DIRECT CURRENT TECHNOLOGY AS A MEANS TOWARDS INCREASED VESSEL EFFICIENCY

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ABSTRACT

The amount of electrical power that is used on-board has grown exponentially over the last years. This, in combination with the requirements for greener shipping, led researchers to consider new versatile and more efficient electric power distribution schemes as a means. Future ships, will enjoy the flexibility of electrical power distribution from different power generation modules to be connected to propulsion and ship service loads in any arrangement that supports the ships mission with maximum efficiency and reliability. This widespread electrification of ship systems introduces novel concepts, with a favorable one being the introduction of Direct Current. In this paper an Integrated Power System (IPS) with Medium Voltage Direct Current (MVDC) distribution for a modern cruise ship is presented. The model, consists of the power generation module, the power conversion modules, the DC distribution line, and the several distribution loads. The second part of the paper highlights whether the DC systems eliminate reactive power circulation and losses, and, hence, could improve ship efficiency indices in terms of the Energy Efficiency Design Index (EEDI). Also several other issues are taken into account and investigated, such as power quality problems and faults. To this end, some of the main results of the ongoing research project "DC-Ship" are presented and discussed.

NOMENCLATURE

EEDI	Energy Efficiency Design Index
EEOI	Energy Efficiency Operational Indicator
GHG	Greenhouse Gas
IMO	International Maritime Organisation
IPS	Integrated Power System
MECP	Marine Environmental Protection Committee
MVDC	Medium Voltage Direct Current
MCR	Maximum Continuous Rating (kW)
P_{ME}	Main Engine Power (kW)
P_{PTI}	Shaft Motor Power (kW)
P_{PTO}	Shaft Generator Power (kW)
SEEMP	Ship Energy Efficiency Management Plan
SFOC	Specific Fuel Oil Consumption (g $kW^{-1}h^{-1}$)

1. INTRODUCTION

The increasing need for more efficient ships, has led the researchers to start considering new versatile and more efficient power distribution architectures. Several studies have shown that the extensive electrification of ship systems, known as the All Electric Ship, if electric propulsion motors is used, can lead to a "greener" and more efficient ship. To this end, novel concepts are explored, with a promising one being the introduction of Direct Current Distribution abroad [1].

DC grids for shipboard power systems have shown resurgence in recent times, mainly due to the evolution of power electronic devices and because of the fact that recent trends in electric power consumption indicate an increasing use of DC-based power and constant-power loads [1],[2].

Moreover, the concept of Direct Current technology presents several advantages such as improved efficiency, ability to incorporate renewable energy sources and energy storage systems into the ship power plant, reduced size and rating of switchboards, increased reconfiguration capability and so on.

In this work, the Integrated Power System (IPS) of a cruise ship with Medium Voltage Direct Current (MVDC) distribution and electric propulsion is modelled and presented. The network topology resembles to the IPS that was constructed in [2], but is significantly altered, while being fairly generic. Furthermore, this paper deals with the method of calculation of the attained EEDI for ships using electric propulsion and specifically this specific power system configuration. Also, a case study is presented. Finally, several other issues regarding the operation of a DC grid are taken into account and investigated, such as power quality problems and faults.

2. GRID ARCHITECTURE

An Integrated Power System (IPS) is a novel power distribution architecture, where a common bus is used to supply both service and propulsion loads and instantly redistribute power as necessary. In contrast to a typical mechanical drive system, an IPS would not require different prime movers for the propulsion and the ship service systems, a fact that offers significant architectural flexibility and allows decentralization of the ships systems and component arrangements [2], [3]. A conceptual IPS with DC Power Distribution is shown in Figure 1. In this section, the ship power system is discussed and a detailed description of each component is given.

