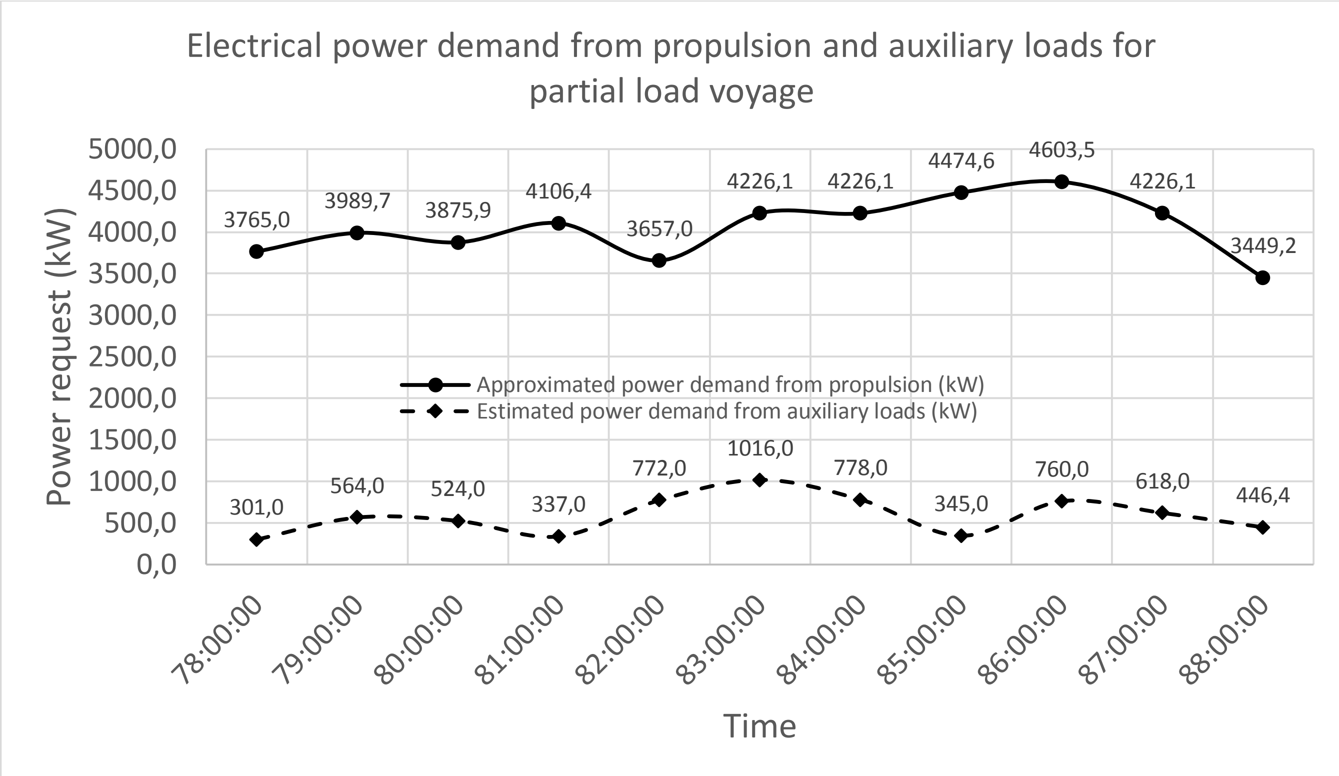


Figure C.4 – Power Demands for Partial Load Voyage.

C.5 STANDBY OPERATION

Table C.5 – Power samples for Standby mode.

Standby operation load profile					
Sample Time (hour)	**Power Request (kW)**	**Sample Time (hour)**	**Power Request (kW)**	**Sample Time (hour)**	**Power Request (kW)**
90:00:00	258	98:00:00	210	106:00:00	197
91:00:00	456	99:00:00	241	107:00:00	194
92:00:00	710	100:00:00	180	108:00:00	265
93:00:00	423	101:00:00	194	109:00:00	321
94:00:00	564	102:00:00	230	110:00:00	362
95:00:00	325	103:00:00	204	111:00:00	332
96:00:00	302	104:00:00	217	112:00:00	254
97:00:00	654	105:00:00	199	113:00:00	214
				114:00:00	223

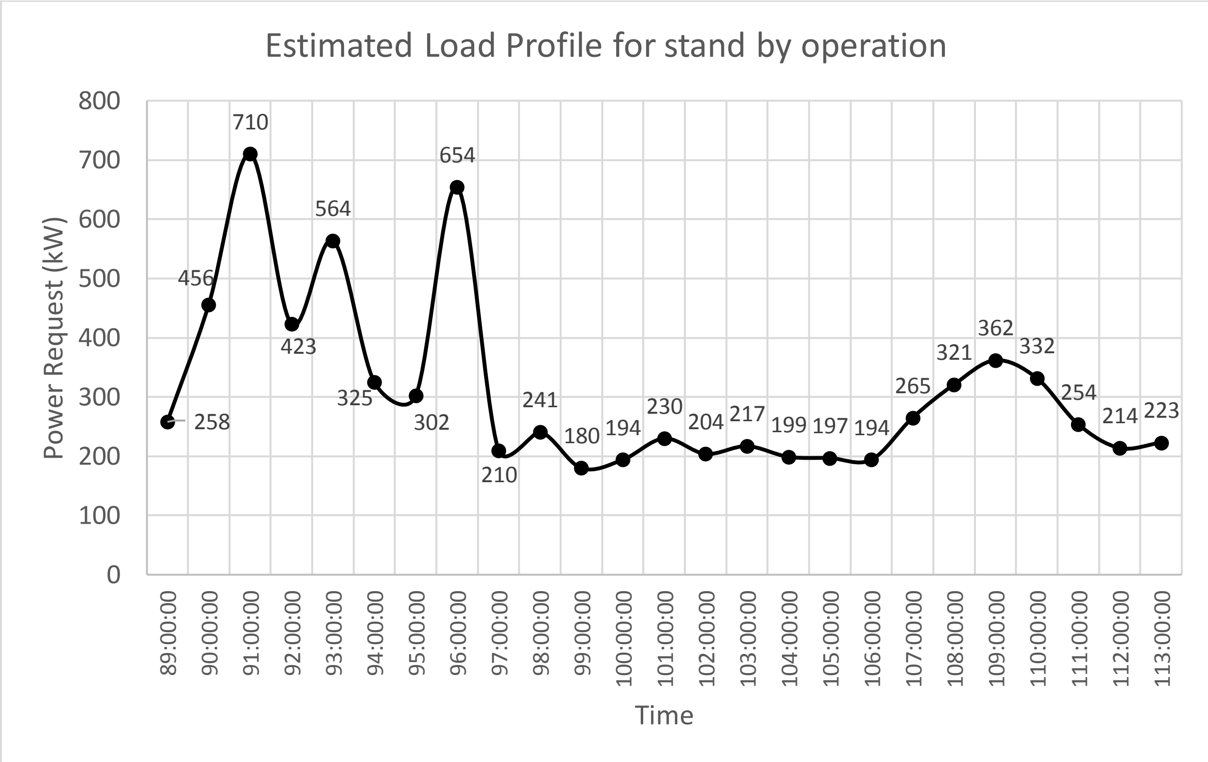


Figure C.5 – Power demands for standby operation mode.

APPENDIX D – AHP METHODOLOGY

D.1 METHODOLOGY DESCRIPTION

The Analytic Hierarchy Process (AHP), is a methodology to support the decision making process through the specific evaluation of the proposed alternatives, resulting in the selection of the one that best fits a set of criteria. The AHP method allows to simplify a complex selection process with multiple alternatives and criteria by evaluating the alternatives, comparing them by pairs for each selection criterion in an isolated way (GARBER, 2002; PEREIRA, 2007).

The decision making process through AHP is divided in four stages (GARBER, 2002):

- Project structuration: implies the identification of the objective, the selection criteria and the proposed alternatives.
- Determination of the preferences by comparison between each pair of decision factors, subdivided in objectives, criteria and alternatives.
- Sintesis and definition of the relative priority of each decision element, in each level.
- Consolidation of values asigned to the factors for each alternative.

The comparison between alternatives and criteria is established by a hierarchy of values, in a comparison matrix, in which the options are organized depending of their importance. For purposes of the present dissertation, the scale that will be used to rate the elements in the matrix is the presented by Garber (2002) and Pereira (2007), shown in Table D.1.

Table D.1 – Preference Values

Numeric Values	Description (Importance of one alternative over the other)	Explanation
1	Equivalent or equal	The two elements contribute equally for the objective
2		
3	Little importance	One element is slightly favored compared with the other
4		
5	High importance	One element is strongly favored compared with the other
6		
7	Very high importance	One element has a very strong value compared with the other
8		
9	Absolut importance	One activity is favored over the other with high degree of certainty

Each pair of elements (Criteria or alternatives) are compared considering a specific criterion; therefore, many matrix will be constructed as the number of selection criteria. The criteria or alternative matrix is a square matrix in which the elements of the first row are the same as the first column (the elements which are going to be compared). The terms of the matrix (a_{ij}) are the preference values settled in Table D.1 and explains how many one element (i) is preferred related to other(j). The comparison matrix is presented in Table D.2.

Table D.2– Comparison Matrix

	Criteria 1	**Criteria 2**	**.**	**.**	**.**	**Criteria n**
Criteria 1	1	a_{12}	.	.	.	a_{1n}
Criteria 2	$1/a_{12}$	1	.	.	.	a_{2n}
.	.		1			
.	.					
.	.					
Criteria n	$1/a_{1n}$	$1/a_{2n}$	.	.	.	1

The matrix terms presents the following particularities:

- The comparison between the same criteria or alternatives, *i.e.* the term a_{ij} when i=j- result in a value equal to 1, as presented in Table D.2 for equivalent elements. Therefore, all terms of the main diagonal are equal to 1.
- Each term of the matrix a_{ij} is the inverse of the term a_{ji}, hence, the terms have to satisfy the following expression:

$$a_{ij} = 1/a_{ji} \qquad \text{(D.1)}$$

  The above as consequence of the reciprocity condition: if comparison of one element of the column (named C1) vs. the element of the row (named C3) have a value **A**, the inverse comparison C1 in the row vs. C3 in the column have to result in a value **B=1/A**

- All the terms of the matrix are greater than 0.

The AHP method allows to make decisions using qualitative evaluation or quantitative evaluation for deterministic values. For qualitative comparison, in which one element is preferred x times that other element, the Table D.1 is used to assign values to each comparison. For deterministic values, the hierarchy is performed by maximizing or minimizing the values by means of a normalization process. The normalization is performed dividing each term by the sum of all elements of each row of the matrix.

For each matrix with both type of values (qualitative or deterministic), it is necessary to normalize each term of the matrix dividing it by the sum of all elements of the respectively column. Thus, each term will be dimensionless and be in decimal format. The process requires the calculation of average value of each row arranging them in a column vector.

In order to perform a coherent comparison it is necessary to check the consistency of the values resulting of the alternative evaluation. Garber (2002) and Pereira (2007) presents an expression named inconsistency coefficient presented by Saaty (1980), which provides the possible inconsistencies owing to the qualitative estimation associated to the judge of the decision maker. The inconsistency index is defined in the following expression:

$$IC = \frac{\lambda_{max} - m}{m - 1} \tag{D.2}$$

Where: λ_{max} is the greater autovalue of the square matrix with order m and m is the number of rows and columns of the square matrix.

The consistency ratio, which define the consistency of the values of the comparison matrix is:

$$RC = \frac{IC}{CA} \tag{D.3}$$

Where CA is the random consistency index, which magnitude depends of m and is provided in the following table by Saaty (1980):

Table D.3 – Random Consistency Index Values as Function of m.

m	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
CA	0	0	0.58	0.9	1.12	1.24	1.32	1.4	1.45

The highest limit of RC in which the results will be considered as coherent is 10%. If greater, the matrix has to be created again adjusting the preferences, making the judgments one more time. Finally, a consolidated alternative matrix formed with the average column vector of each alternative matrix is performed. This matrix is multiplied by the average column vector of the criteria matrix resulting in the total value of the alternatives in which the best alternative can be selected.

D.2 AHP METHODOLOGY CALCULATION PROCEDURE

The importance of the selection criteria for Scenario 1 and 2 are settled in Figures 4.35 and 4.36; the correspondent matrices, named as main criteria matrices, are shown in Table D.4 and D.5. In the tables, the total sum of each column is shown.

Table D.4 – Main Criteria Matrix for Scenario 1.

Main Criteria Matrix With Respect to the Main Goal – Scenario 1			
	C1	**C2**	**C3**
C1-Size and mass	1	1/4	2
C2-NPV	4	1	5
C3-Exhaust gases	1/2	1/5	1
Total	5,50	1,45	8

Table D.5 – Main Criteria Matrix for Scenario 2

Main Criteria Matrix With Respect to the Main Goal – Scenario 1			
	C1	**C2**	**C3**
C1-Size and mass	1	1/2	1/5
C2-NPV	2	1	1/4
C3-Exhaust gases	5	4	1
Total	8	5,5	1,45

Each element of the main criteria matrix is divided by the sum of the elements of the column. The weigh of each criteria is obtained through the calculation of the average of each row, as shown in Tables D.6 and D.7. The consistency vector is obtained by the multiplication of the main criteria matrix (Tables D.4 and D.5) by the vector with the average values of each column; the maximum autovalue of the matrix is obtained by the sum of the elements of the consistency vector, as shown in Tables D.6 and D.7.

Table D.6 – Consistency Index for Main Criteria Matrix for Scenario 1.

Main Criteria Matrix With Respect to the Main Goal – Scenario 1					
	C1	**C2**	**C3**	**Criteria Importance**	**Consistency Vector**
C1-Size and mass	0,18	0,17	0,25	0,20	0,61
C2-NPV	0,73	0,69	0,63	0,68	2,08
C3-Exhaust gases	0,09	0,14	0,13	0,12	0,35
Consistency Index		0.033		λ_{max}	3,04

Table D.7 – Consistency Index for Main Criteria Matrix for Scenario 2.

Main Criteria Matrix With Respect to the Main Goal – Scenario 2					
	C1	**C2**	**C3**	**Criteria Importance**	**Consistency Vector**
C1-Size and mass	0,13	0,09	0,14	0,12	0,35
C2-NPV	0,25	0,18	0,17	0,20	0,61
C3-Exhaust gases	0,63	0,73	0,69	0,68	2,08
Consistency Index		0.033		λ_{max}	3,04

Using the same procedure, the sub-criteria matrix with respect to size and mass criterion is determined in Tables D.8 and D.9.

Table D.8 – Sub-Criteria Matrix With Respect to Size and Mass Criterion.

Sub-Criteria Matrix With Respect to Size and Mass Criterion			
	C1	**C2**	**C3**
C1-Mass	1	1/4	2
C2-Volume	4	1	5
C3-Fuel Consumption	1/2	1/5	1
Total	2,20	2,2	11,00

Table D.9 – Consistency Index for the Sub-Criteria Matrix With Respect to Size and Mass Criterion.

Sub-Criteria Matrix With Respect to Size and Mass Criterion					
	C1	**C2**	**C3**	**Criteria Importance**	**Consistency Vector**
C1-Mass	0,45	0,45	0,45	0,45	1,4
C2-Volume	0,45	0,45	0,45	0,45	1,4
C3-Fuel Consumption	0,09	0,09	0,09	0,09	0,3
Consistency Index		0.00009		λ_{max}	3,0

The sub-criteria matrix with respect to the exhaust gases is shown in Table D.10. Since only two elements are compared, it is not necessary to obtain the consistency index. In the same matrix, the importance of the sub-criteria are shown.

Table D.10 – Sub-Criteria Matrix With Respect to the Exhaust Gases Criterion.

