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ANALYSIS AND EXPERIMENTAL VERIFICATION OF IMPROVING THE EEDI OF A SHIP USING A THRUSTER SUPPLIED BY A HYBRID POWER SYSTEM

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ABSTRACT

In this study, the authors present a theoretical analysis and experimentally verified methods to improve the Energy Efficiency Design Index (EEDI) of ships. The improvements were studied via the application of an innovative solution of a thruster supplied by a hybrid power system on board a passenger-car ferry. The authors performed sea trials of a ship's electrical power system supplied by battery packs with diesel generating set power units. The experimental study focused on energy balance and management, which were considered together with related power quality issues. The authors found that the application of an energy storage system to the ferry, such as batteries, with the simultaneous adaption of the operation modes of the electrical power system for current exploitation, significantly improved energy efficiency. Fuel consumption and CO_2 emission were reduced, while adequate parameters of electrical power quality were maintained to meet classification standards.

Keywords: Energy Efficiency Design Index, thruster supplied by hybrid power system, energy balance, power management, electrical power quality parameters, classification institutions

INTRODUCTION

Increased energy/fuel efficiency and reduced greenhouse gas emissions, such as CO_2, NOX and SO_2, have become important challenges for shipbuilders, operators and regulators. These challenges are the most intensively explored issues in the domain of maritime transport. Greenhouse gas emissions are typically limited to CO_2 emissions [1] and are associated with fuel consumption by ships. Ship fuel consumption is dependent on the total energy demand of the ship, including electrical energy. Therefore, optimising and utilising generated electricity is important for limiting fuel consumption and, consequently, CO_2 emissions. CO_2 emissions in global maritime transport are controlled by the International Maritime Organisation (IMO), and other organisations, via the internationally regulated Energy Efficiency Design Index (EEDI). This index applies to all vessels built after 2013 with a tonnage exceeding 400 GT and the goal is to establish the minimum energy efficiency of ships according to their type and size. The EEDI is expressed as the ratio of CO_2 emissions (in grams) to the transport work of a vessel in ton-miles. Following the IMO concept [1], the CO_2 reduction level for the first phase has been set to 10%, covering the following ship types: tankers, bulk carriers, gas carriers, general cargo ships, container ships, refrigerated cargo carriers and combination carriers. In 2014, the IMO stated [1] that the adopted amendments to the EEDI regulations will extend the scope of this coefficient to LNG carriers, ro-ro cargo ships (vehicle carriers), ro-ro cargo ships, ro-ro passenger ships and cruise passenger ships with non-conventional propulsion. This extension also includes ships equipped with hybrid power systems, such as battery-powered systems.

The next step of the considered rules development proceeded under the auspices of the Marine Environment Protection Committee (MEPC), during its last session on July 3-7, 2023. The MEPC 80 session adopted the 2023 IMO Strategy on the 'Reduction of GHG Emissions from Ships', with enhanced targets, to tackle harmful emissions [2]. The revised IMO GHG Strategy includes an enhanced common ambition to reach net-zero GHG emissions from international shipping close to 2050, a commitment to ensure an uptake of alternative zero and near-zero GHG fuels by 2030, and indicative check-points for 2030 and 2040. Amendments to the International Convention for the Prevention of Pollution from Ships (MARPOL) Annex VI came into force on 1 November 2022. Developed under the framework of the Initial IMO Strategy on the Reduction of GHG Emissions from Ships (agreed in 2018), these technical and operational amendments require ships to improve their energy efficiency in the short term, thereby reducing their greenhouse gas emissions [3]. From 1 January 2023 it is mandatory for all ships to calculate their attained Energy Efficiency Existing Ship Index (EEXI), to measure their energy efficiency and to initiate the collection of data for the reporting of their annual operational carbon intensity indicator (CII) and CII rating [3]. EEXI is calculated using the same formula as EEDI and represents "the amount of CO_2 emissions from a ship when the ship sail transports one ton cargo for one nautical mile". Regardless of a ship's delivery date, ships of 400 GT and above, which are engaged in international voyages, are subject to the EEXI regulations and the EEXI of each ship needs to be calculated. Ships of a specific size are subject to the EEXI regulations and need to comply with the requirements, equivalent to the EEDI requirements of 2023. Under the EEXI regulations, vessels classified as a 'Bulk carrier', 'Tanker', and 'Ro-ro cargo ship (vehicle carrier)' need to comply with the EEXI requirement equivalent to the Phase 2 EEDI requirement, while a 'Containership', 'General cargo ship', 'LNG carrier', and 'Gas carrier' would need to comply with the EEXI requirement equivalent to the Phase 3 EEDI requirement. Therefore, a ship subject to EEDI regulations, which complies with the Phase 2 or Phase 3 requirement, automatically complies with the EEXI regulations. If a ship does not meet the EEXI requirement, the ship needs to implement any countermeasures, such as engine power limitation or the installation of energy saving devices, etc., to improve their EEXI.

In recent years, battery-powered ships have been widely explored in various studies [4–7]. These studies analysed many aspects. For example, [4], [5], and [8], analysed the impact of new conversion technologies, such as power electronics, battery energy storage and DC power systems, on overall energy efficiency, power quality and emission levels and discussed them thoroughly. Some studies [6] used specific methods and tools to provide accurate estimates of the battery state of charge (SoC), which is a critical factor for the safe and reliable operation of battery systems. A few papers have presented the main problems encountered by designers of small, hybrid-powered ferries powered by lithium batteries, including energy balance issues and the development of an energy management policy [7]. In this study, the authors considered and compared their results with existing state-of-the-art research in this field and present an analysis and experimental verification of methods to improve the energy efficiency of ships using a thruster supplied by a hybrid power system. The presented article focuses on the new challenges in energy balance and energy management policy and considers related power quality issues in modern ferries, when using innovative propulsion systems. This study focuses on a passenger-car ferry, which began operation in 2021.

In this paper, improving the EEDI is presented by using an example of a modern, two-way hybrid electric ferry. The ferry was designed for coastal shipping between Norwegian fjords and designed with the understanding that, during crossings between ports, energy will be primarily sourced from battery banks, which will be charged during stops. However, in unforeseen situations, it is possible to use diesel generating set power units (part of a hybrid propulsion system) in the electric power system of passenger-car ferries. Using the operational strategy adopted by the Norwegian ferry operator, the project focuses on minimising energy consumption. This involves the following solutions: (I) powering the vessel from battery banks combined with diesel generating sets, (II) energy-efficient LED lighting, (III) flexible power supply systems using power electronic frequency converters, (IV) underwater hull coatings to reduce friction, (V) specially designed hull shapes to minimise water resistance, and (VI) lightweight ship hull construction. All of these solutions were implemented in practice by the designers and shipbuilders of the ferry but they are presented in this paper with different importance. The solutions I, II and III, concerning the limitation of electrical energy consumption on board the ship, are considered in this way, and the authors concentrate on examining the impact of implementing the conditions outlined in the introduction, mainly solution I. This examination was experimentally verified on the basis of the sea trials case study and is presented in the related chapters of the article. Solutions II and III were analysed and discussed on the basis of the literature on the subject and the authors' professional experiences, but only in the context of their influence on a worsening of power quality in the considered ship electrical power system. The remaining solutions, i.e. solutions IV, V and VI, concern improving the EEDI by minimising ship hull friction and reducing its resistance to water. Moreover, the latter solution enables the increase in deadweight tonnage of cargo transported by the ship. In consequence, the aforementioned solutions provide the means to increase the ship's transport work and reduce fuel consumption.