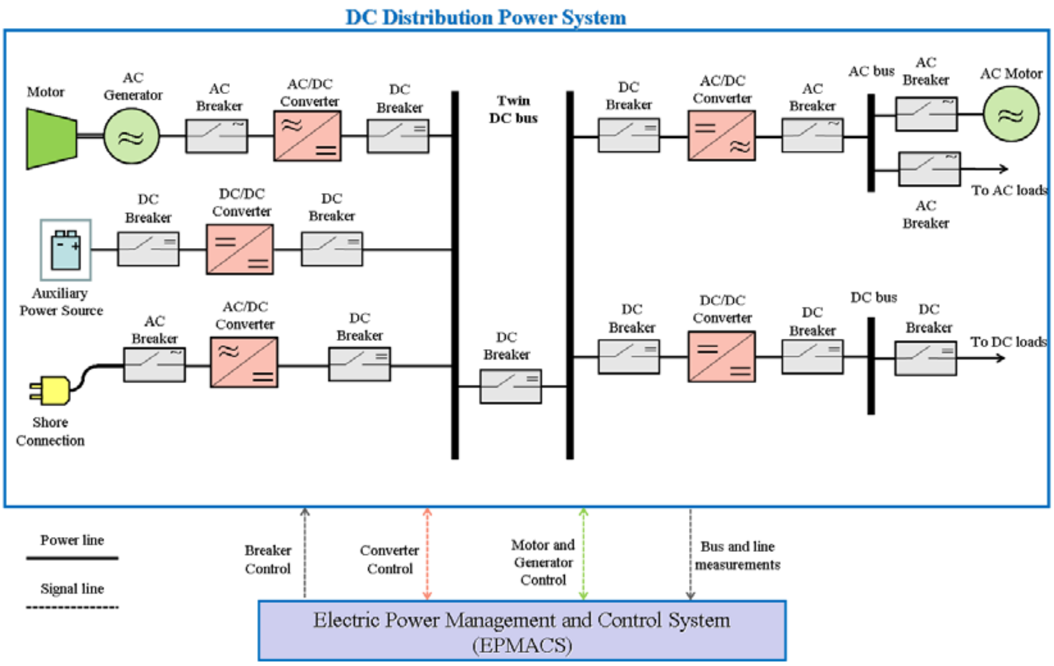

Figure 1: Conceptual DC Distribution Power System

2.1 Power Generation

The marine generators form the heart of the ship electrical design. That means that their careful selection is essential for a workable and economical system. When sizing, a marine generator cognisance must be given to the nature of the load. The generator often works on its own and is accordingly susceptible to large system load swings, loads causing distortion, the connection of motors and the connection of large heater elements for air conditioning systems. International maritime regulations [5], require at least two generators for a ship main electrical power system. The generators are normally driven by their own dedicated diesel engine but this can be expensive, taking up additional space that could be used for other purposes. For ships engaged on long sea voyages, it can be economically appealing to drive the generators from the main propulsion plant. International maritime regulations also require at least one electrical generator to be independent of the speed and rotation of the main propellers and associated shafting and accordingly at least one generator must have its own prime mover. In the system under study, there are three marine diesel generators and a shaft generator. Due to their differences in aspects of operation and design, each type of generator is discussed differently.

2.1.1 Diesel Generators

The main parts of a marine Diesel generator set are the Diesel prime mover, the speed governor, the synchronous machine and its exciter. The block diagram of a Diesel Generator is shown in Figure 2.

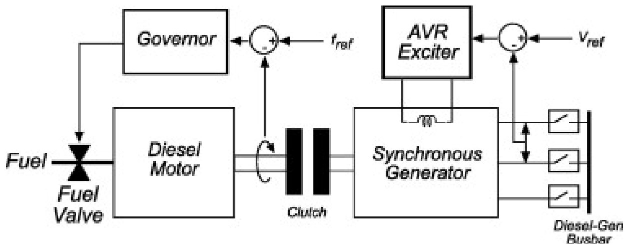

Figure 2: Diesel Generator Set block diagram

This system has two closed-loop feedback control systems: a speed feedback control system and an excitation feedback control system. These two feedback loops, ensure that the synchronous generator will operate at a steady speed and generate power at a fixed electrical frequency and voltage. The produced power is controlled via appropriate regulation of the field winding current. A detailed description of a diesel generator model can be found in [4].

