

LAPPEENRANTA UNIVERSITY OF
TECHNOLOGY
Faculty of Technology
Department of
Electrical Engineering



Author of the thesis: Sergey Balashov

**Design of marine generators for alternative diesel-electric
power systems**

Examiners: Professor, D.Sc. Juha Pyrhönen,
D.Sc. Pia Lindh

ABSTRACT

Author: Sergey Balashov

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59 pages, 41 figures, 7 table and 2 appendices.

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This study compares different electric propulsion systems. Results of the analysis of all the advantages and disadvantages of the different propulsion systems are given. This thesis estimates possibilities to apply different diesel-electric propulsion concepts for different vessel types. Small and medium size vessel's power ranges are studied. The optimal delivery system is chosen. This choice is made on the base of detailed study of the concepts, electrical equipment market and comparison of mass, volume and efficiency parameters. In this thesis three marine generators are designed. They are: salient pole synchronous generator and two permanent magnet synchronous generators. Their electrical, dimensional, cost and efficiency parameters are compared. To understand all the benefits diagrams with these parameters are prepared. Possible benefits and money savings are estimated.

As the result the advantages, disadvantages and boundary conditions for the permanent magnet synchronous generator application in marine electric-power systems are found out.

Keywords: propulsion system, diesel-electric system, marine generator, vessel power system, ship propulsion, permanent magnet synchronous generator.

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List of symbols and abbreviations

Abbreviations:

EP	electric propulsion
DE	diesel electric
FPP	fixed pitch propeller
CPP	controlled pitch propeller
FPC	full power converter
HFO	heavy fuel oil
MDF	marine diesel fuel
IG	induction generator
SG	synchronous generator
PMSG	permanent magnet synchronous generator
AVR	automatic voltage regulator
CRP	counter rotating propeller
VSR	voltage source rectifier
LLC	low loss concept
FPC	full power converter
ROV	remotely operated underwater vehicle

Symbols:

P	rated output power , W
U_{ph}	phase voltage , V
U_1	line voltage , V
η	efficiency
m	number of phases
n	revolution speed , rpm
f	rated frequency , Hz
p	number of poles
a	number of the parallel branches
σ_{Ftan}	tangential tension , Pa
A	linear current density , A/m
J	current density , A/m ²
δ_{load}	load angle , rad

T_r	rated torque , Nm
T_{max}	maximal torque , Nm
R_a	phase resistance , Ohm
L_d	direct-axis inductance , H
L_{md}	magnetizing inductance, in d-axis , H
L_q	quadrature-axis inductance , H
L_{mq}	magnetizing inductance, in q-axis , H
$L_{s\sigma}$	stator leakage inductance , H
D_{si}	stator inner diameter, mm
D_{so}	stator outer diameter , mm
A_{fuel}	work of fuel combustion , J
c_{diesel}	specific heat of combustion , J/kg
m_{fuel}	fuel mass , kg

Content

Acknowledgments.....	3
List of symbols and abbreviations	4
Content.....	6
1 Introduction.....	7
1.1 Objectives	7
1.2 Historical overview	7
1.3 Contemporary propulsion systems.....	8
1.4 Efficiency.....	10
1.5 Electric power system.....	12
1.5.1 Power generation	13
1.5.2 Power distribution.....	16
1.6 Propulsion units	19
1.6.1 Propulsion thruster.....	19
1.6.2 Propulsion drive.....	23
2 Basic power system concepts.....	25
2.1 Fixed frequency and voltage AC system (typical diesel-electric power-line nowadays)	26
2.2 Fixed frequency and voltage AC system, LLC construction.....	27
2.3 Full power converter AC system and DC system.....	29
2.4 Variable frequency AC system	31
2.5 Concepts comparison.	32
3 Design of the generator and result analysis	40
3.1 Generator comparison.....	41
3.2 Numerical analysis.....	47
3.3 Price analysis	49
3.4 Consumption estimation	51
3.5 Masses analysis.....	52
3.6 Volume analysis.....	53
4 Summary.....	55
5 References.....	57
6 APPENDIXES	58
APPENDIX 1: Nor Valiant general arrangement [15].....	58
APPENDIX 2: Designed generator in the scale of 1:10.....	59

1 Introduction

1.1 Objectives

This Master's thesis introduces a study which is necessary for designing marine generators as part of whole vessel electric power system in different diesel-electric applications.

The task of designing an electrical generator for the vessel power system is not only computational, but also global task of systems engineering. It is a wide and difficult task which requires deep background knowledge. During the designing process it is important to look up both to the required parameters, such as: output power, frequency, rotational speed as well as limitations from the power system and compatibility of the characteristics and working modes of the generator and other electrical equipment. These limitations are required for making possible operation: in wide speed range and smooth, without vibration and big losses. Within this work some different types of electrical equipment configurations will be analyzed for finding out the most reliable, flexible and energy efficient type. For the chosen arrangement the electric power generator will be designed.

1.2 Historical overview

From the historical point of view the idea of electric drive for propulsion propeller isn't new. In the end of the 19th century in some countries such as Russia and Germany took place experiments which were directed for designing vessels with electric propulsion (EP) drives (electric power transmission).

The first workable specimen of an electric ship was a river tanker and built in 1903 in Russia and was called "Vandal". The power system contains DC generators (3×87 kW at 500 V) which were driven by prime movers (diesel engines 89.5 kW at 250 rpm each) and a DC motor connected to the propeller shaft. Power delivering was arranged by cables. Also magnetic clutches were located between the diesel engines and DC generators. The control was arranged by excitation adjustment. This ship had good maneuverability. Operation time from full ahead to full reverse took 8–10 seconds.

In spite of all advantages this system had quite big losses. From the 290 kW of diesel output only 216 kW was found on the screws, which corresponds to 20 % transmission losses, without taking diesel-engine losses into account. Also the first power system was very heavy. The electric system equipment mass was almost the same as the diesel system mass. The other vessels of the same time had similar arrangements. In those days the only reason for electric power system usage was the fact that diesel engines were not reversible and it was a big disadvantage because of significantly decreased maneuvering ability. Some makeshift arrangements for the ahead and reverse modes combination were invented and partly applied but they weren't reliably and adaptable to streamlined production. When in 1906 two- and four-stroke directly reversible diesel engines were invented and become into production, all attractiveness of the bulky electric propulsion system seemed to be lost. Due to new engine generation designer's attentions were switched to the direct drive, as it allowed getting higher efficiency not wasting energy for electricity generation, distribution and utilization of electric energy in propulsion. Therefore, the propulsion efficiency fully depended on the engine efficiency. But from the 1920's there was new interest arising to the diesel-electric configuration. It was again very popular to assemble electric propulsion, especially, in icebreakers (due to the requirements for high torque on the shaft of propeller, especially in cases when the propeller was surrounded by ice) and in research vessels. The first icebreaker with electric power system onboard was Finish built by SISU in 1930. "The speed of the driving motor could be altered by switching a relatively low inducing current in the generator." [1]

Since 1930's Strömberg began all range works directed to design and building ships with electric propulsion systems and in 1939 the first diesel electric icebreaker was built. By the moment the amount of the icebreakers, powered by ABB, reaches 80. The other vessels with EP were built even more. The latest revival and new interest in electric propulsion systems appeared since 1980, when power electronics and information technology began to develop intensively. Modern power electronics controlled drives have been widely used because of possibilities to control the propulsion motors' speeds in a wide range, and because of the high reliability, good cost-competitiveness and high space-saving equipment. [2]

1.3 Contemporary propulsion systems

By the moment in the world the most widespread propulsion systems are:

- Diesel-mechanical (Diesels engines through a gear connected to a shaft and consequently to a propeller), Fig.1
- Conventional diesel-electric arrangement (Diesel engines (sometimes as prime mover may be used a steam turbine in a nuclear-powered ships) – electric generators – distribution and energy delivering system – electric motor-gear-shaft-propeller), Fig. 2
- Pod propulsion- so called azimuth thrusters (Prime movers – electric generators – distribution, delivering and energy conversion system – podded motors with on shaft propellers), Fig. 3

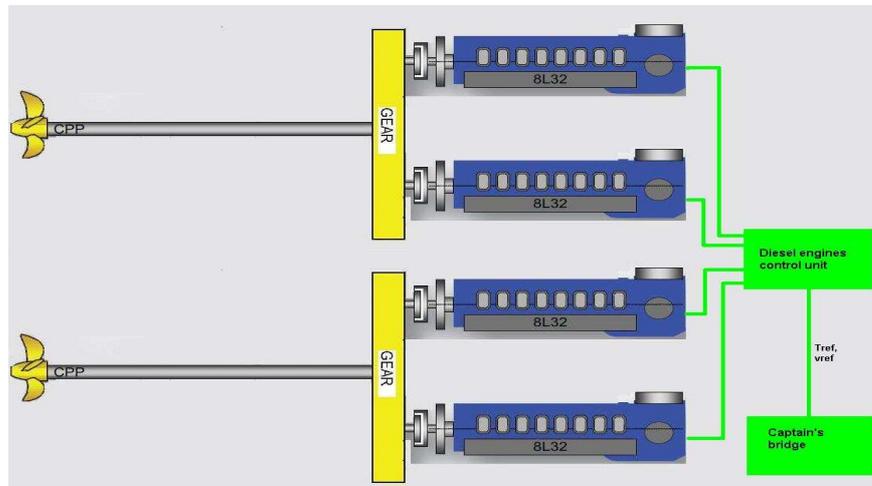


Figure 1 Typical diesel mechanical propulsion configuration.

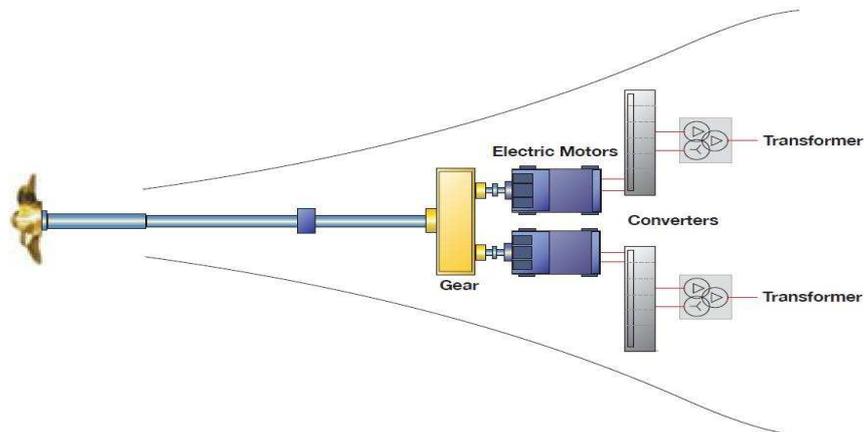


Figure 2 Conventional diesel-electric arrangement [2]

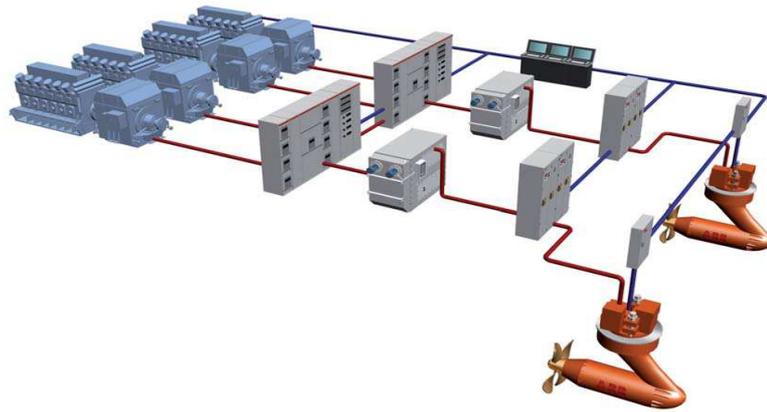


Figure 3 Podded propulsion- so called Azimuth thrusters or Azipod, made by ABB [2]

Nowadays, the electric propulsion is used in more and more application areas and replaces the classical mechanical configuration. In most cases azimuth thrusters or combined assemblies are used. Electrical propulsion is applied in a wide range of vessels such as: icebreakers, drilling vessels, cruise vessels, shuttle tankers, cable and pipe layers, war ships. Such a wide spread got a reality because of advantages inherent EP:

- Reduced consumption of the fuel, especially, in maneuvering operation modes
- Reduced maintenance cost due to flexible and smooth operating, avoiding jerky torque and speed change, decreasing tear modes
- Optimized load of prime mover (prime mover operates at rated parameters and life cycle is prolonged)
- Decreased vibrations (absence long shaft) and noise (important on cruise vessels)
- Higher level reliability directed for preventing blackouts
- Opportunity to locate power equipment properly based on load in different vessel's parts
- Mounting places of thrusters are not restricted because of delivering energy via cables

1.4 Efficiency

One of the most important question and challenges in EP system applications is the system efficiency. Having low efficiency all systems loose their economical attractiveness. That is why designers must pay a lot of attention on this aspect.

The efficiency of an EP system is a product of the efficiencies of typical independent parts of system in series such as:

- Electrical generator
- Switchboard
- Transformer
- Frequency converter
- Electric motor

The power system can be simplified and reflected in the next figure.

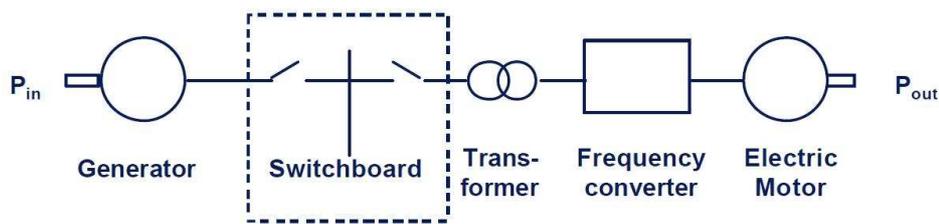


Figure 4 Simplified power system presentation

Electrical efficiency of the system:

$$\eta = \frac{P_{out}}{P_{in}} = \frac{P_{out}}{P_{out} + P_{losses}} \quad (1.1)$$

Typical efficiency of each component of the power system in the power level of ship components:

- generator: 95 – 97 %
- switchboard: 99.99 %
- transformer 99.1 – 99.7 %
- frequency converter 95 – 99 %
- electric motor 93 – 97 %

The total electric power system efficiency (prime mover is not taken into account) at full load reaches 88 – 92 % and of course the efficiency depends on the load. Total losses in the EP system on average reach 10 %. Consequently fuel savings are achieved by other solutions, such as thruster's location. In designing classical diesel-mechanical systems there are limitations which do not allow placing the propeller deep enough. That is why the propeller gets to the area where the influence of the vessel's hull is significant. Podded propulsion can be placed on the optimal depth and optimal area. Also for speed control diesel-mechanical power system can be applied in 2 ways: by changing the prime engine speed and by controlling the propeller pitch (if controllable pitch propeller (CPP) is employed). Anyway, in the idling mode when mechanical

control is used losses (from prime mover and hydrodynamic) are big vs. almost zero losses in EP system.

In an EP system, usually, a fixed pitch propeller is employed. It allows reducing money investments and simplifying the construction without any drops in efficiency. As the example can be taken field support vessel with DE propulsion (diagram of operation see Fig. 5), total fuel savings are up to 700 tons/year of diesel fuel. If the fuel price is 0.5 euro/liter, total money savings are 350 000 €/year, this rapid calculation, of course, strongly depends on vessel operational modes. [3]

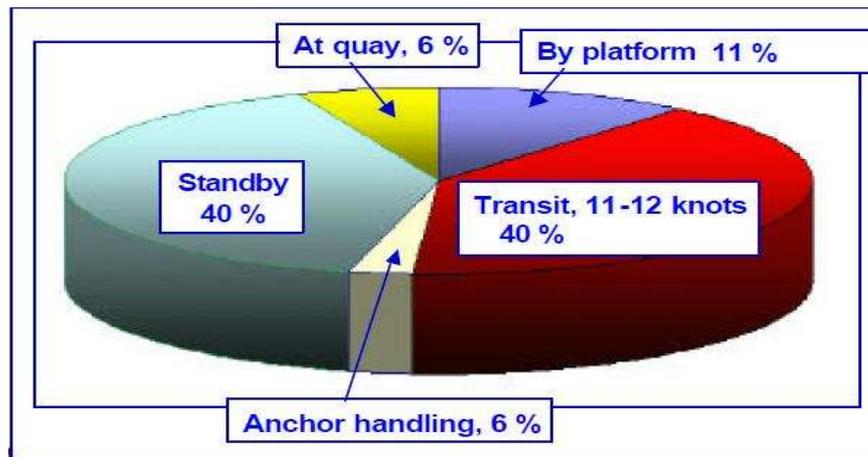


Figure 5 Operational modes for a field support vessel [3]

1.5 Electric power system

Vessel's power system differs a lot in comparison with land power systems.