This paper is organised as follows. In the second section, we provide a short description of the selected design and operational indexes characterising the energy efficiency of the ship. The following sections present a standard passenger-car ferry as the object of investigation, formulation of the problem, and a short description of the plan and conditions of experiments performed during the sea trials. The fifth section highlights the issues of energy balance, energy management and power quality as the main aspects of the experimental verification of the improvement of the ship's energy due to the hybrid power system. The experimental results are then presented and discussed. The last section concludes the study and includes recommendations.

ENERGY EFFICIENCY MEASURES

The full description of the algorithm for the EEDI is complicated [8]. However, its simplified form can be found in [9].

$$EEDI = \frac{1}{E}\,(A + B + C - D) \quad (1)$$

A, B, and C represent the CO_2 emissions of the main engine(s), auxiliary engine(s), and shaft generator/motor(s), respectively. D is the reduction in CO_2 owing to innovative technologies and E is the transport work of the ship.

Detailed descriptions of the parts in Eq. (1) are described in [9].

Additionally, another simplified version of the EEDI can be expressed as follows [6]:

$$EEDI = \frac{P_{installed} \times SFC \times CF}{DWT \times V_{ref}} \quad (2)$$

where $P_{installed}$ is the installed power of a ship (in kW), SFC is the specific fuel consumption (in g/kWh), CF is the carbon conversion factor, DWT is the deadweight tonnage of the ship, and V_{ref} is the reference speed.

The initial analysis of Eq. (1) leads to the conclusion that the value of the EEDI will be smaller and more favourable for the intended objectives when A, B, and C are smaller and when D and E are larger.

It is also worth noting that, on the basis of Eq. (2), the EEDI value is directly proportional to the installed ship power and the coefficients characterising the specific fuel consumption and carbon conversion of this ship, as well as varying inversely proportional to the product of deadweight capacity and speed of the vessel.

Technologies and methods for improving the EEDI that implement the above actions are widely described in the literature [10,11]. These methods include hydrodynamic optimisations (hull design optimisations), propulsion optimisations (innovative propulsion system solutions), alternative fuels (LNG - Liquefied Natural Gas, CNG - Compressed Natural Gas), and other approaches (the use of renewable energy sources, operational methods, and innovative solutions for controlling the equipment in shipboard electrical systems).

The lower the design value of the EEDI from Eq. (1), compared to the threshold value established based on the reference line concept [12,13], the more energy-efficient the ship will be according to the IMO criteria, which can be expressed by Eqs. (3), (4) and (5).

$$EEDI_{attained} \leq EEDI_{required} \quad (3)$$

Here, $EEDI_{attained}$ is the calculated index based on the complete algorithm described in [4] and $EEDI_{required}$ is defined by The International Convention for Prevention of Pollution from Ships (MARPOL), following conventional requirements [7]:

$$EEDI_{required} = \left(1 - \frac{X}{100}\right) \times L_{ref} \quad (4)$$

where X is the reduction factor for selected types of ships and L_{ref} is the line reference value, described by the following formula [7]:

$$L_{ref} = a \times b^{(-c)} \quad (5)$$

Here, a, b, and c are the tabulated parameters for individual ship types.

The EEDI threshold value ($EEDI_{required}$) will be successively limited and extended to new ship types following the extension program schedule and guidelines adopted by the IMO [1]. Finally, these amendments mean that ship types responsible for approximately 85% of the CO_2 emissions from international shipping are included under the international regulatory regime.

It should be noted that EEDI represents a measure of the design efficiency of a new ship but it does not explain its operational efficiency [9]. Additionally, twin ships with the same EEDI may have different operational efficiencies due to their different operational profiles and sailing conditions [14]. To extend the EEDI design approach, the IMO has also developed the Energy Efficiency Operational Indicator (EEOI), to indicate the fuel consumption of a specific ship, including detailed information, such as cargo mass and the number of passengers carried. Appropriate values of EEOI are given for single and multiple vessels, according to the description and explanation in [15].

OBJECT OF THE INVESTIGATION

The object of this study was a standard double-ended passenger-car ferry (Fig. 1) equipped with an innovative electric propulsion system, operating in a diesel–electric hybrid configuration. It was powered by battery packs working in combination with generators using biodiesel fuel.

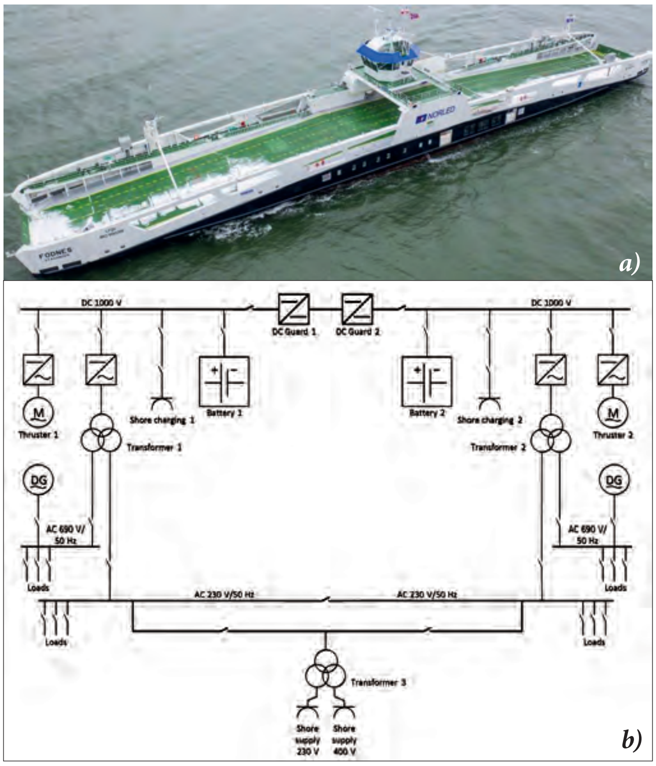

Fig. 1. Standard double-ended passenger-car ferry: (a) ship view based on [16] and (b) diagram of the power system equipped with diesel–electric hybrid electric propulsion

The electrical power system of this ferry is divided into two symmetrical sections: the bow (FWD – Forward part of vessel) and the stern (AFT – After part of vessel). Each section contains a power generation unit supplying an AC distribution board rated at 690 V / 50 Hz, a transformer with ratings of 500/99/500 kVA and 690/230/540 V / 50 Hz connecting the

AC distribution board at 230 V / 50 Hz and the DC at 1000 V, battery banks and a propulsion system with a motor rated at 960 kW, 600 V, and 64 Hz, which is powered by a DC/AC converter. The propulsion unit from SCHOTTEL is supplied from a DC 1000 V distribution board using a VACON NXI power electronic converter, which is an inverter. The inverter consists of IGBT switches and produces a symmetrical, 3-phase PWM-modulated AC voltage to the motor.

