IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received July 8, 2020, accepted August 6, 2020, date of publication August 17, 2020, date of current version August 28, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.3017133

Power Quality and Energy-Efficient Operation of Marine Induction Motors

PIOTR GNACIŃSKI, (Member, IEEE), TOMASZ TARASIUK, (Member, IEEE),
JANUSZ MINDYKOWSKI, (Senior Member, IEEE), MARCIN PEPLIŃSKI, (Member, IEEE),
MARIUSZ GÓRNIAK, DAMIAN HALLMANN, AND ANDRZEJ PIŁAT
Department of Ship Electrical Power Engineering, Gdynia Maritime University, 81-225 Gdynia, Poland

Corresponding author: Piotr Gnaciński (p.gnacinski@we.umg.edu.pl)

This work was supported by the International Association of Maritime Universities through the research Project under Grant 20190202.

ABSTRACT Ship power systems are characterised by a comparatively high level of various power quality disturbances, such as voltage deviations, frequency deviations, voltage waveform distortions and sometimes voltage unbalance, which exert a detrimental effect on energy receivers. Among other things, power quality disturbances may cause an extraordinary increase in power losses occurring in on-board induction motors as well as ineffective utilisation of their mechanical output power. In this study, the results of empirical research which demonstrates how power quality disturbances in real ship microgrids affect induction motors are shown. The results of power quality monitoring in ship power systems from the point of view of the energy-efficient operation of induction motors are presented for various vessels and operating conditions. Recommendations concerning the revision of power quality standards and rules are elaborated to provide more energy-efficient ship operation.

INDEX TERMS Energy efficiency, induction motors, marine technology, power systems, power quality.

I. INTRODUCTION

Ship power systems are characterised by specific technical solutions and operating conditions [1]–[7] leading to a high level of power quality (*PQ*) disturbances, such as voltage and frequency deviations, voltage waveform distortions and voltage unbalance. One of the characteristics of on-board microgrids is the limited number of voltage sources and the presence of various disturbing loads, for example, bow thrusters or electric propulsion [1], [3], [4]. Many of these loads are supplied with power converters, sometimes of high powers [2], [3], [5]–[7]. As a result, the work of various non-linear loads may cause significant voltage waveform distortions [1], [4], [5]. A specific technical solution applied only in an on-board microgrid is a shaft generator—a special kind of a generator driven by a propulsion engine. Possible changes in its rotational speed might result in frequency deviations or fluctuations, especially under rough seas [8]. Another source of frequency variation is the common application of the droop control method for distribution of active power between generators working in parallel.

It should be noted that key components of a ship power system are exposed to particularly stressful environmental conditions, such as vibrations, the presence of salt mist and rapid changes in the ambient temperature [9], which exert negative effects on the reliability and durability of electrical equipment. It is also worth mentioning that the occurrence of significant *PQ* disturbances is often interconnected with breakdowns of various on-board equipment. To compound the problem, *PQ* disturbances caused by equipment failures may linger for several months.

To limit *PQ* disturbances in on-board microgrids, appropriate standards and rules have been introduced [9]–[12]. The power quality rules of ship classification societies generally follow the standard IEC 60092-101 Electrical installations in ships – Part 101: Definitions and general requirements [9]. The standard [9] and rules [10]–[12] usually admit ±5% frequency permanent deviation, a voltage permanent deviation within the range of -10% to $+6\%$ and significant harmonic contamination, *THD* even up to 8% and unbalance up to 3%. It should be stressed that the level of *PQ* disturbance is limited separately, neglecting the cumulative impact on energy receivers. As a result, even *PQ* disturbances within the limit prescribed by [9]–[12] exert a deleterious effect on various elements of ship power systems, including

The associate editor coordinating the review of this manuscript and approving it for publication was Narsa T. Reddy.

This work is licensed under a Creative Commons Attribution 4.0 License. For more information, see https://creativecommons.org/licenses/by/4.0/

induction motors. In induction motors, they cause, among other things, an increase in power losses and overheating [13]–[16]. According to the authors' investigations, *PQ* disturbances may even result in about a 50% increase in power losses in comparison to the nominal supply. In addition, *PQ* disturbances permitted in a ship power system may cause up to a 5% increase in the rotational speed of induction motors. As for fans and centrifugal pumps, the power on the shaft is proportional to the cubed rotational speed, *PQ* disturbances may cause an increase of up to 15% in output power of on-board induction motors. In many cases, an increase above the design level should be deemed unnecessary.