The main differences are:

- Line long;
- Compact placement (generation equipment near by utilization equipment);
- One control system and one power system (no sub-systems);
- Much less amount of energy transformation.

It means that much power is concentrated in a small area. That is why it gives engineering challenge, and requires high accuracy and deep analyses in safety and reliability fields.

Fig. 6 shows presently the most spread electric power system configuration, which can be divided into the following parts:

- power generation;
- power distribution;
- variable speed drives;
- propulsions ;

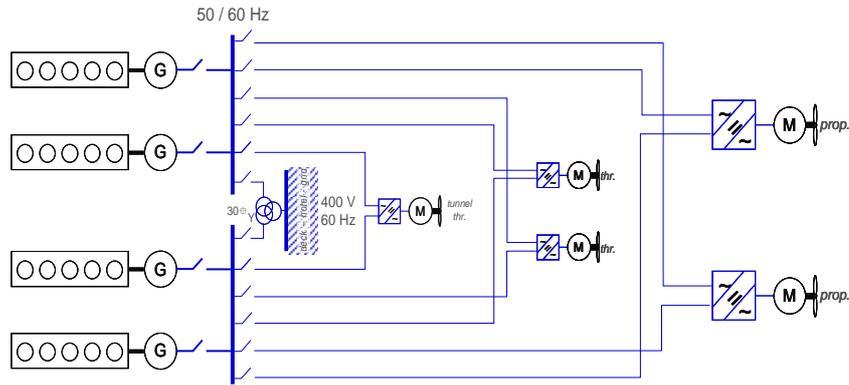


Figure 6 Power system configuration diagram

1.5.1 Power generation

The power generation unit consists of a prime mover (as a rule diesel engine) and an electric generator driven by the prime mover. For increasing efficiency, reliability, for better distribution of power there are more than one power generation unit (in most cases the amount is even). Usually, this power unit installation is placed in the centre of the ship at both boards symmetrically with respect of the middle longitudinal axis to dispense weight uniformly and proportionally.

Prime mover

The prime mover is usually a diesel engine but sometime other types such as: gas engines, gas turbines, steam turbines or also combined cycle turbines, can be employed instead of traditional diesel engines. The source of energy for traditional engine is diesel oil or heavy fuel oil, sometimes diesel oil and natural gas are employed in parallel.

Diesel-Electric (DE) power systems apply diesel engines which are medium to high-speed engines. Such an arrangement allows getting benefits in engine's weight and cost. In whole mechanical systems low speed engines are required. Also DE power system does not limit the number of power units what decreases the power per unit, increases reliability, redundancy, increases control and diagnostic requirements and decreases maintenance time and consequently shows better results.

Modern primary engines are equipped by a wide range of monitoring systems and gauges for being able to control the rotating speed, avoiding speed droops, and preventing failures connected with overheating, losing lubrication pressure, over

speeding or turbocharger over speeding. Such an arrangement is an electronic speed control system which is built in and is supplied with engine. This system works directly with an actuator which is adjusting fuel injection. Beside the speed regulation speed control unit compensates droops which occurs when load is increasing. The droop ratio depends on the engine, for example for Wärtsilä Auxpac gensets speed control unit is adjusted at the factory and droop is 4 % at the rated load. Speed droop compensating is important to keep rotation speed constant and consequently generated voltage frequency and brings proper sharing of the load between generators connected in parallel.

Diesel engine can be fed either by diesel fuel, so called Marine Diesel Fuel (MDF), or heavy fuel oil (HFO). Since HFO has a high density a pre-heater is required. Also for both types of fuel separators (based on centrifuge) are compulsory for preventing water penetration in the engine fuel system and engine and damage diesel.

Another important point is exhaust fumes and gases emission. Nowadays, there are requirements for marine diesel engines. These requirements direct to decreasing Nitrogen oxides (NO_x), Sulphur Oxides (SO_x), soot and Particulate Matter (PM). For regulating this aspect International maritime organization (IMO) was created. IMO made and published the first set of emission regulations, the Annex VI of MARPOL 73/78.

According to this regulation there are 3 limits: Tier 1, Tier 2 and Tier 3. Tier 1 was entered into force in January 1, 2000, Tier 2- January 1, 2011, Tier 3- January 1, 2016. The illustration of emission limits on the example of nitrogen oxides (NO_x) is shown in Fig. 7 [4]

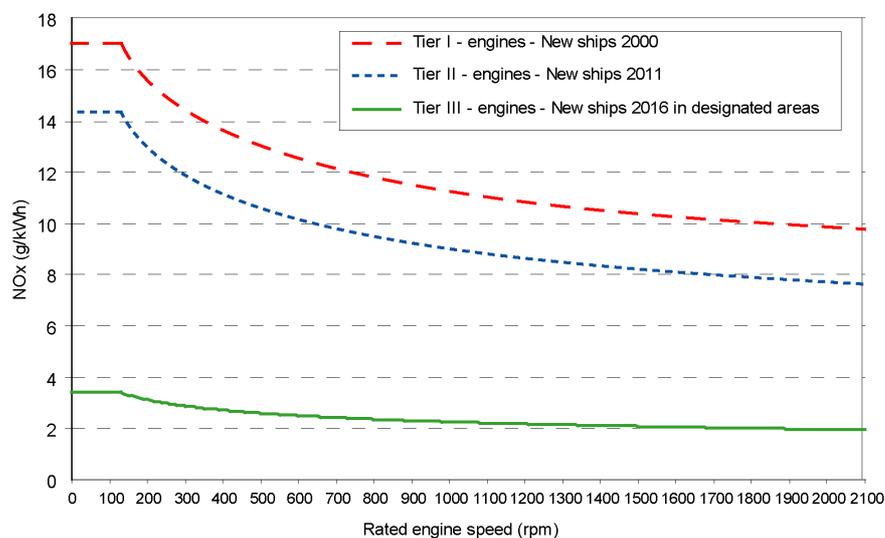


Figure 7 Annex VI of MARPOL 73/78 NO_x emission limitation.[4]

Generators

To save space and make the construction more cost efficient in DE power systems the generator could be directly connected to the flywheel of the engine or could even be supplied by factory as integrated gensets (e.g. Wärtsilä Auxpac gensets). In conventional DE schemes, as electric generator usually synchronous machine is used. Synchronous marine generators have some differences compared with classical ones.

Typical marine generator has:

- number of poles: from 4 to 10 (rated rotational speed from 1800 rpm (60 Hz) to 600 rpm (50 Hz) respectively, marine generators power range distribution see in Fig. 8);
- excitation: brushless by auxiliary outer pole synchronous generator (DC on the stator, AC induced the rotor windings and then rectifying) placed on the same shaft;
- specific mounting standards (usually designed for the chosen diesel engine);
- cooling systems: (open air (standard with protection IP 23), closed circuit with water cooler (with protection IP44))

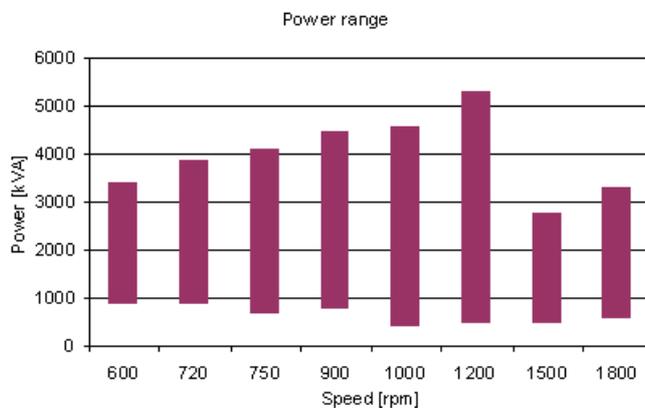


Figure 8 Generators' power range distribution [6]

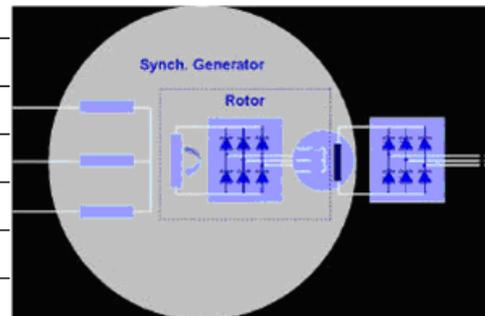


Figure 9 Brushless excitation arrangement [3]

Excitation, in its turn, is controlled by automatic voltage regulator (AVR). The AVR unit is built-in the generator. The duty of the AVR is comparing voltage at the generator terminals with reference value and keeping voltage at generator terminals constant. If voltage gets drifting AVR affects the excitation. For keeping active-reactive power balance and equal reactive power distribution in generators, connected in parallel the AVR uses voltage droop which is preset at the factory and is about 3.5%

at the rated load. Another challenge for AVR- limit voltage hops in the range of – 15 to +20% of the nominal voltage when the largest transients occur.

In designing process engineers may choose either equip a vessel by a primary engine and a generator separately or by an integrated product – a genset. Genset is the end products and has range of benefits inherent to it. These advantages are: working parameters of both machines are adjusted, conformed and designed for each other, primary engine and generator mount on one plate and some equipment are designed for dissipation of vibration, noise and impact stress which may spread on the vessel's hull. Consequently implementation of integrated gensets is most reasonable and studied step.

As examples, Wärtsilä gensets can be shown. The nowadays available range of Auxpac gensets is the following:

Table 1 Wärtsilä gensets power range

Frequency power (weight)	50 Hz (1000 rpm)	60Hz (900 rpm)
P_{min} , kW _e (m, ton)	520 (14)	520 (14)
P_{max} , kW _e (m, ton)	2850 (45.7)	2700 (46.9)

1.5.2 Power distribution

Power distribution components form a group of the three most important parts of a DE propulsion system. Power distribution includes switchboards and transformers for supplying either local consumer (deck, hotel grid) or propeller drives.

Switchboards

In its turn switchboards strongly affect the reliability and if switchboards were connected without respect to redundancy it might cause a black out in case of short circuit, fire or flooding. That is why in main or so called generator switchboards usually 2, 3 or even four independent sections are used. System redundancy in general is made for avoiding consequence after short circuits, but for strictest requirements anti flood and fire protection is employed. Such arrangement is made for ability to continue movement in congested waters when stopping may cause an accident. For example, in

case of switchboard split in to 2 sections and a single failure (short circuit), vessel can continue movement at 50 % power.

Since with fixed voltage and increasing power range rated and especially short circuit currents flowing through the switchboards increase. This current raise is limited by physics (mechanical forces), temperature mode and capacity of the switchgears, and hence, after some current level it is necessary to implement higher generating and distribution voltage. There are some recommendations for matching required energy for generating and voltage of distribution system. One of the prescriptions is NORSOK [5]

- 11 kV. Medium level of generating and distributing voltage. Used when total installed generation power exceeds 20 MW and when motors have power from 400 kW and above.

- 6.6 kV. Medium level of generating and distributing voltage. Used when total installed generation power exceeds 4–20 MW and when motor powers vary from 300 kW onwards.

- 690 V. Low level of generating and distributing voltage. Used when total installed generation power is below 4 MW and single consumers below 400 kW.

- For utility distribution lower voltage is used, e.g. 400/230V [5]

As the example can be shown modern switchboard powered by Wärtsilä:

- low voltage: voltage is up to 690 V, current is up to 220 kA
- medium voltage: voltage is 7.2, 12, 17,5 V, current is up to 106 kA

Transformers

In EP vessels' transformers are used for converting the input voltage (e.g. generator or line) to required voltage in order to feed propulsion drives, local consumers (deck- hotel- grid) and for phase shifting. Phase shifting transformers sometimes are used when variable speed drives technology is implemented for feeding frequency converters. It is made for cancelation of some (the biggest and little number) harmonics for preventing high output signal distortion.

Also transformers have some damping reaction and behave like filters for high frequency noise, which is produced by frequency converters. It helps avoiding electro magnetic interference and emissions.



Figure 10 ABB dry transformer for marine applications [10]

The most common transformer types which find applications are:

- dry (air insulated, the typical dry transformer for marine application is shown in Fig.10);
- resin insulated;
- oil insulated.

In common, transformer is a three-phase one at the input and 3-phase at the output. It contains three-phase primary and secondary coils which are wound on the magnetic core. Magnetic core is made of electrical-sheet steel and constitutes close circuit for providing close path for magnetic flux. There are three steel legs where windings are placed and two yokes which connect legs. There are 2 types of windings, one mount inside another. Inner (secondary) is low voltage, outer (primary)- high voltage. The ratio of numbers turns is a transformer coefficient and equal to the primary and secondary voltages ratio. The connection of primary and secondary terminals (windings) may be either star, zigzag or delta. It is not necessary to connect both terminals in the same way, but if connections are different then a phase shift is obtained.

When designing a marine application transformer additional losses and consequently temperature should be taken into account because of a wide range of higher harmonics.

1.6 Propulsion units

1.6.1 Propulsion thruster

By the moment it is worth to highlight some of the typical and some very challenging propulsion realizations.

Shaft propulsion

Shaft propulsion is a conventional propulsion system and is known from the end of wheel type vessels' era. Get wide spread with diesel-engine as a driver, but in spite of long life, this technology is implemented nowadays. Disadvantages of the direct diesel drive are length of the shaft, difficulties in balancing and as the result high vibration and noise level. By implementing EP it is possible to avoid these disadvantages because of much shorter shaft. The reasons for such propulsion arrangement are the following:

- required power for propulsion is higher than available podded units or azimuth thrusters;
- lack of reasons for podded propulsion (e.g. maneuvering or position keeping are not required) ;
- price of realization is much lower.

For maneuverability in case of shaft propulsion rudders are used; one rudder per propeller.

Also for this aim use tunnel thrusters, sometimes it is cheaper than azimuth thruster technology.

The propeller suitable for this application is FPP (fixed pitch propeller) which is used with variable speed drives. Much rarely with variable speed drives CPP (controllable pitch propeller) is used. It allows getting higher efficiency in a wider range of operation, but does not normally justify the extra investment cost of the equipment.

The propeller drive either in diesel or electric motor applications might be connected to the shaft in two ways: directly or through a gear. Direct connection requires low speed and high torque from the drive, when in case of a gear high speed and lower torque drive can be accepted. Also there is possibility for coupling two electric motors with gear and shaft. Implementing gear in EP allows getting benefits in

dimensions and as result in weight of the drive. But such a system is more complex, requires maintenance, has lower efficiency and reliability.

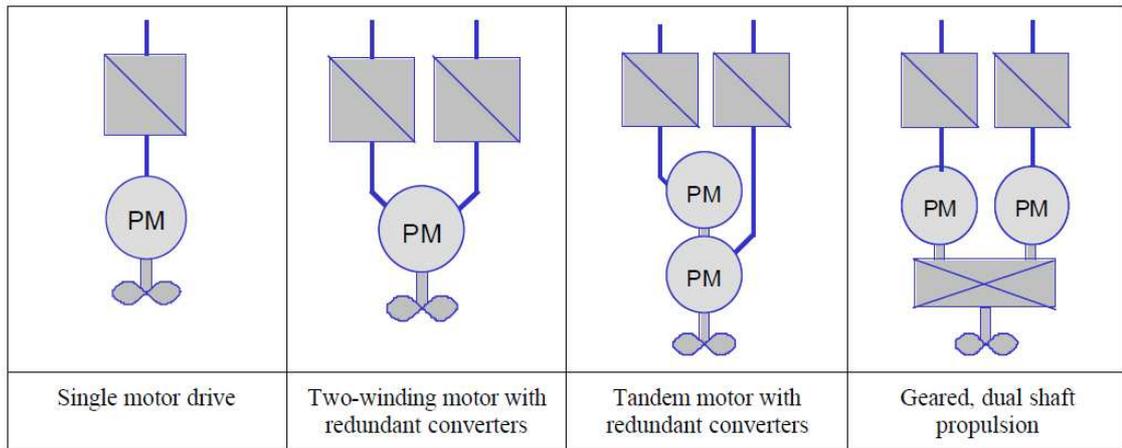


Figure 11 Shaft propulsion configuration [3]

The typical applications for shaft propulsion are:

- tankers;
- large anchor handler vessels;
- research vessels.

Azimuth thruster

In order to develop improved maneuverability the azimuth thruster was introduced. There are L type and Z type gears with a propeller on the one end and shaft on the other. Z type applies when the motor is horizontally mounted (when the height of room is limited). In L type the motor is installed vertically. Such kinds of thrusters are used with variable speed drives and FPP (much simpler construction and decreased low-thrust losses) or constant speed drives and CPP.

Azimuth thrusters have some limitations. The power of a thruster is up to 6–7 MW. Also counter rotating is limited because they are designed and optimized for unidirectional rotation. [3]

The azimuth thruster contains: 2 gears, sealing unit for prevention water leaking, at least 6 shaft bearings. Such construction is complex, needs good maintenance and gears make noise. In spite of disadvantages azimuth thrusters find application as units for station keeping and maneuvering and nowadays even as main thruster in DE propulsion systems.