The elements on the configuration diagram (Fig. 1b) have designated indexes. '1' refers to the forward part of the electrical power system and '2' refers to the aft part of this system. 'DG' indicates the generating sets and the diesel generator. The ship's electrical power system is equipped with shore charging and shore supply (SS), connections for charging battery packs and supplying the ship from the shore, and DC guard protection modules [17], which enable fast disconnection and full selectivity between forward and aft DC grids.

FORMULATION OF THE PROBLEM

The goal of this study was to examine the impact of implementing the conditions outlined in the Introduction ((I), (II), and (III)) for improving the energy balance of the ship while maintaining the appropriate parameters of electrical energy quality, following the standards of Det Norske Veritas (DNV) [16], which surveys the construction process before classification of the vessel. Notably, the DNV rules for DC battery-powered systems are exclusively focused on the DC busbar voltage as the main supply of the system. Other switchboards supplying ship systems, such as AC 690 V / 50 Hz and AC 230 V / 50 Hz in complementary configurations of electric power systems (without energy storage systems), fulfil the function of the main switchboards and should comply with full verification conditions according to the requirements defined in the appropriate rules [18]. However, additional checking of the power quality standards related to currents is justified by the fact that the systems described under conditions (II) and (III) can significantly minimise electrical energy consumption on one side. However, strongly non-linear elements (LED lighting and power electronic inverters) can cause a worsening of the power quality in the considered electrical power system.

The first condition (the use of an electric power system powered by batteries with DG generating sets) is an energy–saving solution without the additional consequences of power quality degradation in the power system.

The second condition (the application of energy-saving LED lighting) has negative effects on the selected electricity quality parameters [19]. Results have shown that LED lamps result in significant savings in electricity consumption but they behave as nonlinear loads, generating higher frequency harmonics, which can worsen power quality in the distribution network [20].

In our case, with a DC main switchboard, the problem concerns the large number of power supplies equipped with rectifiers applied to supply a large number of LED lamps in the AC system.

The third implemented option includes flexible power supply systems of selected devices using power electronic inverters. Some of the load circuits consist of systems with motors driven by power converters, such as propulsion drives, ventilation and air conditioning systems and cooling systems. Powering motors with variable frequency drives allows the adaptation of the motor load to real needs. In such cases, the total energy consumed by all electric motors on the ship can be considerably reduced. The consequence of using multiple-power electronic converters may be an increase in total harmonic distortion (THD) in the current waveforms.

Thus, although the primary concern for the shipbuilder and operator is energy saving, checking whether the power quality parameters comply with the classifying institution standards is justified and required.

RESEARCH PLAN

The study involved the improvement of electricity generation and its use for effective power management supported by solutions that minimise energy consumption. We also determined the power quality parameters for this power system.

To determine the power quality parameters, the authors measured the voltages and currents during sea trials of the ferry using the FWD system as follows: FWD Generating set (DG1), FWD Transformer with 540 V side (Transformer 1), FWD DRIVE SWBD at DC 1000 V (DC 1000 V) and FWD Thruster Unit (Thruster 1). In the DC 1000 V distribution board, there was an installed DC/AC converter, producing up to 600 V / 64 Hz voltage to supply the Thruster 1 motor. Therefore, the measurement system consisted of 15 channels, as specified in Table 1. The voltage measurements were carried out via transducers from LEM (Life Energy Motion) and current measurements were conducted using Rogowski coils from PEM (Power Electronic Measurements). The measurement system consisted of an industrial computer from National Instruments, equipped with a PXIe-8135 controller and three PXIe-6358 data acquisition cards. The measurement results, recorded as instantaneous samples of voltage and current values, were used to determine the parameters in the sea trial. The voltage and current parameters (Table 1) were calculated using home-built software and a dedicated spreadsheet.

Tab. 1. Specifications of the measurement channels and parameters

No.	Channels	Object	Measured parameters	Connection points for measuring probes
1	1,2,3	DG1	U12, U23, U31	AC 690 V / 50 Hz
2	4,5	Transformer 1	U12, U23	Transformer 1
3	6	DC 1000 V	U	DC 1000 V
4	7,8,9	DG1	I1, I2, I3	AC 690 V / 50 Hz
5	10,11,12	Transformer 1	I1, I2, I3	Transformer 1
6	13,14,15	Thruster 1	I1, I2, I3	DC 1000 V / DC/ AC Converter 1

ENERGY BALANCE AND ENERGY MANAGEMENT

The energy balance includes the specification of DC and AC energy sources and their parameters and the specifications and characteristics of the most important loads in the analysed system. These specifications are provided in Table 2. The table was prepared with loads active during the sea trials highlighted. The other loads have been presented as a complementary component.

Table 2 shows that the total sum of the energy loads from the thrusters supplied by the 1000 V DC voltage (and other loads supplied from the 690 V AC and 230 V AC voltages) reaches up to 2619.7 kW (including 1920 kW in the thrusters) and exceeds the sum of the energy sources corresponding to 978 kVA (DGs, generating sets) plus 1130 kWh (batteries). However, many of the loads shown in Table 2 (for positions 1-4, 9-17, and 19-23) only work during limited and different time intervals, and depend on the given mode of ferry operation. Thrusters typically work by using power below their rated values and an appropriately designed simultaneity coefficient for the analysed power system. With regard to the scope of the article focusing on the sea trials case study, only the simplified energy balance for the ferry operation in electric mode and hybrid mode, corresponding to normal, routine voyages between the Norwegian fjords, is analysed more carefully. Under these circumstances the thrusters do not work together at full power in the continuous work regime. Thrusters can either work

Tab. 2. Specifications of the loads and sources of energy for the analysed ferry's electrical power system

No	Name of device	Power [kW]	Switchboard	Estimated load [kW]	Simultaneity load factor / degree of power source use
Loads active during the sea trials					
1	HP-1 Aers Central Heat/Cool System	43.0	AC 690V/50Hz FWD	16.0	0.37
2	Steering, Cooling, SW Circulation, LO Transfer and Fuel Oil Pumps	53.0	AC 690V/50Hz FWD	32.0	0.60
3	HP-2 Aers Central Heat/Cool System	43.9	AC 690V/50Hz AFT	13.5	0.31
4	Provision Cooling Plant 1	1.5	AC 690V/50Hz AFT	1.5	1.00
5	Lighting, navigation and hotel load (superstructure load)	≤60.0	AC 230V/50Hz	48.0	0.80
6	CP1/2/3-Fans	17.1	AC 230V/50Hz	9.0	0.53
7	Thruster FWD	960.0	DC 1000V FWD	528.0	0.55
8	Thruster AFT	960.0	DC 1000V AFT	432.0	0.45
Other Loads					
9	Bilge Pump 1	11.0	AC 690V/50Hz FWD	NA*	NA
10	Fire Bilge Pump 1	43.6	AC 690V/50Hz FWD	NA	NA
11	Fire Pump 1	30.0	AC 690V/50Hz FWD	NA	NA
12	Deluge Pump	160.0	AC 690V/50Hz FWD	NA	NA
13	MOB Davit	10.2	AC 690V/50Hz FWD	NA	NA
14	Watermist Pump 1	22.0	AC 690V/50Hz FWD	NA	NA
15	Deck Foam System	13.2	AC 690V/50Hz FWD	NA	NA
16	HPU Pump 1	30.0	AC 690V/50Hz FWD	NA	NA
17	HPU Pump 2	30.0	AC 690V/50Hz FWD	NA	NA
18	Provision Cooling Plant 2	1.5	AC 690V/50Hz FWD	NA	NA
19	Deck Washing Pump	5.5	AC 690V/50Hz FWD	NA	NA
20	Bilge Pump 2	11.0	AC 690V/50Hz AFT	NA	NA
21	Fire Bilge Pump 2	43.6	AC 690V/50Hz AFT	NA	NA
22	Fire Pump 1	30.0	AC 690V/50Hz AFT	NA	NA
23	Watermist Pump 2	22.0	AC 690V/50Hz AFT	NA	NA
24	Black Water Pump, Hydrophore Pumps, Oily Bilge Pumps, Grey Water Pump, SW Circulation 2, Cooling 2 and Transfer Pumps	18.5	AC 230V/50Hz	NA	NA
*NA - not applicable, loads out of the work during the sea trials					
Sources of power active during the sea trials					
1	DG1	489 kVA / 440 kW	AC 690V/50Hz FWD	388.0	0.88
2	DG2	489 kVA / 440 kW	AC 690V/50Hz AFT	388.0	0.88
3	Battery 1	565 kWh	DC 1000V FWD	260.0 **	0.46 ***
4	Battery 2	565 kWh	DC 1000V AFT	260.0	0.46
** - Power necessary to complete an energy balance during the sea trials *** - Degree of power source use estimated for 1h of the sea trials					