	C1	**C2**	**C1**	**C2**	**Criteria Importance**
C1-SOx	1	2	0,67	0,67	0,67
C2-NOx	1/2	1	0,33	0,33	0,33
Total	1,50	3			

The following step is to normalize the quantitatively values of the alternatives for each criteria and sub-criteria. In Table D.11 the consolidated matrix with the values of each arrangement for the criteria and sub-criteria is shown.

Table D.11 – Consolidated Matrix of the Alternatives

	Mass	Volume	Fuel Consumption	NPV	SOx	NOx
Arrangement 1 - HS	198,8	229,8	42759,9	-$ 37.814.333	1282,8	1476,5
Arrangement 1 - MS	276,9	196,6	39521,8	-$ 27.427.859	2766,5	1821,9
Arrangement 2 - HS	188,3	235,7	42691,4	-$ 37.898.765	1280,7	1473,9
Arrangement 2 - MS	266,3	202,6	39451,6	-$ 27.525.914	2761,6	1818,8
Arrangement 3 - HS	327,7	314,1	38364,6	-$ 36.256.216	1150,9	1398,3
Arrangement 3 - MS	405,7	**280,9**	36241,3	-$ 27.382.326	2536,9	1737,8
Arrangement 4 - HS	322,3	320,0	38316,5	-$ 36.356.658	1149,5	1397,8
Arrangement 4 - MS	400,3	**286,9**	36281,8	-$ 27.537.602	2539,7	1723,8

Before performing the normalization, it is necessary obtain the inverse values of each element of the consolidated matrix. They are obtained dividing 1 by each element. Afterwards, the elements of each column are added. The results are shown in Table D12.

Table D.12 – Inverted Consolidated Matrix

	Mass	Volume	Fuel Consumption	NPV	SOx	NOx
Arrangement 1 - HS	0,005029	0,004352	0,000023	0,000000	0,000780	0,000677
Arrangement 1 - MS	0,003612	0,005086	0,000025	0,000000	0,000361	0,000549
Arrangement 2 - HS	0,005311	0,004242	0,000023	0,000000	0,000781	0,000678
Arrangement 2 - MS	0,003755	0,004936	0,000025	0,000000	0,000362	0,000550
Arrangement 3 - HS	0,003052	0,003184	0,000026	0,000000	0,000869	0,000715
Arrangement 3 - MS	0,002465	0,003560	0,000028	0,000000	0,000394	0,000575
Arrangement 4 - HS	0,003103	0,003125	0,000026	0,000000	0,000870	0,000715
Arrangement 4 - MS	0,002498	0,003486	0,000028	0,000000	0,000394	0,000580
Total	0,029	0,032	0,000	0,000	0,005	0,005

The normalized matrix of the alternatives is then obtained by dividing each element of Table D.12 by the total of the correspondent column. In Table D.13 the results are shown.

Table D.13 – Normalized Matrix of the Alternatives.

	Mass	Volume	Fuel Consumption	NPV	SOx	NOx
Arrangement 1 - HS	0,174	0,136	0,114	0,104	0,162	0,134
Arrangement 1 - MS	0,125	0,159	0,124	0,144	0,075	0,109
Arrangement 2 - HS	0,184	0,133	0,114	0,104	0,162	0,135

Arrangement 2 - MS	0,130	0,154	0,124	0,143	0,075	0,109
Arrangement 3 - HS	0,106	0,100	0,127	0,109	0,181	0,142
Arrangement 3 - MS	0,086	0,111	0,135	0,144	0,082	0,114
Arrangement 4 - HS	0,108	0,098	0,127	0,108	0,181	0,142
Arrangement 4 - MS	0,087	0,109	0,135	0,143	0,082	0,115

The following step is to multiply the normalized matrix of the alternatives by the vectors containing the sub-criteria and criteria importance. First, the elements of the normalized matrix of alternatives correspondent to the columns of the mass, volume and fuel consumption are multiplied by the importance vector of the sub-criteria with respect to size and mass, in Table D.14 the procedure is shown.

Table D.14 – Normalized Values of the Alternatives Matrix Multiplied by the Importance Vector of the Sub-Criteria With Respect to Size and Mass.

	Mass	Volume	Fuel Consumption
Arrangement 1 - HS	0,174	0,136	0,114
Arrangement 1 - MS	0,125	0,159	0,124
Arrangement 2 - HS	0,184	0,133	0,114
Arrangement 2 - MS	0,130	0,154	0,124
Arrangement 3 - HS	0,106	0,100	0,127
Arrangement 3 - MS	0,086	0,111	0,135
Arrangement 4 - HS	0,108	0,098	0,127
Arrangement 4 - MS	0,087	0,109	0,135

✖

Criteria Importance	
0,45	C1-Mass
0,45	C2-Volume
0,09	C3-Fuel Consumption

=

	Partial Importance
Arrangement 1 - HS	0,152
Arrangement 1 - MS	0,141
Arrangement 2 - HS	0,154
Arrangement 2 - MS	0,141
Arrangement 3 - HS	0,105
Arrangement 3 - MS	0,102
Arrangement 4 - HS	0,105
Arrangement 4 - MS	0,101

Next, the columns correspondent to SOx and NOx are multiplied by the importance of these sub-criteria. In Table D.15 the procedure is shown.

Table D.15 – Normalized Values of the Alternatives Matrix Multiplied by the Importance Vector of the Sub-Criteria With Respect to Exhaust Gases.

	SOx	NOx
Arrangement 1 - HS	0,162	0,134
Arrangement 1 - MS	0,075	0,109
Arrangement 2 - HS	0,162	0,135
Arrangement 2 - MS	0,075	0,109
Arrangement 3 - HS	0,181	0,142
Arrangement 3 - MS	0,082	0,114
Arrangement 4 - HS	0,181	0,142
Arrangement 4 - MS	0,082	0,115

✖

Criteria Importance	
0,67	C1-SOx
0,33	C2-NOx

=

	Partial Importance
Arrangement 1 - HS	0,153
Arrangement 1 - MS	0,086
Arrangement 2 - HS	0,153
Arrangement 2 - MS	0,087
Arrangement 3 - HS	0,168
Arrangement 3 - MS	0,093
Arrangement 4 - HS	0,168
Arrangement 4 - MS	0,093

Then, the resulting vector of Table D.14, the column correspondent to the NPV in Table D.13 and the resulting vector of Table D.15 are multiplied by the importance vector of the main criteria with respect to the main goal. The procedure is shown in Table D.16 for Scenario 1 and Table D.17 for Scenario 2.

Table D.16 – Overall Priority for the Alternatives With Respect to Scenario 1.

	Partial Importance for Size and Mass	NPV	Partial Importance for Exhaust Gases
Arrangement 1 - HS	0,152	0,104	0,153
Arrangement 1 - MS	0,141	0,144	0,086
Arrangement 2 - HS	0,154	0,104	0,153
Arrangement 2 - MS	0,141	0,143	0,087
Arrangement 3 - HS	0,105	0,109	0,168
Arrangement 3 - MS	0,102	0,144	0,093
Arrangement 4 - HS	0,105	0,108	0,168
Arrangement 4 - MS	0,101	0,143	0,093

✖

Criteria Importance	
0,20	C1-Size and mass
0,68	C2-NPV
0,12	C3-Exhaust gases

═

	Overall Priority
Arrangement 1 - HS	0,1195
Arrangement 1 - MS	0,1364
Arrangement 2 - HS	0,1200
Arrangement 2 - MS	0,1361
Arrangement 3 - HS	0,1150
Arrangement 3 - MS	0,1295
Arrangement 4 - HS	0,1148
Arrangement 4 - MS	0,1288

Table D.17 – Overall Priority for the Alternatives With Respect to Scenario 2.

	Partial Importance for Size and Mass	NPV	Partial Importance for Exhaust Gases
Arrangement 1 - HS	0,152	0,104	0,153
Arrangement 1 - MS	0,141	0,144	0,086
Arrangement 2 - HS	0,154	0,104	0,153
Arrangement 2 - MS	0,141	0,143	0,087
Arrangement 3 - HS	0,105	0,109	0,168
Arrangement 3 - MS	0,102	0,144	0,093
Arrangement 4 - HS	0,105	0,108	0,168
Arrangement 4 - MS	0,101	0,143	0,093

✖

Criteria Importance	
0,12	C1-Size and mass
0,20	C2-NPV
0,68	C3-Exhaust gases

═

	Overall Priority
Arrangement 1 - HS	0,1429
Arrangement 1 - MS	0,1043
Arrangement 2 - HS	0,1434
Arrangement 2 - MS	0,1044
Arrangement 3 - HS	0,1484
Arrangement 3 - MS	0,1041
Arrangement 4 - HS	0,1485
Arrangement 4 - MS	0,1040

ANNEX A – INTERNET LINKS TO THE DATASHEETS OF VESSELS USED FOR CHARACTERIZATION

Vessel	link for access	Retrieved in
LAB 150	http://www.labordemarine.com/brazil/vessels/lab150.pdf	September 2013
LAB 151	http://www.labordemarine.com/brazil/vessels/lab151.pdf	September 2013
LAB 152	http://www.labordemarine.com/brazil/vessels/lab152.pdf	September 2013
BOURBON LIBERTY 105-120	http://www.bourbon-online.com/medias/offshore/psv/bourbon-liberty-100-1509-t-dp2.pdf	September 2013
AMY CANDIES	http://www.ottocandies.com/specs/amy.pdf	September 2013
KERI CANDIES	http://www.ottocandies.com/specs/keri.pdf	September 2013
MARY FRANCIES CANDIES	http://www.ottocandies.com/specs/mary-frances.pdf	September 2013
OLIVIA CANDIES	http://www.ottocandies.com/specs/olivia.pdf	September 2013
DOUBLE EAGLE	http://www.gulfmark.com/_filelib/FileCabinet/pdfs/DOUBLE_EAGLE.pdf	September 2013
FIRST AND TEN	http://www.gulfmark.com/_filelib/FileCabinet/pdfs/FIRST_AND_TEN.pdf	September 2013
HAT TRICK	http://www.gulfmark.com/_filelib/FileCabinet/pdfs/HAT_TRICK.pdf	September 2013
TRIPLE PLAY	http://www.gulfmark.com/_filelib/FileCabinet/pdfs/TRIPLE_PLAY.pdf	September 2013
ANNE CANDIES	http://www.ottocandies.com/specs/anne.pdf	September 2013
KIMBERLY CANDIES	http://www.ottocandies.com/specs/kimberly.pdf	September 2013
SIEM SUPPLIER	http://www.siemoffshore.com/Files/Filer/Vessels/siemoffshore_specifications_siemsupplier.pdf	September 2013
BIGUÁ, FULMAR, PETREL, FRAGATA, PELÍCANO, SKUA	http://www.wilsonsons.com.br/servicos/offshore/bigua-fulmar-fragata-petrel-skua-atoba-pelicano	September 2013
SKANDI CAPTAIN	http://www.mzweb.com.br/norskan/web/arquivos/NorSkan_Skandi_Captain.pdf	September 2013
CELIA CANDIES	http://www.ottocandies.com/specs/celia.pdf	September 2013
TALHA - MAR	http://www.wilsonsons.com.br/servicos/offshore/talha-mar-torda-e-cormoran	September 2013
TAGAZ	http://www.wsutoffshore.com.br/psv-tagaz-psv-prion-psv-alcatraz	September 2013
ISLAND PATRIOT	http://www.ulstein.com/kunder/ulstein/mm.nsf/lupGraphics/Yard%20269_Island%20Patriot.pdf/$file/Yard%20269_Island%20Patriot.pdf	September 2013
KL BREVIKFJORD	http://www.klineoffshore.no/files/KL-Brisfjord_220612.pdf	September 2013

ANNEX B – DATASHEET OF 2940KW, 3.4KV, IC81W INDUCTION MOTOR FOR THE ARRANGEMENT 1.

(Source WEG Brazil)

WEG	FOLHA DE DADOS Motor Trifásico de Indução - Rotor de Gaiola	Data: 27/FEV/2014 Nº: FD 23411-0/2014 Desenho Dimensional DM23411-0/2014

Cliente: WEG EQUIP.ELETS.S.A
Referência do Cliente: PROPULSOR PRINCIPAL
Linha: MGW

Identificação da Máquina

Carcaça: 560B	Classe de isolamento: F
Potência: 2940 kW	Elevação da Temperatura: classe F
Freqüência: 60 Hz	Fator de serviço: 1.00
Número de pólos: 6	Tempo de rotor bloqueado: 17 s
Rotação nominal: 1192 rpm	Regime de serviço: S1
Escorregamento: 0.67 %	Temperatura de Entrada de Água: 38 ºC
Tensão primária: 3400 V Ligação:Y	Temperatura Ambiente: 50 ℃
Corrente primária: 599.1 A	Grau de proteção: IP55
Tensão secundaria: Não aplicável	Refrigeração: IC81W
Corrente secundária: Não aplicável	Forma construtiva: B3R
Corrente de partida: 4194 A	Vibração: A 2.8 mm/s rms
Ip/In: 7	Momento de inércia: 109.8 kgm²
kVA/kW: 8.4	Nível de ruído: 79 dB(A), tol: 3 dB(A) (alimentação senoidal)
Corrente a vazio: 179.7 A	Sentido de rotação: AMBOS
Conjugado nominal: 23555 Nm	Método de Partida: INVERSOR DE FREQUÊNCIA
Conjugado de partida: 70 %	Acoplamento: DIRETO
Conjugado máximo: 220 %	

Características de Desempenho (Alimentação Senoidal)

Potência	50%	75%	100%
Rendimento(%)	96.8	97	96.9
cos ø	0.75	0.83	0.86

Dados da Carga

Tipo da Carga: PROPULSOR NAVIO PRINCIPAL
Conjugado Resistente:
J(J=GD²/4):

Observações/Acessórios

- PERDA SUPLEMENTAR 0.50% DA POTÊNCIA ABSORVIDA.
- A temperatura de saída de água não deve ser 10ºC superior à temperatura de entrada de água.

Normas

Especificação:	IEC 60034-1 / ABNT NBR 17094-1
Ensaios:	IEC 60034-2 / ABNT NBR 5383-1
Ruído:	IEC 60034-9
Vibração:	IEC 60034-14
Tolerância:	IEC 60034-1 / ABNT NBR 17094-1

Limites de Operação com Inversor de Frequência

Valores nos terminais do motor

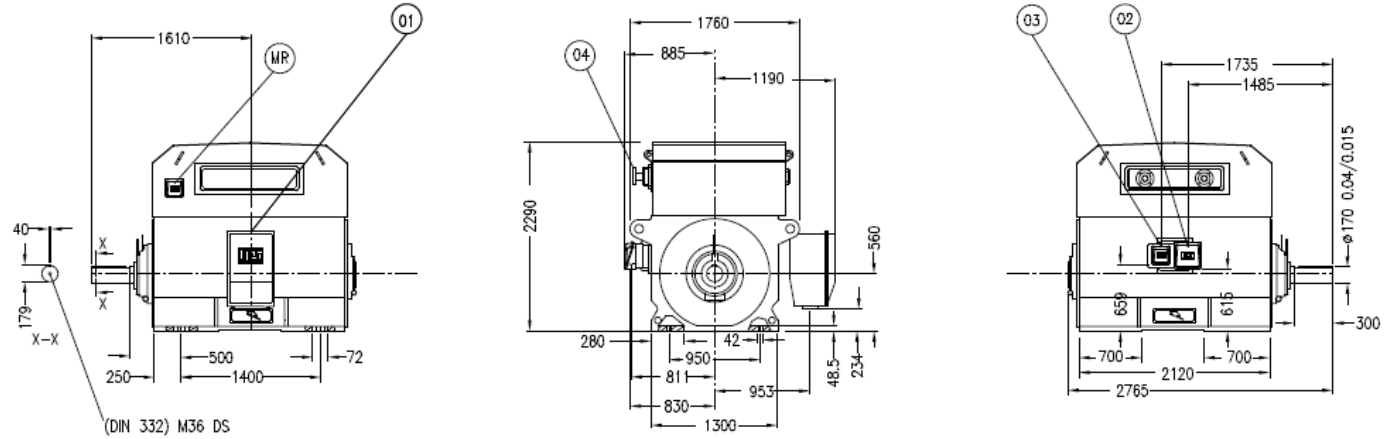
dV/dt	2700 V/us
Tensão de pico fase-fase máxima	9300 V
Tensão de pico fase-terra máxima	5400 V

Execução

Executado	Liberado	Data	Local
ALEXCARLOS	EMORAES	27/FEV/2014	WEN

DOCUMENTO PRELIMINAR

Modificações	Executado	Liberado	Data



01 – Caixa de ligação do estator – 1 X G 3"	
02 – Caixa de ligação de acessórios – 3 X G 3/4"	
03 – Cx. Lig. Res. Aquecimento – 3 X G 3/4"	
04 – Flange DIN 2633	

PROTEÇÃO NOS MANCAIS
ALARME: 110°C
DESLIGAMENTO: 120°C

OBSERVAÇÕES/ACESSÓRIOS

- MASSA APROXIMADA: 10300 KG ±10%
- PARA CONFECÇÃO DA BASE E ACOPLAMENTO, AGUARDAR DESENHO CERTIFICADO.
- DIMENSÕES EM MILIMETROS.