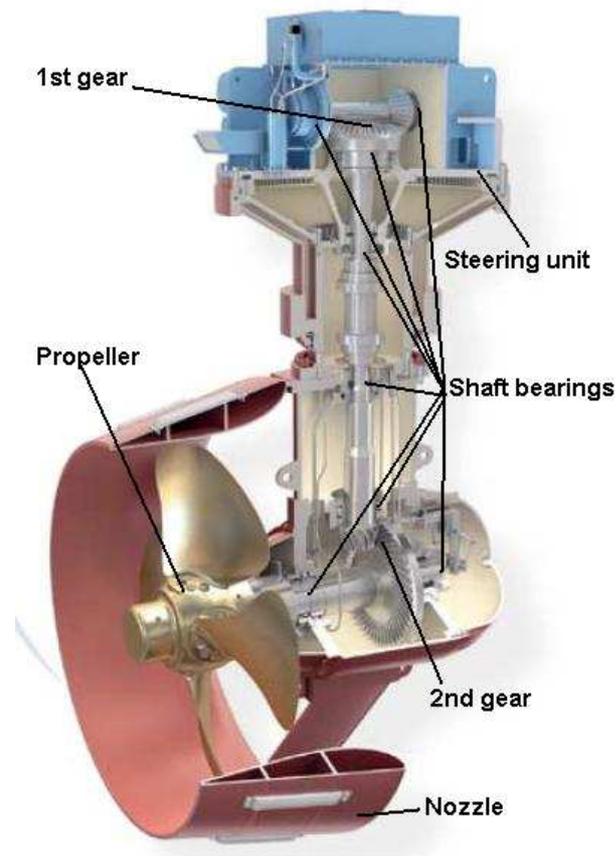


Figure 12 Z-type azimuth thruster. [Rolls-Royce propulsion]

Podded propulsion

Next step toward improving construction, increasing reliability and efficiency is making direct drive for propeller which placed outside of vessel hull. The motor is placed in sealed pod and have the same ability for 360 degree rotation as azimuth thrusters. The direct drive implementing helps to avoid gears and make construction simpler, also absence of the system for pitch control make podded propulsion efficiency higher. Electric energy supply to the motor via flexible cable or slipping rings. Typically, podded propulsion is designed for pulling configuration, but pushing is also possible. Employing pulling type is due to the hydrodynamic science and optimization for increasing efficiency. So, in addition it helps to avoid cavitations phenomena and as the result noise, vibration and fast propeller wearing-out.

Firstly podded propulsion was design for ice-breakers due to requirements of high shaft and propeller torque, but then was implemented for wide range vessel types because of high efficiency and maneuvering ability. Also one more advantage comparing with azimuth thruster, it is available power range from 1 MW and up to 25 MW. The biggest ones have access for maintenance. [3]

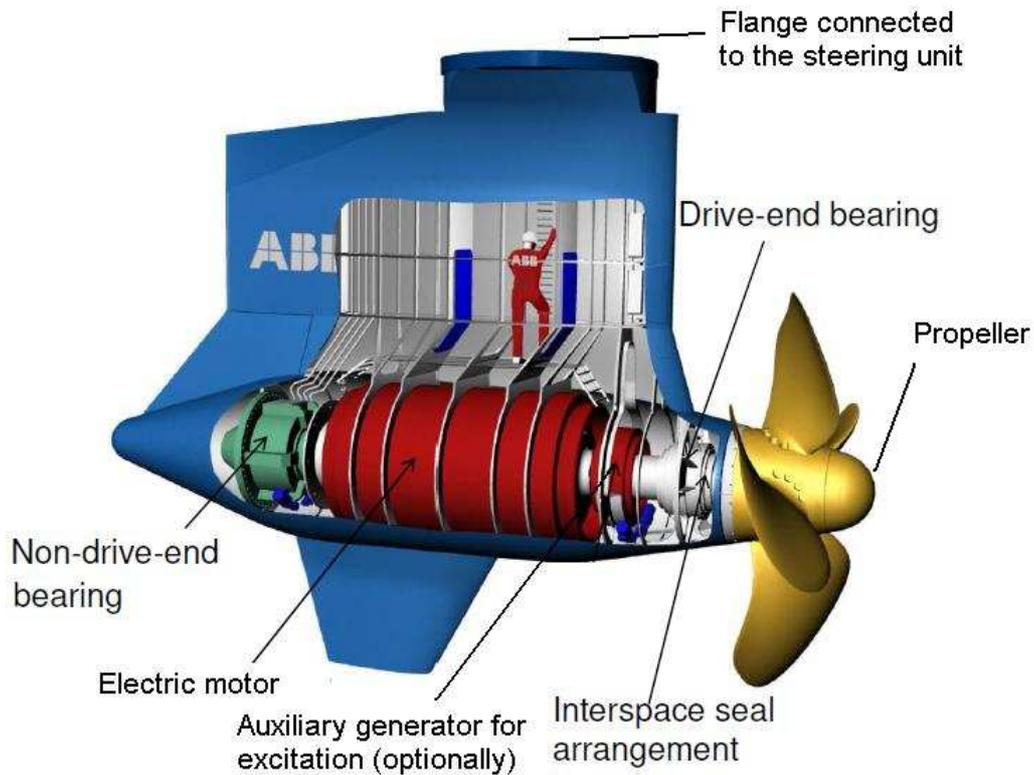


Figure 13 Podded propulsion [7]

Combined thruster

Sometimes, hybrid systems based on the previous propulsion systems appear. It happens because of development simulation applications and opportunity for modeling and optimization. The result of optimization is creation some technical arrangement such as:

- counter rotation propellers CRP (Fig. 14)
- combination of the different propulsion types (shaft propulsion, podded propulsion, azimuth thrusters) (Fig. 15)

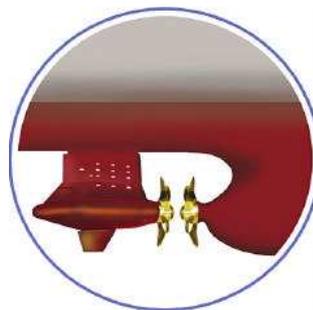


Figure 14 CRP concept [3]

CRP propulsion type significantly improves efficiency due to recovering losses caused by the water rotation created by the primary propeller and because of operation

secondary propeller in wake field area. Also CRPs improve redundancy because of avoiding cavitations [8]

The second combined scheme contains all previous propulsion types. Shaft propulsion- main propulsion unit, podded propulsion units is utilized for pulling and for steering and maneuvering and the last one- azimuth thrusters for maneuvering.

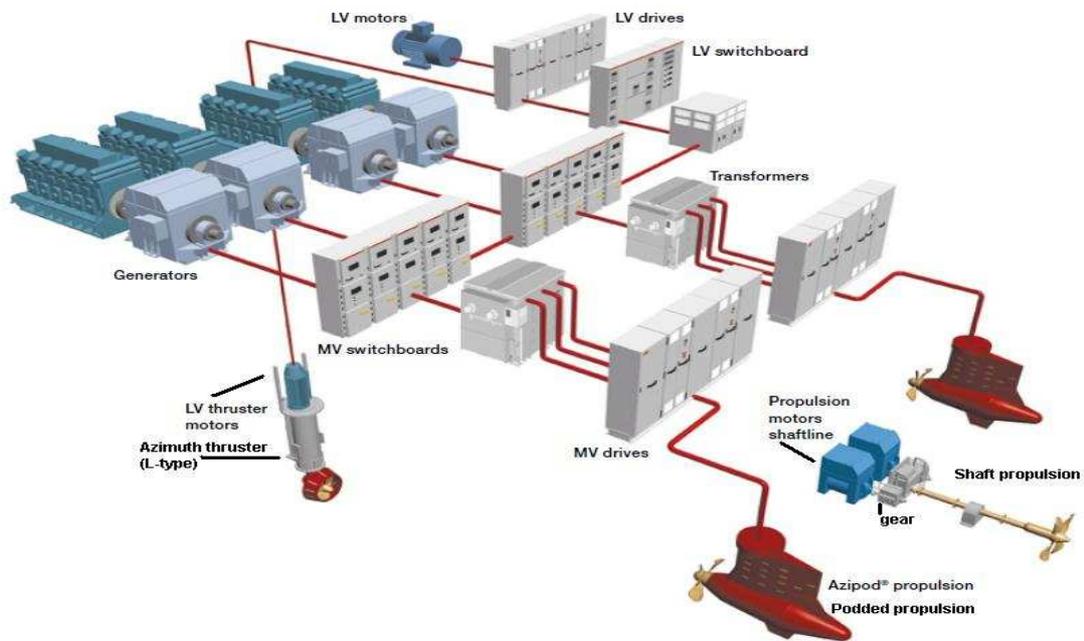


Figure 15 Combined propulsion arrangement

1.6.2 Propulsion drive

The biggest part of generated electric energy is spent for propulsion and the bigger vessel speed is required the bigger energy part is used for feeding the propulsion electric motors. As an example the following electric energy distribution diagram can be shown.

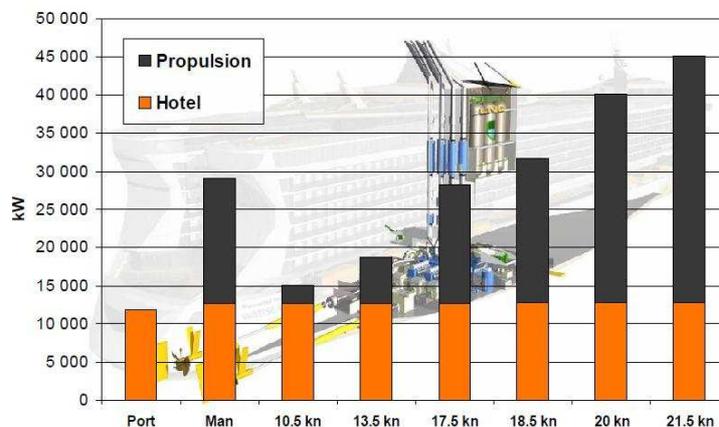


Figure 16 Electric power distribution for a 125000 gt cruise ship with service speed of 21 knots, 47 MW summary propulsion power [9]

The electrical machine types used in propulsion are:

- induction motors;
- synchronous motors;
- permanent magnet synchronous motors.

Induction motor is the most wide spread type of machine which is used in the propulsion drive and moreover for almost all rest applications (air conditioners, fans, water pumps, winches). Such prevalence is due to its simple construction, high reliability and rare need for maintenance, also price is lower compared to other motor types. Induction motor drive suits for application in all propulsion types which were discussed above, but only limitation: in the big power range the price of synchronous motors is more cost-competitive. Synchronous machine is utilized for both drive types: constant speed- direct-on-line and variable speed coupled with frequency converter.

Synchronous machine as a propulsion drive in the most cases not in use. The exception is high power range- more than 5 MW (direct shaft propulsion) and more than 8-10 for motor coupled with gear also is applied for podded propulsion. In the less power range induction motors are most attractive. Synchronous motors find their implementation in the high power and torque demands. Design principles hardly differ from typical synchronous machine design, but there are some especial arrangements for adapting motor for marine application. Marine operation features require choosing and keeping necessary speed and as the result all electric machine is equipped by variable frequency converter.

Permanent magnet synchronous motors apply because of the benefits:

- high efficiency;
- high reliability (on the induction motor level);
- more compact size (important for podded propulsion).

It is used for propulsion in the power range from a few kilowatts up to several Megawatts. Development of permanent magnet material technology allows implementing stronger magnets and make the end price lower (make product cost competitive), it leads to widest and more frequent permanent magnet synchronous machine application.

2 Basic power system concepts

All the elements which were discussed above constitute the whole EP system. There are some variants of possible system realization. Each of the arrangements has its own benefits as well as disadvantages and it is designed for operation in the predefined conditions for specified type of vessel. The reason for researching in this area is requirements for vessels which should provide wide power range and operation modes. So for a yacht the power system structure is much different as for a bulk carrier or a high speed cruise liner one. The differences concern a number of the parameters such as efficiency (fuel consumption per unit of mechanical energy), maneuverability, vessel speed, deck-hotel energy consumption. In addition if the power required for the vessel is high (more than 50 MW) there are probably no alternatives and it is the reason for implementation high power ship delivering system (medium voltage 1 - 15 kV generators, medium voltage delivery, transformers distributed everywhere for supplying low voltage consumers). Also, in spite of the same equipment in the different schemes, the each element has the list requirements which should be satisfied to have possibility for implementing in such power system or has to be design for it. Within the framework of the thesis topic the most important elements in these schemes, are generators. For the generators in the systems it is necessary to find out the next points: freedom in design and implementation, limitations and boundary conditions.

At this chapter five principled circuit diagrams are examined, they are:

- Fixed frequency and voltage AC system (typical diesel-electric power-line nowadays);
- Fixed frequency and voltage AC system, LLC construction;
- Full power converter AC system;
- DC system;
- Variable frequency AC system.

For understanding requirements basic power system concepts will be described.

2.1 Fixed frequency and voltage AC system (typical diesel-electric power-line nowadays)

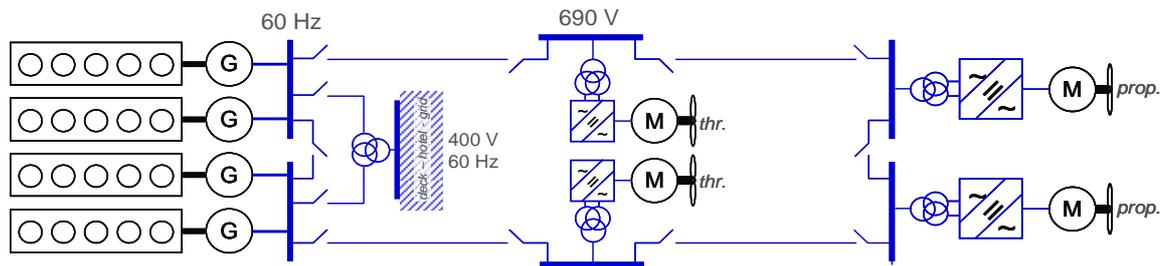


Figure 17 Fixed frequency and voltage AC system

All the schemes of this type contain at least two diesel engines and generators. The maximum number can be derived for each case separately. This number is a function of reliability, efficiency, weight and dimensions and price. Increasing the number of gensets significantly increases reliability and redundancy, decreases may slightly the efficiency per genset, but due to better power management summary the overall efficiency increases, increases weight and obviously increases the price due to more work and material required. So, the number of genset is in the middle point between these criteria.

As it was noticed earlier the designing principles and the types of implemented equipment depend on the vessel type and as the result on the power level of the system. So, using the fixed frequency and voltage AC system concept for a 100 MW ship leads to switching from the low voltage to the medium voltage system for avoiding significant currents increase. But it requires some actions and arrangements for providing safe operation and maintenance. The challenge of this task is the fact that all the electric equipment is placed in a small area. An additional insulation improvement is required. Medium voltage arrangement includes voltage range from 1 up to 15 kV (1–60 MVA). In such a power level there are not many variants for choosing of the generator type. In almost all cases it is a medium voltage synchronous generator which is equipped with damper winding for preventing torque pulsations and unstable states. There is not much freedom for designing such a system.

In the case of lower power demands, for example 10 MW, there is much more freedom for the power supplier designing. Coming to this power level it is possible to operate with a low voltage system. At least part of the system can be operated at low voltage (< 1 kV AC). Delivering system can be made by using standard industry

delivering components designed for the voltage range up to 690 V. In such an arrangement transformers and converters are also required but obviously differences between primary voltage and secondary are much lower and as the result mass, size and price of equipment are lower.

2.2 Fixed frequency and voltage AC system, LLC construction

The low loss concept was designed and patented by Wärtsilä. The main idea of implementing such a system is reducing and eliminating losses for energy transformations. Comparing with the first arrangement the second one (See Fig.18) does not have any transformers except common 30 degrees phase shifting transformer. This device is used for eliminating and cancelling the highest current harmonic components which usually are induced by the rectifying bridges of the frequency converters. In comparing with the previous scheme, the total harmonic distortion is better and less than 5%.