individually or in sequence, e.g. at 55% (first thruster) and 45% (second thruster) of the load, i.e. a total thrusters' power of 960 kW. During the sea trials, the remaining load of the system listed in positions 1-6, was about 120 kW. This means that the total sum of the load of the system was 1080 kW, taking into account the simultaneity coefficients for the thrusters and remaining loads shown in Table 2, listed in positions 1-8. At the same time, the related sources of power active during the sea trials corresponded to 776 kW (DGs) and 520 kWh (batteries). Some of the simultaneity load coefficient and degrees of power source values shown in Table 2 have been determined on the basis of the shipyards' ferry documentation and the sea-going practice experience of the authors. It was assumed that the sea trials combinations of loads and power sources corresponded to the routine, regular conditions of shipping planned between two Norwegian fjords. Therefore, the operating conditions assumed the estimated values of the load coefficients and degrees of power sources used, as well as a very specific regime of ferry operation, i.e. a vessel operating a 15 minute crossing of the Norway fiords, 26 times in a normal day, where a single crossing distance is 3 km. It is, therefore, possible to achieve an energy balance in the analysed electrical power system. This balance was achieved in all possible modes of operation of the ferry by implementing energy management recommendations. These recommendations focused on improving energy efficiency, analysing and implementing appropriate operational maintenance of the batteries, and analysing and verifying all required functionalities in all modes of operation of the ferry.

The lifetime and reliability of the batteries are crucial for realising the recommendations. These recommendations were formulated by the batteries' manufacturer and the ship's designers. The lifetime of the installed batteries is closely related to the number of charge and discharge cycles. Batteries must operate within their optimal discharge and charge limits. Table 3 presents the essential parameters (and their values) for energy storage systems (ESSs) for the optimisation of fuel consumption and safety.

Figure 2 provides the planned operational profile of the ship sailing during very bad weather conditions (changing SoC from 70% to 56%). Based on this plan (Fig. 2) and agreements with the shipowner, suitable ESS parameters were selected (Table 3) to ensure the proper operation of the thruster supplied by the hybrid power system. Detailed data concerning battery exploitation are described by the energy and power management system (EPMS), which allows for the monitoring and control of power flow, battery charge levels, charge and discharge limits, and coordination with the SSs and shore chargers (Fig. 1b).

Tab. 3. Recommended parameters of battery-powered systems

ESS parameters	Unit	Value
Battery capacity	[kWh]	565
Setpoint: *Low Low Level*	[kWh]	190
Setpoint: *Low Level*	[kWh]	225
Take-me-home (return to nearest port)	[kWh]	35
SoC after sailing	[%]	56
SoC after charging	[%]	70
Setpoint: *Low safe level limit*	[kWh]	14
	[%]	2.5

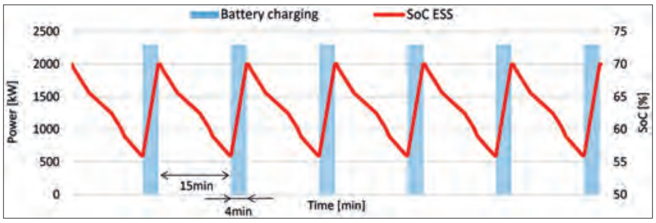

Fig. 2. Planned operational profile of sailing for the studied ferry: red line indicates change of SoC ESS, blue columns represent available high power DC-plug from the built shore infrastructure

In the case of a low-level alarm (indicating a low level of available energy from the batteries), the diesel generator (DG) starts automatically and, in the case of a low low-level alarm (indicating critically low ESS charge), less critical/important devices are automatically shut down. Exceeding the low safe level limit can result in permanent damage to the ESS. In the case of hybrid mode operation (e.g. navigation to the shipyard), the DGs transfer energy to the ESS and, during normal navigation in the electric mode (M1), they work as an emergency power source. Redundancy is based on the previously discussed separation into two ship power systems: AFT and FWD. In the case of a failure in one system, there is the possibility of full control and operation of the other. Redundancy also applies to the integrated automation system (IAS), meaning that the control of devices, such as valves, fans, and pumps, is divided into two separate and independent parts of the system. The ESS has been designed to provide full power to both thrusters, while satisfying the superstructure load requirements (approximately 60 kW). Additionally, during the design phase, considerations were given to the possibility of adverse weather conditions, which could result in higher ESS loads. The connection to the SS at 230/400 V is realised at the AC distribution switchboard at 230 V / 50 Hz. The primary role of the SS is to supply the hotel load and additional systems when the ship is docked in port or at a quay. There is also the possibility of charging the batteries with low power through the SS. The SS system also synchronises and verifies the voltage phase compatibility between the vessel and the port power system.

EXPERIMENTAL VERIFICATION

The examination of the impact of implementing the conditions outlined in the Introduction, as solution I, was experimentally verified on the basis of the sea trials, which mainly addressed electric and hybrid modes of the ferry operation.

Table 4 shows the five possible operational modes of the ferry.

The purpose of the trials was to examine the correct operation of the ship's electrical power system in each of the tested modes and to verify the efficiency of the cooperation between the battery banks and the associated power generation units for optimal power management by the system.

The analysis of the results depends on three operating cases of the electrical power system resulting from positions M1 and M2, as shown in Table 4. The selected cases, T1, T2 and T3, subjected to tests during sea trials, are explained in Table 5.

