TRANSNAV
http://www.transnav.eu
the International Journal
on Marine Navigation
and Safety of Sea Transportation
Volume 19
Number 4
December 2025

DOI: 10.12716/1001.19.04.XX

Power Quality Assessment of a Modern Ship Power System With Batteries and Diesel Generators – Case Study

J. Mindykowski[1], M. Górniak[1], A. Piłat[1] & Ł. Wierzbicki[2]
[1] *Gdynia Maritime University, Gdynia, Poland*
[2] *Gdansk Remontowa Ship-Repair Yard S.A., Gdańsk, Poland*

ABSTRACT: In this study the authors firstly present a generic diagram of power quality assessment methodology for a modern ship power system with batteries and diesel generators, and secondly, illustrate all methodology procedures in the form of the case study results, obtained from sea trials. The proposed methodology is based on analysis of the configuration and load of the system under consideration, taking into account the system's operation modes, while excluding the modes in which the ship is supplied via shore grid. The authors experimentally examined and analysed the electric and hybrid modes using data collected from sea trials results of the passenger-car ferry. Finally, an overall assessment of power quality in the considered power system is presented.

1 INTRODUCTION

The challenges associated with modern electric ship propulsion, including a hybrid AC/DC systems and pure DC systems, have gained significant attention. These issues have become increasingly important due to the pressing need for greater energy efficiency and fuel savings, as well as the reduction of greenhouse gas emissions, including CO_2, NO_x, and SO_2. These challenges represent some of the most intensively studied topics in the maritime transport sector and pose critical problems for shipbuilders, operators, and regulatory bodies to address. Such challenges are closely linked to issues as electrical stability, harmonic distortion and power quality stand-alone microgrids, like as those found in marine vessels. Furthermore, the role of battery energy storage systems in enabling emission-free operation within these microgrids is a key area of interest.

Taking into account the historical context the authors of the papers [1-3] have analyzed the impact of new conversion technologies, such as power electronics, battery energy storage and DC power system on overall energy efficiency, power quality, and emission level. These studies explore various possibilities of using the batteries in different configurations of ship power systems and present cases where the BESS (Battery Energy Storage System) is connected to the main bus (switchboard) in an Integrated Power System Configuration or where BESS is a part of a motor drive for propulsion. In the first option an AFE power converter (Active Front End) is installed alongside the BESS as a solution for supervision and control purposes [3]. A few papers have presented the main problems encountered by designers of small, hybrid-powered ferries supplied by lithium batteries, including energy balance issues and the development of an energy management policy [4].

One of the most important solutions belonging to the class of hybrid AC/DC systems is a modern ship power system with batteries and diesel generators, presented, among others, in the papers [5, 6]. In these papers, the authors considered and compared their results with existing state-of-the-art methods in the field of widely understood means to improve the energy efficiency of ships, using a thruster supplied by a hybrid power system [5] or by using an autonomous hybrid system with a PMSG (Permanent Magnet Synchronous Generator) [6]. It is worth noting that in the first case [5], a ship power plant configuration is equipped with two MSB (Main Switchboards): DC and AC, respectively, but in the second case [6], the related power plant configuration includes only AC MSB. Another important property of the both aforementioned ship power systems with batteries and diesel generators is that their specific operational characteristics must be analyzed in five basic modes, as defined by the ship designers and operators [5, 6].

In this paper, the case study concerning the modern, two-way hybrid electric ferry is presented and thoroughly analyzed. The ferry was designed for coastal shipping between Norwegian fjords with the assumption that, during crossings between ports, energy will be primarily sourced from battery banks, which will be charged during stops at quay. 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, aligned with of the policy of the reduction of greenhouse gases emission. Achieving energy consumption reduction requires to implement of several solutions, including innovative hybrid power systems and selected electrical installations such as: (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 [5].

The goal of this study is to examine the impact of implementing conditions (I), (II) and (III) for improving the energy efficiency of the ship in accordance with philosophy and strategy of its operation, while maintaining the appropriate values of electrical energy quality parameters following the standards of Det Norske Veritas (DNV) [7], which surveys the construction process before classifying 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 regulations [7]. However, additional checks of power quality standards related to currents are justified by the fact that the systems described under conditions (II) and (III) can significantly minimise electrical energy consumption. Nevertheless, strongly non-linear elements (LED lighting and power electronic inverters) can negatively affect the power quality in the considered electrical power system.