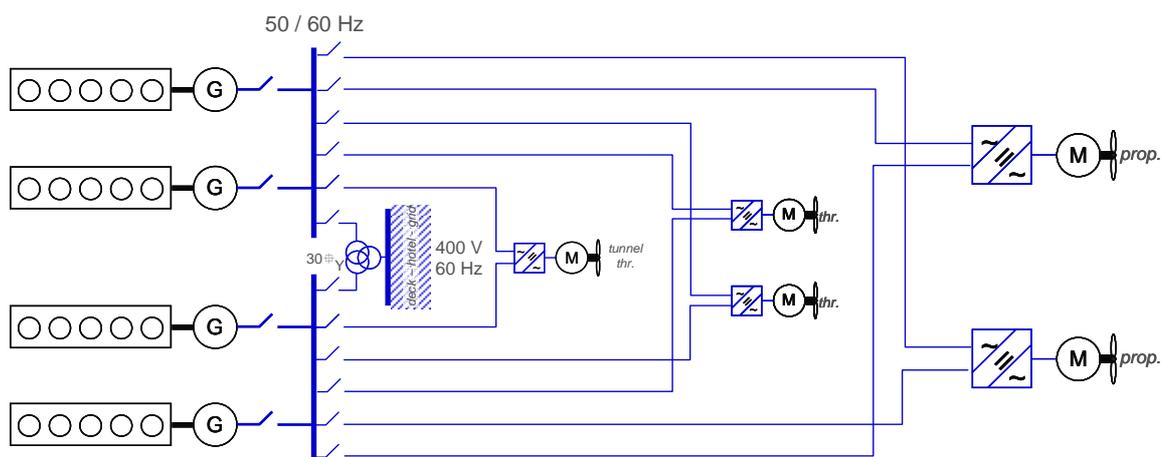


Figure 18 Fixed frequency and voltage AC system, LLC construction

Also excluding additional transformers leads to significantly reduced mass and volume. This fact is very important in case of small vessels' building, where the question of space and mass is one of the main ones. Speaking about the generator designing freedoms it is worth noticing that the fact of transformers lack requires either low voltage generators and distribution system or powerful full power converters with embedded VSRs (voltage source rectifiers) which are capable to keep output voltage on the rated level.

The power range covered by LLC is from 5 MW up to 70 MW. The main challenge in the power propulsion design is matching system parameters and

operational requirements (profile). This requirement directed to optimize available power, required power and time of idling or partial duty. The well fitted system allows reaching up to 10 % fuel economy. Also in case of the proper applications the mass of the power system may be reduced up to 35 % – 40 % compared to the typical diesel-electric power system [11].

But in the same time there are disadvantages of the LLC EP system. All the generators work for the common bus. There is no dependence between the prime mover speed and the power demands. Even if consumers require 20 % of the rated power, the generator should be rotated at the rated speed. This objective comes from the consumer's requirement for keeping voltage and frequency constant. The prime mover is operated out of the optimal work region and consumes much more fuel (the consumption reaches the level about 300 % comparing with optimal operational area when the output energy reduces only for approximately 30 %). This fact takes place not only for the LLC concept but also for the typical DE propulsion system. For more detailed description, please see the fuel consumption analysis part.

Also, except energy losses for keeping the rated frequency and voltage, gensets require precise controlling of the fuel consumption for providing the constant rotational speed and as the result frequency. The auxiliary system for speed control is shown in the Fig. 19. This requirement comes from hotel and deck grid equipment. There are a lot of electrical devices which are sensitive for input signal. These equipments also include navigation ware, radio link, azimuth thruster control unit and other devices in the captain's bridge.[11]

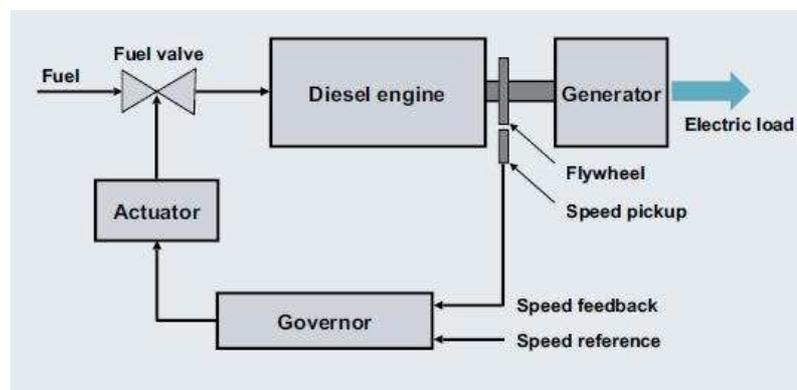


Figure 19 The governor principle in the speed control loop of a diesel engine.[11]

2.3 Full power converter AC system and DC system

The previous two concepts are widely used nowadays and suitable generally for high power ships, such as heavy container ships or cruise vessels. The most effective application they find in the power range about 100 MW. But at present new power system concepts try to find application and generally in the lower power range (about 10 MW). Such concepts are full power converter AC system and DC system (Fig. 20, Fig. 21). These two power systems include the best arrangements taken from the LLC power system. The main advantage of which is eliminating additional energy transformations or at least significant reducing the number of the transformers, comparing with typical DE power system. It allows getting benefits in the system mass, dimensions, cost and efficiency.

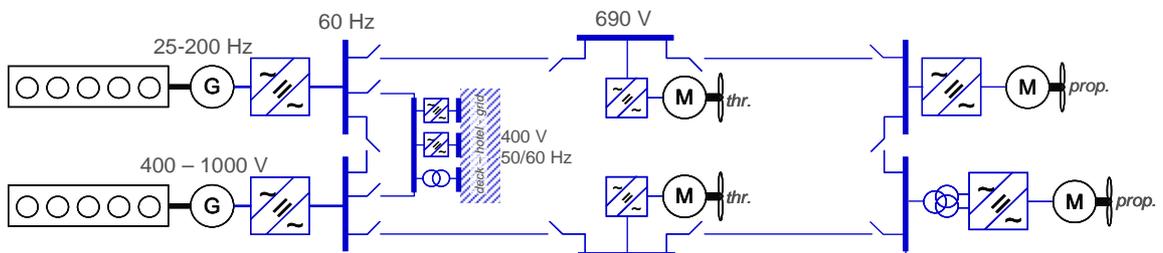


Figure 20 Full power converter AC system concept

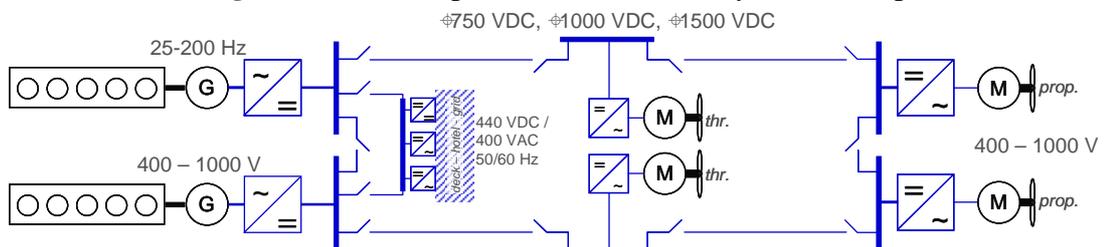


Figure 21 DC system concept

In general from the generator view point these systems are similar. They give a lot of freedom for the generator parameters design since there is no importance to keep certain frequency and there is no point in keeping rated voltage on the generator terminals. It gets possible to avoid frequency controlling since in the schemes the frequency converters are employed. In the first concept there are two AC-DC-AC converters and in the second AC-DC converters are used. In full power converters step-up functionality is inherently embedded to keep constant DC or AC voltage on the terminals. These facts distinguish these two concepts from LLC and gives wide freedom in the generator design and fuel consumption benefit.

Designing freedoms

Since it is not necessary to control the frequency on the terminals it is possible to apply different generators:

- asynchronous (cheap, but slightly lower efficiency, low $\cos\varphi$, heavy)
- synchronous (more expensive than IG, has lower efficiency than PMSG)
- permanent magnet synchronous (high efficiency (up to 98%), high $\cos\varphi$, expensive)

Also designing of the generator for the higher frequency makes such concepts more attractive. Increasing frequency leads to significant reducing in the generator mass and dimensions when the power remains the same. If there are transformers in the circuit their dimensions are reduced too if higher frequencies than normally are used. The SG and PMSG if they are implemented in such schemes do not have to contain damper windings in the rotor, due to the fact of working for rectifiers or full power converters. It means that there is no torque pulsation and as the result there is no energy dissipation in the damper winding, it allows saving some more energy.

Fuel consumption

For analyzing fuel consumption it is worth to look at the diesel engine power curve. Figure12 is the energy efficiency estimating curve for 2 MW diesel engines. The weakest point of LLC is the fact that a diesel should work in rated speed even in the case of low load. In the power curve there are closed equal consumption lines- areas with the same specific fuel consumption. 100 % is used for the most efficient mode and in this area ratio watt-hour per gram is highest, typically in the range of 200g/kWh. From the figure it can be seen that for keeping the highest power per consumption ratio (to stay in 100 % loop) it is worth to reduce the crankshaft speed, but not just reduced power taken from generator (that is equal going straight down). Judging by the curve it is clear that full power converter AC system and DC system have significantly bigger efficiency in the partially loaded modes. Even losses for converting from AC to DC and back are less than the estimated efficiency increase. For example, when generating 1.3MW with reduced speed (825 rpm) the specific fuel consumption increases from 100 % to 115 %, but in case of typical DE propulsion or LLC EP system is the specific consumption can reach e.g. 155 % at 900 rpm constant speed operation.

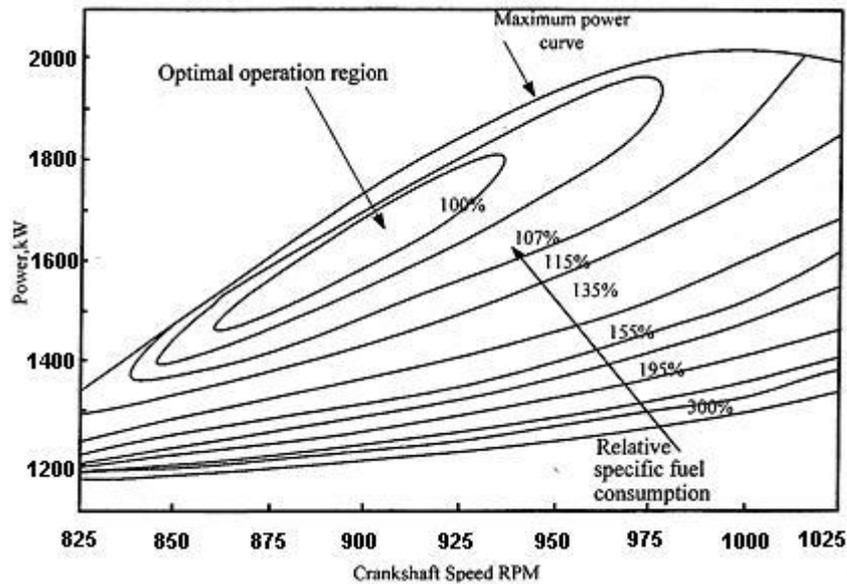


Figure 22 Approximated power curve for diesel engine. [12]

As it was noticed above these concepts are the same from the generator point of view but judging by efficiency they are different. The main difference is an extra power conversion in full power converter AC system; It does not look necessary (clever) to apply 8 extra conversions and 2 additional transformers. From the efficiency point of view the DC concept looks much more attractive. But it is worth keeping in mind, that the high efficiency cannot be achieved without high level power management.

2.4 Variable frequency AC system

This concept is a modification of the full power converter system. The FPC (full power converter) concept was improved by the elimination of the part of the power converters. Such a configuration might have even higher efficiency than the DC system concept, but has significant disadvantages. This arrangement allows avoiding at least half of the propulsion losses but requires additional special electrical equipment.

The generator for the variable frequency AC system should be equipped with a damper winding for preventing torque pulsation on the shaft. The damper winding in the combination with torque pulsation causes additional losses, which can not be taken into account in the efficiency estimation. Also there is problem with changing the system frequency. By using the generator without converter it is easy to change frequency and as result rotational speed of propulsion drive. But when the other generator, connected in parallel, is switched on it can cause problems with the

frequency synchronization of the 1st generator and the frequency on the terminals of the second generator's inverter. Also not only frequency should be adjusted, but there is requirement of the precise synchronization of the voltage from the different power sources. It is necessary for avoiding overloads of one of the generators. And of course smart power management is mandatory.

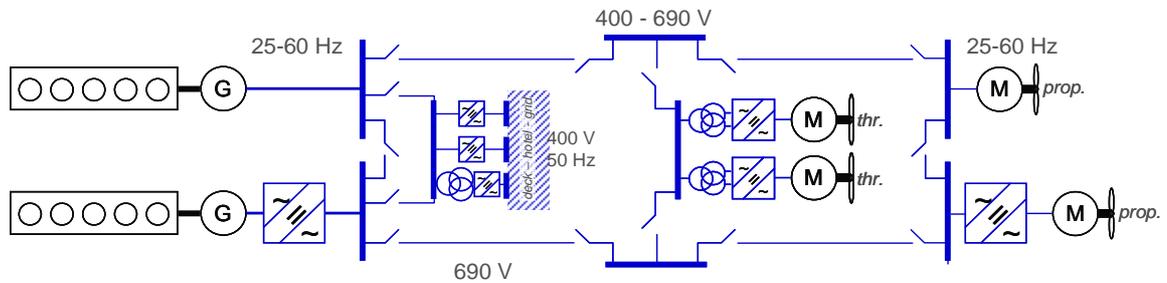


Figure 23 Variable frequency AC system concept

The requirements listed above cause to significant sophistication of the system. And as the result it influences the reliability, troubleshooting, period and complexity of the maintenance.

An optimal generator for this power system is low voltage synchronous generator with damper winding. As a variant IG can be implemented but all the benefits connected with increasing efficiency will be eliminated and on the output there will be complex, unreliable power system with low efficiency.

2.5 Concepts comparison.

For proving the information and the description of the propulsion system concepts provided above it is necessary to make a comparison which should includes different parameters such as mass, volume, efficiency. Unfortunately the prices comparison cannot be provided in the framework of this thesis due to the fact that the price is a function of the big list parameters and cannot be estimated.

For being correct in the comparison of the power system concepts it is necessary to select the power range. As was noticed early the first two concepts are optimal for the high power systems, but they might be implemented for the medium and low power vessels, when the rest of the concepts are designed generally for low and medium power. Consequently for having possibility to compare concepts a 6 MW ship power

plant was chosen. As the example of the implementation such a plant Nor Valiant ship (Fig. 24) was taken.



Figure 24 Nor Valiant ship, the base for the concept comparison [13]

Nor Valiant is the vessel for providing a wide range of the subsea support work for ROVs (underwater remote operated vehicle) and for a semisubmersible drilling platform service. This ship was taken for analyzing according to the chosen power level and the operational modes. Nor Valiant has the system of dynamic positioning and significant part of the time is spent for such operations. That is why the benefits of using EP system are predictive.

Nor Valiant was built in 2008 by PT Jaya Asiatic Shipyard. She is equipped with two Wärtsilä diesel engines of 2 MW each which are the drives for the Z-type azimuth thrusters. Table 2 contains the main parameters of the ship. The main deck is 700 m² which provides enough space for ROVs and equipment safe keeping and usage. Nor Valiant is fitted with a helicopter deck for small and medium size helicopters for personnel transporting and evacuation. [14]

For detailed ship configuration and space arrangement see the Appendix 1.

Initially the requirement of the generation power was selected equal to 6MW. In spite of changing propulsion system from the mechanical to electrical, the power of each engine was saved on the level of 2 MW. But it was decided to install 3 gensets in spite of 2 diesel engines, with the auxiliary generators removal.

Table 2 Main characteristics of Nor Valiant [14]

Name	Nor Valiant
Type	Subsea Operation Vessel
Owner	NOR Offshore
Shipyard	PT Jaya Asiatic Shipyard
Delivered	2008
Ship characteristics	
Tonnage	3111 dwt
Length overall	78.00 m
Breadth	20.40 m
Service speed	11.50 knots
Propulsion system	
Main engines	2 × 2040 kW, 1000 rpm Wärtsilä 6L26A
Propulsion type	Direct diesel drive in combination with Z-type azimuth thrusters
Main generators	3 × 500 kW, 1800 rpm Caterpillar 3412 440V / 3 Ph / 60 Hz
Emergency generator	1 × 58 kW, 1800 rpm Caterpillar C4.4, 440V / 3 Ph / 60 Hz
Shaft alternator	2 × 1600 kW, 1800 rpm at 440V / 3 Ph / 60 Hz
Bow thruster	2 × 600 kW Electric-driven Wärtsilä LIP tunnel type (CPP)
Steering gear	ASD
Propulsion	2 × ASD, CPP with nozzles, Wärtsilä Lips
Rudders	ASD
Type of fuel	Marine Gas Oil
Fuel consumption	25 m ³ /24 hours at max speed (12 knots) 16 m ³ /24 hours at eco speed (9 knots)

The power level of the thruster was saved but azimuth thrusters were replaced with 2 podded thrusters Azipods CO supplied by ABB 2.3 MW each. The bow thrusters were left without changing. Since this vessel was built for the subsea support work, the main operational task is the power supply of the hotel-deck and partly is keeping the position. There are possibilities for utilization almost all energy for the operational purposes. 5 MW of the electric energy can be supply to the hotel-deck grid. For meeting this requirement it is necessary to increase the power of supplied transformers or inverters depending on the concept.