2.1.2 Shaft Generators

A shaft generator is usually coupled to the ship mechanical shaft through a step-up gear. It is known to the worldwide bibliography as Shaft generator and according to its position, the type of coupling and the control equipment can be categorized into fourteen types [4]. It aims not only to produce electric power for the ship but, also, in certain cases to operate as a propulsion motor and assist the main motor engine. In typical fixed-speed shaft generator system, the generator is driven by the ship main engine, which is also driving the ship propeller. In this case, the grid frequency is tightly tied to propeller rotational speed. Any change in speed has a direct impact on network frequency. Thrust and ship speed can therefore only be controlled by propeller pitch, leading to undesired loading of the main engine, decreased efficiency and increased CO_2 emissions[6]. To eliminate these undesired effects the usage of an electrical drive is employed. A shaft generator drive (SGD) allows a wide speed range for the main engine. Propeller pitch and main engine speed can always be optimized for any desired sailing speed. The shaft generator drive maintains a stable voltage and frequency regardless of the main engine speed. When the SGD is placed between the shaft generator output and the distribution network, the shaft generator can be used independently of the shaft speed, enabling optimization of the ship operation for each route. The SGD also allows the shaft generator to run in parallel with the auxiliary generators. This means that the full benefits of lower specific fuel oil consumption (SFOC) for the main engine compared with the auxiliary engine can be fully exploited. If the auxiliary engines use marine diesel oil (MDO) instead of heavy fuel oil (HFO), the difference is even greater: the costs of lubrication oil and maintenance are relatively higher for auxiliary engines than for main engines [7].

2.2 DC Grid

The scheme that was used to implement the DC grid, comprised a twelve-pulse rectifier. This rectifier is simply yielded from the connection of two six-pulse thyristor bridges in series. The six-pulse rectifiers are supplied from the secondary and the tertiary of a three-winding transformer. The transformer winding connection is wye (Y) at the primary and wye (Y)-delta

(Δ) at the two other windings (Figure 3). As a consequence, the voltage angle of the second group of thyristors would be 30-degrees lagging. Thus, multiples of sixth ±1 current harmonics which are present in the secondary and tertiary windings of the feeding transformer, will be cancelled in the primary winding and the remaining harmonic components will be of order: $h = 12n \pm 1$ on the AC side (current harmonics) and $h = 12n$ on the DC side (voltage harmonics). This results in major economy in the filters. High power filters are usually undesirable components because they are large and so they occupy useful space, the have reduced efficiency and important impact on power system stability. Moreover, filters provide fault current even after the circuit breakers are open. If the current magnitude is too large it can cause ancillary damage. Thus, a design balance must be met between voltage stability and excessive fault currents. This indicates that the filters used with power electronics need to be designed carefully as they can be used to mitigate faults in MVDC architectures [2], [3].

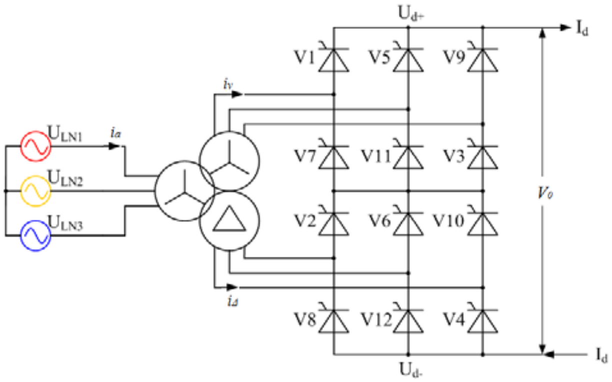

Figure 3: The twelve-pulse rectifier

The mean value of the output DC voltage, which is produced from the 12-pulse rectifier, is:

$$\overline{V_0} = \overline{V_{0_Y}} + \overline{V_{0_\Delta}} = \frac{3}{\pi}\int_{\alpha-\frac{\pi}{6}}^{\alpha+\frac{\pi}{6}} \sqrt{6}\widetilde{V}_1 \cos(\omega t)d(\omega t)$$

$$+\frac{3}{\pi}\int_{\alpha-\frac{\pi}{6}}^{\alpha+\frac{\pi}{6}} \sqrt{6}\widetilde{V}_1 \cos(\omega t)d(\omega t) = \frac{6\sqrt{6}}{\pi}\widetilde{V}_1 \cos\alpha$$

Equation 1: Mean output DC voltage of the 12-pulse rectifier

The total input current i_a that flows through the primary of the transformer is calculated from eq. 2:

$$i_A = \left(\frac{N_2}{N_1}\right) i_Y + \left(\frac{N_3}{N_1}\right) i_\Delta = \frac{i_Y}{\alpha} + \frac{\sqrt{3}}{\alpha} i_\Delta.$$

Equation 2: Total input current at the primary of the three-winding transformer

2.3 Propulsion System

The Propulsion System consists of 2 x 8.5MW induction motors with slip frequency current control. A three-phase inverter connects each induction motor with the DC bus. The three-phase inverter is controlled with the hysteresis current control method. A block diagram of the propulsion system can be found at Fig. 4 below.