Tab. 4. Five possible modes of operation of the ferry

Operating modes			
No	Name	Source of power	Description of the system operation
M1* (T1)	Electric mode	ESS	Normal operating mode: AC 690 V / 50 Hz and AC 230 V / 50 Hz distribution boards are powered by a converter from DC 1000 V.
M2* (T2/T3)	Hybrid mode	ESS & DG	Mode used during extended voyages: depending on current power needs, generators provide propulsion requirements and extra energy is transferred to the batteries (charging of battery). With an increased power demand, the batteries release/transfer power to the grid, known as „*peakshaving*".
M3	Diesel–electric mode	DG	Emergency operation mode: DG supplies AC 690 V / 50 Hz, AC 230 V / 50 Hz distribution boards, and thrusters through DC 1000 V.
M4	Shore mode	Shore grid	Supply via SS: the possibility of charging ESS with low power; normal battery-charging mode at night.
M5	Charging mode	Shore grid	High-power charging from shore: the ability to charge the battery banks quickly during a few-minute stop in port.
* under consideration in this study			

In the first mode, Thruster 1 and Thruster 2 operate with step load changes in the range of 20-100% and power is delivered from the ESSs, with their initial SoC ranging from 58-59%.

In the next mode, Thruster 1 operates with the load continuously changing from 0 to 100%, while DG 1 and 2 provide power to the grid and the ESS battery banks charge from the initial state of 49 and 51% up to 55 and 56% (for each battery set). In the last considered mode, T3, there are step changes in the loads of Thruster 1 and 2, in the range 20-100%. In this mode, both DG 1 and 2 operate in parallel and the ESS battery banks cooperate with the grid.

After exceeding the discharge level threshold, the DGs are switched on according to the set priority and their allowed number.

Tab. 5. Modes of operation of the electrical power system verified during the sea trials

Mode of work	Thruster 1	Thruster 2	DG1	DG2	Battery 1	Battery 2
T1	Step load change 20...100%	Step load change 20...100%	–	–	Load	Load
T2	Continuous load change 0...100%	–	Load	Load	Hybrid	Hybrid
T3	Step load change 20...100%	Step load change 20...100%	Load	Load	Hybrid	Hybrid

An essential part of the energy management process is analysing the power management of the thrusters, considering the battery charge/discharge process. An example of this analysis, conducted for operating mode T3 (described in Table 5), is illustrated in Fig. 3.

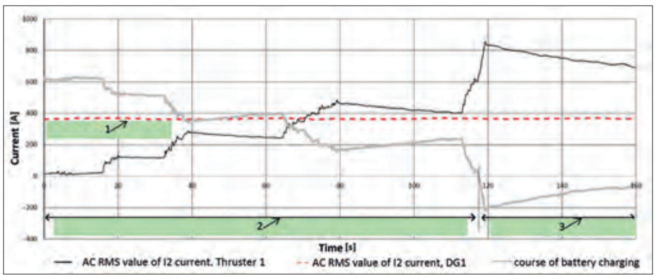

Fig. 3. Time and current traces of DG 1 and Thruster 1 for the T3 operating mode in the context of the energy charging/discharging from the battery packs; 1 - effective point of work of DG1, a constant load of the generator unit DG1, 2 - energy delivered to the battery, charging of the battery, 3 - energy taken from the battery, an increase in the level of available power

The plots in Fig. 3 show the currents when the battery is being charged and discharged, while maintaining a constant current from generator unit DG1, corresponding to the effective operating point of DG1. The battery provides electrical energy when increased power is required and it charges (takes power from the grid) when the system can operate with less available power. The effective DG1 current (dashed red line) is set using the ESS manufacturer's software. It is a result of how the battery charging/discharging processes are controlled, as defined in the ship's control system (SoC, charging current limit and discharging current limit) and in accordance with the previously discussed operational profile of the vessel for various conditions. During battery charging from the DG (hybrid mode M2), the load capacity of the thrusters is limited until the batteries are charged to a level that enables safe operation of the system. Fixed-pitch propellers allow economic ship operation with a shipping speed of 10 knots. During the sea trials (T3 mode), the effective point of work of DG1 was established for a load less than its nominal value, which was approximately 88% of the nominal value.

POWER QUALITY ISSUES

Another objective of the study was to determine and analyse selected parameters of electrical power quality related to voltage and current, in both the DC and AC parts of the system and the frequency values in the AC part. This was to assess the shape of the voltage and current waveforms and to verify whether these parameters were within the limits set by the DNV classification guidelines. Maintaining these parameters at appropriate levels is crucial for ensuring the safety and reliability of maritime systems [21].

The configuration diagram of this power system (Fig. 1b) shows that the 1000 V DC bus bars are the main supply for this ship. Therefore, appropriate DNV limits and measurement results from the tests were compared. The results of this comparison are presented in Table 6.

Tab. 6. Comparison of the DNV voltage limits and test results for electric DC battery-powered systems

Indexes of power quality	DNV voltage limits	Ship tested	
		Measurement results	Mode of tests
δU_{dev} Voltage deviation in equipment connected to battery during charging	+30 to −25%	−11.90% −10.90%	T2 T3
δU_{dev} Voltage deviation in equipment connected to the battery not being charged	+20 to −25%	−13.70%	T1
δU_{var} Voltage cyclic variation	max 5%	4.07% 4.12% 4.07%	T1 T2 T3
δU_{rip} Voltage ripple	max 10%	<<10.00%*	T1, T2 and T3
*did not observe considerable voltage ripples			

The measurement results in Table 6 are illustrated in Figs. 4 and 5.

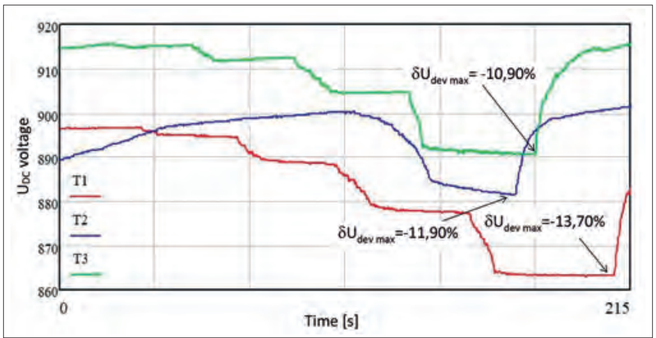

Fig. 4. Changes in the UDC voltage on main bus bar FWD 1000 V for different modes of operation of the hybrid thruster power supply system: T1 - red line, T2 - blue line, T3 - green line

Examples of voltage cyclic variations (δU_{var}) are shown in Fig. 5.