All the information concerning the required electrical equipment which was necessary for comparison is in the Table 3 and Table 4. The data for the concept comparison have been obtained from the suppliers of the power equipment (in such cases it is reflected on the tables or bellow them) or on the base of analyzing market and selecting average values.

Table 3 Power system concept comparison¹ (first part):

Power system concept Units: quantity (mass)	Fixed frequency and voltage AC system, typical DE propulsion (Fig. 17)				Fixed frequency and voltage AC system, LLC construction (Fig. 18)			
	quantity, type	mass, kg	dimensions, m	efficiency,%	quantity, type	mass, kg	dimensions, m	efficiency,%
Prime movers	3 × 2040 kW, Wärtsilä 6L26A	18100	4.2×1.9×2.0	46?	3 × 2040 kW, Wärtsilä 6L26A	18100	4.2×1.9×2.0	46?
Generators	3 × SG	7200	n/a	95	3 × SG	8100	n/a	95
Propulsion motors	2 × AZIPOD (2300 kW)	27000	4.8×5.7×2.6	94	2 × AZIPOD (2300 kW)	27000	4.8×5.7×2.6	94
Drives transformers	2 × 400V/6kV ⁵ (2500 kVA)	5500	2.6×1.6×2.4	99.3	no			
Main stream converters	2 × AC/DC/AC ² (2300 kW)	4780	5.3×0.7×2.3	95.3	2 × AC/DC/AC ² (2300 kW)	4780	5.3×0.7×2.3	95.3
Main stream rectifiers	no				no			
Bow thrusters	2 × 600 kW Wärtsilä	no data			2 × 600 kW Wärtsilä	no data		
Bow thruster converters	2 × AC/DC/AC ³ (900kW)	2000	2.4×0.6×2.4	94.8	2 × AC/DC/AC ³ (900kW)	2000	2.4×0.6×2.4	94.8
Bow thruster transformers	2 × 400V/6kV ⁴	2180	2.0×1.3×2.0	99.1	no			
Hotel, deck transformers	2 × 400V/6kV ⁵	5500	2.6×1.6×2.4	99.3	400V/690V ⁵	2500	1.5×0.6×2.4	99.3
Auxiliary, hotel converters	no				no			
Summary		169820	V= 276.5 m ³			154160	V= 258,3 m3	

Table 4 Power system concept comparison¹ (second part):

Power system concept Units: quantity (mass)	Full power converter AC system (Fig. 20)				DC system (Fig. 21)				Variable frequency AC system (Fig. 23)			
	quantity, type	mass, kg	dimensions, m	η ,%	quantity, type	mass, kg	dimensions, m	η ,%	quantity, type	mass, kg	dimensions, m	η ,%
Prime movers	3 × 2040 kW, Wärtsilä 6L26A	18100	4.2x1.9x2.0	46	3 × 2040 kW, Wärtsilä 6L26A	18100	4.2x1.9x2.0	46?	3 × 2040 kW, Wärtsilä 6L26A	18100	4.2x1.9x2.0	46?
Generators	3xPMSG ^b	7500	2.4x1.4x1.2	97	3xPMSG ^b	7500	2.4x1.4x1.2	97	3xPMSG ^b	7500	2.4x1.4x1.2	97
Propulsion motors	2 x AZIPOD (2300 kW)	27000	4.8x5.7x2.6	94	2 x AZIPOD (2300 kW)	27000	4.8x5.7x2.6	94	2 x AZIPOD (2300 kW)	27000	4.8x5.7x2.6	94
Drives transformers	no				no				no			
Main stream converters	4 x AC/DC/AC ² (2300 kW)	4780	5.3x0.7x2.3	95.3	2 x DC/AC ⁶ (2300kW)	2500	3.5x0.6x2.1	97.6	2 x AC/DC/AC ² (2300 kW)	4780	5.3x0.7x2.3	95.3
Main stream rectifiers	no				2 x AC/DC ⁶ (2030kW)	1800	3.5x0.6x2.1	97.7	no			
Bow thrusters	2 x 600 kW Wärtsilä	no data			2 x 600 kW Wärtsilä	no data			2 x 600 kW Wärtsilä	no data		
Bow thruster converters	2 x AC/DC/AC ³ (900kW)	2000	2.4x0.6x2.4	94.8	2 x DC/AC ⁶ (600kW)	1000	1.5x0.6x2.4	96.5	2 x AC/DC/AC ³ (900kW)	2000	2.4x0.6x2.4	94.8
Bow thruster transformers	no				no				no			
hotel, deck transformers	no				no				no			
Auxiliary, hotel converters	2 x AC/DC/AC ² (2300kW)	4780	5.3x0.7x2.3	95.3	2 x DC/AC ⁶ (2030kW)	2500	1.5x0.6x2.4	97.6	2 x AC/DC/AC ² (2300kW)	4780	5.3x0.7x2.3	95.3
Summary		163480	V = 251.8 m ³			146400	V = 226.4 m ³			153920	V = 234.8m ³	

Table notes:

- 1 All the data provided in the table may be found either on official web sites (in case when make is indicated) or in the internet as the average values for the equipment;
- 2 ACS800-37 inverter(2300kW) powered by ABB;
- 3 ACS 800-37 inverter (900kW) powered by ABB;
- 4 $2 \times 400\text{V}/6\text{kV}$ (630 kVA) TC3ГЛ-630;
- 5 $2 \times 400\text{V}/6\text{kV}$ (2500 kVA) TC3ГЛ-2500;
- 6 Average data.

The results for comparison were obtained on the base of study of the electrical propulsion concepts and also an electrical equipment market. Using Fig. 25 and Fig. 26 it is possible estimate benefits and disadvantages each of the EP systems in the mass and volume criteria.

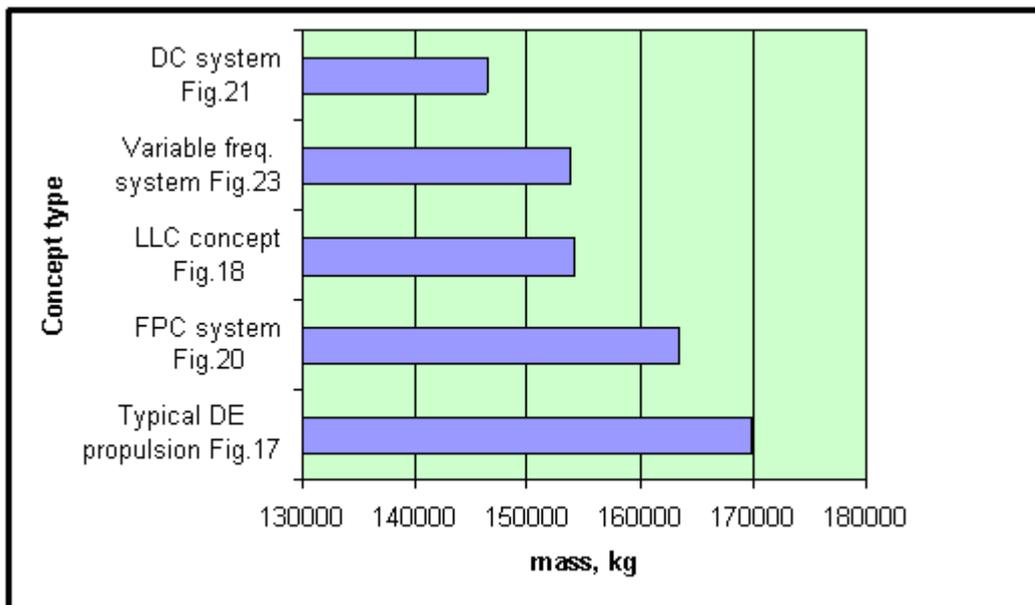


Figure 25 The results of the electrical equipment mass.

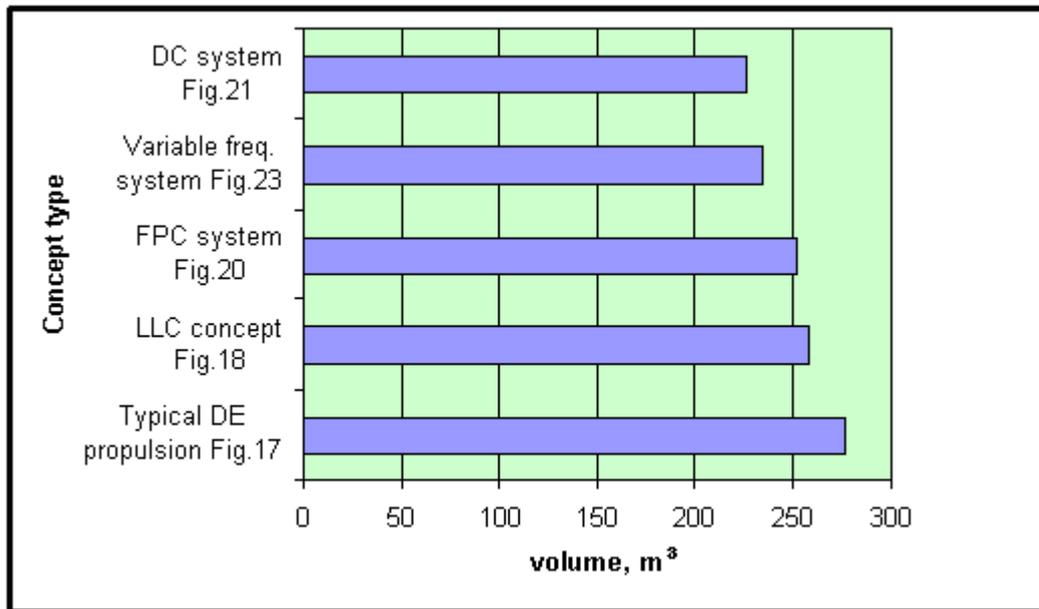


Figure 26 The results of the electrical equipment volumes.

It must be noticed that DC system is a leader in both of the criteria. And it has significant benefits in comparison with typical DE propulsion. It is almost 25000 kg of the mass and more than 50 m³ of the volume. Even in comparison with the nearest competitor (variable frequency AC system) the benefits are 7500 kg of the mass and 8.5 m³ of the volume.

For comparison of the EP systems efficiencies it is necessary to know the mode of operation and power distribution and how much power supply to each unit. It is worth noticing that efficiencies reflected in Tables 3 and 4 are estimated and generally the highest values which can be achieved gave for rated load. In some cases this requirement can not be met and it cause to mistake. But the mistakes' influence generally for the absolute values and do not spoil relative results.

So it was assumed that ship operated at ahead mode, it means 2 gensets (~4 MW of the power) supply propulsion units, the rest genset generates energy for board grid (~1 MW) and for bow thrusters (~1MW). The power losses were calculated for each concept from the diesel engine crankshafts till the propellers and consumers. Some of the equipment was neglected.

The results obtained after calculation reflected in Table 5 and for convenience on Fig.27

Table 5 Power losses in the different EP systems

Power system concept	W	%
Typical DE propulsion Fig.17	846342	14.1
LLC concept Fig.18	815022	13.6
FPC system Fig.20	939987	15.7
DC system Fig.21	698029	11.6
Variable freq. system Fig.23	536246	8.9

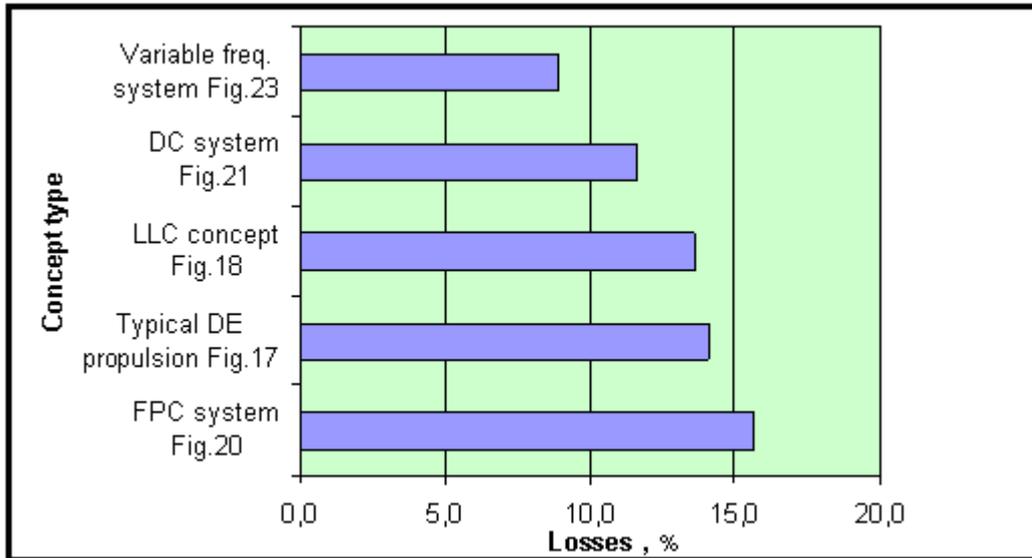


Figure 27 Power losses distribution

Judging by the result the leader of the efficiency is the Variable frequency AC propulsion system, but as was noticed earlier Variable frequency system is very complex one and all the benefits are overlapped by disadvantages of the system. On the base of the three criteria (mass, volume, efficiency) the conclusion can be made that the best and the most suitable propulsion system for Nor Valiant is the DC system.

The DC EP system is 14 % lighter, occupies 18 % less space and is 5 % more efficient compared with typical DE system concept. If we compare with the nearest rival (LLC), the DC system is 7 % lighter, occupies 15 % less space and is 2 % more efficient (not taking into account the variable frequency AC system because of the reason listed above).

3 Design of the generator and result analysis

After estimation of the attractiveness of the propulsion concept DC power system was chosen as the most efficient and suitable for small and medium size ships. As a continuation of the efficiency and mass-volume ratio values improving, two generators for the DC system were designed. Judging by the system requirements and boundary conditions, in DC power system a permanent magnet synchronous generator might be applied. The reasons for implementing are:

- lack of the requirement to keep rated voltage on the terminals
- lack of the requirement to keep rated frequency on the terminals
- lack of the requirement to adjust excitation and $\cos\varphi$

These facts get possible because of the fact that the generator works with a rectifying boost-converter. Also lack of the requirement of keeping rated frequency on the terminals allows us to design a generator with a higher frequency. It helps saving much of steel and space and makes the integration of the generator to the diesel possible.

For analyzing the material, mass, volume and cost savings a two PMSG were designed. Also for having an opportunity to estimate and compare benefits from such an arrangement a typical salient pole synchronous generator was also designed.

Design of the generators can be done by defining and initial certain characteristics, which are:

- Choosing machine type (synchronous, asynchronous, DC, etc.).
- Type of construction (external pole, internal pole, axial flux, radial flux machine, etc.).
- Rated power (for generator active output power)
- Power factor ($\cos\varphi$ for SM)
- Rated rotational speed
- Number of pole pairs or rated frequency
- Rated voltage U_n of the machine
- Number of phases m of the machine.

For the DC power system generators were taken the following requirements:

- Both are synchronous generator (PMSG and SG)
- Rated output power $P_2 = 2000000$ W
- Power factors: 0.95 (PMSG), 0.9 (SG)
- Revolution speed $n = 1000$ rpm
- Rated frequencies: 200 Hz (PMSG), 50 Hz (SG)
- Rated voltage $U_n = 690$

The main points of designing synchronous generators are:

- Checking initial design parameters
- The tangential stress σ_{\tan} determination
- Main dimensions and parameters determination ($V_r, D_r, l, \delta, A, B_\delta$)
- Stator winding and stator configuration design ($q, W_{tp}, Q, a, N, k_w, z_Q$)
- The air-gap flux density updating
- Slot designing
- Magnetic circuit calculation
- Final dimensions determination ($h_{ys}, h_{yr}, h_{PM}, D_{si}, D_{so}$)
- Electric parameters determination (resistances, inductances)
- Masses calculations
- Losses calculations
- Heat removal evaluation
- Efficiency calculation
- Static loadability checking

3.1 Generator comparison

In this table alternative PMSG was added. This generator has equal stator diameter with the salient pole SG. The aim of designing this generator was making slots wider for simplification winding. In spite of the big changes in the geometry the main parameters, volume, mass, cost are almost equal. And all the benefits from the usage second PMSG instead of the first one are the same. That is why analysis and comparison of the generators contain only SG and first PMSG.

The results of the generation design and parameters of the generators see in the Table 6.