At the same time, there is a pressing need for the reduction of greenhouse gas emission. For this reason, the International Convention for the Prevention of Pollution from Ships (MARPOL Annex VI) introduced energy efficiency requirements, including constraints concerning the Energy Efficiency Design Index (*EEDI*) for new vessels. The concept of *EEDI* was implemented in 2012 by means of the *IMO* (International Maritime Organization) Resolution MEPC 214(13) [17] as a tool for improving energy efficiency of ships. This *IMO* guideline sets minimum energy requirements for new ships built after 2013. Those requirements concern limitation of power losses and reduction of greenhouse gas emissions of the ship's systems.

The *EEDI* calculation [3], [18] reflects the theoretical design efficiency of a new ship and provides an estimation of CO_2 emission per capacity-mile. A mathematical description of the index is very complex and takes into account various adjustments and correction factors customized for a specific vessel class and operating conditions [3]. For example, correction factors include ship-specific design elements, capacity adjustment for any technical/regulatory limitation on capacity, availability of individual energy efficiency technologies (for example, waste energy recovery system) and a non-dimensional coefficient indicating the decrease in ship speed due to weather and environmental conditions.

It should be noted that *PQ* monitoring is not taken into consideration during the process of design and implementation of this index. In addition, the measures to improve energy efficiency discussed in the literature often avoid *PQ* monitoring as a tool for improving energy efficiency of a ship. For example, those measures may cover [3]: ship design, fuel substitution, operational profile, new system architecture (DC on-board system), cold ironing and other measures, without *PQ* monitoring. The reason for such a situation is rather obvious and partially justified. Namely, a mandatory recommendation of the International Association of Classification Societies concerning continuous monitoring of voltage distortions for newly built ships was approved in 2016 [19], a few years after the *EEDI* concept was introduced.

Under these new circumstances, now is good time to consider a power quality-related index, to complete the *EEDI* idea. In a previous study [16], a tool dedicated to assessment of *PQ* from the point of view of energy-efficient operation of induction motors was proposed and experimentally verified—namely a coefficient of voltage energy efficiency–c_{vee} (its mathematical description is presented in the Appendix). The c_{vee} coefficient is a synthetic *PQ* factor, whose value is proportional to power losses occurring in induction motors due to *PQ* disturbances. For purely sinusoidal, balanced voltage of the rated value and frequency, the coefficient takes the value $c_{vee} = 1.00$. An increase in power losses in induction motors due to *PQ* disturbances is reflected by the value of the c_{vee} coefficient [16]. It is worth mentioning that the increase in mechanical output power due to *PQ* disturbances significantly affects ohmic power losses in a motor, and consequently is also reflected by the value of the coefficient of voltage energy efficiency [16].

In this context, a main contribution of the paper is to present the proposed c_{vee} coefficient as a complementary tool to the *EEDI* index. This coefficient could complete an existing gap concerning power quality assessment from the point of view of energy-efficient operation of marine induction motors. An important component of the authors' contribution is the results and in-depth analysis of experimental investigations demonstrating how power quality disturbances in a real ship power system affect induction motors. These elements justify the thesis, that the proposed c_{vee} coefficient could be complementary to the *EEDI* index. Finally, the main results of the paper consist of an elaboration of recommendations set out concerning application of the coefficient of voltage energy efficiency addressed to the researchers, system designers, and legal bodies, as well as the crew and technical service of a ship-owner. These recommendations include specific indications related to appropriate c_{vee} value, which could be recommended for attainment by new ships as the *EEDI* is.

This study includes the results of experimental investigations demonstrating how *PQ* disturbances in a real ship power system affect induction motors (Section II). The results of *PQ* monitoring in ship microgrids, applying the c_{vee} coefficient, are presented for various vessels (Section II). Recommendations concerning the application of the coefficient of voltage energy efficienc *y* are elaborated and justified in Section III.