2.3.1 Induction Motor

The three-phase 12-pole 8.5MW induction motor is the propulsion drive. The voltage equations of the induction motor stator and rotor windings are given below. It is assumed that both induction motors are operating at the same phase voltage.

The 4^{th} order transient model of the induction motor expressed in a reference frame rotating at the synchronous speed with the q-axis leading the d-axis by 90° is used. The differential equations forming the model of the generator are given in set of **Equations (3)-(10)**.

$$u_{sd} = r_s \cdot i_{sd} - \omega_s \cdot \Psi_{sq} + p\Psi_{sd} \quad (3)$$

$$u_{sq} = r_s \cdot i_{sq} + \omega_s \cdot \Psi_{sd} + p\Psi_{sq} \quad (4)$$

$$u_{rd} = r_r \cdot i_{rd} - (\omega_s - \omega_r) \cdot \Psi_{rq} + p\Psi_{rd} \quad (5)$$

$$u_{rq} = r_r \cdot i_{rq} + (\omega_s - \omega_r) \cdot \Psi_{rd} + p\Psi_{rq} \quad (6)$$

$$\Psi_{sd} = (L_{ls} + L_m) i_{sd} + L_m i_{rd} \quad (7)$$

$$\Psi_{sq} = (L_{ls} + L_m) i_{sq} + L_m i_{rq} \quad (8)$$

$$\Psi_{rd} = (L_{lr} + L_m) i_{rd} + L_m i_{sd} \quad (9)$$

$$T_e = \frac{3}{2}\frac{P}{2}(\Psi_{sd} i_{sq} - \Psi_{sq} i_{sd}) \quad (10)$$

Where, $p = \frac{d}{dt}$, $\frac{P}{2}$ is the number of pairs of poles, ω_s is the rotating speed of the reference frame and subscripts *{d}, {q}, {s}, {r}* denote *d, q* axis, stator and rotor, respectively.

Motion equation of the rotor is used to derive its rotating speed ω_r ,

$$J_m \frac{d\omega_r}{dt} = T_m - T_e \quad (11)$$

A more detailed analysis of induction motor operation can be found in [10] and [11].

2.3.2 Motor Drive

The three-phase IGBT/diode inverter is given by Matlab/SimPower Systems Toolbox. The gate input signal for controlled inverter consists of six firing signals for each IGBT, based on the inverter hysteresis current control output. The current control method applied here is the hysteresis control method [11]. Using this method the switching of the inverter does not depend only on an external control signal but also on the instantaneous currents in the circuit. The switching action is performed each time the current error reaches the limits of the hysteresis bandwidth defined in advance [12].

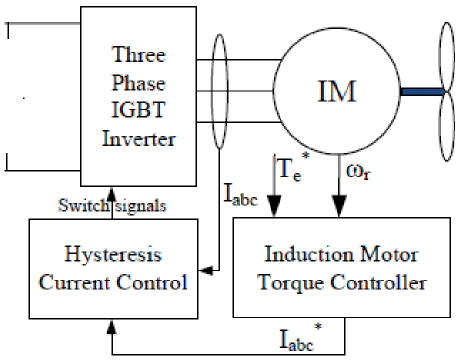

Figure 4: Propulsion motor and drive block diagram

3. ENERGY EFFICIENCY

3.1 IMO Regulations

Environmental pollution caused by ships, worldwide concern about air quality, greenhouse gas (GHG) emissions, and oil supplies have led to stricter emissions regulations and fuel economy standards[7]. Annex VI of the MARPOL Convention, adopted by the

International Maritime Organization (IMO) in 1997, sets regulations for the prevention of air pollution (Cox, NOx, SOx, etc) caused by ships. The above conditions create the need for:

- the shipbuilding industry to continue optimizing traditional ship types with the goal of increased safety and environmental protection
- existing vessels to become more energy-efficient, in order to be competitive for the remaining of their life cycle.

Thus, according to the directives of the International Maritime Organization (IMO), the ship efficiency is to be quantitatively evaluated via the two following indices:
- Energy Efficiency Design Index (EEDI),
- Energy Efficiency Operation Index (EEOI).

Both indices express the ship efficiency in terms of the produced CO_2 per ship capacity and/or transport work, with the EEDI-index addressing new buildings, and the EEOI-index addressing existing ones. Moreover, in the near future all ships must have a well designed Ship Energy Efficiency Management Plan (SEEMP), the mission of which will be to monitor on-line and control the efficiency indices of the ship in an optimum way. The production of CO_2 is mainly due to the operation of the main propulsion engine(s) and of the auxiliary engines used as prime movers for the electric generators [6], [7].