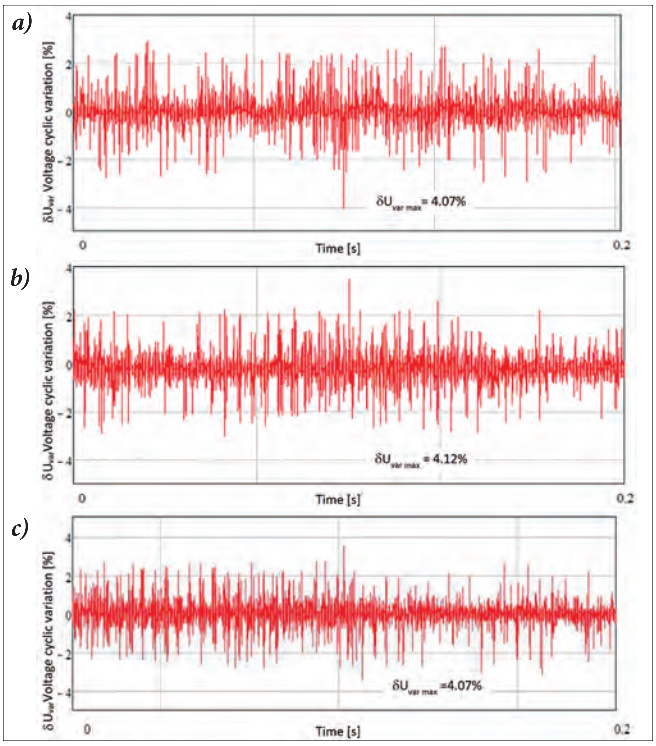

Fig. 5. Voltage cyclic variation (δUvar) based on the measurements in the FWD DRIVE SWDB 1000 V (channel 6) for the different modes of operation: a) T1, b) T2 and c) T3

Examples of the cyclic voltage variations (δU_{var}) in DC voltage, within the range of 0.2 s, are illustrated in Fig. 5. We also determined the highest observed values of the δU_{var} (%) parameter obtained during full-time recording for the T1, T2 and T3 modes of operation. Calculations of the δU_{var} values were carried out based on the relative instantaneous difference in UDC voltage values from the average.

The maximum δU_{var} was 4.12% (for T2 mode) and values of this index complied with the DNV standards for all of the regimes (T1, T2 and T3).

The experiments on voltage limits, as well as the analysis of the supply voltage parameters characterising the related DC network presented in Table 6 and Figs. 4 and 5, confirmed that all the requirements set by the DNV classification limits were met by a significant margin. The results were used to receive the appropriate DNV certificate for this passenger-car ferry.

In addition to the research on the 1000 V DC network, regarding voltage limits following DNV standards, experiments were carried out for AC voltage limits at 690 V / 50 Hz. The results of these experiments are presented in Table 7.

Tab. 7. Comparison of the DNV voltage limits and test results for electric AC-powered systems

Analysed parameters	DNV limits	Measurement results	Test modes
δU_{dev}, Voltage deviation - Steady state			
Deviation of nominal AC system voltage for main power distribution	±2.5%	<0.19%	T2 and T3
Deviation of nominal AC system voltage for emergency power distribution	±3.5%	–	T2 and T3
δU_{dev}, Voltage deviation - Transient state			
Deviation of nominal AC voltage	from −15 to +20%	<0.35%	T2 and T3
δf_{dev}, Frequency deviation			
Deviation of nominal frequency of AC voltage: - under steady state load - under transient load	±5% ±10%	<0.24% <0.6%	T3 T2
Voltage harmonic distortion			
THD_u	8%	<4.5%	T2 and T3

All of the results in Table 7 complied with the DNV classification requirements.

The research scope not only included the acceptable voltage DC and AC deviations from their reference values, but also the acceptable levels of higher voltages and current harmonics in the ship's electrical power system (690 V AC, inverter supplying the thruster).

Research on the variability of current distortion factors has been performed using measured factors: Subgroup total harmonic distortion (THDS), Subgroup total waveform distortion (TWDS) and Subgroup total interharmonic distortion (TIHDS) [22,23]. These are more demanding criteria than the traditional THD factor, as included in [18]. These factors, based on [23], were determined for frequency spectra up to the 100^{th} harmonic.

Figure 6 shows waveforms of the changes in TWDS and THDS distortions of the I1 current of Thruster 1, as a function of time during various system operation modes.

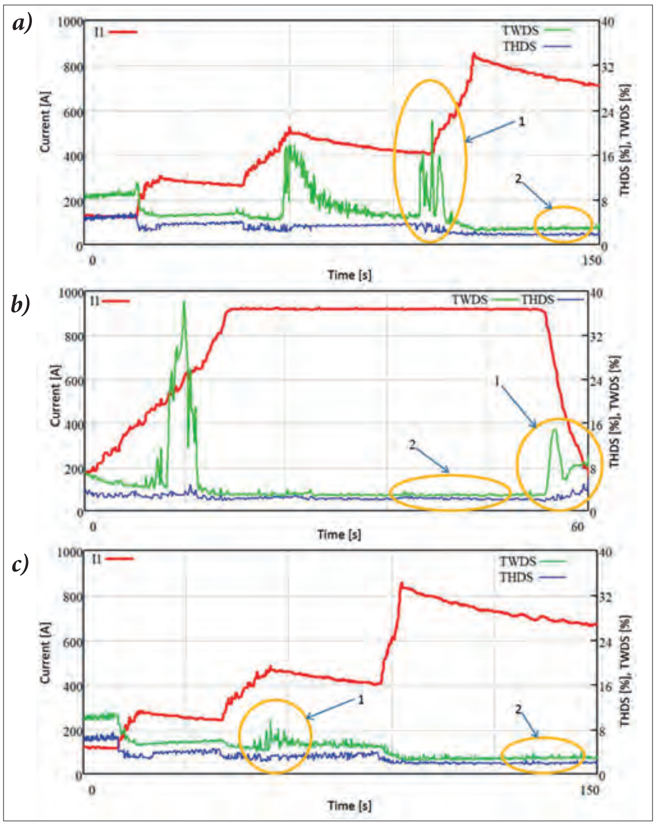

Fig. 6. Selected courses of changes in TWDS and THDS current distortion coefficients for the I1 current of Thruster 1 and its root mean square (RMS) values for different modes of operation; 1 - Transient state values, 2 - Steady state values: T1 - energy delivered from the battery (a), T2 - continuous load change of Thruster 1 (b), T3 - step load change of the Thruster 1 (c)

Figure 6 shows the courses carried out for the T1, T2 and T3 modes and additionally scaled (T1) to the full power of the DC/AC converter, which was dependent on the switching on power procedure during sea trials realisation. The applied inverter was constructed as a switchable device with two symmetrical power levels [24].

The TWDS values are higher than the THDS values at the same moments of time because of their definitions, except for the higher harmonics and other components distorting the signals, such as inter-harmonics. Higher TWDS values were mainly observed in the transient states of the thruster rpm control, which is connected with related step load changes. By contrast, in the steady state, they tend towards values similar to the THDS coefficient (Fig. 6a, 6b, and 6c). The analysed TWDS values should be considered at the ship-design stage, in reference to the selection of the related power-supplying cable cross sections. The operation in T1 mode permits a larger thruster load than in T2 and T3 modes. In T2 and T3, the battery charging process limits the available power of the cooperating generators, which are started and switched on to charge the battery. The course differences in RMS values of the current (shown in Fig. 6) result from the different characteristics of the set load (battery mode, continuous or step load) and the manual value-setting procedure. Additionally, ship operation under the T1 mode (energy delivered from the battery) resulted in a local reduction in the ship's environmental impact, as manifested by noiselessness, a lack of vibrations and CO_2 emission-free navigation.

This effect also concerns the T3 mode but to a lesser degree, because the sources of power are environmentally friendly ESS and DG, as complementary options. The thruster is controlled with step load changes, which is an advantageous option from an environmental point of view. The discussed effect does not apply to the T2 mode, where sources of power are mainly DGs, and the thruster is controlled with continuous load changes, which have more harmful influences on the local environment.