Mancal		Intervalo Lubrificação(h)	Quantidade de Graxa(g)	Tipo Lubrificação(h)	Vida Estimada L10(h)
Dianteiro	NU1036C3+6036C3	3100	65	POLYREX EM 103	40000
Traseiro	NU228C3	4400	55	POLYREX EM 103	40000

NORMAS

Proteção: ABNT NBR IEC 60034-5
Dimensão: IEC 60072 / ABNT NBR 15623
Tolerância: ISO 286 / ABNT NBR 6158
Chaveta: ISO R773 / ABNT NBR 6375

Constr.Sold: DIN ISO 8015
Usinados: NBR ISO 2768
Fundidos: ISO 8062
Caracter(MS): IEC 60034-1 / ABNT NBR 5117
Caracter(CA): IEC 60034-1 / ABNT NBR 17094-1
Caracter(CC): IEC 60034-1 / ABNT NBR 5116
Ensaios(MS): IEC 60034-2/4 / ABNT NBR 5052
Ensaios(CA): IEC 60034-2 / ABNT NBR 5383-1
Ensaios(CC): IEC 60034-2 / ABNT NBR 5165

LOC	RESUMO DAS MODIFICAÇÕES	EXECUTADO	LIBERADO	DATA LIBER	Rev.

EXECUTADO	ALEXCARLOS	Folha de Dados: FD23411-0/2014
LIBERADO	EMORAES	
DATA LIBER	27/FEV/2014	Desenho Dimensional: DM23411-0/2014
LOCAL	WEN	

Cliente: WEG EQUIP.ELETS.S.A
Referência: PROPULSOR PRINCIPAL
Descrição da Máquina: MGW 560B – 2940 kW – 3400 V – 60 Hz – 6 Pólos – B3R

ANNEX C – DATASHEET OF THE 2500KW, 690V, IC71W INDUCTION MOTOR FOR THE ARRANGEMENT 1.

(Source: WEG Brazil)

WEG	**FOLHA DE DADOS** Motor Trifásico de Indução - Rotor de Gaiola	Data: 15/OUT/2013 Nº: FD 37277-0/2013 Desenho Dimensional DM37277-0/2013

Cliente: WEG EQUIP.ELETS.S.A
Referência do Cliente: PROPULSOR PRINCIPAL
Linha: WGM

Identificação da Máquina

Carcaça: 560B	Classe de isolamento: 155(F)
Potência: 2500 kW	Elevação da Temperatura: classe 155(F)
Freqüência: 60 Hz	Fator de serviço: 1.00
Número de pólos: 6	Tempo de rotor bloqueado: 30 s
Rotação nominal: 1195 rpm	Regime de serviço: S1
Escorregamento: 0.42 %	Temperatura de Entrada de Água: 38 ºC
Tensão primária: 690 V Ligação:Y	Grau de proteção: IP55
Corrente primária: 2492 A	Refrigeração: IC71W
Tensão secundaria: Não aplicável	Forma construtiva: B3D
Corrente secundária: Não aplicável	Vibração: A 2.8 mm/s rms
Corrente de partida: 17444 A	Momento de inércia: 130.1 kgm²
Ip/In: 7	Nível de ruído: 78 dB(A), tol: 3 dB(A) (alimentação senoidal)
kVA/kW: 8.34	Sentido de rotação:
Corrente a vazio: 1096 A	Método de Partida: INVERSOR DE FREQUÊNCIA
Conjugado nominal: 19979 Nm	Acoplamento: DIRETO
Conjugado de partida: 70 %	
Conjugado máximo: 220 %	

Características de Desempenho (Alimentação Senoidal)

Potência	50%	75%	100%
Rendimento(%)	97.5	97.6	97.6
cos ø	0.76	0.83	0.86

Dados da Carga

Tipo da Carga: PROPULSOR NAVIO PRINCIPAL
Conjugado Resistente:
J(J=GD²/4):

Observações/Acessórios

- PERDA SUPLEMENTAR 0.50% DA POTÊNCIA ABSORVIDA.
- A temperatura de saída de água não deve ser 10ºC superior à temperatura de entrada de água.

Normas

Especificação:	IEC 60034-1 / ABNT NBR 17094-1
Ensaios:	IEC 60034-2 / ABNT NBR 5383-1
Ruído:	IEC 60034-9
Vibração:	IEC 60034-14
Tolerância:	IEC 60034-1 / ABNT NBR 17094-1

DOCUMENTO PRELIMINAR

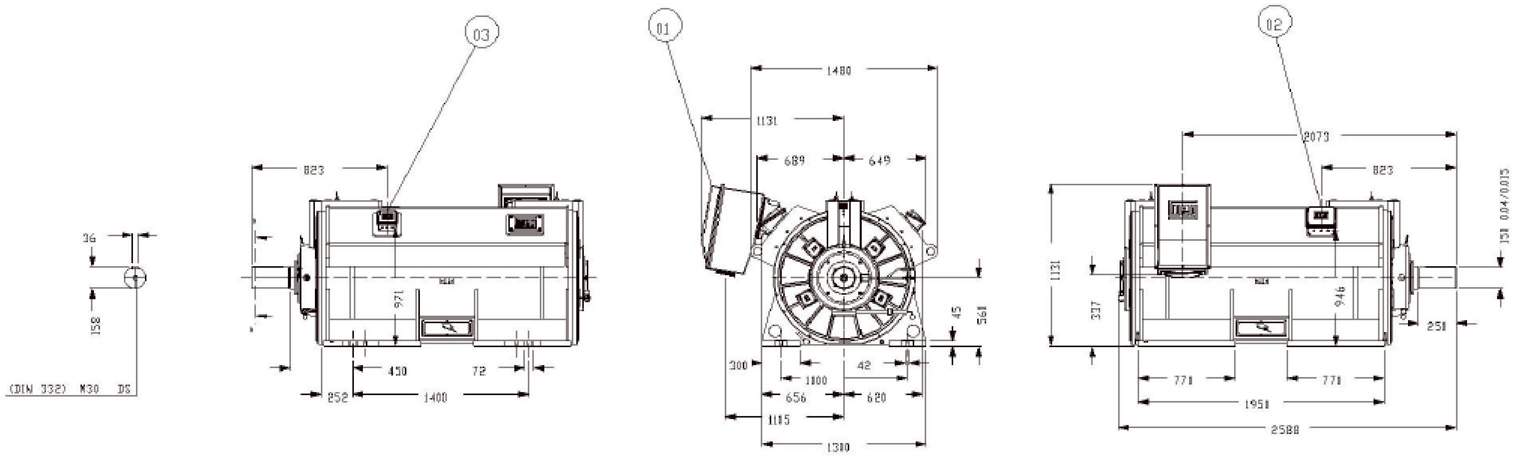
Execução

Executado	Liberado	Data	Local
CELIORJ	EMORAES	15/OUT/2013	WEN

Modificações

Executado	Liberado	Data

DOCUMENTO PRELIMINAR



01	Caixa de ligação do estator - 1 X G 3"
02	Caixa de ligação de acessórios - 3 X G 3/4"
03	Cx. Lig. Res. Aquecimento - 3 X G 3/4"

PROTEÇÃO NOS MANCAIS
ALARME: 110°C
DESLIGAMENTO: 120°C

OBSERVAÇÕES/ACESSÓRIOS

- MASSA APROXIMADA: 12118 KG ±10%
- PARA CONFECÇÃO DA BASE E ACOPLAMENTO, AGUARDAR DESENHO CERTIFICADO.
- DIMENSÕES EM MILÍMETROS.

Mancal		Intervalo Lubrificação(h)	Quantidade de Graxa(g)	Tipo Lubrificação	Vida Estimada L10(h)
DIANTEIRO	NU232C3+6232C3	3300	60	POLYREX EM 103	80000
TRASEIRO	NU228C3	4400	55	POLYREX EM 103	80000

NORMAS

Proteção	ABNT NBR IEC 60034-5
Dimensão	IEC 60072 / ABNT NBR 15623
Tolerância	ISO 286 / ABNT NBR 6158
Chaveta	ISO R773 / ABNT NBR 6375
Constr.Sold	DIN ISO 8015
Usinados	NBR ISO 2768
Fundidos	ISO 8062 :

Caracter(MS): IEC 60034-1 / ABNT NBR 5117
Caracter(CA): IEC 60034-1 / ABNT NBR 17094-1
Caracter(CC): IEC 60034-1 / ABNT NBR 5116

Ensaios(MS): IEC 60034-2/4 / ABNT NBR 5052
Ensaios(CA): IEC 60034-2 / ABNT NBR 5383-1
Ensaios(CC): IEC 60034-2 / ABNT NBR 5165

LOC	RESUMO DAS MODIFICAÇÕES	EXECUTADO	LIBERADO	DATA LIBER	Rev.

EXECUTADO	CELIORJ	Folha de Dados: FD 37277-0/2013
LIBERADO	EMORAES	
DATA LIBER	15/OUT/2013	Desenho Dimensional: DM37277-0/2013
LOCAL WEN		

Cliente WEG EQUIP.ELETS.S.A

Referência PROPULSOR PRINCIPAL

Descrição da Máquina
WGM 560B - 2500 kW - 690 V - 6 Pólos - B3D

ANNEX D - SPECIFICATIONS OF THE VARIABLE FREQUENCY CONVERTER FOR MAIN PROPULSION

(Source Siemens (2011b))

SINAMICS S120 Cabinet Modules

System overview

Overview

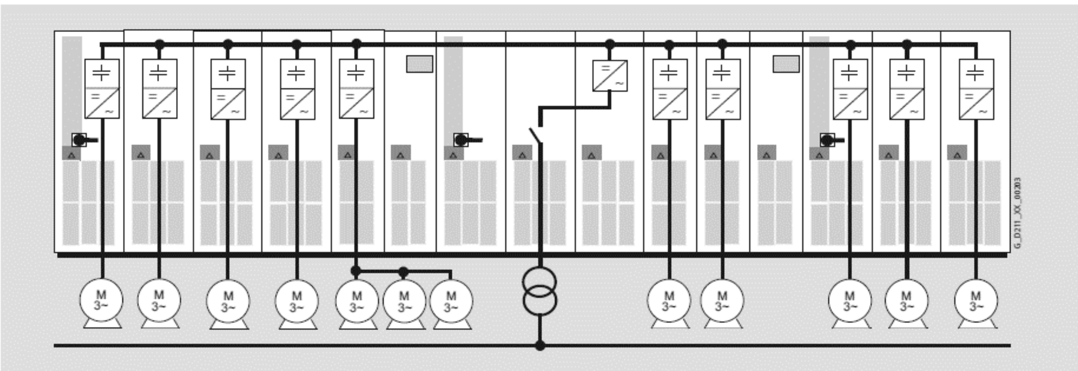
SINAMICS S120 Cabinet Modules are components forming part of a modular cabinet system for multi-motor drives with a central line infeed and a common DC busbar of the type typically used in, for example, paper-making machines, roller mills, test stands, or hoisting gear. As standard, they are installed side by side in a row. Other installation types (e.g. back to back) are possible on request. They include the chassis units from the SINAMICS S120 series in booksize format (Motor Modules) and chassis format, thus making the range an ideal supplement to the SINAMICS G150 and SINAMICS S150 cabinet unit series for single-motor drives.

All drive components, from the line infeed to the motor-side inverters, are configured in a clear, compact layout in the individual Cabinet Modules. They can be combined with great flexibility and can be optimally adapted to customer-specific requirements thanks to a comprehensive array of options.

The main components of the system are as follows:

- Line Connection Modules with line-side components such as contactors, fuses and circuit breakers, as well as line reactors for Basic Line Modules.
- Line Modules for the infeed in the following variations:
  - Basic Line Modules for two-quadrant operation
  - Smart Line Modules for four-quadrant operation
  - Active Line Modules for four-quadrant operation with negligible line harmonics
- Central Braking Modules for braking operation
- The following types of Motor Modules:
  - Booksize Kit
  - Chassis
- Control Units
- Auxiliary Power Supply Modules

Standardized interfaces for both the power and the control connections facilitate configuration and installation. Communication between the power modules and the central Control Unit takes place via DRIVE-CLiQ, the internal drive serial interface.



Example of a drive line-up with SINAMICS S120 Cabinet Modules for a multi-motor drive

SINAMICS S120 Cabinet Modules

System overview

Technical data

General technical specifications

Electrical specifications	
Line voltages	380 … 480 V 3 AC, ±10 % (-15 % < 1 min) 500 … 690 V 3 AC, ±10 % (-15 % < 1 min)
Line supply types	Grounded TN/TT systems and non-grounded IT systems
Line frequency	47 … 63 Hz
Output frequency [1]	
• Control type Servo	0 … 650 Hz
• Control type Vector	0 … 600 Hz
• Control type *V/f*	0 … 600 Hz
Line power factor Fundamental	
• Basic Line Module	> 0.96
• Smart Line Module	> 0.96
• Active Line Module	Adjustable (factory-set to cos φ = 1)
Efficiency	
• Basic Line Module	> 99.0 %
• Smart Line Module	> 98.5 %
• Active Line Module	> 97.5 % (including Active Interface Module)
• Motor Module	> 98.5 %
Overvoltage category	III to EN 61800-5-1
Control method	Vector/servo control with and without encoder or *V/f* control
Fixed speeds	15 fixed speeds plus 1 minimum speed, parameterizable (in the default setting, 3 fixed setpoints plus 1 minimum speed are selectable using terminal block/PROFIBUS/PROFINET)
Skipped speed ranges	4, parameterizable
Setpoint resolution	0.001 rpm digital (14 bits + sign) 12 bit analog
Braking operation	With Active Line Modules and Smart Line Modules, four-quadrant operation as standard (energy recovery). With Basic Line Modules, single-quadrant operation as standard. Braking when the power fails using an optional braking module.
Mechanical specifications	
Degree of protection	IP20 (higher degrees of protection up to IP54 optional)
Protection class	I acc. to EN 61800-5-1
Touch protection	EN 50274/BGV A3 for the intended purpose
Cabinet system	Rittal TS 8, doors with double-barb lock, three-section base plates for cable entry
Paint finish	RAL 7035 (indoor requirements)
Type of cooling	Forced air cooling AF to EN 60146

[1] Please note:
- The correlation between the maximum output frequency, pulse frequency and current derating. Higher output frequencies for specific configurations are available on request.
- The correlation between the minimum output frequency and permissible output current (current derating).
  Information is provided in the SINAMICS Low Voltage Engineering Manual.

Motor Modules chassis format

Overview

Motor Modules in the chassis format are available in the power range from 75 kW to 1200 kW.