II. RESULTS OF POWER QUALITY-RELATED INVESTIGATIONS ON BOARD SELECTED VESSELS

A. RESULTS OF INVESTIGATIONS ON BOARD THE RESEARCH SURVEY VESSEL HORYZONT II

In this subsection, the results of empirical investigations are provided, demonstrating how *PQ* disturbances in a real ship power system affect induction motors, performed on board the research survey vessel of Gdynia Maritime University–Horyzont II.

Horyzont II represents a typical ship with mechanical propulsion. Her electric power plant consists of three synchronous generators with a rated power of 376 kVA, driven by a four-stroke diesel engines with a rated power of 357 kW. The load with the greatest power on board is the bow thruster motor (125 kW), supplied by a variable frequency power converter. It is completed by a number of mainly linear loads, for instance, auxiliary machinery such as fresh and sea-water pumps in the cooling system, ballast pumps, fuel transport pumps and electric heaters. The ship under investigation is shown in Fig. 1 and her engine room in Fig. 2.

FIGURE 1. Research/survey vessel of Gdynia Maritime University–Horyzont II [20].

FIGURE 2. General view of the engine room on board Horyzont II.

The research on board Horyzont II was carried out in a controlled environment. The research scenarios included emergency states such as increase in power frequency within the permissible limits or the occurrence of unbalanced load in addition to standard exploitation states. During these scenarios, the authors monitored the instantaneous voltage on the main bus bars, generators; and the bow thruster instantaneous currents, complemented by the instantaneous currents of the motors driving a sea-water pump, a freshwater pump, a firefighting/ballast pump and a fuel transport pump. On the basis of the data recorded, the power components and *PQ* parameters as well as c_{vee} coefficient were determined.

For the purpose of the paper, the detailed analysis of *PQ* parameters, currents and active powers of the motors driving the sea-water pump (*motor SW*) and the fuel transport pump (*motor FT*) were selected and examined during bow thruster operation and power frequency deviations. It should be noted that the sea-water pump, the freshwater pump and the firefighting pump are centrifugal pumps, and their behaviour was very similar and typical for a fan-type load. In contrast, the fuel transport pump is a piston pump and can be considered as a constant torque load. The basic parameters of both motors are presented in Table 1.

TABLE 1. Basic parameters of motors investigated on board Horyzont II and driven appliances.

Motor	Motor SW	Motor FT
Driven appliance	sea-water cooling pump	fuel transport pump
load type	fan-type load	constant torque load
Motor type	M2AA 132 SC	M2AA 100LA
Rated power (kW)	9.5	2.2
Rated frequency (Hz)	50	50
Rated voltage (V)	380	380
Rated current (A)	17.6	5
Rated rotational speed (rpm)	2855	1430

During this research, the power system was supplied from a single generator. The bow thruster load was increased up to approximately 95 kW and remained more or less constant, leading to a value of voltage *THD* from 6.2% up to 6.8%. The voltage, frequency and *THD* during the presented research are shown in Fig. 3. The corresponding currents and active power of the considered motors are shown in Fig. 4. The grey area marks the changes related to increase in bow thruster load and represents the system's natural response (not controlled by the authors) due to generator characteristics as well as automatic voltage regulator and governor settings and characteristics. In particular, the decrease in frequency by approximately 0.85 Hz was related to the governor settings and used the droop control method for active power sharing control.

For *motor SW* (working with a fan-type load) the increase in frequency led to a significant increase in current and input power (Fig. 4). In contrast, for *motor FT* (working with a load of constant torque) the increase in frequency caused a decrease in current and a rather moderate increase in input power. This example demonstrates that the impact of *PQ* disturbances on electric motors depends on the motor load characteristics as well as the disturbance itself. This justifies the proposed mathematical model of c_{vee} coefficient [16]. The calculated value of the coefficient is presented in Fig. 5. The above figure clearly shows that frequency increase in particular can lead to an unacceptable value of the c_{vee} coefficient. Such a situation is sometimes observed in maritime microgrids.