The first condition (using the power system with batteries and DG generating sets) is an energy–saving solution without negative consequences for power quality. The second condition (applying energy-saving LED lighting) may have a negative impact on selected electricity quality parameters [8]. Results have shown that LED lamps provide significant savings in electricity, however they behave as nonlinear loads, generating higher frequency harmonics, which may degrade power quality in the distribution network [8, 9]. In our case, the problem concerns the large number of devices equipped with rectifiers used to power multiple of LED lamps in the AC system. The third implemented solution involves flexible power supply systems, using power electronic inverters. Some load circuits consist of systems with motors controlled by power converters, including propulsion, ventilation, air conditioning and cooling systems. Powering motors with variable frequency drives enables load adjustment to actual operational needs. In such cases, the total energy consumed by all electric motors on the ship can be significantly reduced. However, using multiple-power electronic converters may increase total harmonic distortion (THD) in the current waveforms. Therefore, although the primary concern for the shipbuilders and operators is energy saving, verifying power quality compliance with the classifying institution standards remains essential. To sum up, the main objective of this article is to draw attention to the power quality on modern ships equipped with different energy sources, operating under various modes, and to emphasize the necessity of its overall assessment.

The paper is organized as follows. In the second section, we provide a short description of power quality assessment methodology for a modern ship power system with batteries and diesel generators, based on the authors' proposed flow-chart. In the next section a recommended methodology is developed as a case study using the test results obtained from sea trials. This section covers various aspects, including a brief characterization of the investigated object, analysis of its configuration and load, measurements and calculations of power quality parameters, and overall power quality assessment for DC and AC busbars as well as for selected PCC (Point of Common Coupling) related to the thruster.

2 PROPOSED METHODOLOGY

Power quality assessment methodology for a modern ship power system with batteries and diesel generators is based on the authors' concept presented in the form of flow-chart in Fig.1.

The proposed methodology is based on analysis of the configuration and load of the system under consideration, taking into account its operational modes, while excluding modes, when the ship is supplied via shore grid such as shore supply (SS). These modes, namely electric mode, hybrid mode and diesel – electric mode are generally defined by appropriate configurations of cooperating sources of power, such as ESS (Energy Storage Systems) and DG (Diesel Generator), together with the system's load conditions. Table 1 presents the five possible operational modes of the ferry's exploitation [5,6].

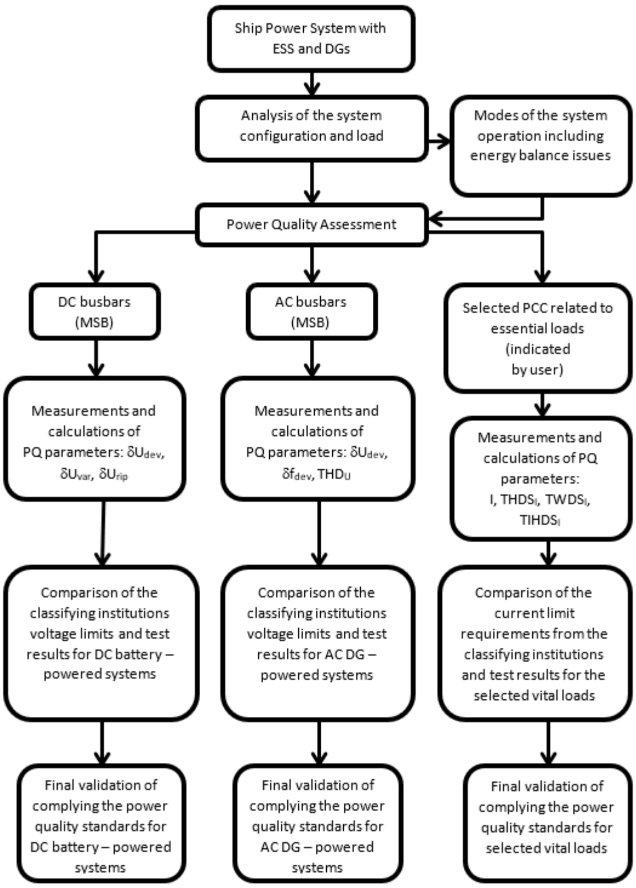

Figure 1. Flow-chart of the performed investigation and procedure for validation of the overall power quality assessment.