Line voltage	DC link voltage	Type rating
380 … 480 V 3 AC	510 … 720 V DC	110 … 800 kW
500 … 690 V 3 AC	675 … 1035 V DC	75 … 1200 kW

By connecting in parallel up to 4 Motor Modules, which are operated on one Control Unit and supply one motor, it is possible to increase the available shaft power to max. approx. 4500 kW (taking into account the derating factors according to the SINAMICS Low Voltage Engineering Manual).

SINAMICS S120 Motor Modules in the chassis format and Cabinet Modules can also be used as a braking module, if, instead of a motor, a 3-phase braking resistor is connected. For more detailed information on this topic, please refer to the SINAMICS Low Voltage Engineering Manual.

Design

Motor Modules in the chassis format contain the following components:

- Retaining device for the DC busbar, including the connection to the DC connections of the Motor Module
- Nickel-plated connection busbars for motor cables for Motor Modules, frame sizes FX and GX; for Motor Modules, frame sizes HX and JX, the connection is made directly on the unit
- Cable propping bar for the electric power cables
- DRIVE-CLiQ interface (3 DRIVE-CLiQ sockets), without Control Unit
- Customer interface -X55
- Auxiliary power supply system (6-pole) for the auxiliary power supply, including cable connections for looping through to the next Cabinet Module
- Nickel-plated PE busbar (60 × 10 mm), including jumper for looping through to the next Cabinet Module
- EMC-compliant design thanks to additional shielding measures and appropriate laying of cables.

Selection and ordering data

Type rating at 400 V or 690 V	Rated output current I_N	**Motor Module chassis format**
kW	A	Order No.
Line voltage 380 … 480 V 3 AC (DC link voltage 510 … 720 V DC)		
110	210	**6SL3720-1TE32-1AA3**
132	260	**6SL3720-1TE32-6AA3**
160	310	**6SL3720-1TE33-1AA3**
200	380	**6SL3720-1TE33-8AA3**
250	490	**6SL3720-1TE35-0AA3**
315	605	**6SL3720-1TE36-1AA3**
400	745	**6SL3720-1TE37-5AA3**
450	840	**6SL3720-1TE38-4AA3**
560	985	**6SL3720-1TE41-0AA3**
710	1260	**6SL3720-1TE41-2AA3**
800	1405	**6SL3720-1TE41-4AA3**
Line voltage 500 … 690 V 3 AC (DC link voltage 675 … 1035 V DC)		
75	85	**6SL3720-1TG28-5AA3**
90	100	**6SL3720-1TG31-0AA3**
110	120	**6SL3720-1TG31-2AA3**
132	150	**6SL3720-1TG31-5AA3**
160	175	**6SL3720-1TG31-8AA3**
200	215	**6SL3720-1TG32-2AA3**
250	260	**6SL3720-1TG32-6AA3**
315	330	**6SL3720-1TG33-3AA3**
400	410	**6SL3720-1TG34-1AA3**
450	465	**6SL3720-1TG34-7AA3**
560	575	**6SL3720-1TG35-8AA3**
710	735	**6SL3720-1TG37-4AA3**
800	810	**6SL3720-1TG38-1AA3**
900	910	**6SL3720-1TG38-8AA3**
1000	1025	**6SL3720-1TG41-0AA3**
1200	1270	**6SL3720-1TG41-3AA3**

Motor Modules chassis format

Technical data

Line voltage 500 ... 690 V 3 AC DC link voltage 675 ... 1035 V DC		Motor Modules chassis format			
		6SL3720-1TG38-1AA3	6SL3720-1TG38-8AA3	6SL3720-1TG41-0AA3	6SL3720-1TG41-3AA3
Type rating					
• For I_L (50 Hz 690 V) [1]	kW	**800**	**900**	**1000**	**1200**
• For I_H (50 Hz 690 V) [1]	kW	710	800	900	1000
• For I_L (50 Hz 500 V) [1]	kW	560	630	710	900
• For I_H (50 Hz 500 V) [1]	kW	500	560	630	800
• For I_L (60 Hz 575 V) [2]	hp	800	900	1000	1250
• For I_H (60 Hz 575 V) [2]	hp	700	800	900	1000
Output current					
• Rated current $I_{N\,A}$	A	810	910	1025	1270
• Base load current I_L [3]	A	790	880	1000	1230
• Base load current I_H [4]	A	724	814	917	1136
• Maximum current $I_{max\,A}$	A	1185	1320	1500	1845
DC link current					
• Rated current $I_{N\,DC}$ when supplied from					
- Basic/Smart Line Module	A	972	1092	1230	1524
- Active Line Module	A	875	983	1107	1372
• Base load current $I_{L\,DC}$ [3] when supplied from					
- Basic/Smart Line Module	A	947	1064	1199	1485
- Active Line Module	A	853	958	1079	1337
• Base load current $I_{H\,DC}$ [4] when supplied from					
- Basic/Smart Line Module	A	865	971	1094	1356
- Active Line Module	A	778	874	985	1221
Current demand					
• 24 V DC auxiliary power supply	A	1.25	1.4	1.4	1.4
• 690 V AC	A	3.1	3.1	3.1	3.1
DC link capacitance	µF	11100	14400	14400	19200
Pulse frequency [5]					
• Rated frequency	kHz	1.25	1.25	1.25	1.25
• Pulse frequency, max.					
- Without current derating	kHz	1.25	1.25	1.25	1.25
- With current derating	kHz	7.5	7.5	7.5	7.5
Power loss, max. [6]					
• At 50 Hz 690 V	kW	11.5	11.7	13.2	16.0
• At 60 Hz 575 V	kW	10.5	10.6	12.0	14.2
Cooling air requirement	m^3/s	1.474	1.474	1.474	1.474
Sound pressure level L_{pA} (1 m) at 50/60 Hz	dB	72	72	72	72

1) Rated power of a typ. 6-pole standard induction motor based on I_L or I_H with 500 V or 690 V 3 AC 50 Hz.

2) Rated power of a typ. 6-pole standard induction motor based on I_L or I_H with 575 V 3 AC 60 Hz.

3) The base load current I_L is the basis for a duty cycle of 110 % for 60 s or 150 % for 10 s with a duty cycle duration of 300 s.

4) The base load current I_H is the basis for a duty cycle of 150 % for 60 s or 160 % for 10 s with a duty cycle duration of 300 s.

5) Information regarding the correlation between the pulse frequency and max. output current/output frequency is provided in the SINAMICS Low Voltage Engineering Manual.

6) The specified power loss represents the maximum value at 100 % utilization. The value is lower under normal operating conditions.

Technical data

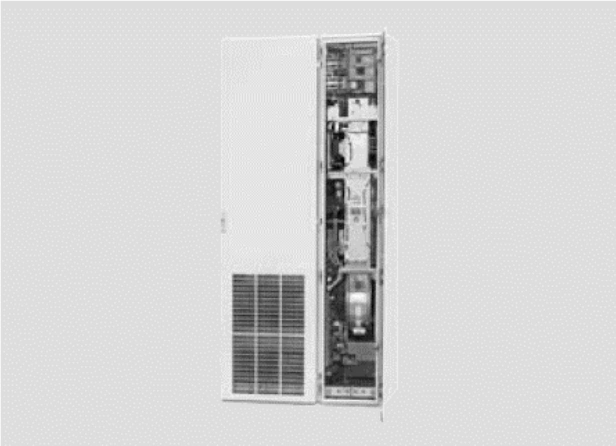
Line voltage 500 ... 690 V 3 AC DC link voltage 675 … 1035 V DC		Motor Modules chassis format			
		6SL3720-1TG38-1AA3	6SL3720-1TG38-8AA3	6SL3720-1TG41-0AA3	6SL3720-1TG41-3AA3
Motor connection U2, V2, W2		M12 screws	M12 screws	M12 screws	M12 screws
• Conductor cross-section, max. (IEC)	mm^2	6 x 240	6 x 240	6 x 240	6 x 240
Cable length, max. 7)					
• Shielded	m	300	300	300	300
• Unshielded	m	450	450	450	450
PE/GND connection		PE bar	PE bar	PE bar	PE bar
• Busbar cross-section	mm^2	600	600	600	600
• Conductor cross-section, max. (IEC)	mm^2	240	240	240	240
Degree of protection		IP20	IP20	IP20	IP20
Dimensions					
• Width 8)	mm	800	800	800	800
• Height 9)	mm	2200	2200	2200	2200
• Depth	mm	600	600	600	600
Weight, approx.	kg	700	700	700	700
Frame size		JX	JX	JX	JX

7) Sum of all motor cables. Longer cable lengths for specific configurations are available on request. For additional information, please refer to the SINAMICS Low Voltage Engineering Manual.

8) With option **L10** (dv/dt filter plus VPL):
- Frame sizes FX/GX/HX/JX → Supplementary cabinet, 600 mm wide
With option **L34** (output-side circuit breaker):
- Frame sizes FX/GX → Supplementary cabinet, 400 mm wide
- Frame sizes HX/JX → Supplementary cabinet, 600 mm wide.

9) The cabinet height increases by 250 mm with IP21 degree of protection, and by 400 mm with IP23, IP43 and IP54 degrees of protection.

Overview



Basic Line Modules (BLM) are compact line infeeds for two-quadrant operation, i.e. without regenerative feedback.

They are used when energy does not to be fed back into the network.

If regenerative conditions occur in the drive line-up, Braking Modules must be used because they convert the excess energy into heat in braking resistors.

Basic Line Modules are available for the following voltages and power ratings:

Line voltage	Rated power
380 … 480 V 3 AC	200 … 900 kW
500 … 690 V 3 AC	250 … 1500 kW

The power ratings can be increased by connecting up to four identical Basic Line Modules in parallel.

For an infeed with the Basic Line modules, depending on the line short-circuit power, a line reactor must be provided at the connection point. For additional information, please refer to the SINAMICS Low Voltage Engineering Manual. This reactor is available as standard in the Line Connection Module. However, it can be omitted if it is not required (option **L22**).

Design

The Basic Line Modules are available in different frame sizes.

With frame sizes FB and GB, a fully controlled thyristor bridge is used to pre-charge the Basic Line Modules and connected Motor Modules. The thyristors normally operate with a trigger delay angle of 0°.

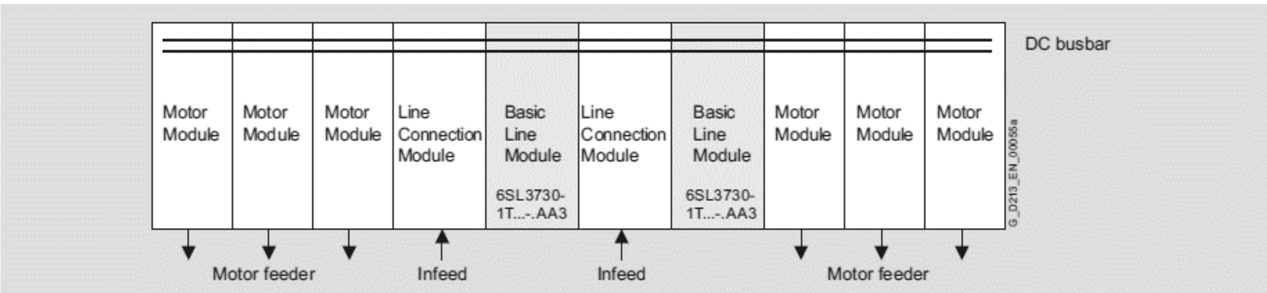
Basic Line Modules, frame size GD for 900 kW (400 V) or 1500 kW (690 V) include a diode bridge, and the DC link is pre-charged via a separate line-side pre-charging device that is located in the Line Connection Module (option **L43**, Line Connection Module for Basic Line Module).

Parallel connection of Basic Line Modules to increase the power rating

Line Modules can be connected in parallel (relative to the line supply) in two ways for the purpose of creating drive line-ups with a higher power rating.

Two Basic Line Modules supplied with power via two separate Line Connection Modules

With this arrangement, a Basic Line Module is supplied by a Line Connection Module and the Basic Line Modules are protected by fuses or circuit breakers (at $I > 800$ A) in the Line Connection Module. A Basic Line Module is assigned to a Line Connection Module and is mechanically coupled. It is not necessary to mechanically directly couple both "groups" comprising Line Connection Module and Basic Line Module. Other modules can also be inserted in between.



Technical data

Line voltage 500 ... 690 V 3 AC		Basic Line Modules					
		6SL3730-1TG33-0AA3	6SL3730-1TG34-3AA3	6SL3730-1TG36-8AA3	6SL3730-1TG41-1AA3	6SL3730-1TG41-4AA3	6SL3730-1TG41-8AA3
For a parallel circuit configuration, mounted to the right at the Line Connection Module		–	–	–	*6SL3730-1TG41-1BA3*	*6SL3730-1TG41-4BA3*	*6SL3730-1TG41-8BA3*
For a parallel circuit configuration, mounted to the left at the Line Connection Module		–	–	–	*6SL3730-1TG41-1BC3*	*6SL3730-1TG41-4BC3*	*6SL3730-1TG41-8BC3*
Rated power							
• For $I_{N\,DC}$ (50 Hz 690 V)	kW	**250**	**355**	**560**	**900**	**1100**	**1500**
• For $I_{H\,DC}$ (50 Hz 690 V)	kW	195	280	440	710	910	1220
• For $I_{N\,DC}$ (50 Hz 500 V)	kW	175	250	390	635	810	1085
• For $I_{H\,DC}$ (50 Hz 500 V)	kW	165	235	365	595	755	1015
• For $I_{N\,DC}$ (60 Hz 575 V)	hp	250	350	600	900	1250	1500
• For $I_{H\,DC}$ (60 Hz 575 V)	hp	200	300	450	800	1000	1250
DC link current							
• Rated current $I_{N\,DC}$	A	300	430	680	1100	1400	1880
• Base load current $I_{H\,DC}$ [1]	A	234	335	530	858	1092	1467
• Maximum current $I_{max\,DC}$	A	450	645	1020	1650	2100	2820
Input current							
• Rated current $I_{N\,E}$	A	260	375	575	925	1180	1580
• Maximum current $I_{max\,E}$	A	390	563	863	1388	1770	2370
Current demand							
• 24 V DC auxiliary power supply	A	1.1	1.1	1.1	1.1	1.1	1.1
• 500 V/690 V AC [2]	A	Internal	Internal	Internal	Internal	Internal	Internal
DC link capacitance							
• Basic Line Module	µF	3200	4800	7300	11600	15470	19500
• Drive line-up, max.	µF	25600	38400	58400	92800	123760	78000
Power loss, max. [3]							
• At 50 Hz 690 V	kW	1.5	2.1	3.0	5.4	5.8	7.3
• At 60 Hz 575 V	kW	1.5	2.1	3.0	5.4	5.8	7.3
Cooling air requirement	m^3/s	0.17	0.17	0.17	0.36	0.36	0.36
Sound pressure level L_{pA} (1 m) at 50/60 Hz	dB	66/68	66/68	66/68	71/73	71/73	71/73
PE/GND connection		PE bar	PE bar	PE bar	PE bar	PE bar	PE bar
• Busbar cross-section	mm^2	600	600	600	600	600	600
• Conductor cross-section, max. (IEC)	mm^2	240	240	240	240	240	240
Cable length, max. [4]							
• Shielded	m	1500	1500	1500	2250	2250	2750
• Unshielded	m	2250	2250	2250	3375	3375	4125
Degree of protection		IP20	IP20	IP20	IP20	IP20	IP20
Dimensions							
• Width	mm	400	400	400	400/*600*/*600*	400/*600*/*600*	400/*600*/*600*
• Height [5]	mm	2200	2200	2200	2200	2200	2200
• Depth	mm	600	600	600	600	600	600
Weight, approx.	kg	166	166	166	320/*440*/*480*	320/*440*/*480*	320/*440*/*480*
Frame size		FB	FB	FB	GB	GB	GD

[1] The base load current $I_{H\,DC}$ is the basis for a duty cycle of 150 % for 60 s or $I_{max\,DC}$ for 5 s with a duty cycle duration of 300 s.