Table 6 Parameters of the generators

Generator type	Salient-pole synchronous generator (SG)	1 Permanent magnet synchronous generator (PMSG)	2 Permanent magnet synchronous generator (PMSG) ⁴
Parameters			
Parameters			
Rated output power P , W	2000000	2000000	2000000
Rated voltage U_{ph}/U_l , V	400/691	400/690	400/692
Efficiency, η	95.8	97.54	97.68
Number of phases m	3	3	3
$\cos\phi$	0.9	0.94	0.98
Revolution speed n , rpm	1000	1000	1000
Rated frequency f , Hz	50	200	200
Number of poles	6	24	24
Winding type	Short-pitch double-layer. $q = 4$	Full pitch one-layer. $q = 2$	Full pitch one-layer. $q = 1$
Short pitching	10/12	6/6	3/3
Peak torque per rated torque	1.8	1.8	1.7
a . Number of the parallel branches	3	2	3
σ_{Ftan} . Pa	24200	40400	40400
A . kA/m	38.2	61.2	60.8
J . A/mm ²	5.8	5	5
x_{dpu}	0.81	0.60	0.68
x_{qpu}	0.44	0.6	0.68
r_{apu}	0.00744	0.0072	0.0063
δ_{load} . degree	24.2	32	36.8
T_r . kNm	19.1	19.1	19.1
T_{max} . kNm	33.2	35.9	31.9
T_{max}/T_r ¹	1.7	1.8	1.7
R_a . mOhm	1.59	1.66	1.43
L_d . mH	0.57	0.11	0.12
L_{md} . mH	0.53	0.039	0.043
L_q . mH	0.32	0.11	0.12
L_{mq} . mH	0.28	0.039	0.043
L_{so} . mH	0.04	0.07	0.08
Losses, kW			
Iron	19.0	19.5	16.4
Mechanical	11.2	6.0	7.9
Additional	10	10	10
Stator resistive	24.1	15.0	13.2
Rotor resistive	18.6	no	no
Total	82.9	50.5	47.8
Dimensions			
Shaft height	560	450	560
Stator inner diameter. D_{sj} . mm	730	610	800
Stator outer diameter. D_{so} . mm	990	770	990
Number of stator slots	72	144	72
Length of stator l . mm	1300	940	480
Rotor yoke height. mm	81.7	21.4	27.6
Stator yoke height. mm	86.15	21.4	27.6
Permanent magnet height mm		10.8	13.3
Masses, kg			

Copper	254.5	266.2	255.7
Rotor yoke	608.3	239.2	235.6
Stator yoke	2473.5	320.4	294.7
Total teeth	495.8	462.6	370.4
Permanent magnet	-	105.4	95.88
Excitation winding	208.3	-	-
Pole core	1736	-	-
Rotor hub	-	750	790
The total mass of the active parts	5750	2150	2050
Cost, EURO			
Copper	2420	2530	2430
Rotor yoke	850	500	500
Stator yoke	3450	670	620
Total teeth	700	970	780
Permanent magnet	-	10540	9590
Excitation winding	1980	-	-
Pole core	3300	-	-
Rotor hub	-	630	660
The total mass of the active parts	12700	15200	14600
Alternative cost	14700 ³	9400 ²	9300 ²
Specific parameters			
Power density , MW / m ³	1.2	2.8	2.85
Power density , MW / Ton	0.35	0.93	0.97
Cost per MW , Euro / MW	7350	7600	7300

Table notes:

1. See load curves in the Fig. 27, Fig. 28;
2. alternative magnet was taken into account (quality verification is necessary);
3. excitation system was taken into account
4. In this table alternative PMSG was added. This generator has equal stator diameter with the salient pole SG. The aim of designing this generator was making slots wider for simplification winding. In spite of the big changes in the geometry the main parameters, volume, mass, cost are almost equal. And all the benefits from the usage second PMSG instead of the first one are the same. That is why analysis and comparison of the generators contain only SG and first PMSG.

On the Figs. 28, 29, 30 there load characteristic of the designed generators

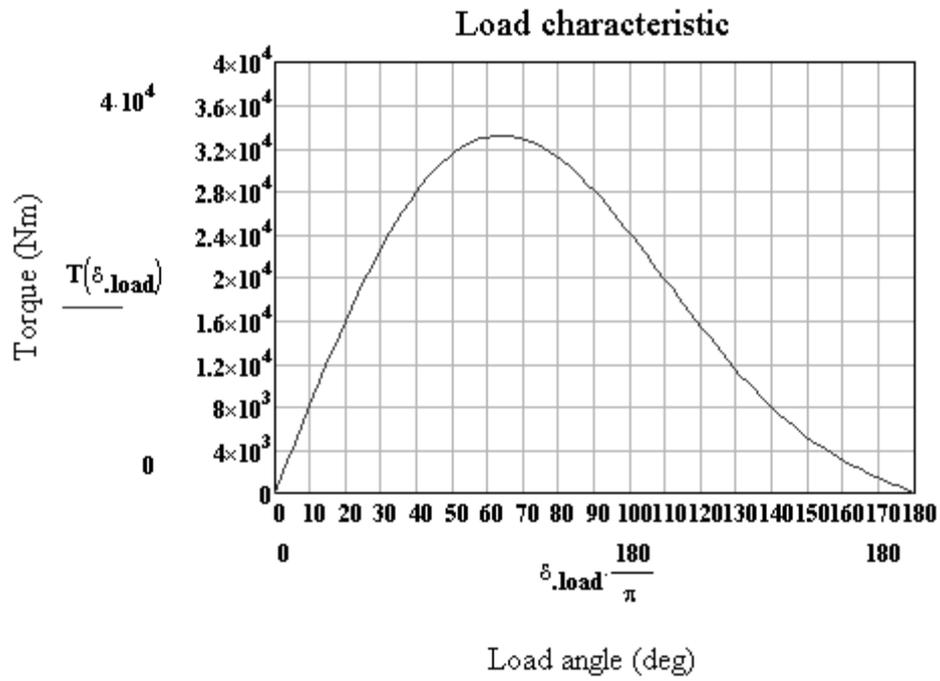


Figure 28 Synchronous generator load characteristic

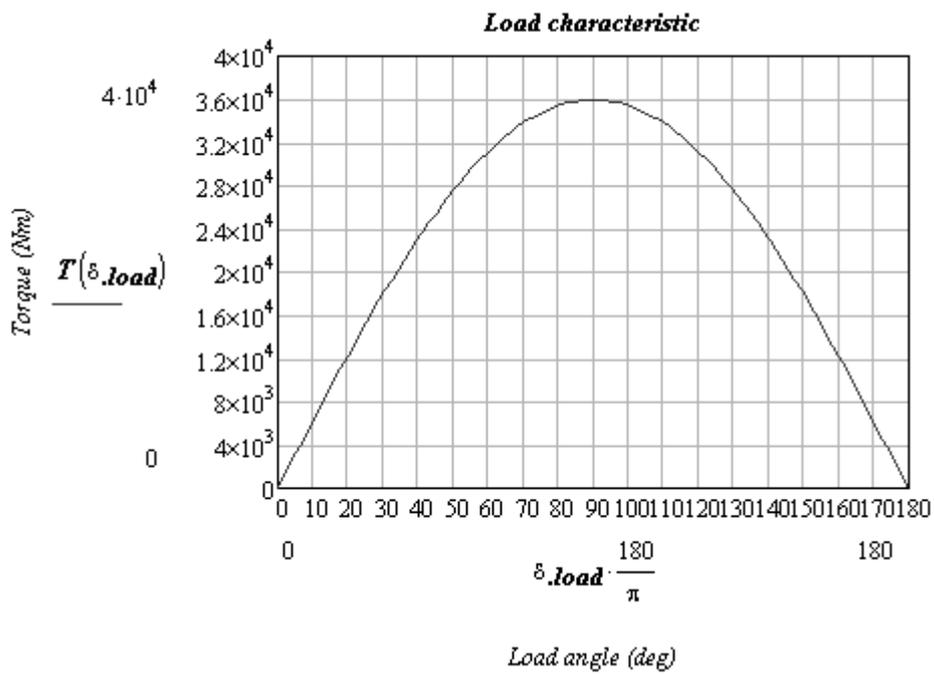


Figure 29 PM synchronous generator load characteristic ($D_s = 610$ mm)

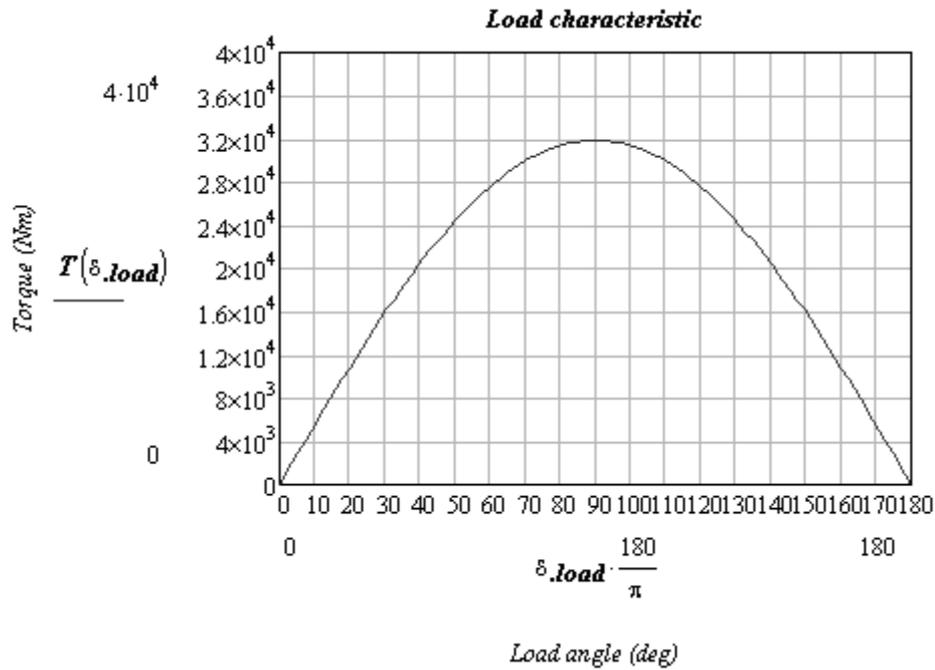


Figure 30 2 PM synchronous generator load characteristic ($D_s = 990$ mm)

Up to date data was used for cost calculation which was obtained from the field-oriented companies. The costs per kg of the material see in the Table 7.

Table 7 Approximate Materials price

Material	Producer	Make	Price, EUR / kg
Electric steel ¹	Surahammars Bruk	M210-27A	2.10
Electric steel ¹	Surahammars Bruk	M235-35A	1.90
Electric steel ¹	Surahammars Bruk	M400-50A	1.40
Electric steel ¹	Surahammars Bruk	M800-50A	1.20
Permanent magnet ²	Neorem	Neorem 793a ³	100-150
Permanent magnet ²	Chinese analogue (alternative design)	n/a	45.00
Copper ⁴	n/a	n/a	9.50
Construction steel ⁴	n/a	n/a	3.00

Table notes:

1. Source: Surahammars Bruk (buying 15-20 tones once)
2. Prices of the permanent magnets are very much variable, they depend on prices for rare-earth metals, shape and mass of the required magnets, volume of supply and others.
3. Such a magnet type was chosen and used
4. This prices are not high quality, they are in share access and were taken in the Internet. May be used only estimation and comparison in the first approach.

On the Figs. 31, 32, 33 all the generators are shown. Drawings were carried out on using original dimensions.

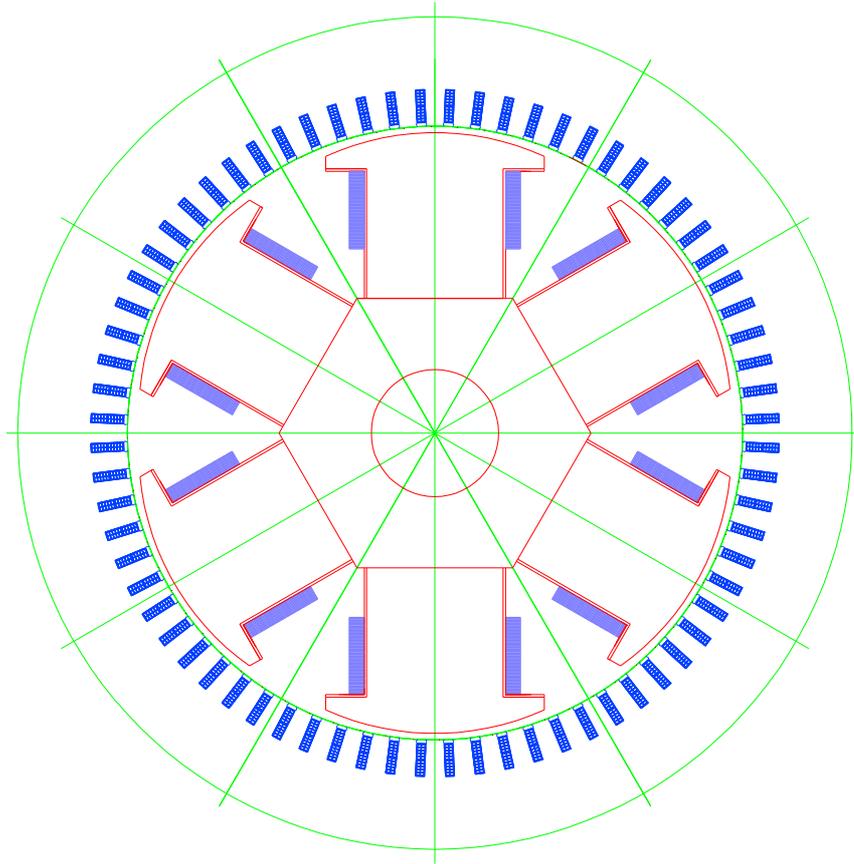


Figure 31 Salient pole synchronous generator drawing, $D_s = 730$ mm

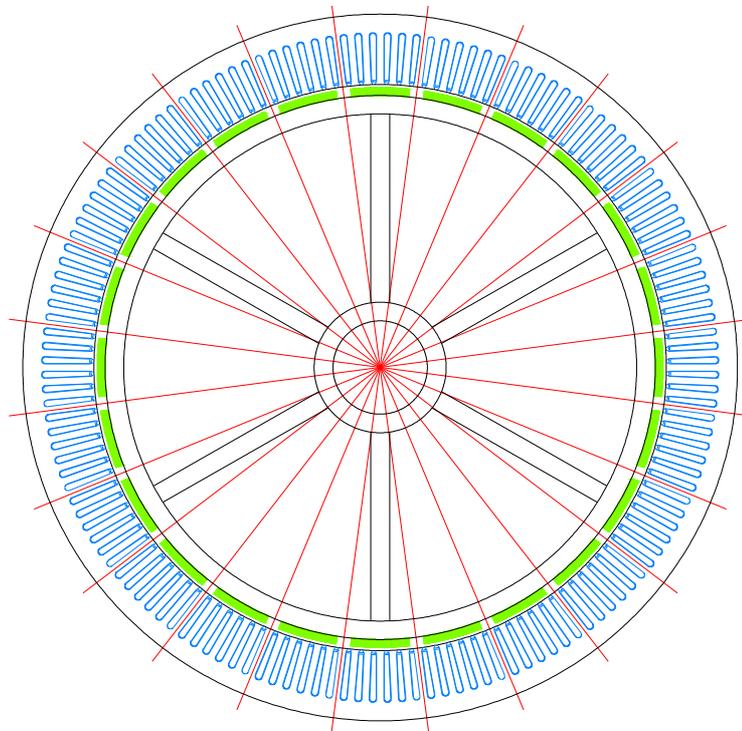


Figure 32 1 PM synchronous generator drawing $D_s = 610$ mm

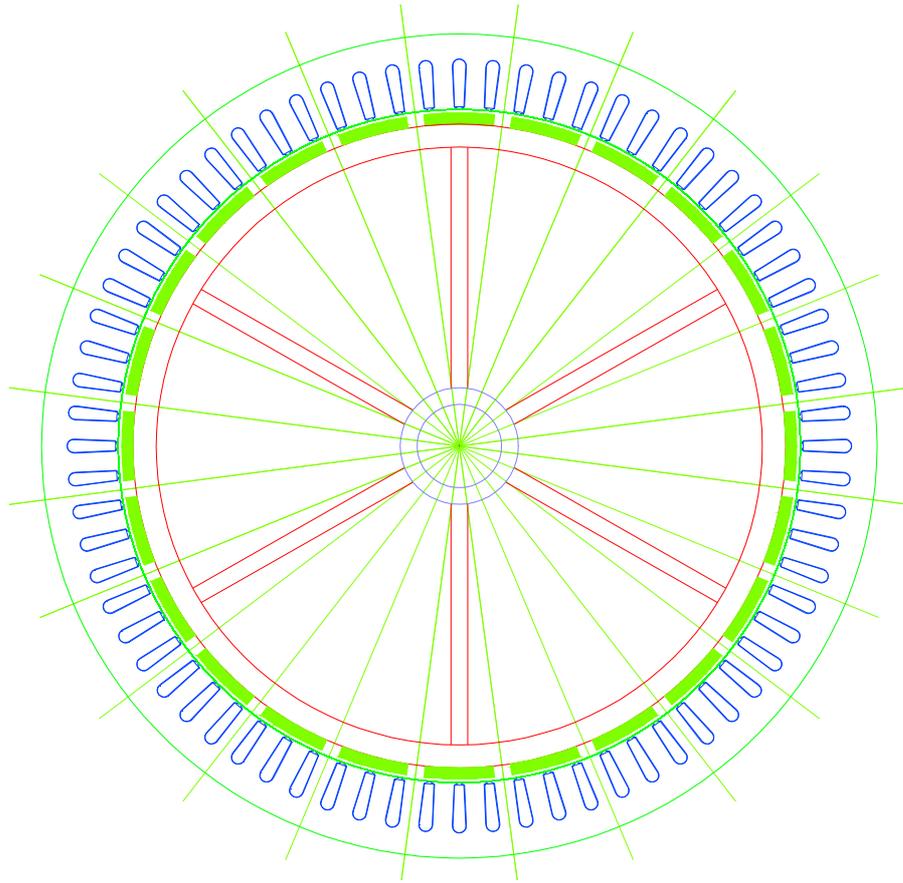


Figure 33 2 PM synchronous generator drawing $D_s = 990$ mm

See, also, the generator drawings in scale of 1:10 in the APPENDIX 2

3.2 Numerical analysis

These two generators were analyzed with the finite element program ELCUT. And the following results were obtained, see Figs. 34 35 and 36. Using ELCUT, flux densities in the air gap, yokes, poles, teeth were obtained. Results of the calculation were proven with allowable mistakes. Simulations correspond to the idling when flux is rated.