Table 1. 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 demands, generators provide propulsion power and extra energy is transferred to the batteries (battery charging). With higher power demand, the batteries discharge power into the grid, a process known as "peak shaving".
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: allows for charging ESS at low power; normal battery-charging mode operates during night time.
M5	Charging mode	Shore grid	High-power charging from shore: provides the ability to charge the battery banks quickly during short stop in port.

*under consideration in this study

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 1. The selected cases - T1, T2 and T3, were subjected to tests during sea trials and are explained in Table 2.

Table 2. 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

Analysis of the load primarily focuses on the essential load identified by the user, however, other important loads were also taken into account from the energy balance perspective. Next, the power quality assessment procedure was developed with focus on three aims of main objectives: DC busbars, AC busbars and selected PCC (Point of Common Coupling) related to the essential loads identified by operator of the system (e.g. thrusters or important pumps). All parameters were analyzed in appropriate operational modes. The obtained results were compared with the voltage and current limits established by the relevant classifying institutions for DC battery-powered systems, AC DG-battery-powered systems and for the selected vital loads, respectively. Finally, a validation of compliance with power quality standards established by classifying institutions for the all analyzed parts of the system under consideration, will be conducted.

3 ANALYZED CASE STUDY

3.1 *The object of the investigation*

A simplified diagram of the considered modern ship power system with batteries and diesel generators is illustrated in Fig.2.

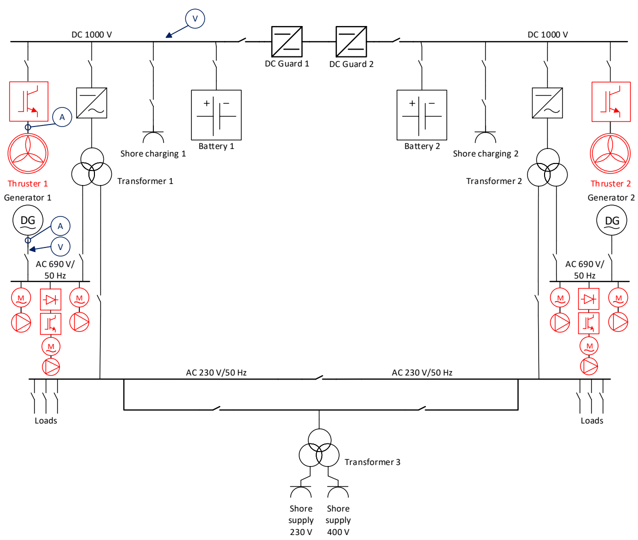

Figure 2. Simplified diagram of the modern passenger-car ferry power system with batteries and diesel generators, the elements shown in red colour indicate the selected loads of the system.

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 DG 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 with a total capacity of 1,13 MWh and a propulsion system with a motor rated at 960 kW, 600 V, and 68 Hz, which is powered by a DC/AC converter. The propulsion unit from SCHOTTEL is supplied from the 68 Hz DC 1000 V distribution board using a VACON NXI power electronic converter, which functions as an inverter. The inverter consists of IGBT switches and generates a symmetrical, 3-phase PWM-modulated AC voltage for the motor. The elements in the configuration diagram are designated indexes as follows: '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 generators. 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 [10], which enable fast disconnection and full selectivity between forward and aft DC bus bars sections.

3.2 *Analysis of the system configuration and load*

Analysis of the load primarily focused on the essential load represented by thrusters (main ship propulsion). However, other important loads were also considered from the energy balance perspective. The energy balance includes the specification of DC and AC energy sources and their parameters, as well as specifications and characteristics of the most important loads in the analyzed system. Detailed specifications and in-depth analysis concerning energy balance in the considered case study can be found in [5]. It is important to note that carried out analysis mainly covered loads active during sea trials. Among them, certain devices were supplied from AC 690 V, using power electronic frequency converters, aspect particularly relevant from the perspective of power quality standards. These loads are shown in Table 3.