[2] The current demand for the 500 V/690 V AC auxiliary power supply is drawn from the line input voltage.

[3] The specified power loss represents the maximum value at 100 % utilization. The value is lower under normal operating conditions.

[4] Sum of all motor cables and DC link. Longer cable lengths for specific configurations are available on request.

[5] The cabinet height increases by 250 mm with IP21 degree of protection, and by 400 mm with IP23, IP43, IP54 degrees of protection.

Overview

Line Connection Modules (LCM) contain the line-side infeed with main circuit breaker and fuse switch disconnector or circuit breaker and provide the connection between the plant power system and the Line Modules.

Line Connection Modules are available for the following voltages and currents:

Line voltage	Rated infeed/regenerative feedback current
380 … 480 V 3 AC	250 … 3200 A
500 … 690 V 3 AC	280 … 3200 A

Design

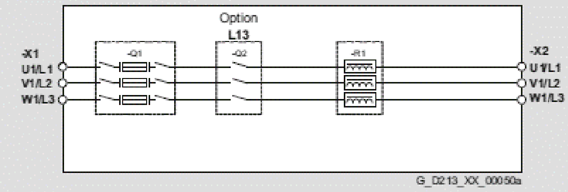
Different versions exist depending on the input current:

- Units ≤ 800 A include a main control switch with fuse switch disconnector
- Units > 800 A include a fixed-mounted circuit breaker (a withdrawable circuit breaker is optionally possible)

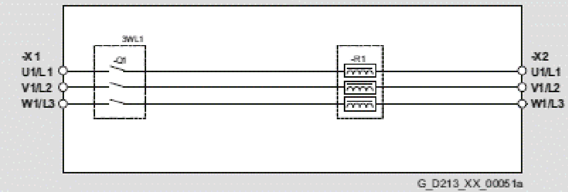
When Line Connection Modules are ordered, the type of Line Module used must be specified:

- for Basic Line Modules: Option **L43**
- for Smart Line Modules: Option **L44**
- for Active Line Modules: Option **L42**

When using a Basic Line Modules, a reactor is included in the scope of delivery, and when required, can be deselected (option **L22**).
For additional information, please refer to the SINAMICS Low Voltage Engineering Manual.



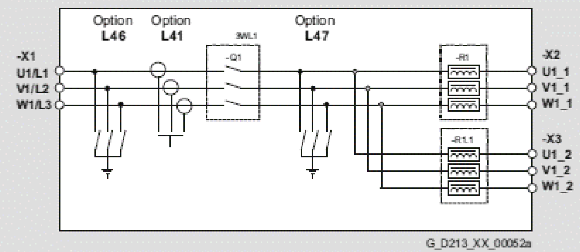
Connection example of a Line Connection Module for units ≤ 800 A to connect to Basic Line Modules, option **L43**,
Option main contactor, order code **L13**



Example of connection of a Line Connection Module for units > 800 A, < 2000 A to connect to the Basic Line Modules, option **L43**

For input currents ≥ 2000 A, additional options are available:

- Grounding switch upstream of main circuit breaker: Option **L46**
- Current transformer upstream of main circuit breaker: Option **L41**
- Grounding switch downstream of main circuit breaker: Option **L47**

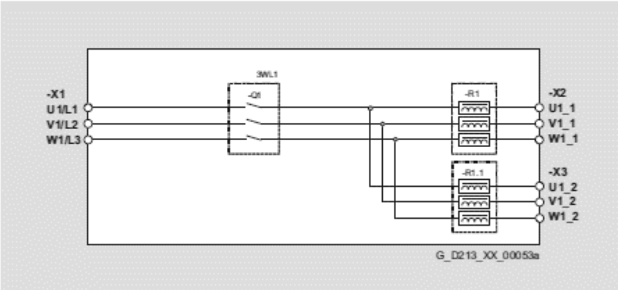


Example of connection of a Line Connection Module ≥ 2000 A

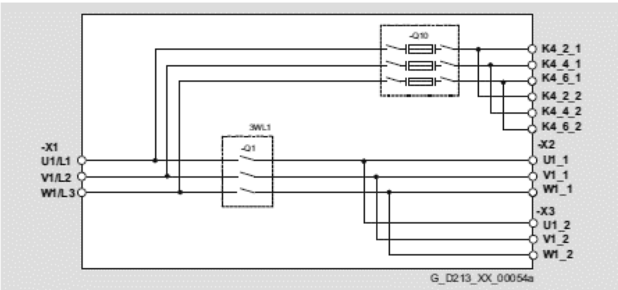
Line Connection Modules

Design

When Basic Line Modules that are fed via a common Line Connection Module are connected in parallel, line reactors are generally required. These are installed in the Line Connection Module.



Example of connection of a Line Connection Module ≥ 2000 A to connect to the Basic Line Modules, option **L43**



Example of connection of a Line Connection Module ≥ 2000 A to connect to the Active Line Modules in a parallel connection, option **L42**

Selection and ordering data

Rated infeed/regenerative feedback current [1)]	Line Connection Module
A	Order No.
Line voltage 380 ... 480 V 3 AC	
250	**6SL3700-0LE32-5AA3**
380	**6SL3700-0LE34-0AA3**
600	**6SL3700-0LE36-3AA3**
770	**6SL3700-0LE38-0AA3**
1000	**6SL3700-0LE41-0AA3**
1250	**6SL3700-0LE41-3AA3**
1600	**6SL3700-0LE41-6AA3**
2000	**6SL3700-0LE42-0AA3**
2000	**6SL3700-0LE42-0BA3**
2500	**6SL3700-0LE42-5BA3**
3200	**6SL3700-0LE43-2BA3**
Line voltage 500 ... 690 V 3 AC	
280	**6SL3700-0LG32-8AA3**
380	**6SL3700-0LG34-0AA3**
600	**6SL3700-0LG36-3AA3**
770	**6SL3700-0LG38-0AA3**
1000	**6SL3700-0LG41-0AA3**
1250	**6SL3700-0LG41-3AA3**
1600	**6SL3700-0LG41-6AA3**
2000	**6SL3700-0LG42-0BA3**
2500	**6SL3700-0LG42-5BA3**
3200	**6SL3700-0LG43-2BA3**

Note:

When ordering Line Connection Modules, the option order code must be attached to the Order No. to indicate whether the Line Connection Module is to be connected to a Basic Line Module (option **L43**), to a Smart Line Module (option **L44**) or to an Active Line Module (option **L42**).

This information is required to ensure that the Line Connection Module is correctly equipped at the factory. This particularly applies to the busbar connection at the 3-phase end (3 AC), to any pre-charging circuits required and to the specified line reactors for Basic Line Modules.

When selecting and combining Cabinet Modules, the specified equipping and preparation of the Line Connection Modules is realized in the factory corresponding to the following assignment table. For all other combinations deviating from this, this is not the case. In such cases, the 3 AC busbar connections will have to be engineered and installed on site.

1) The current values listed are based on an ambient temperature (air intake temperature) of 40 °C.

Integration

Line Connection Module Rated infeed/ regenerative feedback current [1)] A		Basic Line Module Rated input current A		Smart Line Module Rated infeed/ regenerative feedback current A		Active Line Module Rated infeed/ regenerative feedback current A	
Line voltage 380 ... 480 V 3 AC							
250	6SL3700-0LE32-5AA3	–	–	–	–	210	6SL3730-7TE32-1BA3
380	6SL3700-0LE34-0AA3	–	–	–	–	260	6SL3730-7TE32-6BA3
600	6SL3700-0LE36-3AA3	365	6SL3730-1TE34-2AA3	463	6SL3730-6TE35-5AA3	380	6SL3730-7TE33-8BA3
		460	6SL3730-1TE35-3AA3			490	6SL3730-7TE35-0BA3
770	6SL3700-0LE38-0AA3	710	6SL3730-1TE38-2AA3	614	6SL3730-6TE37-3AA3	605	6SL3730-7TE36-1BA3
1000	6SL3700-0LE41-0AA3	–	–	883	6SL3730-6TE41-1AA3	840	6SL3730-7TE38-4BA3
1250	6SL3700-0LE41-3AA3	1010	6SL3730-1TE41-2AA3	1093	6SL3730-6TE41-3AA3	985	6SL3730-7TE41-0BA3
1600	6SL3700-0LE41-6AA3	1265	6SL3730-1TE41-5AA3	1430	6SL3730-6TE41-7AA3	1405	6SL3730-7TE41-4BA3
2000	6SL3700-0LE42-0AA3	1630	6SL3730-1TE41-8AA3	–	–	–	–
2000	6SL3700-0LE42-0BA3	*2 × 935*	*6SL3730-1TE41-2BA3*	*2 × 817*	*6SL3730-6TE41-1BA3*	*2 × 936*	*6SL3730-7TE41-0BA3*
			6SL3730-1TE41-2BC3		*6SL3730-6TE41-1BC3*		*6SL3730-7TE41-0BC3*
2500	6SL3700-0LE42-5BA3	*2 × 1170*	*6SL3730-1TE41-5BA3*	*2 × 1011*	*6SL3730-6TE41-3BA3*	–	–
			6SL3730-1TE41-5BC3		*6SL3730-6TE41-3BC3*		
3200	6SL3700-0LE43-2BA3	*2 × 1508*	*6SL3730-1TE41-8BA3*	*2 × 1323*	*6SL3730-6TE41-7BA3*	*2 × 1335*	*6SL3730-7TE41-4BA3*
			6SL3730-1TE41-8BC3		*6SL3730-6TE41-7BC3*		*6SL3730-7TE41-4BC3*
Line voltage 500 ... 690 V 3 AC							
280	6SL3700-0LG32-8AA3	260	6SL3730-1TG33-0AA3	–	–	–	–
380	6SL3700-0LG34-0AA3	375	6SL3730-1TG34-3AA3	–	–	–	–
600	6SL3700-0LG36-3AA3	575	6SL3730-1TG36-8AA3	463	6SL3730-6TG35-5AA3	575	6SL3730-7TG35-8BA3
770	6SL3700-0LG38-0AA3	–	–	757	6SL3730-6TG38-8AA3	735	6SL3730-7TG37-4BA3
1000	6SL3700-0LG41-0AA3	925	6SL3730-1TG41-1AA3	–	–	–	–
1250	6SL3700-0LG41-3AA3	1180	6SL3730-1TG41-4AA3	1009	6SL3730-6TG41-2AA3	1025	6SL3730-7TG41-0BA3
1600	6SL3700-0LG41-6AA3	1580	6SL3730-1TG41-8AA3	1430	6SL3730-6TG41-7AA3	1270	6SL3730-7TG41-3BA3
2000	6SL3700-0LG42-0BA3	*2 × 855*	*6SL3730-1TG41-1BA3*	*2 × 700*	*6SL3730-6TG38-8BA3*	*2 × 698*	*6SL3730-7TG37-4BA3*
			6SL3730-1TG41-1BC3		*6SL3730-6TG38-8BC3*		*6SL3730-7TG37-4BC3*
		–	–	*2 × 934*	*6SL3730-6TG41-2BA3*	*2 × 974*	*6SL3730-7TG41-0BA3*
					6SL3730-6TG41-2BC3		*6SL3730-7TG41-0BC3*
2500	6SL3700-0LG42-5BA3	*2 × 1092*	*6SL3730-1TG41-4BA3*	–	–	*2 × 1206*	*6SL3730-7TG41-3BA3*
			6SL3730-1TG41-4BC3				*6SL3730-7TG41-3BC3*
3200	6SL3700-0LG43-2BA3	*2 × 1462*	*6SL3730-1TG41-8BA3*	*2 × 1323*	*6SL3730-6TG41-7BA3*	–	–
			6SL3730-1TG41-8BC3		*6SL3730-6TG41-7BC3*		

Entries in italics: *Parallel circuit of two Line Modules connected to a Line Connection Module.*
The required derating factors listed below are already included in the current values given above:
- *7.5 % for Basic Line Modules*
- *7.5 % for Smart Line Modules*
- *5.0 % for Active Line Modules*

1) The current values listed are based on an ambient temperature (air intake temperature) of 40 °C.

ANNEX E – VFD TRANSFORMER CATALOG

(Source EMG Transformers (2013))

Transformers for rectifier

PRINT

Transformers for rectifier (Serie: TTR)

Description Construction:

The windings of these transformers are made of copper wire (double insulated with Class H insulation or double Nomex tape) or performed with aluminum tape. On request, a copper band version is possible.

The transformers are protected by a vacuum pressure impregnation with a solvent-free polyester resin and anschließßender heat treatment. The magnetic core is made from grain oriented sheets. The transformer is designed for natural air cooling. With enhanced cooling size and weight can be reduced.

Applications:

These transformers are used in power rectifiers. They are used both for isolation and voltage matching between the main network and load. Transformers with one secondary winding (Dy11) are suitable for 6-pulse rectifier and f ¨ r 12-pulse rectifier used those with two secondary windings (Dd0y11).

Product range:

Three-phase transformers (Serie: TTR)	
Primary-/Secondary Voltage	690V/690V
One secondary winding	Rated power: 50...1600kVA
Two secondary windings	Rated power: 70...1600kVA

Technische Daten:

Frequency	50/60Hz
Short-circuit voltage U_{CC}	4%
HS-Test I-II and Mass, 50Hz	3kV, 60s
Protection class	IP00
Cooling	normal air
Ambient temperature	-5...+40°C
Installation Site	<1000m above the sea (asl)
Environment-Climatic-Res. To Fire Class	E1-C1-F0

Considered standards / norms

- IEC EN 60076
- IEC 60076-11
- IEC EN 60146-1-3
- HD 464 (VDE 0532-6)
- CEI 14-4
- CEI 14-32
- CEI 22-8

Specifications:

Rectifier transformers TTR with a secondary winding 50/60Hz, U_{cc}=4%, Dy11

P (kVA)	Po (W)	$P_{j,115°C}$ (W)	dimension (mm) L	B	H	Mass (kg)	Typ
50	370	1600	450	300	480	200	TTR-0050
63	380	2100	460	320	520	230	TTR-0063
80	410	2400	530	370	540	260	TTR-0080
100	600	2900	570	380	560	315	TTR-0100
125	850	3100	690	410	610	380	TTR-0125
160	950	3400	690	470	610	450	TTR-0160
200	1000	4400	720	530	680	510	TTR-0200
250	1150	5000	720	580	680	600	TTR-0250
315	1600	5600	800	550	850	750	TTR-0315
400	1800	6200	870	600	850	890	TTR-0400
500	2200	7000	870	680	850	1100	TTR-0500
1000	3500	14800	1250	760	1420	2200	TTR-1000
1600	4550	18250	1250	860	1450	3200	TTR-1600

P: Rated output at 50Hz. At 60Hz, this decreased to 90%.
P_o: Power loss in the iron,
$P_{j,115°C}$: Power loss in the windings at 115 °C.

For more information, see the catalog (Italian / English)

Rectifier transformers TTR with two secondary winding 50/60Hz, U_{cc}=4%, Dd0y11

P (kVA)	Po (W)	$P_{j,115°C}$ (W)	dimension (mm) L	B	H	Mass (kg)	Typ
73	550	1550	730	370	520	310	TTR12P-0073
90	600	1800	730	440	520	330	TTR12P-0090
120	650	2400	750	480	560	390	TTR12P-0120
145	750	2500	880	450	600	490	TTR12P-0145
175	800	3100	800	500	650	520	TTR12P-0175
210	900	3700	840	520	650	570	TTR12P-0210
260	1000	4300	800	590	720	670	TTR12P-0260
315	1100	5500	800	620	800	750	TTR12P-0315
390	1300	6500	850	540	900	910	TTR12P-0390
480	1800	7000	970	560	1000	1140	TTR12P-0480
610	2000	8500	970	700	1000	1380	TTR12P-0610
770	2300	9500	970	800	1000	1500	TTR12P-0770
1000	3700	14850	1250	760	1570	2400	TTR12P-1000
1600	4600	18400	1250	860	1600	3300	TTR12P-1600

P: Rated output at 50Hz. At 60Hz, this decreased to 90%.
P_o: Power loss in the iron,
$P_{j,115°C}$: Power loss in the windings at 115 °C.