3.2 EEDI for Ships with Electric Propulsion

The purpose of the EEDI is to provide a fair basis for comparison, to stimulate development of more efficient ships in general and to establish the minimum efficiency of new ships depending on ship type and size. The EEDI Calculation Guidelines describe in detail the formula for the EEDI calculation, but the formula was not applicable until recently for ships having electric propulsion. The ANNEX 17/RESOLUTION MEPC.233(65) [8], that was adopted on 17 May 2013 provides the guidelines for calculation of reference lines for use with the EEDI for cruise ships having non-conventional propulsion. These guidelines apply to cruise passenger ships that utilise diesel-electric propulsion, turbine propulsion, and hybrid propulsion systems. The reference line value for cruise passenger ships having non-conventional propulsion is formulated as:

$$\textit{Reference line value} = 170.84 \cdot b^{-0.214}$$

Equation 12: Reference Line calculation for vessels with non-conventional propulsion

where b represents the gross tonnage of the ship. To calculate the reference line, an index value for each cruise passenger ship having non-conventional propulsion is calculated using the following assumptions: The carbon emission factor is constant for all engines, including engines for diesel-electric and hybrid propulsion cruise passenger ships, i.e. $C_{F,ME} = C_{F, AE} = C_F = 3.1144$ g CO_2/g fuel. The carbon factor for hybrid propulsion ships equipped with gas turbines $C_{F,AE}$ is calculated as an average of the carbon factors of auxiliary engines (i.e. 3.1144 g CO_2/g fuel) and the carbon factor of gas turbines (i.e. 3.206 g CO_2/g fuel) weighted with their installed rated power. $P_{ME(i)}$ is reflected as 75 % of the rated installed main power ($MCR_{ME(i)}$). Where a ship only has electric propulsion $P_{ME(i)}$ is zero. The specific fuel consumption for all ship types, including diesel-electric and hybrid propulsion cruise passenger ships, is constant for all auxiliary engines, i.e. SFC_{AE}=215g/kWh. The specific fuel consumption for hybrid propulsion cruise passenger ships equipped with gas turbines SFC_{AE} is calculated as an average of the specific fuel oil consumption of the auxiliary engines (i.e. 215 g/kWh) and the specific fuel oil consumption of the gas turbines (i.e. 250 g/kWh) weighted according to their installed rated power. P_{AE} is calculated according to paragraph 2.5.6.3 of the 2012 Guidelines on the Method of Calculation of the Attained Energy

Efficiency Design Index (EEDI) for new ships (resolution MEPC.212 (63)) [9] considering a given average efficiency of generator(s) weighted by power of 0.95. Innovative mechanical energy efficiency technology, shaft generators and other innovative energy efficient technologies are all excluded from the reference line calculation, i.e. $P_{AE,eff} = 0$ and $P_{eff} = 0$. $P_{PTI(i)}$ is 75% of the rated power consumption of each shaft motor divided by a given efficiency of generators of 0.95 and divided by a given propulsion chain efficiency of 0.92.

The equation for calculating the index value for cruise passenger vessels having non conventional propulsion is as follows:

$$Estimated\ Index\ Value = \frac{3{,}1144 \cdot 190 \sum_{i=1}^{nME} P_{ME} + C_{F,AE} \cdot SFC_{AE} \cdot (P_{AE} + \sum_{i=1}^{nPTI} P_{PTI(i)})}{GrossTonnage \cdot V_{ref}}$$

Equation 13: Estimated Index Value for ships using non-conventional propulsion

4. CASE STUDY

The investigated vessel is a cruise passenger ship, whose general characteristics are presented in Table 1 and it’s electrical characteristics were analysed in section 2. The required ship propulsion power of 17MW is delivered by two induction motors rated at 8.5MW each, whereas three marine diesel generators of 5MW each and a shaft generator of 5MW are required for covering the ship electric energy demand. The ship is considered to in a route of 560NM which includes a part of 340NM inside ECA zones (60% sailing in ECA, 40% sailing in non-ECA). An example of this route is an itinerary between Portsmouth and Santander, Spain. Each part of the ship voyage lasts approximately 36h considering a sailing speed of 21 knots, 28h of sailing, 0.5h of maneuvering and 1h that remains in port.