Table 3. The loads controlled by power electronic frequency converters supplied from AC 690 V network

No	Name of device	Power [kW]	Current [A]	Switchboard
1*	HP-1 Aers Central Heat/Cool System	17,9 kW	16,6 A	FWD
2	Fire Bilge Pump 1	43,6 kW	40,5 A	FWD
3	Fire Pump 1	30 kW	27,9 A	FWD
4	Deluge Pump	160 kW	148,8 A	FWD
5	Steering Pump Fwd	22 kW	20,5 A	FWD
6*	HP-2 Aers Central Heat/Cool System	45 kW	41,8 A	AFT
7	Fire Bilge Pump 2	43,6 kW	40,5 A	AFT
8	Fire Pump 2	30 kW	27,9 A	AFT
9	Deluge Pump	160 kW	148,8 A	AFT
10	Steering Pump Aft	22 kW	20,5 A	AFT

* - In these control loops of the system a VLT® HVAC Drive FC 102 unit was used as inverter

The analyses presented in [5] indicate that the total sum of the energy loads from the thrusters supplied by the 1000 V DC voltage (along with other loads powered from the 690 V AC and 230 V AC voltages) reaches up to 2619.7 kW (including 1920 kW for 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 [5] only operate during limited and different time intervals, depending on ferry operation mode. Thrusters typically consume power below their rated values, governed by appropriately designed simultaneity coefficient for the analyzed power system. Some simultaneity load coefficient and degrees of power source values shown in Table 2 [5] have been determined on the basis of the shipyards' ferry documentation and the authors sea-going practice. It was assumed that the sea trials loads and power sources combinations corresponded to the routine, regular conditions for scheduled ferry crossings between two Norwegian fjords. Therefore, the operating conditions were defined based on estimated values for load coefficients, degrees of power sources utilized, and a specific operational regime, i.e. a vessel operating during a 15 minute crossing between Norway fiords, 26 times in a normal day, where a single crossing distance is 3 km. Therefore, achieving energy balance in the analyzed electrical power system is possible. This balance was maintained across all possible operational modes of the ferry by implementing energy management recommendations. These recommendations focused on improving energy efficiency, analyzing and implementing appropriate battery maintenance strategies, and analyzing and verifying all required functionalities across all operational modes of the ferry.

3.3 *Measurement and calculations of power quality parameters*

In order to obtain power quality parameters for the power system of the considered ferry measurements of instantaneous values of voltages and currents were performed based on the diagram presented in Fig. 3a. The voltage measurements were carried out via transducers from LEM (Life Energy Motion) and the current measurements were made using Rogowski's coils from PEM (Power Electronic Measurements). The measurement system (Fig.3a) consisted of an industrial computer from National Instruments, equipped with PXIe-8135 controller and three PXIe-6358 data acquisition cards. The registered samples of the voltages and currents were used to determine the power quality parameters. The parameters were calculated using home-built software and a dedicated spreadsheet. Technical realizations of the exemplary voltage and current measurements are illustrated in Fig.3b and 3c.

A main objective of the study was to determine and analyse selected parameters of power quality related to voltage and current, in both the DC and AC parts of the system as well as to the frequency in the AC part. The research scope not only included acceptable deviations DC and AC voltages from their reference values, but also the permissible levels of higher voltages and current harmonics in the selected PCC of ship's electrical power system i.e. inverter supplying the thruster (Fig.2). 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 [11]. In the presented case study three objectives were defined as follows: the 1000 V DC busbars as the main supply for the ship, 690 V AC busbars as the complementary supply and the PCC 600 V AC related to the inverter supplying the thruster. The obtained measurement and calculations results aimed to determine parameters that characterize power quality at designated locations in Fig.2, are: δU_{dev}, δU_{var} and δU_{rip} at the DC busbars, δU_{dev}, δf_{dev} and THD_U at the AC busbars and I, $THDS_I$, $TWDS_I$ an $TIHDS_I$ in the PCC corresponding to DC/AC thruster converters. All parameters were analysed in electric and hybrid modes (Table 1 and Table 2). Examples of the cyclic voltage variations (δU_{var}) in DC voltage, within the range of 0.2 s, are illustrated in Fig.4. Authors 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.