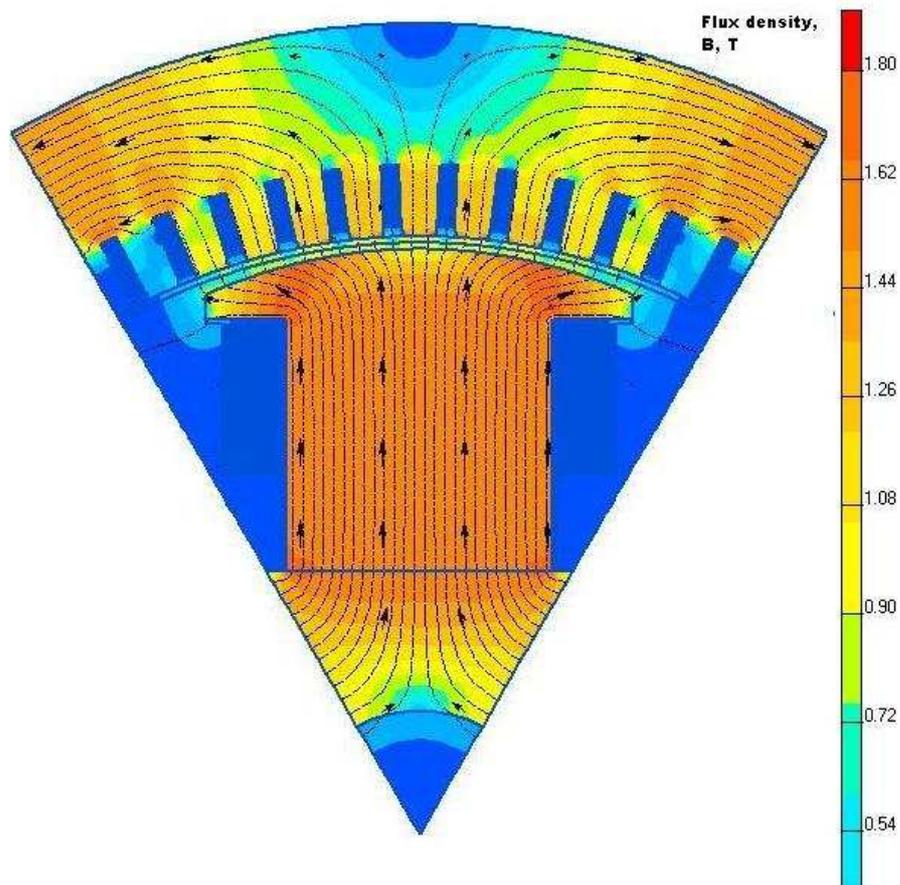


Figure 34 Result of the Salient pole SG simulation in the ELCUT

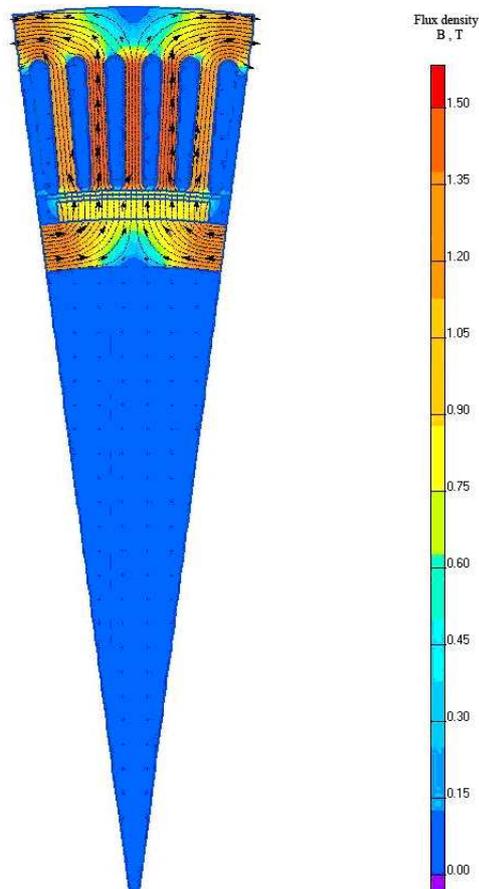


Figure 35 Result of the first PMSG simulation in the ELCUT

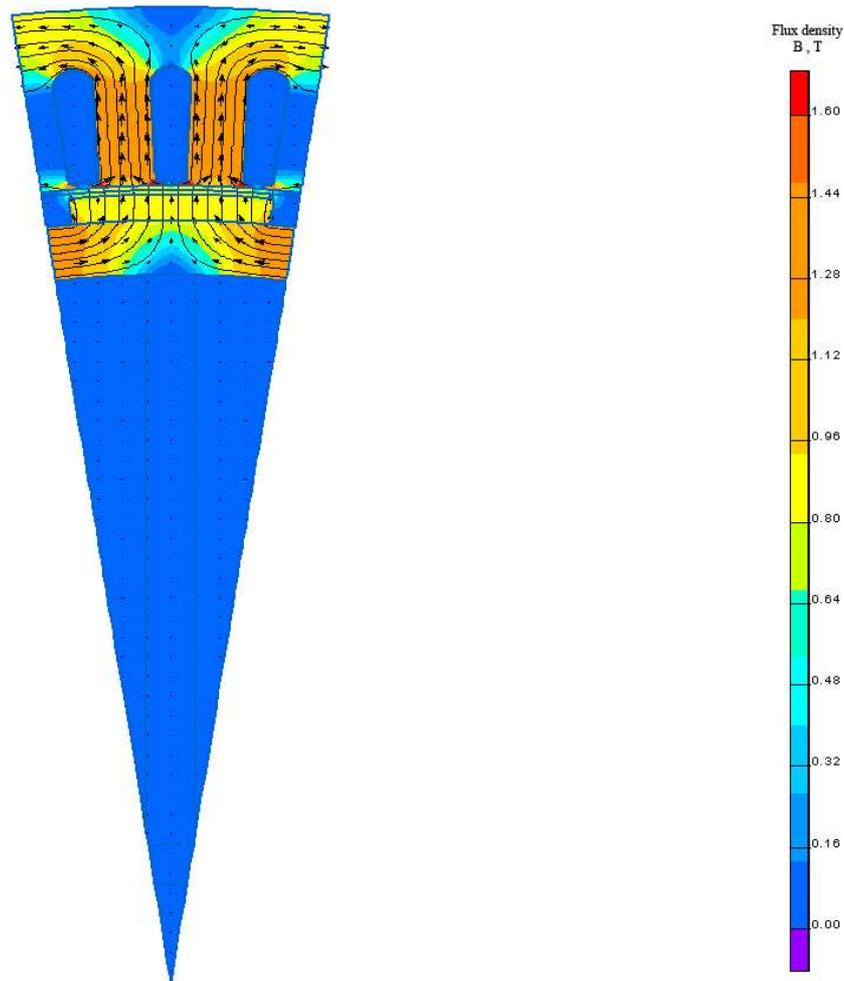


Figure 36 Result of the second PMSG simulation in the ELCUT

3.3 Price analysis

It is worth noticing that the prices obtained as the result of study are the prices for active part materials, when a real price includes: study, tools, materials, staff salary, spent energy, handling and a lot of the additional spending. But in the first approach we can judge by this result and assume that the additional costs are about equal.

Also in the result the excitation system price for the synchronous generator was not included. The necessary power for excitation is 16 kW. Price for such a system were taken 2000 euro (according to the average euro/kW value for electrical machines).

On the base of the previous calculation Fig. 37 – Fig. 41 were made.

In Fig. 37 there is comparison of the PMSG and SG prices in different configuration. The leader of the price is the PMSG in alternative configuration. It means that it is equipped by alternative magnets. The next is the SG, but in such configuration SG can not work because it needs an exciter. Taking into account the exciter price we get the third result. The most expensive is the PMSG with Neorem

magnets. In Euros the difference between the PMSG and SG is about 1000. But anyway this difference is not high compared with the cost of the end product and installation. But the benefit from the increasing of the efficiency is significant.

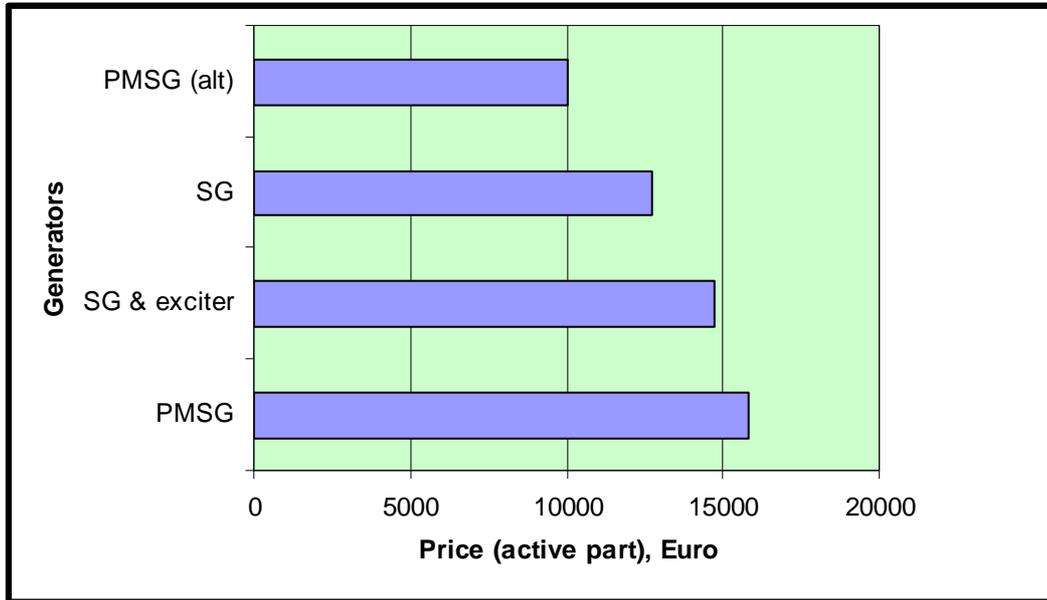


Figure 37 Prices distribution (in euro)

The difference in the rated efficiency is 1.74 %.

Further some estimate calculation for analyze a potential benefit with the improved efficiency

SG:

$$P_2 = 2000000 \text{ W} \times 3 = 6000000 \text{ W}$$

$$\eta_{\text{gen}} = 0.958$$

$$\eta_{\text{diesel}} = 0.45$$

$$t = 24 \text{ hours}$$

$$A_{\text{fuel_SG}} = \frac{P_2 \cdot t}{\eta_{\text{gen}} \cdot \eta_{\text{diesel}}} = \frac{6000000 \cdot 24}{0.958 \cdot 0.45} = 3.34 \cdot 10^8 \text{ W} \cdot \text{h} = 1201543984 \cdot 10^3 \text{ J}$$

$$A_{\text{fuel_SG}} = c_{\text{fuel}} \cdot m_{\text{fuel}}$$

$$c_{\text{diesel}} = 42 \cdot 10^6 \frac{\text{J}}{\text{kg}}$$

$$m_{\text{fuel_SG}} = \frac{A_{\text{fuel_SG}}}{c_{\text{diesel}}} = \frac{1201543984 \cdot 10^3 \text{ J}}{42 \cdot 10^6 \frac{\text{J}}{\text{kg}}} = 28608 \text{ kg}$$

first PMSG:

$$P_2 = 2000000 \text{ W} \times 3 = 6000000 \text{ W}$$

$$\eta_{\text{gen}} = 0.9754$$

$$\eta_{\text{diesel}} = 0.45$$

$$t = 24 \text{ hours}$$

$$A_{\text{fuel_PMSG}} = \frac{P_2 \cdot t}{\eta_{\text{gen}} \cdot \eta_{\text{diesel}}} = \frac{6000000 \cdot 24}{0.9754 \cdot 0.45} = 3.28 \cdot 10^8 \text{ W} \cdot \text{h} = 1180109839 \cdot 10^3 \text{ J}$$

$$A_{\text{fuel_PMSG}} = c_{\text{fuel}} \cdot m_{\text{fuel}}$$

$$c_{\text{diesel}} = 42 \cdot 10^6 \frac{\text{J}}{\text{kg}}$$

$$m_{\text{fuel_PMSG}} = \frac{A_{\text{fuel_PMSG}}}{c_{\text{diesel}}} = \frac{1180109839 \cdot 10^3 \text{ J}}{42 \cdot 10^6 \frac{\text{J}}{\text{kg}}} = 28097 \text{ kg}$$

$$\Delta m = m_{\text{fuel_SG}} - m_{\text{fuel_PMSG}} = 511 \text{ kg}$$

Every 24 hours it helps saving about 510 kg of the fuel at full load. If take fuel price equal 0.5 euro/l, it helps saving 260 Euros per full-operated day. When ship is full loaded for example one thirds of the year the summary economy reaches 31630 euro Also it is worth take into account lower requirements of the PMSG for maintenance because of lack of the exciter.

3.4 Consumption estimation

$$P_2 = 2000000 \text{ W}$$

$$\eta_{\text{gen}} = 0.958$$

$$\eta_{\text{diesel}} = 0.45$$

$$t = 1 \text{ hour}$$

$$A_{\text{fuel_PMSG}} = \frac{P_2 \cdot t}{\eta_{\text{gen}} \cdot \eta_{\text{diesel}}} = \frac{2000000 \cdot 1}{0.958 \cdot 0.45} = 4.64 \cdot 10^6 \text{ W} \cdot \text{h} = 1.67 \cdot 10^{10} \text{ J}$$

$$A_{\text{fuel_PMSG}} = c_{\text{fuel}} \cdot m_{\text{fuel}}$$

$$c_{\text{diesel}} = 42 \cdot 10^6 \frac{\text{J}}{\text{kg}}$$

$$m_{\text{fuel_PMSG}} = \frac{A_{\text{fuel_PMSG}}}{c_{\text{diesel}}} = \frac{1.67 \cdot 10^{10} \text{ J}}{42 \cdot 10^6 \frac{\text{J}}{\text{kg}}} = 398 \text{ kg}$$

$$\text{Consumption} = \frac{m_{\text{fuel_PMSG}}}{P_2} \cdot 10^3 = \frac{398 \text{ kg}}{2000 \text{ kW}} = 0.199 \frac{\text{kg}}{\text{kW}}$$

$$P_2 = 2000000 \text{ W}$$

$$\eta_{\text{gen}} = 0.9754$$

$$\eta_{\text{diesel}} = 0.45$$

$$t = 1 \text{ hour}$$

$$A_{\text{fuel_PMSG}} = \frac{P_2 \cdot t}{\eta_{\text{gen}} \cdot \eta_{\text{diesel}}} = \frac{2000000 \cdot 1}{0.9754 \cdot 0.45} = 4.56 \cdot 10^6 \text{ W} \cdot \text{h} = 1.64 \cdot 10^{10} \text{ J}$$

$$A_{\text{fuel_PMSG}} = c_{\text{fuel}} \cdot m_{\text{fuel}}$$

$$c_{\text{diesel}} = 42 \cdot 10^6 \frac{\text{J}}{\text{kg}}$$

$$m_{\text{fuel_PMSG}} = \frac{A_{\text{fuel_PMSG}}}{c_{\text{diesel}}} = \frac{1.64 \cdot 10^{10} \text{ J}}{42 \cdot 10^6 \frac{\text{J}}{\text{kg}}} = 390 \text{ kg}$$

$$\text{Consumption} = \frac{m_{\text{fuel_PMSG}}}{P_2} \cdot 10^3 = \frac{390 \text{ kg}}{2000 \text{ kW}} = 0.195 \frac{\text{kg}}{\text{kW}}$$

Unfortunately, efficiency and benefits study at partial load can not be done in the frame of this paper because of lack data for the diesel engine. In the Fig. 22 there is load and efficiency curve for the diesel engine. But this curve can be taken only for understanding. Each engine has its own load/efficiency curve. And evaluating efficiency using this figure lead to the significant mistakes, and cannot be taken as the truth.