The THDS, TWDS and TIHDS coefficient results characterising the current supply of the thruster (Thruster 1) motor are presented in Table 8. These data are steady-state values for the maximal thruster load.

Tab. 8. Comparison of the current limit requirements from the classifying institutions and test results for the DC battery power systems on the AC side of the inverter installed on the Thruster 1 line

Indexes of power quality from [21]	DNV current harmonic limits	I1 current measurement results for the ship [%]	Mode of test
THDS	Not applicable	1.90	T1
TWDS		2.96	
TIHDS		1.86	
THDS	Not applicable	2.07	T2
TWDS		2.89	
TIHDS		1.70	
THDS	Not applicable	1.96	T3
TWDS		2.99	
TIHDS		1.86	

The measured I2 and I3 current results for Thruster 1 are approximately the same as the values for the I1 current.

Due to the lack of appropriate DNV standards regarding the limitation of emission of harmonic current in thruster power supply systems, the power quality criteria for THDS and TWDS for the I1 thruster current were examined with reference to the PN/IEC 61000-3-4 standard. This standard addresses the "limitation of emission of harmonic current in low-voltage power supply systems for equipment with rated currents greater than 16 A" [25].

Although this standard could be helpful, due to its scope, a rough analysis showed that, unfortunately, this standard only covers devices with a rated current limited to 75 A. Next, for equipment exceeding 75 A, as the input current per phase, it has been stated: "*… the supply authority may accept the connection of the equipment on the basis of the agreed active power of the consumer's installation. The local requirements of the power supply authority apply in this case*". Taking into account the fact that the analysed passenger-car ferry, classified under DNV rules, successfully began operation on February 2021 [16], this means that all technical conditions for regular shipping, including power quality conditions, were fulfilled and accepted by the ferry operator.

CONCLUSIONS AND RECOMMENDATIONS

- According to the theoretical analysis, and based on the experimental results for improving a ship's energy efficiency using existing energy efficiency measures (primarily the

EEDI), the limitation of CO_2 emissions in this case study was realised, based on increases in the 'D' and 'E' components in Eq. (1) with the application of innovative technologies. These innovative technologies concern solutions for minimising energy consumption, which are expressed by the solutions outlined in the Introduction I, II and III and related to the reduction of the demand for the ship's electrical energy (component D in Eq. (1)). These also include the solutions IV, V and VI, leading to minimising ship hull friction and reducing its resistance to water, related to the increase of the value of the product DWT × Vref, which is the transport work of the ship (component E in Eq. (1)).

- In the analysed system, energy consumption was minimised by implementing solutions, such as an appropriately controlled power supply of battery packs, in combination with generator sets. This was partly achieved by selecting a fixed efficient generator operation mode (Fig. 3), using energy-efficient lighting and power supply systems of selected devices, such as propulsion drives, ventilation and air conditioning systems controlled by power electronic converters.
- The implementation of the solutions given above and adaptation of the operating modes of the ship's power system to current operational needs (based on the strategy from the shipbuilder and Norwegian ferry operator), provided a considerable improvement in the vessel's energy balance, while reducing fuel consumption and CO_2 emissions.
- This operation, which assumes that the passenger-car ferry is dedicated to inland shipping and crossing between Norwegian fiords, is achieved using energy from a battery system that is charged during port stays, requiring an appropriate schedule of ship operation. This schedule (Table 4 and Table 5) has been successfully tested during sea trials, especially regarding the electric and hybrid mode functionalities. The study confirmed the functionality and effectiveness of powering the ferry's thrusters using the hybrid battery system, combined with generator units, for effective power management in the system and minimising energy consumption.
- The improved energy balance, in this case, was possible due to appropriately supplied thrusters, many other specific load controls and operations (Table 2) and an appropriately designed simultaneity factor for the loads and degree of power source use. Special attention was paid to the energy balance analysis during the sea trials, which corresponded to the routine operation of the ferry.
- The energy balance was determined in all possible modes of operation for the ferry (Table 4) in combination with energy management recommendations, which are based on the verification of all required functionalities in all operation modes. The authors also used the energy management guidelines within the range of appropriate operational maintenance of batteries (Table 3), in combination with the ESS characteristics and the operational shipping profile (Fig. 2).
- One very important component for the successful realisation of energy management, besides the appropriate choice of the operation mode of the analysed system (Table 4), is the experimental verification of the related design assumptions. The test results are consistent with the ship's design assumptions and confirmed the ability to achieve fuel savings and reduce CO_2 emissions. Moreover, it has been shown that the influence of the ferry operation on the local environment mainly depends on the characteristics of the load changes and the mode of the ferry operation. The most advantageous option is connected with the step load changes and the operation mode supplied by batteries, T1. Under these conditions a local reduction in the ship's environmental impact, as manifested by noiselessness, a lack of vibrations and CO_2 emission–free navigation, will occur.
- The experimental verification of the improvements in ship energy due to the application of a hybrid thruster power supply system considered the variables mentioned above, including the energy balance and management combined with power quality issues. Although the primary concern for a shipbuilder and operator is energy saving, checking whether the power quality parameters are complying with the classification standards is also important and should be required. The checked power quality parameters for 1000 V DC network cover are: $\delta U_{dev} \in <-10.90\%, -13.70\%>$, $\delta U_{var} \in <4.07\%, 4.12\%>$, $\delta U_{rip} << 10\%$, and for 690 V AC network: $\delta U_{dev} < 0.19\%$ (steady state), $\delta U_{dev} < 0.35\%$ (transient state), $\delta f_{dev} < 0.24\%$ (steady state), $\delta f_{dev} < 0.6\%$ (transient state), and THDu < 4.5%. All of the analysed parameters characterising power quality in the 1000 V DC and 690 V AC networks fully comply with the mandatory requirements of the classification standards.
- Additionally, some power quality parameters, related to the thruster current on the AC side of the inverter, were tested in this case study and the following results were obtained: THDS $\in <1.90\%, 2.07\%>$, TWDS $\in <2.89\%, 2.99\%>$ and TIHDS $\in <1.70\%, 1.86\%>$. Taking into account the fact that the presented data are steady-state values for the maximal thruster load, these values are acceptable from a practical operating point of view. However, this analysis was outside the IEC standards.
- In summary, the detailed conclusions and findings regarding the experimental verification for improving the ship's energy with the application of a hybrid thruster power supply system are:
  - Hybrid power supply systems for thrusters enable efficient load compensation, resulting in fuel savings and a reduction in CO_2 emissions.
  - Hybrid systems, along with the operational profile, increase the vessel's operational safety because the energy from battery packs can provide a stable power source and immediate backup power in the case of DG failures. This design approach for ship power systems is necessary and recommended for use in the future.
  - In this analysed system, the DG worked successfully at an optimal, fixed point of work with a constant load of its generator, which also reduced emissions.
  - The installed battery system allows their charging using shore power and replacing with DGs during stays at the port. Consequently, this provides a local reduction in the ship's environmental impact when operating in battery mode.

– The advantages described above were achieved due to the innovative application of the thruster supplied by the hybrid power system without altering the power quality requirements of the analysed system.