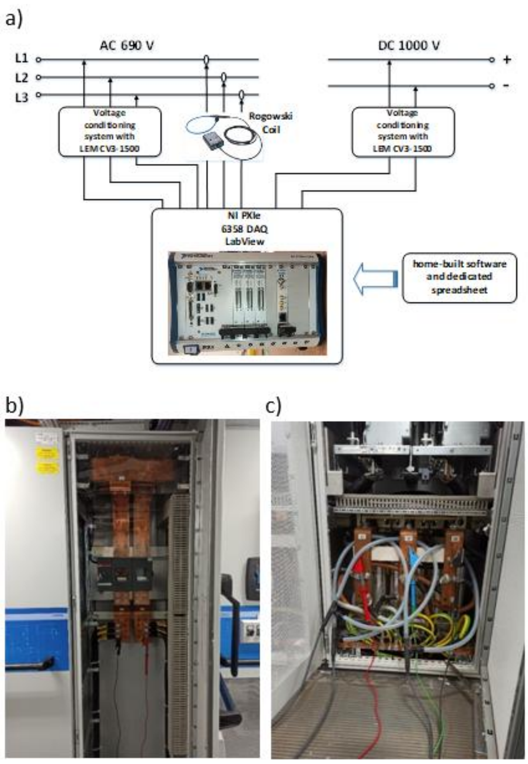

Figure 3. Measurements of voltage and currents in the passenger-car ferry power system: a) measurement system diagram, b) voltage measurement on the DC busbars, c) voltages and currents measurement on the AC terminals.

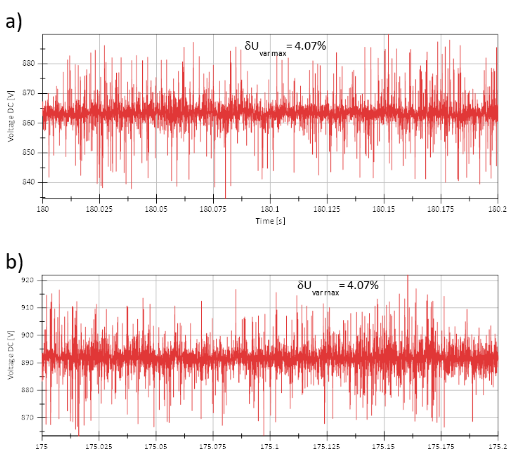

Figure 4. Voltage cyclic variation (δU_{var}) based on the measurement in the DC main switchboard of 1000 V (performed according to Fig.3a and 3b) for the different modes of operation: a) T1, b) T3.

The configuration diagram of this power system (Fig.2) 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 4.

Table 4. 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 maximum value of δU_{var} was 4.12% (for T2 mode) and the obtained results of this index complied with the DNV standards for all of regimes (T1, T2 and T3). In addition to the research on the 1000 V DC network, regarding voltage limits following DNV standards, experiments for AC voltage limits at 690 V / 50 Hz were carried out. Exemplary waveforms are illustrated in Fig.5 and the results of these experiments are presented in Table 5.

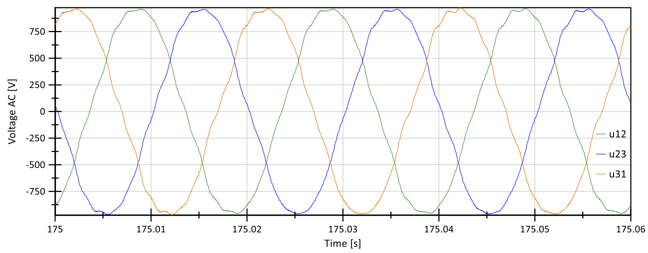

Figure 5. The phase-to-phase voltage waveforms registered on the AC main switchboard of 690 V (performed according to Fig.3a), hybrid mode is T3, current load of DG is equal 367 A in all time of the test.