Table 1. Cruise Ship Main Particulars

Characteristic	Value
Size	35000 GT
Length	220 m
Beam	28.2 m
Draft	7.0 m
Service Speed	21.0 knots
Deadweight	12500mt
Propulsion Power	17 MW
Aux. Power(Installed)	20 MW
Propulsion	Elect. Propulsion

The Energy Efficiency Design Index for the specific cruise ship was calculated regarding the assumptions that were made above in 3.2. The main advantages of the configuration that was discussed in section 2, which result in the reduction of the EEDI value are a) the usage of electric propulsion b) the utilization of shaft generators as auxiliary power and c) the specific DC grid configuration that reduces the total weight and volume of the electrical installations across the ship. The calculation results can be summarised at Fig. 5 below. In the suggested approach, the attained EEDI was calculated to **13,044** while the minimum required that was calculated from the reference line for this specific vessel is **18,052**. This means that the obtained EEDI is about 27% below the required index. Also, as it can be deduced from Figure 5, the investigated vessel will comply with all IMO regulations including the future ones.

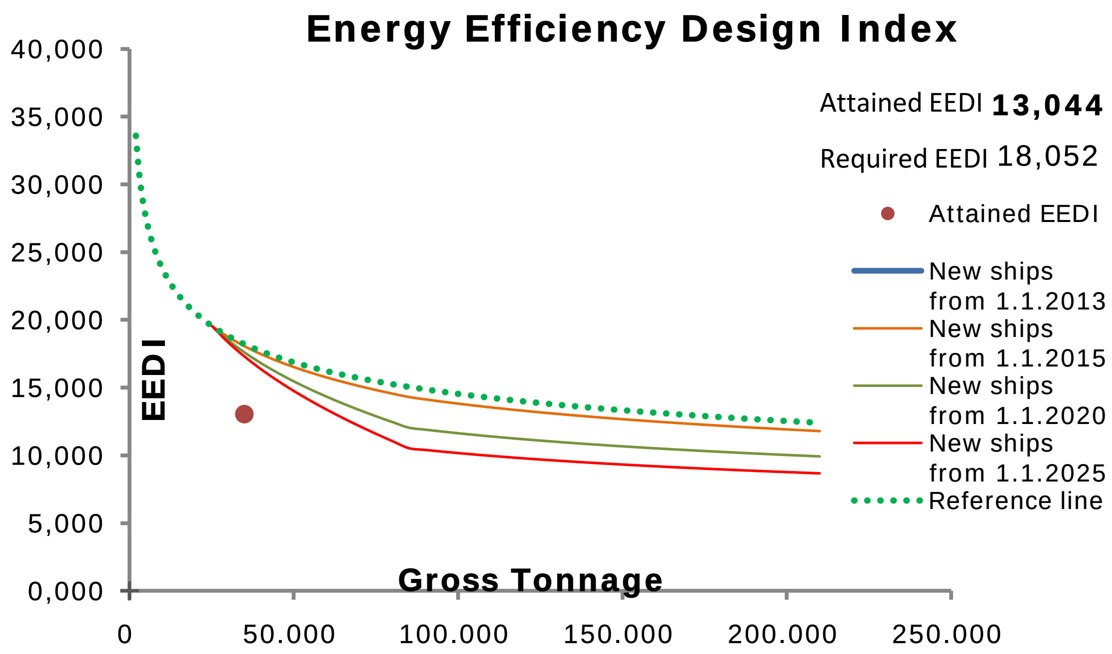

Figure 5: EEDI of the ship under study in contrast to reference lines of IMO.

5. CONCLUSIONS AND FUTURE WORK

The aim of this paper has been the modelling of an IPS with MVDC power distribution for a reference cruise passenger ship. Each component of the electric grid was separately discussed and presented regarding its role in the power distribution network. Also, an approach to determine the efficiency and environmental gains from DC power distribution was made. The technical measure that was used for this study was the Energy Efficiency Design Index (EEDI). The recent EEDI regulations for ships with electric propulsion were cited and a preliminary case study was presented to demonstrate the energy efficiency benefits that arise from this novel grid configuration. The findings indicated that new ships that will adopt this power distribution concept, will have sufficiently reduced EEDI and will comply with even stricter future regulations regarding CO_2 emissions.

Future work includes further deepening on All-Electric Ship power quality and stability issues, investigation of new techniques for MVDC grid optimal operation, further deepening on the impact of integrating DC technology upon the ship efficiency, and examination of the operation, maintenance and procurement costs of vessels with DC power distribution.

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