For more information, see the catalog (Italian / English)

ANNEX F – DATASHEET OF THE 880KW, 690V, IC71W INDUCTION MOTOR FOR THE BOW THRUSTERS

(Source: WEG Brazil)

WEG	FOLHA DE DADOS Motor Trifásico de Indução - Rotor de Gaiola	Data: 15/OUT/2013 Nº: FD 37279-0/2013 Desenho Dimensional DM37279-0/2013

Cliente: WEG EQUIP.ELETS.S.A
Referência do Cliente: PROPULSOR MANOBRA
Linha: WGM

Identificação da Máquina

Carcaça: 400D
Potência: 880 kW
Freqüência: 60 Hz
Número de pólos: 6
Rotação nominal: 1195 rpm
Escorregamento: 0.42 %
Tensão primária: 690 V Ligação:Y
Corrente primária: 919.3 A
Tensão secundaria: Não aplicável
Corrente secundária: Não aplicável
Corrente de partida: 6435 A
Ip/In: 7
kVA/kW: 8.74
Corrente a vazio: 367.7 A
Conjugado nominal: 7033 Nm
Conjugado de partida: 100 %
Conjugado máximo: 230 %

Classe de isolamento: 155(F)
Elevação da Temperatura: classe 155(F)
Fator de serviço: 1.00
Tempo de rotor bloqueado: 16 s
Regime de serviço: S1
Temperatura de Entrada de Água: 30 ºC
Grau de proteção: IP55
Refrigeração: IC71W
Forma construtiva: V1
Vibração: A 2.8 mm/s rms
Momento de inércia: 38.95 kgm²
Nível de ruído: 77 dB(A), tol: 3 dB(A) (alimentação senoidal)
Sentido de rotação: AMBOS
Método de Partida: INVERSOR DE FREQUÊNCIA
Acoplamento: DIRETO

Características de Desempenho (Alimentação Senoidal)

Potência	50%	75%	100%
Rendimento(%)	96.3	96.6	96.5
cos ø	0.67	0.78	0.83

Dados da Carga

Tipo da Carga: PROPULSOR NAVIO MANOBRA
Conjugado Resistente:
J(J=GD²/4):

Observações/Acessórios

- PERDA SUPLEMENTAR 0.50% DA POTÊNCIA ABSORVIDA.
- A temperatura de saída de água não deve ser 10ºC superior à temperatura de entrada de água.

Normas

Especificação:	IEC 60034-1 / ABNT NBR 17094-1
Ensaios:	IEC 60034-2 / ABNT NBR 5383-1
Ruído:	IEC 60034-9
Vibração:	IEC 60034-14
Tolerância:	IEC 60034-1 / ABNT NBR 17094-1

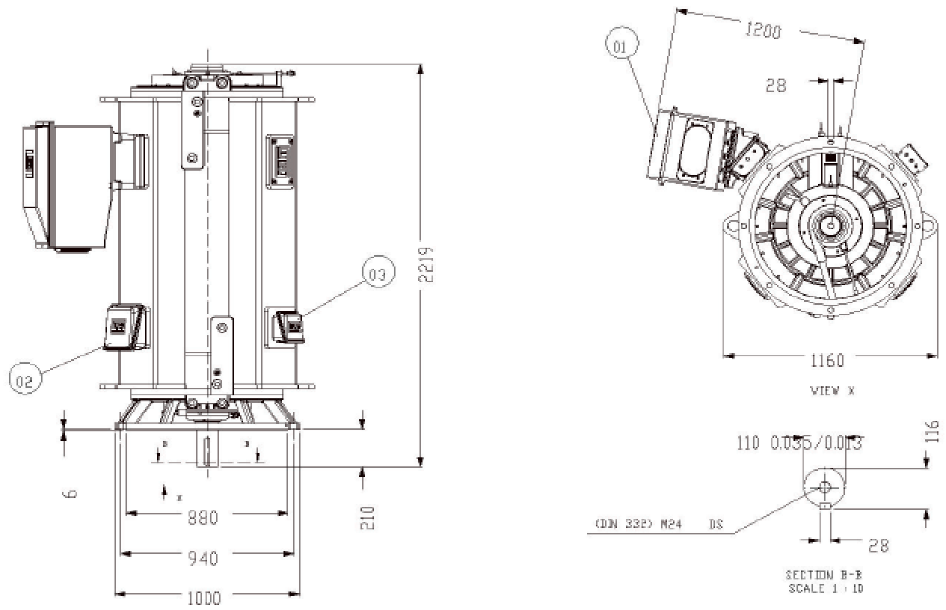
DOCUMENTO PRELIMINAR

Execução

Executado	Liberado	Data	Local
CELIORJ	EMORAES	15/OUT/2013	WEN

Modificações	Executado	Liberado	Data

DOCUMENTO PRELIMINAR



01	Caixa de ligação do estator - 1 X G 3"
02	Caixa de ligação de acessórios - 3 X G 3/4"
03	Cx. Lig. Res. Aquecimento - 3 X G 3/4"

PROTEÇÃO NOS MANCAIS
ALARME: 110°C
DESLIGAMENTO: 120°C

OBSERVAÇÕES/ACESSÓRIOS

- MASSA APROXIMADA: 6533 KG ±10%
- PARA CONFECÇÃO DA BASE E ACOPLAMENTO, AGUARDAR DESENHO CERTIFICADO.
- DIMENSÕES EM MILÍMETROS.

Mancal		Intervalo Lubrificação(h)	Quantidade de Graxa(g)	Tipo Lubrificação	Vida Estimada L10(h)
DIANTEIRO	6330C3	4500	105	POLYREX EM 103	40000
TRASEIRO	6322C3	4500	60	POLYREX EM 103	40000

NORMAS

Proteção	ABNT NBR IEC 60034-5
Dimensão	IEC 60072 / ABNT NBR 15623
Tolerância	ISO 286 / ABNT NBR 6158
Chaveta	ISO R773 / ABNT NBR 6375
Constr.Sold	DIN ISO 8015
Usinados	NBR ISO 2768
Fundidos	ISO 8062 :

Caracter(MS): IEC 60034-1 / ABNT NBR 5117
Caracter(CA): IEC 60034-1 / ABNT NBR 17094-1
Caracter(CC): IEC 60034-1 / ABNT NBR 5116

Ensaios(MS): IEC 60034-2/4 / ABNT NBR 5052
Ensaios(CA): IEC 60034-2 / ABNT NBR 5383-1
Ensaios(CC): IEC 60034-2 / ABNT NBR 5165

LOC	RESUMO DAS MODIFICAÇÕES	EXECUTADO	LIBERADO	DATA LIBER	Rev.

EXECUTADO	CELIORJ
LIBERADO	EMORAES
DATA LIBER	15/OUT/2013
LOCAL WEN	

Folha de Dados: **FD 37279-0/2013**

Desenho Dimensional: **DM37279-0/2013**

Cliente: **WEG EQUIP.ELETS.S.A**

Referência: **PROPULSOR MANOBRA**

Descrição da Máquina: **WGM 400D - 880 kW - 690 V - 6 Pólos - V1**

ANNEX G – AUXILIARY LOAD INVENTARY OF THE ELECTRICALLY PROPELLED PSVs

(Source Arcoverde (2013))

PSV Electrical Load Inventary													
Group No. 1		Installed Units	Rated Power	Load Factor	Power Requirement	TRANSIT				DYNAMIC POSITIONING/LOADING-DISCHARGE		PORT/STAND BY	
						Essential Loads		Normal Loads					
Machinery Room - Continous Service						No. Of Units in Service	Power Demanded	No. Of Units in Service	Power Demanded	No. Of Units in Service	Power Demanded	No. Of Units in Service	Power Demanded
Item	Consumer Description		kW		kW		kW		kW		kW		kW
1	Salt water circulation pump	3	65	0,9	58,5	1	58,5	1	58,5	2	117,0	1	58,5
3	Diesel oil circulation pump	2	10,2	0,71	7,2	1	7,2	1	7,2	1	7,2	0	0,0
4	Diesel oil pump	2	8,4	0,64	5,4	1	5,4	1	5,4	1	5,4	0	0,0
5	Auxiliar pump for exhaust system	4	44,5	0,5	22,3	1	22,3	1	22,3	0	0,0	0	0,0
6	Diesel oil pump for cilinders	4	87,7	0,87	76,3	1	76,3	1	76,3	1	76,3	0	0,0
7	Lubricating System oil pump	4	13,6	0,72	9,8	1	9,8	1	9,8	1	9,8	0	0,0
8	Diesel oil purificator	2	33,5	0,87	29,1	1	29,1	2	58,3	1	29,1	0	0,0
9	Diesel oil purificator pump	2	5	0,73	3,7	1	3,7	1	3,7	1	3,7	0	0,0
10	Lubricating oil purificator	2	18,6	0,91	16,9	1	16,9	1	16,9	1	16,9	1	16,9
11	Machine room fans	4	79	0,77	60,8	4	243,3	4	243,3	2	121,7	2	121,7
12	Pump for preheating the Diesel Generator sets	4	22	1	22,0	2	44,0	2	44,0	4	88,0	2	44,0
13	Lubricating oil pump for the Diesel Generator Sets	6	7,2	0,8	5,8	3	17,3	3	17,3	5	28,8	3	17,3
14	Diesel Oil Filter	2	6	0,75	4,5	1	4,5	1	4,5	1	4,5	0	0,0
15	Lubricating oil purificator pump	2	8,7	0,82	7,1	1	7,1	1	7,1	1	7,1	1	7,1
16	Viscometer	2	3,6	0,85	3,1	1	3,1	1	3,1	1	3,1	0	0,0
17	Lubricating oil filter	2	2,2	0,75	1,7	1	1,7	1	1,7	1	1,7	0	0,0
19	Diesel oil pump for the boiler	4	21	0,82	17,2	0	0,0	0	0,0	2	34,4	1	17,2
20	Distillatory group	2	38,4	0,78	30,0	0	0,0	1	30,0	0	0,0	0	0,0
21	Main air compressor	3	86,3	0,84	72,5	0	0,0	1	72,5	1	72,5	0	0,0
22	Purificator exhaust	1	4,7	0,8	3,8	0	0,0	1	3,8	1	3,8	1	3,8
TOTAL POWER REQUESTED						550,1		609,2		554,7		282,7	
DEMAND FACTOR						1		1		1		1	
TOTAL POWER FOR CALCULATION						550,1		609,2		554,7		282,7	

Group No. 2		Installed Units	Rated Power	Load Factor	Power Requirement	TRANSIT				DYNAMIC POSITIONING/LOADING-DISCHARGE		PORT/STAND BY	
Machinery Room - Intermitent Service						Essential Loads		Normal Loads		No. Of Units in Service	Power Demanded	No. Of Units in Service	Power Demanded
						No. Of Units in Service	Power Demanded	No. Of Units in Service	Power Demanded				
Item	Consumer Description		kW		kW		kW		kW		kW		kW
1	General service air compressor	2	67,1	0,9	60,4	0	0,0	1	60,4	2	120,8	1	60,4
2	Diesel oil transfer pump	3	17	0,9	15,3	1	15,3	1	15,3	0	0,0	1	15,3
3	Lubricating oil transfer pump	3	8,4	0,87	7,3	1	7,3	1	7,3	0	0,0	0	0,0
4	Heavy fuel oil transfer pump	3	7,8	0,87	6,8	1	6,8	1	6,8	0	0,0	1	6,8
5	Bomba de borra	2	12,5	0,91	11,4	1	11,4	1	11,4	1	11,4	0	0,0
6	Pump for water circulation in the boiler	3	12,8	0,76	9,7	1	9,7	1	9,7	2	19,4	1	9,7
7	Incinerator	2	14,6	0,8	11,7	0	0,0	0	0,0	1	11,7	1	11,7
8	Turnstile	1	14,1	0,88	12,4	0	0,0	0	0,0	0	0,0	0	0,0
9	Auxiliary air blower	2	116,2	0,8	93,0	0	0,0	0	0,0	2	186,0	0	0,0
10	Auxiliary air compressor	2	47,5	0,9	42,8	0	0,0	0	0,0	0	0,0	0	0,0
TOTAL POWER REQUESTED						**50,5**		**110,9**		**349,3**		**103,9**	
DEMAND FACTOR						**0,5**		**0,5**		**0,6**		**0,5**	
TOTAL POWER FOR CALCULATION						**25,3**		**55,5**		**209,6**		**52,0**	

Group No. 3		Installed Units	Rated Power	Load Factor	Power Requirement	TRANSIT				DYNAMIC POSITIONING/LOADING-DISCHARGE		PORT/STAND BY	
Machinery Room - Varied						Essential Loads		Normal Loads		No. Of Units in Service	Power Demanded	No. Of Units in Service	Power Demanded
						No. Of Units in Service	Power Demanded	No. Of Units in Service	Power Demanded				
Item	Consumer Description		kW		kW		kW		kW		kW		kW
1	Charging pump	4	39,5	0,94	37,1	0	0,0	0	0,0	0	0,0	0	0,0
2	Drain pump (Charge)	4	1,5	0,82	1,2	0	0,0	0	0,0	0	0,0	0	0,0
3	Ballast pump	4	86	0,94	80,8	0	0,0	0	0,0	0	0,0	0	0,0
4	Drain pump (Ballast)	4	2	0,82	1,6	0	0,0	0	0,0	0	0,0	0	0,0
5	Oil-Water separation pump	2	2,9	0,73	2,1	0	0,0	1	2,1	0	0,0	0	0,0
6	Emergency fire pump	2	58	0,96	55,7	0	0,0	0	0,0	0	0,0	0	0,0
7	Hidrofor tanks pump	2	24	0,73	17,5	0	0,0	1	17,5	1	17,5	1	17,5
8	Machinery room drain pump	2	1,3	0,9	1,2	0	0,0	0	0,0	0	0,0	0	0,0
9	Lubricating oil pump	4	68	0,5	34,0	0	0,0	1	34,0	0	0,0	1	34,0

Item	Consumer Description	Installed Units	Rated Power	Load Factor	Power Requirement	TRANSIT Essential Loads No. Of Units in Service	TRANSIT Essential Loads Power Demanded	TRANSIT Normal Loads No. Of Units in Service	TRANSIT Normal Loads Power Demanded	DYNAMIC POSITIONING/LOADING-DISCHARGE No. Of Units in Service	DYNAMIC POSITIONING/LOADING-DISCHARGE Power Demanded	PORT/STAND BY No. Of Units in Service	PORT/STAND BY Power Demanded
10	Fire pump	2	70,6	0,97	68,5	0	0,0	0	0,0	0	0,0	0	0,0
TOTAL POWER REQUESTED						**0,0**		**53,6**		**17,5**		**51,5**	
DEMAND FACTOR						**0,3**		**0,3**		**0,4**		**0,4**	
TOTAL POWER FOR CALCULATION						**0,0**		**16,1**		**7,0**		**20,6**	