Table 5. Comparison of the DNV voltage limits and test results for AC 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

The THD_u limit value specified in DNV standards based on IEC 61000-2-4 class 2 norm is defined as the ratio of root sum of squares of the RMS values of all the harmonic components up to the 50th order to the RMS value of the fundamental component. On the other hand the acceptance of the THDS definition (Total Harmonic Distortion Subgroup) applied in the IEC 61000-4-7 norm improves an evaluation of harmonic distortion compared to the THD_u criterion, especially in ship systems, known as "soft systems" [3,11]. Therefore THDS factor is calculated as follows:

$$THDS = \frac{\sqrt{\sum_{h=2}^{50} SG_h^{\,2}}}{SG_1} \cdot 100\,[\%] \qquad (1)$$

where: SG_1 – RMS value of fundamental component subgroup and harmonic subgroups SG_h of h-order are calculated as:

$$SG_h = \sqrt{\sum_{i=-1}^{1} C_{10h+i}^{2}} \qquad (2)$$

where: SG_h – RMS value of harmonic subgroup of h-order, C_{10h} – RMS value of respective frequency bin in the Fourier Series, calculated by means of DFT, for 50 Hz system, index *10h* refers to 10 periods (for 60 Hz system, a designation C12h appears as referring to 12 periods).

An approach described by formulae (1) and (2) does not cover distortions above 50th – order harmonics. Even extension of the frequency band up to the 100th harmonic does not provide a comprehensive solution for many cases in ship networks, particularly where the AFE PWM (Active Front End-Pulse Width Modulation) drives are used [12]. In this kind of ship power systems, only viable solution is the TWD (Total Waveform Distortion) factor, defined as the ratio of the RMS value of the voltage residue, after elimination of the fundamental component, to the RMS value of the fundamental component, expressed as a percentage. Taking into account the above mentioned concept of subgroups, this factor is calculated as follows [13, 14]:

$$TWDS = \frac{\sqrt{U_{rms}^{\;2} - SG_1^{\,2}}}{SG_1} \cdot 100[\%] \qquad (3)$$

where: U_{rms} – is the voltage RMS value.

To complete a description of the waveform distortions in ship power systems, a concept of TIHDS (Total Interharmonic Distortion Subgroups) factor, similarly to the formulae (1) and (3) may be described as follows:

$$TIHDS = \frac{\sqrt{\sum_{h=1}^{49} SGi_h^{\,2}}}{SG_1} \cdot 100\,[\%] \qquad (4)$$

where interharmonic subgroups are expressed as:

$$SGi_h = \sqrt{\sum_{i=2}^{8} C_{10h+i}^{2}} \qquad (5)$$

where: SGi_h is the RMS value of interharmonic subgroups between harmonic *h* - order and *h+1* order. A relationship (4) covers interharmonic distortions up to 50th – order.

In the analyzed case study the maximum registered values of voltage distortion factors on the busbars AC 690 V, 50 Hz, (Fig.2), determined for the frequency band up to 50th - harmonic order and up to 100th – harmonic order were compared in Table 6.

Table 6. Comparison of maximal registered values of voltage distortion factors on the busbars AC 690 V, 50 Hz determined for both frequency bands, up to 50th and 100th harmonic order

Analysed parameters	Frequency band	Obtained values [%]
TWDSU	Up to 50th – harmonic order	3.72%
THDSU		3.66%
TIHDSU		0.55%
TWDSU	Up to 100th – harmonic order	3.72%
THDSU		3.69%
TIHDSU		0.68%

All results presented in Table 5 complied with the DNV classification requirements. Additionally, the results shown in Table 6, although based on more demanding criteria than those complied with the DNV classification requirements [7].

Research on the variability of current distortion factors in the PCC related to the thruster AC 600V, 68 Hz motor (Fig.2) has been performed using previously presented factors: Total harmonic distortion subgroups (THDS), Total waveform distortion subgroups (TWDS) and Total interharmonic distortion subgroups (TIHDS) [13,14], referred to the thruster current and named as THDSI, TWDSI and TIHDSI respectively. In this case there are more demanding criteria for waveform distortion assessment than the traditional THD factor, as included in [7]. Based on [14], these factors were determined for frequency spectra up to the 100th harmonic. Figures 6 and 7 show current waveforms changes in the three phases and current frequency spectrum up to 50th harmonics in the first phase of thruster's motor (Thruster 1) for its load close to the nominal working in T1 mode.