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LIST OF ABBREVIATIONS

AC	– Alternating Current
AFT	– After part of vessel
CII	– Carbon Intensity Indicator
CNG	– Compressed Natural Gas
DC	– Direct Current
DG	– Diesel Generator unit
DNV	– Det Norske Veritas
DWT	– Deadweight Tonnage of the Ship
EEDI	– Energy Efficiency Design Index
EEOI	– Energy Efficiency Existing Ship Index
EEOI	– Energy Efficiency Operational Indicator
EPMS	– Energy and Power Management Ship
ESS	– Energy Storage System
FWD	– Forward part of vessel
GHG	– Greenhouse Gas Emission (from Ship)
GT	– Gross Tonnage of the Ship
IEC	– International Electrotechnical Commission
IGBT	– Insulated-Gate Bipolar Transistor
IMO	– International Maritime Organization
LED	– Light Emitting Diode
LEM	– Life Energy Motion
LNG	– Liquefied Natural Gas
M	– Motor
MARPOL	– The International Convention for Prevention of Pollution from Ships
MEPC	– Marine Environmental Protection Committee
PEM	– Power Electronic Measurements
PWM	– Pulse Width Modulation
RMS	– Root-Mean-Square (value)
RPM	– Revolutions per minute
SFC	– Specific Fuel Consumption
SoC	– State of Charge
SS	– Shore Supply
SWBD	– Switchboard
THD	– Total Harmonic Distortion
THDS	– Subgroup Total Harmonic Distortion
TIHDS	– Subgroup Total Interharmonic Distortion
TWDS	– Subgroup Total Waveform Distortion

REFERENCES

1. IMO documents on "Improving the energy efficiency of ships", Available online: https://www.imo.org/en/OurWork/Environment/Pages/Improving%20the%20energy%20efficiency%20of%20ships.aspx (accessed on 29.06.2023).

2. https://www.imo.org/en/MediaCentre/MeetingSummaries/Pages/MEPC-80.aspx (accessed on 11.12.2023).

3. IMO Annex 1, Resolution MEPC.328(76), "Amendments to the annex of the protocol of 1997 to amend the international convention for the prevention of pollution from ships, 1973 - As modified by the protocol of 1978 relating thereto". 2021. Revised MARPOL Annex VI. Date of entry into force: 1 November 2022.

4. O. Alnes, S. Eriksen, and B. Vartdal, "Battery-Powered Ships: A Class Society Perspective", IEEE Electrification Magazine. 5(3), pp. 10-21, 2017. doi:10.1109/MELE.2017.2718823.

5. E. Skjong, R. Volden, E. Rødskar, M. Molinas, T.A. Johansen, and J. Cunningham, "Past, Present, and Future Challenges of the Marine Vessel's Electrical Power System", IEEE Transactions on Transportation Electrification. Vol. 2, No 4, pp. 522-537, 2016. doi:10.1109/TTE.2016.2552720.

6. P. Geng, X. Xu, and T. Tarasiuk, "State of Charge Estimation Method for Lithium-Ion Batteries in All-Electric Ships Based on LSTM Neural Network", Polish Maritime Research. 3 (107), Vol. 27, pp. 100-108, 2020. doi:10.2478/pomr-2020-0051.

7. M. Kunicka and W. Litwin, "Energy efficient small inland passenger shuttle ferry with hybrid propulsion - concept design, calculations and model tests", Polish Maritime Research. Vol. 26, No 2, pp. 85-92, 2019. doi:10.2478/pomr-2019-0028.

8. IMO Resolution MEPC 308(73), Annex 5, "Guidelines on the method of calculation of the attained energy efficiency design index (EEDI) for new ships", London, 2018.

9. D. Kumar and F. Zare. "Comprehensive review of Maritime Microgrids", IEEE Access. Volume 7, pp. 67249-67277, 2019. doi:10.1109/ACCESS.2019.2917082.

10. W. Zeńczak, "The selected ways of improving the factors of energy efficiency of ships", Journal of Gdynia Maritime University. No 108, pp.181-196, 2018. doi:10.26408/108.15.

11. T. Szelangiewicz, T. Abramowski, K. Żelazny, and K. Sugalski, "Reduction of Resistance Fuel Consumption and GHG Emission of Small Fishing Vessel by Adding a Bulbous Bow", Energies. 14, 1877, 2021. doi:10.3390/en14071837.

12. IMO Resolution MEPC 62(24) Add.1, Annex 19 – Resolution MEPC 203(62), 2011.

13. IMO Annex 11, Resolution MEPC 337 (76), 2021 Guidelines on the reference lines for use with operational Carbon Intensity Indicators, related to the revised MARPOL Annex VI, November 2022.

14. "Energy Efficiency of Ships: What Are We Talking About?" Accessed on: 29.06.2023, Available: https://www.transportenvironment.org/wp-content/uploads/2021/05/2012_12_Ship_efficiency_briefing.pdf.

15. "Guidelines for Voluntary Use of the Ship Energy Efficiency Operational Indicator (EEOI)", document MEPC.1/arc.684, Aug.2009.

16. "Information materials about considered passenger-car ferry". Available online: https://www.gospodarkamorska.pl/stocznia-remontowa-shipbuilding-przekazala-norwegom-prom-elektryczny-fodnes-57277#lg=1&slide=0 (accessed on 22.06.2023).

17. Information materials about VACON® NXP DCGuard. Available online: https://files.danfoss.com/download/Drives/DKDDPFP906A402_VACON%20NXP%20DCGuard_LR.pdf (accessed on 13.12.2023).

18. DNV, Rules for the Classification of Ships, Part 4 Systems and Components, Chapter 8, Electrical installations, July 2022 edition.

19. A. Wantuch and M. Olesiak, "Effect of LED Lighting on Selected Quality Parameters of Electricity", Sensors. 23(3), 1582, 2023. doi:10.3390/s23031582.

20. IEC 61000-3-2:2019-04-Electromagnetic Compatibility (EMC). Part 3-2: Limits. Limits for Harmonic Current Emissions (Equipment Input ≤ 16A per Phase).

21. P. Gnaciński, T. Tarasiuk, J. Mindykowski, M. Pepliński, M. Górniak, D. Hallmann, and A. Piłat, "Power Quality and Energy – Efficient Operation of Marine Induction Motors", IEEE Access. Vol.8, pp.152193-152203, 2020. doi:10.1109/ACCESS.2020.3017133.

22. J. Mindykowski and T. Tarasiuk, "Problems of power quality in the wake of ship technology development", Ocean Engineering. Vol.107, pp.108-117, 2015. doi:10.1016/j.oceaneng.2015.07.036.

23. J. Mindykowski, T. Tarasiuk, and P. Gnaciński, "Review of legal aspects of electrical power quality in ship systems in the wake of the novelisation and implementation of IACS rules and requirements", Energies. 14(11), 3151, 2021. pp. 1-21, doi:10.3390/en14113151.

24. Technical documentation concerning VACON-NXI-Inverters, FI9-FI14, https://files.danfoss.com/download/Drives/VACON-NXI-Inverters-FI9-FI14-Operating-Guide-DPD00909F-EN.pdf (accessed on 13.12.2023).

25. IEC 61000-3-4 standard, "Limitation of emission of harmonic current in low-voltage power supply systems for equipment with rated current greater than 16A.", First edition 1998-10, Geneva, Switzerland.