Group No. 4		Installed Units	Rated Power	Load Factor	Power Requirement	TRANSIT				DYNAMIC POSITIONING/LOADING-DISCHARGE		PORT/STAND BY	
Conditioned Air/Ventilation/Heating						Essential Loads		Normal Loads					
						No. Of Units in Service	Power Demanded	No. Of Units in Service	Power Demanded	No. Of Units in Service	Power Demanded	No. Of Units in Service	Power Demanded
Item	Consumer Description		kW		kW		kW		kW		kW		kW
1	Air conditioned for accommodation	3	88,8	0,75	66,6	0	0,0	1	66,6	2	133,2	1	66,6
2	Fan/Extractor of the air conditioned for accommodations	2	33,5	0,75	25,1	0	0,0	2	50,3	2	50,3	2	50,3
3	Air conditioned E. C. R.	2	31,8	0,91	28,9	0	0,0	1	28,9	1	28,9	1	28,9
4	Exhaust from the locker room	1	0,6	0,9	0,5	0	0,0	1	0,5	1	0,5	1	0,5
5	Fan of the game room	2	2,9	0,9	2,6	0	0,0	1	2,6	0	0,0	0	0,0
6	Kitchen Fan/Extractor	2	3,5	0,9	3,2	0	0,0	2	6,3	2	6,3	2	6,3
7	Cable storeroom exhaust	1	0,6	0,91	0,5	0	0,0	1	0,5	1	0,5	1	0,5
8	Exhaust of the provision storeroom	1	0,6	0,9	0,5	0	0,0	1	0,5	1	0,5	1	0,5
9	Laudry fan	1	0,9	0,9	0,8	0	0,0	1	0,8	1	0,8	1	0,8
10	Exhaust of the clothes storeroom	1	0,6	0,9	0,5	0	0,0	1	0,5	1	0,5	1	0,5
11	Compressor fan of the emergency generator	3	12,8	0,91	11,6	0	0,0	0	0,0	0	0,0	0	0,0
12	Compressor exhaust of the rudder machine	1	1,3	0,91	1,2	0	0,0	1	1,2	1	1,2	0	0,0
13	Master storeroom exhaust	1	1,3	0,91	1,2	0	0,0	1	1,2	1	1,2	1	1,2
14	Exhaust of the batteries compressor	1	0,9	0,91	0,8	0	0,0	1	0,8	1	0,8	1	0,8
15	CO2 Exhaust compressor	2	0,9	0,91	0,8	0	0,0	1	0,8	1	0,8	1	0,8
16	Exhaust of the deck storeroom	2	0,6	0,91	0,5	0	0,0	1	0,5	1	0,5	1	0,5
17	Exhaust of the additional storeroom	2	0,6	0,91	0,5	0	0,0	1	0,5	1	0,5	1	0,5
TOTAL POWER REQUESTED						**0,0**		**162,8**		**226,8**		**159,0**	
DEMAND FACTOR						**1**		**1**		**1**		**1**	

TOTAL POWER FOR CALCULATION						0,0		162,8		226,8		159,0	
Group No. 5		Installed Units	Rated Power	Load Factor	Power Requirement	TRANSIT				DYNAMIC POSITIONING/LOADING-DISCHARGE		PORT/STAND BY	
Provisions refrigeration (Equipments)						Essential Loads		Normal Loads					
						No. Of Units in Service	Power Demanded	No. Of Units in Service	Power Demanded	No. Of Units in Service	Power Demanded	No. Of Units in Service	Power Demanded
Item	Consumer Description		kW		kW		kW		kW		kW		kW
1	Compressor	4	34,8	0,9	31,3	1	31,3	1	31,3	1	31,3	1	31,3
2	Meat chamber fan	5	2,6	0,9	2,3	5	11,7	5	11,7	5	11,7	5	11,7
3	Fish chamber fan	4	3,6	0,9	3,2	2	6,5	2	6,5	2	6,5	2	6,5
4	Vegetables chamber fan	2	0,6	0,9	0,5	2	1,1	2	1,1	2	1,1	2	1,1
5	Potato chamber fan	1	0,6	0,9	0,5	1	0,5	1	0,5	1	0,5	1	0,5
6	Antechamber fan	1	0,6	0,9	0,5	1	0,5	1	0,5	1	0,5	1	0,5
7	Defrost system	5	3,9	1	3,9	0	0,0	0	0,0	0	0,0	0	0,0
TOTAL POWER REQUESTED						51,7		51,7		51,7		51,7	
DEMAND FACTOR						1		1		1		1	
TOTAL POWER FOR CALCULATION						51,7		51,7		51,7		51,7	
Group No. 6		Installed Units	Rated Power	Load Factor	Power Requirement	TRANSIT				DYNAMIC POSITIONING/LOADING-DISCHARGE		PORT/STAND BY	
Deck machinery						Essential Loads		Normal Loads					
						No. Of Units in Service	Power Demanded	No. Of Units in Service	Power Demanded	No. Of Units in Service	Power Demanded	No. Of Units in Service	Power Demanded
Item	Consumer Description		kW		kW		kW		kW		kW		kW
1	Lifeboat Turks	2	37	0,9	33,3	0	0,0	0	0,0	0	0,0	0	0,0
2	Main Crane	2	100	0,9	90,0	0	0,0	0	0,0	1	90,0	0	0,0
TOTAL POWER REQUESTED						0,0		0,0		90,0		0,0	
DEMAND FACTOR						0,4		0,4		0,6		0,5	
TOTAL POWER FOR CALCULATION						0,0		0,0		54,0		0,0	
Group No. 7		Installed Units	Rated Power	Load Factor	Power Requirement	TRANSIT				DYNAMIC POSITIONING/LOADING-DISCHARGE		PORT/STAND BY	
Dynamic Positioning						Essential Loads		Normal Loads					
						No. Of Units in Service	Power Demanded	No. Of Units in Service	Power Demanded	No. Of Units in Service	Power Demanded	No. Of Units in Service	Power Demanded
Item	Consumer Description		kW		kW		kW		kW		kW		kW

1	Bow Thrusters	2	880	1	880,0	0	0,0	0	0,0	2	1760,0	0	0,0
TOTAL POWER REQUESTED						**0,0**		**0,0**		**1760,0**		**0,0**	
DEMAND FACTOR						**0,7**		**0,7**		**1**		**0,7**	
TOTAL POWER FOR CALCULATION						**0,0**		**0,0**		**1760,0**		**0,0**	
Group No. 8		Installed Units	Rated Power	Load Factor	Power Requirement	TRANSIT				DYNAMIC POSITIONING/LOADING-DISCHARGE		PORT/STAND BY	
						Essential Loads		Normal Loads					
Laundry						No. Of Units in Service	Power Demanded	No. Of Units in Service	Power Demanded	No. Of Units in Service	Power Demanded	No. Of Units in Service	Power Demanded
Item	Consumer Description		kW		kW		kW		kW		kW		kW
1	Washer Machine	2	2,9	1	2,9	0	0,0	2	5,8	0	0,0	2	5,8
2	Dryer	2	4,4	1	4,4	0	0,0	2	8,8	0	0,0	2	8,8
TOTAL POWER REQUESTED						**0,0**		**14,6**		**0,0**		**14,6**	
DEMAND FACTOR						**0,5**		**0,5**		**0,5**		**0,5**	
TOTAL POWER FOR CALCULATION						**0,0**		**7,3**		**0,0**		**7,3**	
Group No. 9		Installed Units	Rated Power	Load Factor	Power Requirement	TRANSIT				DYNAMIC POSITIONING/LOADING-DISCHARGE		PORT/STAND BY	
						Essential Loads		Normal Loads					
Workshops						No. Of Units in Service	Power Demanded	No. Of Units in Service	Power Demanded	No. Of Units in Service	Power Demanded	No. Of Units in Service	Power Demanded
Item	Consumer Description		kW		kW		kW		kW		kW		kW
1	Overhead Crane	2	8,6	0,75	6,5	0	0,0	0	0,0	1	6,5	1	6,5
2	Lathe	2	8,6	0,75	6,5	0	0,0	1	6,5	1	6,5	1	6,5
3	Planer	2	1,7	0,7	1,2	0	0,0	1	1,2	1	1,2	1	1,2
4	Drill	2	3,5	0,7	2,5	0	0,0	1	2,5	1	2,5	1	2,5
5	Soldering Machine	1	22	0,7	15,4	0	0,0	1	15,4	1	15,4	1	15,4
6	Electrical Test Panel	1	6,3	1	6,3	0	0,0	1	6,3	1	6,3	1	6,3
TOTAL POWER REQUESTED						**0,0**		**31,8**		**38,2**		**38,2**	
DEMAND FACTOR						**0,4**		**0,4**		**0,4**		**0,4**	
TOTAL POWER FOR CALCULATION						**0,0**		**12,7**		**15,3**		**15,3**	
Group No. 10		Installed Units	Rated Power	Load Factor	Power Requirement	TRANSIT				DYNAMIC POSITIONING/LOADING-DISCHARGE		PORT/STAND BY	
						Essential Loads		Normal Loads					

Lighting						No. Of Units in Service	Power Demanded	No. Of Units in Service	Power Demanded	No. Of Units in Service	Power Demanded	No. Of Units in Service	Power Demanded
Item	Consumer Description		kW		kW		kW		kW		kW		kW
1	Machinery room	1	15,7	1	15,7	1	15,7	1	15,7	1	15,7	1	15,7
2	Accommodations	1	37,6	1	37,6	1	37,6	1	37,6	1	37,6	1	37,6
3	Main deck	1	15,7	1	15,7	0	0,0	0	0,0	1	15,7	1	15,7
4	Batteries charger	1	6,3	1	6,3	1	6,3	1	6,3	1	6,3	1	6,3
TOTAL POWER REQUESTED						**59,6**		**59,6**		**75,3**		**75,3**	
DEMAND FACTOR						**0,7**		**0,7**		**0,7**		**0,7**	
TOTAL POWER FOR CALCULATION						**41,7**		**41,7**		**52,7**		**52,7**	

Group No. 11		Installed Units	Rated Power	Load Factor	Power Requirement	TRANSIT				DYNAMIC POSITIONING/LOADING-DISCHARGE		PORT/STAND BY	
						Essential Loads		Normal Loads					
Equipment for navigation aid						No. Of Units in Service	Power Demanded	No. Of Units in Service	Power Demanded	No. Of Units in Service	Power Demanded	No. Of Units in Service	Power Demanded
Item	Consumer Description		kW		kW		kW		kW		kW		kW
1	Radio	2	0,6	1	0,6	1	0,6	1	0,6	1	0,6	0	0,0
2	Direction - finder	2	0,2	1	0,2	0	0,0	1	0,2	1	0,2	0	0,0
3	VHF radio	2	0,3	1	0,3	0	0,0	0	0,0	1	0,3	1	0,3
4	Radio and TV antennas system	2	0,2	1	0,2	0	0,0	1	0,2	1	0,2	1	0,2
5	Automatic pilot	1	0,3	1	0,3	1	0,3	1	0,3	0	0,0	0	0,0
6	Gyrocompass	1	0,5	1	0,5	1	0,5	1	0,5	1	0,5	1	0,5
7	Radar	2	3,9	1	3,9	1	3,9	1	3,9	1	3,9	0	0,0
8	Address system	1	0,6	1	0,6	1	0,6	1	0,6	1	0,6	1	0,6
9	Echobathymeter	1	0,3	1	0,3	1	0,3	1	0,3	1	0,3	0	0,0
10	Odometer	1	0,3	1	0,3	1	0,3	1	0,3	1	0,3	0	0,0
11	Intercommunicator	1	0,5	1	0,5	0	0,0	1	0,5	1	0,5	0	0,0
12	Maneuvering intercommunicator	1	0,3	1	0,3	0	0,0	0	0,0	1	0,3	0	0,0
13	Telephony system	1	1,3	1	1,3	1	1,3	1	1,3	1	1,3	1	1,3
14	Windshield wiper	1	0,3	1	0,3	0	0,0	1	0,3	1	0,3	0	0,0
15	Rotating portholes	2	0,3	1	0,3	0	0,0	2	0,6	2	0,6	0	0,0
16	INMARSAT	1	1,9	1	1,9	1	1,9	1	1,9	1	1,9	1	1,9
17	Satellite navigation (GPS)	1	0,3	1	0,3	1	0,3	1	0,3	1	0,3	0	0,0
18	Anemometer	1	0,3	1	0,3	0	0,0	1	0,3	1	0,3	1	0,3

19	Central clock	1	0,3	1	0,3	0	0,0	1	0,3	1	0,3	1	0,3
20	Whistle	1	7,1	1	7,1	0	0,0	0	0,0	0	0,0	0	0,0
21	Load master	1	0,3	1	0,3	0	0,0	0	0,0	0	0,0	0	0,0
22	NAVTEX receiver	1	0,3	1	0,3	0	0,0	1	0,3	1	0,3	1	0,3
23	Recorder	1	0,2	1	0,2	0	0,0	1	0,2	1	0,2	0	0,0
24	Rudder angle indicator	1	0,3	1	0,3	0	0,0	1	0,3	1	0,3	0	0,0
25	Navigation lights	2	5,5	1	5,5	1	5,5	1	5,5	1	5,5	1	5,5
26	Fire detection system	2	3,7	1	3,7	1	3,7	1	3,7	1	3,7	1	3,7
TOTAL POWER REQUESTED						**19,2**		**22,4**		**22,7**		**14,9**	
DEMAND FACTOR						**0,8**		**0,8**		**0,8**		**0,8**	
TOTAL POWER FOR CALCULATION						**15,4**		**17,9**		**18,2**		**11,9**	

Group No. 12		Installed Units	Rated Power	Load Factor	Power Requirement	TRANSIT				DYNAMIC POSITIONING/LOADING-DISCHARGE		PORT/STAND BY	
						Essential Loads		Normal Loads					
Kitchen/Pantry						No. Of Units in Service	Power Demanded	No. Of Units in Service	Power Demanded	No. Of Units in Service	Power Demanded	No. Of Units in Service	Power Demanded
Item	Consumer Description		kW		kW		kW		kW		kW		kW
1	Diverse equipment	2	77,6	1	77,6	0	0,0	1	77,6	1	77,6	1	77,6
2	Electric oven	1	9,4	1	9,4	0	0,0	1	9,4	1	9,4	1	9,4
3	Freezer (4001)	4	1,6	1	1,6	0	0,0	1	1,6	1	1,6	1	1,6
4	Freezer (2601)	4	1,6	1	1,6	0	0,0	2	3,2	2	3,2	2	3,2
5	Freezer (1001)	4	1,6	1	1,6	0	0,0	3	4,8	3	4,8	3	4,8
6	Hot plate	3	3,1	1	3,1	0	0,0	3	9,3	3	9,3	3	9,3
7	Cofee pot	2	2,4	1	2,4	0	0,0	2	4,8	2	4,8	2	4,8
8	Mixer	2	1,6	1	1,6	0	0,0	1	1,6	1	1,6	1	1,6
9	Fountain	6	1,2	1	1,2	0	0,0	6	7,2	6	7,2	6	7,2
10	Potato peeler	1	0,6	1	0,6	0	0,0	1	0,6	1	0,6	1	0,6
TOTAL POWER REQUESTED						**0,0**		**120,1**		**120,1**		**120,1**	
DEMAND FACTOR						**0,6**		**0,6**		**0,6**		**0,6**	
TOTAL POWER FOR CALCULATION						**0,0**		**72,1**		**72,1**		**72,1**	

TOTAL POWER REQUEST	**TRANSIT**		**DYNAMIC POSITIONING/LOADING-DISCHARGE**	**PORT/STAND BY**
	Essential Loads	**Normal Loads**		
	684,1	1046,9	3021,9	725,2

ANNEX H – DATASHEET OF THE AC/DC CONVERTER FOR THE ARRANGEMENTS 3 AND 4

(Source Siemens (2011b))

SINAMICS S120 Cabinet Modules

Active Line Modules including Active Interface Modules

Overview

Active Line Modules can supply energy and return regenerative energy to the supply system.

In contrast to Basic Line Modules and Smart Line Modules, Active Line Modules generate a controlled DC voltage that is kept constant despite fluctuations in the line voltage (the line voltage must remain within the permissible tolerance range). Active Line Modules draw a virtually sinusoidal current from the supply system and therefore do not cause any harmful current harmonics.

Braking Modules and braking resistors are required only if the drives need to be decelerated in a controlled manner after a power failure – i.e. when energy cannot be regenerated into the line supply.