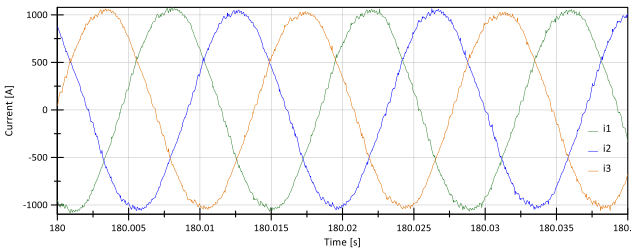

Figure 6. Current waveforms of Thruster 1 (according to Fig.2) in three phases for its load close to nominal I_{rms}=748 A, $TWDS_I$=2.96%, $THDS_I$=1.85%, $TIHDS_I$=1.67%.

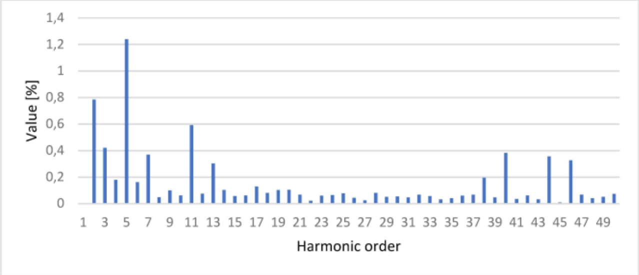

Figure 7. Current frequency spectrum of Thruster 1 determined up to 50th harmonic order for its load close to nominal, for T1 operation mode (for better reliability the fundamental component corresponding to 100% has been removed).

In the presented spectrum of current (Fig. 7) characteristic harmonic of 5th, 7th, 11th, 13th order are visible, but also there are slightly increased values of harmonic near end of the spectrum. The last ones are related to the switching frequency of the drive inverter transistors, which is 3 kHz (current fundamental frequency is about 70 Hz).

It is worth adding that one of the leading classification societies suggests analyzing the signal spectrum up to the 100th harmonic in the case of AFE systems [12]. However, in this case, such an approach is not required for two reasons. Firstly, in a wider frequency band (up to the 100th harmonic), no increased level of harmonics is observed, and secondly, the harmonic content values in the 50th range are relatively small, which is generally reflected in the $TWDS_I$, $THDS_I$, $TIHDS_I$ coefficients values.

Due to the lack of appropriate DNV standards regarding the limitation of harmonic current emission in thruster power supply systems, the power quality criteria for THDSI and TWDSI for the I1 thruster current were examined with reference to the PN/IEC 61000-3-4 standard [15]. 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".

Although this standard could be helpful, due to its scope, a rough analysis showed that, unfortunately, it only applies to devices with a rated current limited to 75 A. Furthermore, for equipment exceeding 75 A as the input current per phase, it states: *"… 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 requirements, were fulfilled and accepted by the ferry operator.

Table 7. 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 in the Thruster 1 line

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

The $THDS_I$, $TWDS_I$ and $TIHDS_I$ coefficient values characterising the current supply of the thruster motor (Thruster 1) are presented in Table 7. These data are calculated in steady-state conditions for the maximum thruster load, close to its nominal.

The measured I2 and I3 current results for Thruster 1 are approximately the same as the values for the I1 current, shown in Table 7.

4 CONCLUSIONS AND RECOMMENDATIONS

In the analysed system, energy consumption was minimised by implementing solutions, such as an appropriately controlled power supply i.e. battery banks, in combination with generator sets. This was partly achieved by selecting fixed and efficient generator operation mode, using energy-efficient lighting and power supply systems for selected devices, such as propulsion, ventilation and air conditioning systems controlled by power electronic converters. Aforementioned technical solutions can significantly reduce electrical energy consumption in line with the strategy of shipbuilder and ferry operator, but on the other hand they pose potential threats regarding power quality deterioration in the system. Thus, checking whether the power quality parameters comply with the classifying institution standards is justified and required.

The proposed methodology for power quality assessment in a modern ship power system with batteries and diesel generators is based on analysis of the configuration and load of exemplary ferry system, taking into account the modes of the system operation, while excluding those modes, when the ship is supplied via shore grid. These modes, namely the electric mode, the hybrid mode i.e. diesel – electric mode are generally defined by appropriate configurations of cooperating sources of power, such as ESS (Energy Storage Systems) and DG (Diesel Generator), together with the system's load conditions.