In the specification for the chosen diesel engine (Wärtsilä 6L26A) there is no such information. And this information is unlikely can be obtained from the official source. But it is obviously that when load is decreasing difference between the SG and PMSG increases because the SG has to be rotated at constant speed when PMSG can be rotated as fast as it is necessary. And according to Fig. 22 the difference between efficiencies can increase in 1.5 times.

3.5 Masses analysis

Judging by the following diagrams the benefits of the PMSG are not only in efficiency, but in mass. Mass is quite important value. The lower mass of the power system more cargo the ship can take.

The mass of the PMSG is about 36 % of the SG with the exciter mass. It is obviously significant benefit of the PMSG which helps decrease mass for more than 50 % (4000 kg)

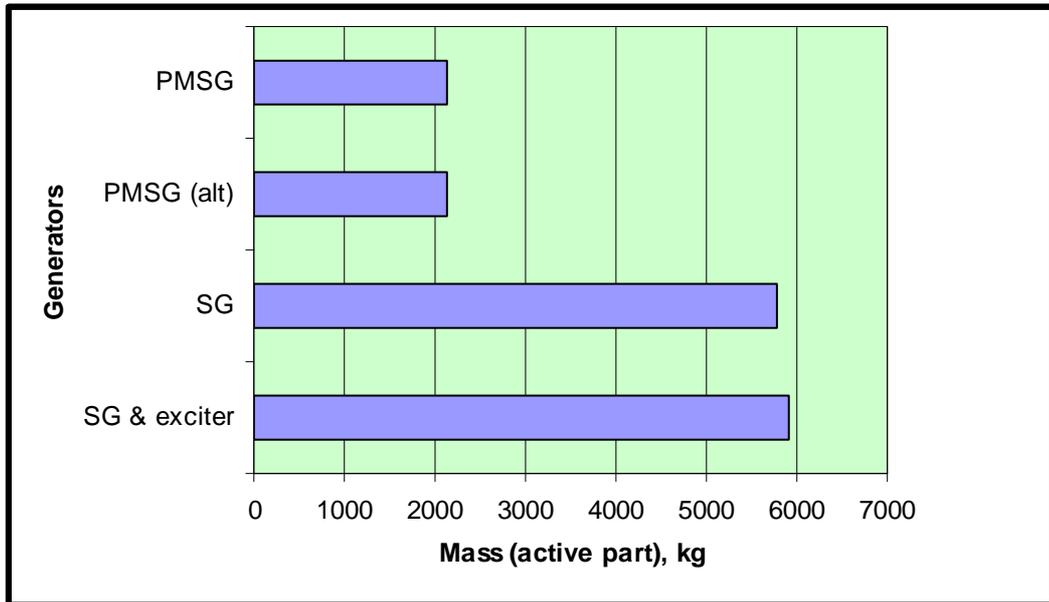


Figure 38 Masses distribution (in kg)

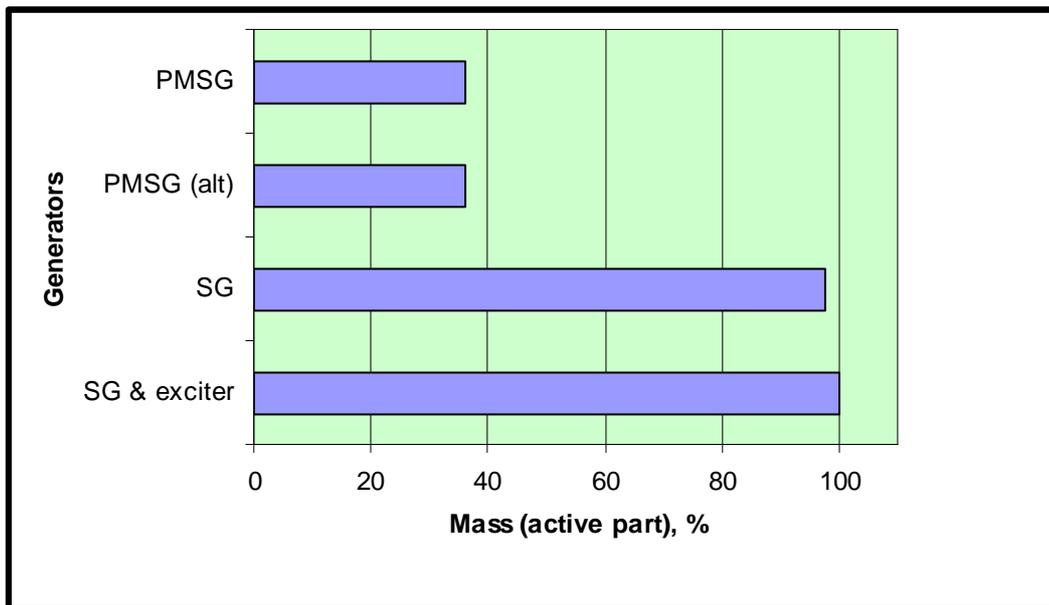


Figure 39 Percentage balance of the masses

3.6 Volume analysis

Also the valuable benefit can be got in volume which is occupied by generators.

The results of the volume distribution are on the Fig. 40 and Fig. 41. The volume results are near of the mass results and the PMSG requires 60 % less volume than the SG with the exciter.

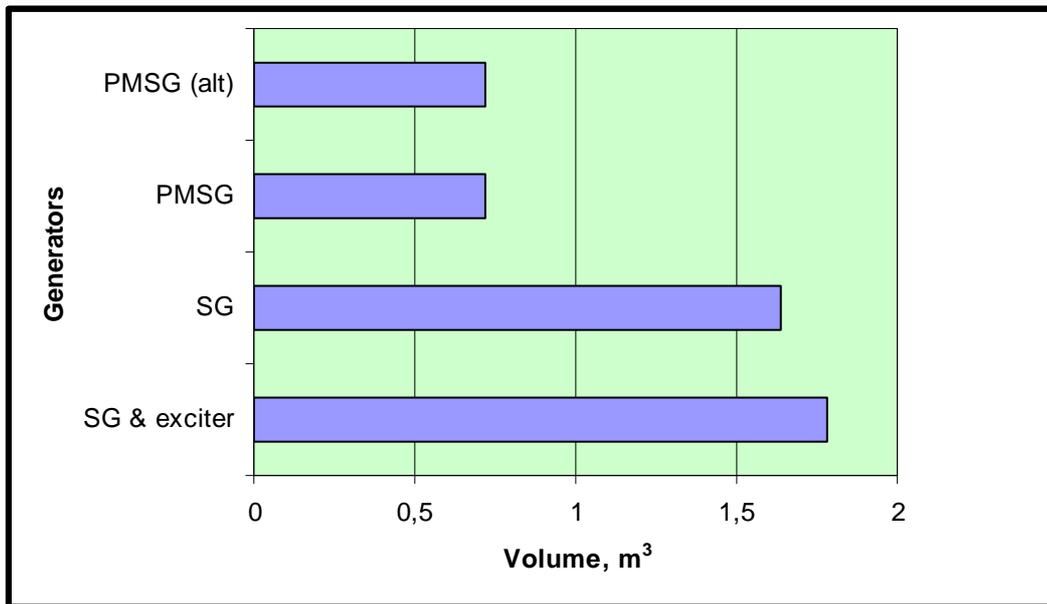


Figure 40 Volume of the generators (in m³)

The requirement for the volume is also very important, the less volume the wider opportunity for the power system placement and more freedom for EP arrangements. Also more space in the rest for the cargo.

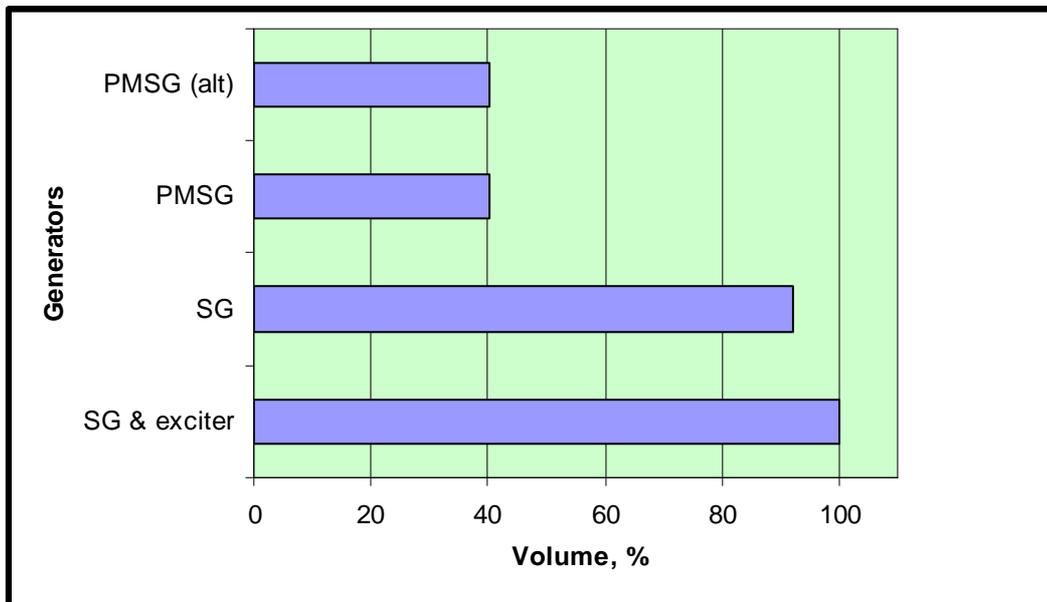


Figure 41 Percentage balance of the volume

4 Summary

As the result of this study several electric propulsion concepts were analyzed.

They are:

- Fixed frequency and voltage AC system (typical diesel-electric power-line nowadays);
- Fixed frequency and voltage AC system, LLC construction;
- Full power converter AC system;
- DC system;
- Variable frequency AC system.

Each of the concepts is good for its own area of application. Their parameters such as efficiency, reliability mostly depend on the vessel size and operational mode.

For analyzes low and medium power range ships were chosen. On the base of required electrical equipment, their sizes, efficiencies (Tables 3, 4) was made. After comparing total efficiencies, volumes, masses two of the five were chosen as the best. They are the DC system and the variable frequency AC system. But the second one requires very sophisticated control system and was therefore excluded from approval.

For the DC power system three different generators were designed. They are:

- traditional salient pole synchronous generator
- Two permanent magnet synchronous generators

The salient pole synchronous generator was designed for typical 50 Hz frequency. The aim of the designing was to make it possible to compare the parameters of the typical marine generators and PMSG.

PMSG generator was designed with the rated frequency of 200 Hz, but for the same rotational speed. This generator contains 24 poles. The idea was to analyze the potential benefits when the frequency is higher.

The result is the next:

- Higher efficiency of the PMSG than SG (it was predictable, and it helps to return the cost of the generator approximately in two years if the PMSG is implemented instead of the SG);
- Reduction of the generator mass at least by 50 %
- Reduction of the volume at least by 50 %

- Taking into account higher efficiency of the PMSG, their cost is competitive;
- DC power system concept with the implemented PMSG consumes in some conditions up to 50 % less fuel at partial load than typical SG in any electric propulsion system. This effect is based on the fact that in the DC power system frequency and voltage at the generator terminals may vary. Only the required power is important, for highest power highest rotational speed is accorded)

The permanent magnet technology has a potential for significant developing in the future, mainly in the field of higher frequency. Also PMSG has potential for improving the efficiency comparing with the traditional wound-field generators. But nowadays significant obstacle is the power range accessible for PMSGs in the frames which were discussed before. The main obstacle is the number of poles and the space for windings and teeth. Looking at the drawing of the PMSG, it is obvious that there is much free space inside the generator. To reduce this space, decreasing pole numbers and as the result decreasing diameters it is required to switch from low speed (1000 rpm) to high rotational speed (approximately 10000 rpm). It, however, should require also switching from diesel engines to gas or steam turbines which is not competitive as diesel has the best efficiency.

The power of such PMSG might reach 40 MW (3600 rpm) [15]

So judging by study [15] the 5 MW PMSG (15000 rpm) mass 1700 kg, when designed in the frame of this study 2 MW PMSG (1000 rpm) mass 2000 kg (only active part).

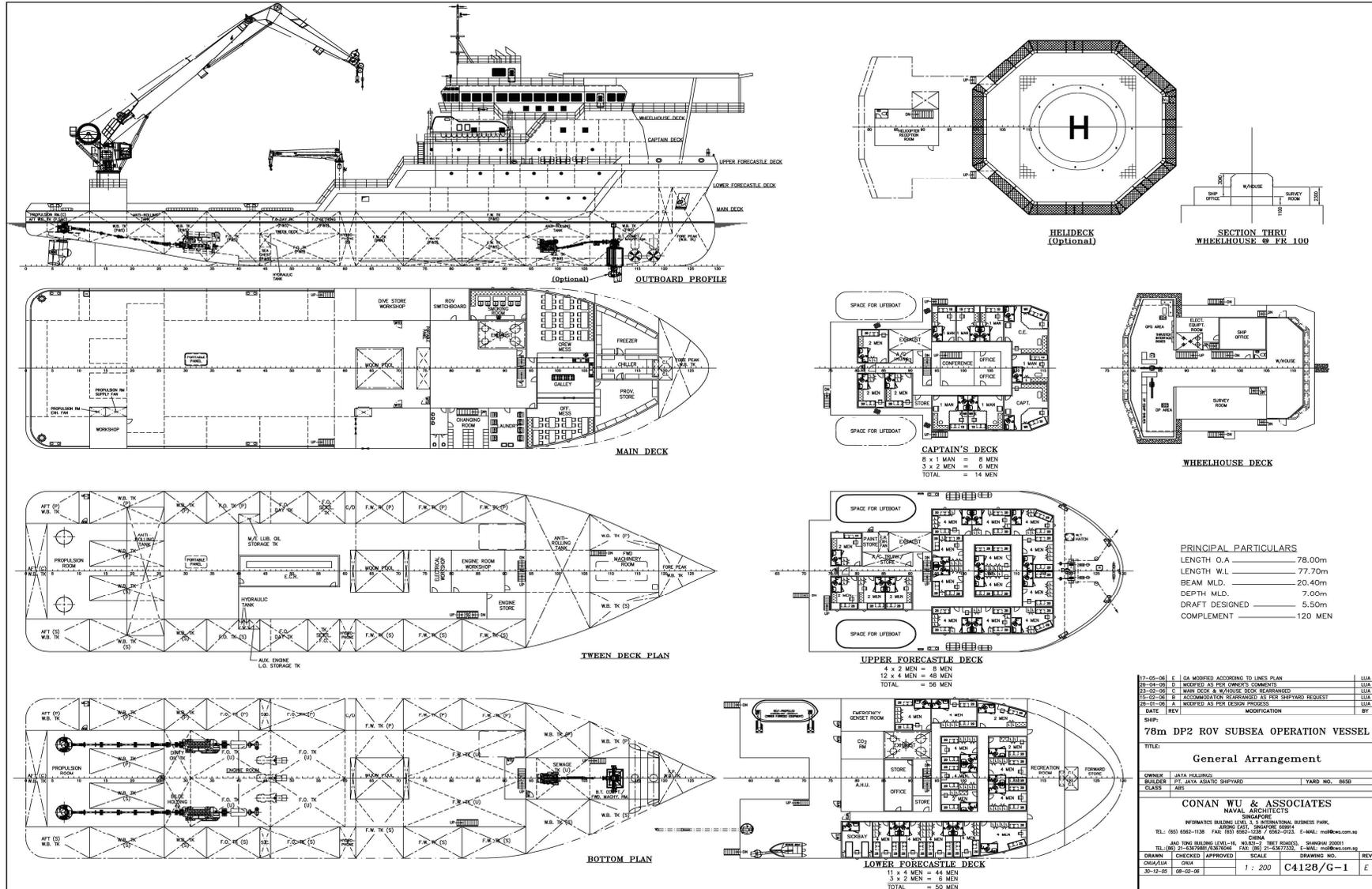
But nevertheless implementation the PMSG even in low speed operation is a significant step towards efficiency improvement and technology development.

5 References

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6 APPENDIXES

APPENDIX 1: Nor Valiant general arrangement [15]



APPENDIX 2: Designed generator in the scale of 1:10