Active Line Modules are available for the following voltages and power ratings:

Line voltage	Rated power
380 … 480 V 3 AC	132 … 900 kW
500 … 690 V 3 AC	560 … 1400 kW

Design

Active Line Modules are always operated together with an Active Interface Module, which contains the associated Clean Power Filter and pre-charging circuit. The integrated line filter ensures compliance with the EMC requirements for the "second environment".

The Active Line Module and Active Interface Module are supplied as a complete, fully wired unit, i.e., the customer does not need to supply any further cables or carry out any other wiring tasks.

Parallel connection of Active Line Modules to increase power rating

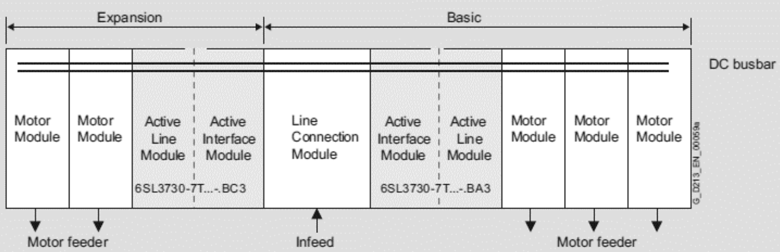
Active Line Modules are available for creating drive line-ups with more power. These modules can be operated in parallel on a common Line Connection Module and are arranged to the right and left of the Line Connection Module.

The power connections on the Active Line Module on the left of the Line Connection Module are a mirror image (Order No. with "**C**" in the next to last position, example: 6SL3730-7T.41.-.B**C**3), which results in a very compact design for the line infeed.

Please note that only Active Line Modules with exactly the same power rating may be connected in parallel. The potential for imbalances in current distribution means that a current derating of 5 % applies; this must be taken into account when the modules are dimensioned.

A connection of the Active Line Modules connected in parallel using DRIVE-CLiQ must be taken into consideration.

For additional information, please refer to the SINAMICS Low Voltage Engineering Manual.



Technical data

Line voltage 500 ... 690 V 3 AC		Active Line Modules			
		6SL3730-7TG35-8BA3	6SL3730-7TG37-4BA3	6SL3730-7TG41-0BA3	6SL3730-7TG41-3BA3
For a parallel circuit configuration, mounted to the left at the Line Connection Module			*6SL3730-7TG37-4BC3*	*6SL3730-7TG41-0BC3*	*6SL3730-7TG41-3BC3*
Rated power					
• For $I_{N\,DC}$ (50 Hz 690 V)	kW	**560**	**800**	**1100**	**1400**
• For $I_{H\,DC}$ (50 Hz 690 V)	kW	550	705	980	1215
• For $I_{N\,DC}$ (50 Hz 500 V)	kW	435	560	780	965
• For $I_{H\,DC}$ (50 Hz 500 V)	kW	400	510	710	880
• For $I_{N\,DC}$ (60 Hz 575 V)	hp	600	900	1250	1500
• For $I_{H\,DC}$ (60 Hz 575 V)	hp	450	600	1000	1250
DC link current					
• Rated current $I_{N\,DC}$	A	644	823	1148	1422
• Base load current $I_{H\,DC}$ 1)	A	573	732	1022	1266
• Maximum current $I_{max\,DC}$	A	966	1234	1722	2133
Infeed/regenerative feedback current					
• Rated current $I_{N\,E}$	A	575	735	1025	1270
• Maximum current $I_{max\,E}$	A	862	1102	1537	1905
Current demand 2)					
• 24 V DC auxiliary power supply	A	1.57	1.67	1.87	1.87
• 230 V AC auxiliary power supply	A	4.6	4.9	4.9	4.9
• 500 V AC	A	3.0	4.4	4.4	4.4
• 690 V AC	A	2.1	3.1	3.1	3.1
DC link capacitance					
• Active Line Module	µF	7400	11100	14400	19200
• Drive line-up, max.	µF	59200	153600	153600	153600
Power loss, max. 3)					
• At 50 Hz 500/690 V	kW	13.6	19.2	22.8	26.1
• At 60 Hz 575 V	kW	13.0	18.6	22.1	24.9
Cooling air requirement	m^3/s	1.58	1.88	1.88	1.88
Sound pressure level L_{pA} 4) (1 m) at 50/60 Hz	dB	77/79	77/79	77/79	77/79
PE/GND connection		PE bar	PE bar	PE bar	PE bar
• Busbar cross-section	mm^2	600	600	600	600
• Conductor cross-section, max. (IEC)	mm^2	240	240	240	240
Cable length, max. 5)					
• Shielded	m	2250	2250	2250	2250
• Unshielded	m	3375	3375	3375	3375
Degree of protection		IP20	IP20	IP20	IP20
Dimensions					
• Width	mm	1000	1400	1400	1400
• Height 6)	mm	2200	2200	2200	2200
• Depth	mm	600	600	600	600
Weight, approx.	kg	930	1360	1360	1360
Frame size		HX + HI	JX + JI	JX + JI	JX + JI

ANNEX I – DATASHEET OF THE FREQUENCY CONVERTER FOR SHIP ELECTRIC PROPULSION SYSTEMS

(Source: WEG Brazil)

1. INVERSOR DE FREQUENCIA

1.1 Inversor de frequência para os propulsores principais - 2500kW / 690V

O inversor de frequência WEG **CFW-11 modular drive** será montado em painel elétrico feito de chapa de aço, fabricado pela WEG AUTOMAÇÃO, grau de proteção **IP-44**, Icc 65kA, próprio para instalação abrigada, autossustentável, com corrimão isolado nas portas, pintura de acabamento na cor **CINZA RAL 7032**, com as seguintes dimensões **aproximadas**:

Drive:

- Altura:.............................. 2300 mm
- Largura:........................... 4500 mm
- Profundidade:.................. 900 mm
- Peso: .... 6500 kg
- Dissipação de calor:........ 3kW
- Temperatura ambiente: .. 45°C
- Entrada e saída de cabos na parte inferior dos painéis.

1.2 Inversor de frequência para os propulsores principais - 880kW / 690V

O inversor de frequência WEG **CFW-11 modular drive** será montado em painel elétrico feito de chapa de aço, fabricado pela WEG AUTOMAÇÃO, grau de proteção **IP-44**, Icc 65kA, próprio para instalação abrigada, autossustentável, com corrimão isolado nas portas, pintura de acabamento na cor **CINZA RAL 7032**, com as seguintes dimensões **aproximadas**:

Drive:

- Altura:.............................. 2075 mm
- Largura:........................... 2700 mm
- Profundidade:.................. 800 mm
- Peso: .... 2800 kg
- Dissipação de calor:........ 1,5kW
- Temperatura ambiente: .. 45°C
- Entrada e saída de cabos na parte inferior dos painéis.

1.3 Notas

Estes inversores possuirão refrigeração com água doce (conexão externa), próprio para instalação no compartimento do propulsor, ambiente com temperatura ambiente de 50 ºC.

O produto aqui ofertado é baseado na família de variadores de velocidade WEG CFW-11 modular drive, que se adequa perfeitamente em aplicações navais. Possui tecnologia PWM (Pulse Widht Modulation), controle vetorial, módulos de potência de saída tipo IGBT e microprocessador RISC 32 Bits. Sua configuração modular da ao usuário grandes benefícios, um único modelo do módulo de potência serve para todos os outros, reduzindo assim o número de sobressalentes. Como os módulos são construídos sobre rodas conforme mostra a figura B, poucos minutos serão necessários para substituir o módulo danificado pelo novo no caso de substituição.


FIGURA A


FIGURA B


FIGURA C

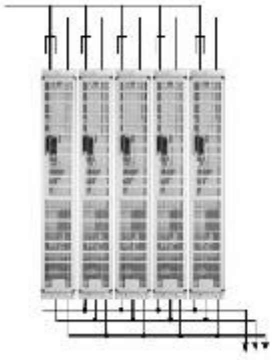


FIGURA D

A figura A mostra o módulo de potência WEG, cada um destes módulos pode administrar 500 kW, para obterem-se potências maiores, módulos de potência são montados em paralelo como mostra a figura D. As mangueiras do sistema de refrigeração podem ser conectadas pela parte frontal do painel, como mostra a figura C.

A Modularidade, obtida pela associação de módulos de inversores de potência alimentados por um único retificador é uma das inovações tecnológicas que o tornam capas de acionar cargas de maiores potências, ocupando um menor volume físico.

O conjunto pode ser formado em módulos inversores; cada um com formato “book”, no qual a largura é muito menor do que a profundidade, o que permite um elevado nível de compactação do acionamento.

O sistema é fornecido com um filtro para manter os níveis de harmônicas (THD) dentro dos níveis aceitos pelas sociedades classificadoras. Todas as dimensões aqui apresentadas já foram devidamente aprovadas pela projetista.

1.4 O filtro passivo WEG Wide-spectrum passive filter (WHF)

O filtro passivo WEG identificado como wide-spectrum passive filter (WHF) é um dispositivo puramente passive que consiste de um novo indutor de design revolucionário combinado com um banco de capacitores relativamente pequeno. Seu design inovador consegue cancelar todas as principais harmônicas de corrente geradas por um variador de velocidade e outras cargas trifásicas com retificador de 6 pulsos. O WHF não é um filtro convencional.

Devido aos problemas que diferentes tipos de variadores de velocidade podem causar em sistemas elétricos, tais como, problemas gerados com harmônicas de corrente de alta frequência, circulação de corrente de modo comum, eventual sobre tensão no barramento principal, regeneração causada por outro tipo de VFD poderia inclusive danificar os geradores principais no caso do nível de regeneração não ser limitado dentro dos limites aceitáveis pelos geradores.

A WEG oferece aqui uma solução que atende as exigências de classe e evita problemas que podem ser criados com a utilização de variadores de velocidade com outras tecnologias, a solução selecionada pela WEG é comprovada e altamente confiável. A WEG adotou uma tecnologia que segue as normas mais atuais do segmento naval, mantendo os níveis de harmônicas aceitáveis até a 100ª harmônica, situação anteriormente quase impossível de se garantir com outras tecnologias que não esta adotada pela WEG. A solução aqui ofertada pode operar inclusive com sistemas que apresentem desbalanceamento de fases.

Como a solução aqui ofertada não opera com entrada ativa, ela evita emissões de alta frequência, normalmente existente nos cabos entre o variador de velocidade e o quadro elétrico principal quando uma solução AFE é aplicada, minimizando assim, problemas em outros equipamentos eletrônicos que poderiam apresentar funcionamento incorrente por causa da interferência emitida através dos cabos elétricos. Para evitar estes problemas, outras soluções exigem filtros adicionais para minimizar a emissão de alta-frequência, bem como a utilização de cabos especiais.

A solução WEG para nossos variadores de velocidade considera a utilização de um filtro passivo "wide-spectrum filter (WHF)" refrigerado a água, que não utiliza elementos eletrônicos. No caso de uma falha, o filtro pode ser "by-passado", o que permitiria o variador a continuar operando com uma potência reduzida, solução que qualquer outro variador com transformador defasador ou do tipo AFE não poderia oferecer.

O filtro WHF consiste num reator com múltiplos enrolamentos numa bobina única e um banco de capacitores com tamanho reduzido. Um enrolamento de alta impedância é utilizado como a principal indutância de bloqueio e é dimensionado para evitar a transferência de harmônicas geradas pela parte de saída do acionamento. Um enrolamento de filtragem combinado com o banco de capacitores oferece uma passagem de baixa impedância para filtrar as harmônicas geradas pelas cargas na entrada do acionamento. Para reduzir através da impedância e minimizar a queda de tensão no filtro, um enrolamento de compensação pode ser utilizado e este é ligado com polaridade oposta ao enrolamento de bloqueio. Uma grande vantagem deste reator único é que ele permite a utilização de um banco de capacitores bastante reduzido, evitando assim picos de tensão ou potência reativa em condições de baixa carga ou carga nula, garantindo assim compatibilidade com os geradores.

O fator de potencia do filtro WHF é capacitivo quando o variador de velocidade está acionando a carga com uma exigência de carga baixa, mesmo quando próximo a zero, por haver uma baixíssima reatância capacitiva, abaixo de 20% do KVA nominal, por esta razão, não há necessidade de chaveamento dos capacitores do filtro.

A alta impedância do filtro WHF oferece vários dos benefícios existentes uma solução com transformador isolador, enquanto também reduz drasticamente a injeção de harmônicas no sistema criadas pelo variador de velocidade. Tudo isso é obtido numa solução com dimensões reduzidas, então, quando não há a necessidade de transformação de tensão, o uso do filtro WHF elimina a necessidade do transformador isolador, e mesmo quando o transformador é necessário, uma taxa de fator K especial não será necessária.

Diversas embarcações ao redor do mundo usam esta solução, mesmo aquelas desenvolvidas para operações especiais como navios tipo "pipe layers", com operações com ROV, ou militares.

O guia do ABS para controle de harmônicas em sistemas elétricos (ABS guidance notes on control of harmonics in electrical power systems) menciona esta solução no capitulo 10, item 7.1 do documento, onde ele claramente fala sobre os filtro tipo " wide spectrum filters" e seus benefícios. No mesmo documento, é possível verificar a preocupação do ABS sobre os problemas que podem ser causados quando soluções diferentes são utilizadas, onde as harmônicas acima da 50ª não são devidamente administradas e controladas dentro dos níveis aceitáveis nas aplicações navais.

ANNEX J – EDDA FRAM DATASHEET

Source (OSTENSJO REDERI, 2014)

Edda Fram

GENERAL

Operator	Østensjø Rederi AS
Built	2007
Builder	Astilleros Gondan
Yard no.	432
Call sign	LNVQ
Flag	Norwegian
Port of Registry	Haugesund
IMO no.	9356995
Classification	DNV, 1A1, Supply Vessel, SF, E0, ICE C, DYNPOS- AUTR, CLEAN, Comfort-C(3)-V(3), LFL* Registered notations: DK(+) and HL(2.8), PMS, ISM
Safety regulations	NMA, Worldwide within GMDSS A3, Solas 1974/1978, International Convention on Load Lines, Pollution Prevention - MARPOL 1973/1978, NLS Certificate

DIMENSIONS

Length o.a.	85,8 m
Length b.p.	77,4 m
Breadth mld.	19,2 m
Depth mld.	8,0 m
Draft max.	6,5 m

TONNAGE - DEADWEIGHT

Gross tonnage	3706 GT
Deadweight max	4100 t

DECK LOADING CAPACITIES

Deck measurements	57,4 m x 16,2 m . 4 pipe lengths a' 12,2 m
Outside deck area	910 m2
Deck cargo capacity	2900 t VCG 1,0 m above main deck. 10 t/m2

DECK EQUIPMENT

Anchor chain	14 shackles PS, 10 shackles SB. Type: 48 mm DNV K3 Stud Link
Anchor Windlass / Mooring Winch	2 x anchor windlass/mooring winches forward
Mooring winch	2 aft
Deck cranes	1 x 4 T at 10 m. 1 x 1,5 T at 8 m
Tugger winches	2 x 10 T

PROPULSION

General	Diesel electric propulsion plant. 2 x Voith Propellers, each 2800 kW. Two AC asynchronous water-cooled motors each 2500 kW (2992 bhp)
Main engines	4 x Mitsubishi
Fuel type	MDO / MGO

AUXILIARIES / ELECTRICAL POWER

Generators	4 x Mitsubishi, each 1920 kW
Harbour generator	338 kW, 690 V, 60 Hz
Emergency generator	99 kW, 690 V, 60 Hz

SPEED / CONSUMPTION

Max speed / Consumption	15,5 knots, 28 tonnes/day
Economy speed / Consumption	13 knots, 13 tonnes/day
DP-operations (weather dependent)	5 tonnes/day
Stand by offshore	4 tonnes/day
In port	1 tonnes/day