Starting from the aforementioned analysis illustrated in flow-chart diagram, the power quality assessment procedure was developed with focus on three main objectives: 1000 V DC busbars as the main power supply, 690 V AC busbars as the complementary power supply and the PCC 600 V AC related to the inverter supplying the thruster's motor.

Although the primary issue for a shipbuilder and operator is energy saving, checking whether the power quality parameters are complying with the classification standards is also important and necessary. The checked power quality parameters for 1000 V DC network are: $\delta U_{dev} \in$ <–10.90%, –13.70%>, $\delta U_{var} \in$ <4.07%, 4.12%>, δU_{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 $THD_u < 4.5\%$. Therefore it should be stated, that 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 DNV classification standards.

Additionally the parameters describing voltage waveform distortions on the AC 690 V busbars determined according to more demanding criteria than those defined above, indicate no significant threats from the power quality point of view. Those parameters were defined for the frequency band up to 50th harmonic order as: $THDS_U$ = 3.66%, $TWDS_U$ = 3.72%, and $TIHDS_U$ = 0.55% as well as for the frequency band up to 100th harmonic order as: $THDS_U$ = 3.69%, $TWDS_U$ = 3.73%, and $TIHDS_U$ = 0.68%.

Furthermore, 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: $THDS_I \in$ < 1.90%, 2.07% >, $TWDS_I \in$ < 2.89%, 2.99% > and $TIHDS_I \in$ < 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 is outside the IEC standards.

In summary, the detailed conclusions and findings regarding a power quality on modern ships equipped with different energy sources such as ESS and DGS with the application of a hybrid thruster power supply system are:

- Electric hybrid systems, along with the operational profile, increase the vessel's operational safety, as energy stored in battery banks can provide a stable power source and immediate backup power in the case of DG failures. This design approach for ship power systems is essential and recommended for future applications.
- The installed battery system ESS enables charging via shore power, providing an alternative source of power to DGs during port stops. This capability reduces the ship's local environment impact when operating in battery mode.
- The advantages outlined above were achieved due to the innovative application of the thruster supplied by the hybrid power system without negative impact on affecting the power quality in the analysed system.

ACKNOWLEDGEMENTS

The authors are grateful to the authorities, designers and shipbuilders from Remontowa Shipbuilding S.A. and Remontowa Electrical Solutions for providing us with company procedures to perform the sea trials and for the related databases and raw measurements for this case study.

REFERENCES

[1] S.Kim, S.Choe, S.Ko, S.Sul, "A Naval Integrated Power System with a Battery Energy Storage System: Fuel efficiency, reliability, and quality of power". IEEE Electrification Magazine, Vol.3, No 2, pp. 22-33, June 2015.

[2] K.Divya, J.Stergaard, "Battery energy storage technology for power systems—An overview", Electric Power Systems Research, Vol.79, No 4, pp. 511-520, April 2009.

[3] 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.

[4] 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.

[5] J.Mindykowski, Ł.Wierzbicki, M.Górniak, A.Piłat, "Analysis and Experimental Verification of Improving the EEDI of a Ship using a Thruster Supplied by a Hybrid Power System", Polish Maritime Research, Vol. 31, No 1, pp. 43-54, 2024.

[6] D.Tarnapowicz, S.German-Galkin, A. Nerc, M.Jaśkiewicz, "Improving the Energy Efficiency of a Ship's Power Plant by Using an Autonomous Hybrid System with a PMSG", Energies, 2023, 16, 3158, pp. 1-19.

[7] DNV, Rules for the Classification of Ships, Part 4: Systems and Components, Chapter 8, Electrical installation, July 2022 edition.

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

[9] IEC 61000-3-2:2019-04-Electromagnetic Compatibility (EMC). Part 3-2: Limits. Limits for Harmonic Current Emissions (Equipment Input ⩽ 16A per Phase), 2019.

[10] 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).

[11] 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.

[12] American Bureau of Shipping, Rules for Building and Classing, Steel Vessels, ABS, Houston, TX, USA, 2008.

[13] 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.

[14] 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.

[15] 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.

[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).