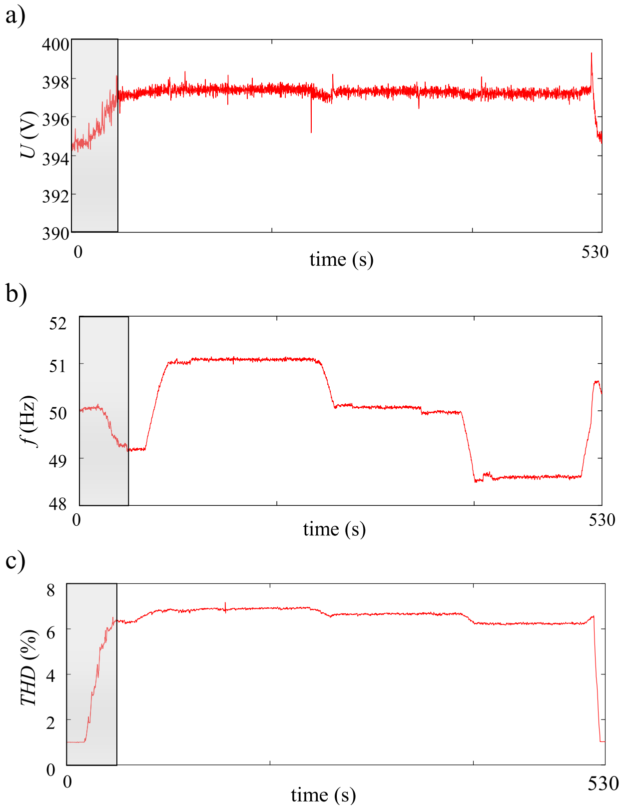

FIGURE 3. The changes in voltage (a), frequency (b) and voltage *THD* (c) during controlled experiments on board *Horyzont II*.

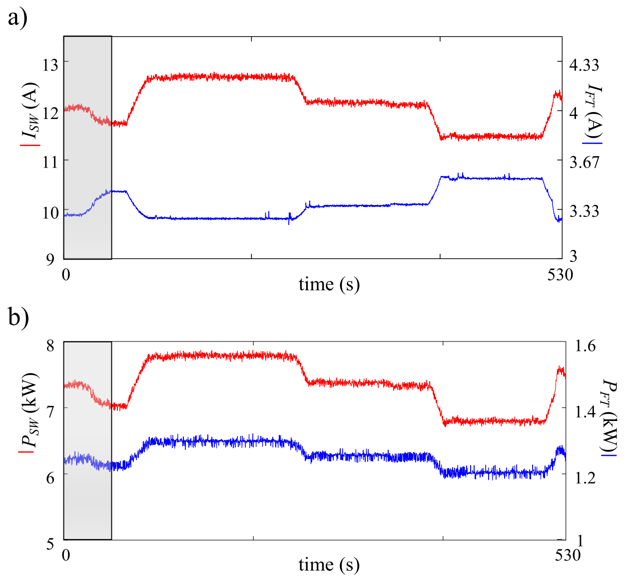

FIGURE 4. Currents of ***motor SW*** and ***motor FT*** (a) and corresponding changes of active powers (b).

The above experiment on board Horyzont II was carried out for a practically balanced supply voltage. To assess the impact of possible voltage unbalance, an additional investigation was conducted. Namely, the impact of the malfunction of an electric heater (lacking one phase due to a blown fuse) was considered. This malfunction led to an unbalanced load and resulted in supply voltage unbalance. The results of the measurement of basic voltage parameters and calculation of the c_{vee} coefficient are compared and given in Table 2. It should be noted that occurrence of significant voltage unbalance (the negative-sequence voltage component $u_{-} = 1.74\%$) affected the value of the c_{vee} coefficient to a much less degree than the increase in frequency (Table 2, Fig. 5).

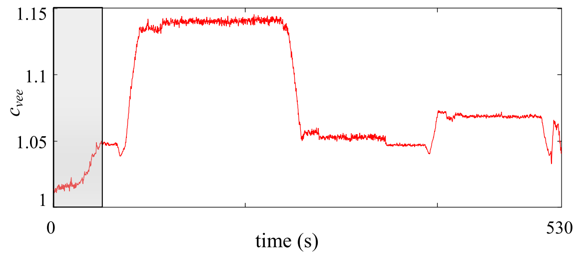

FIGURE 5. Changes in the c_{vee} coefficient during the present investigation.

TABLE 2. Comparison of PQ parameters and c_{vee} coefficient for balanced and unbalanced supply voltage, u_{-} – negative-sequence voltage component, U_{+}– positive-sequence fundamental voltage component.

	Voltage unbalance	Voltage balanced
f [Hz]	49.2	49.2
U_{+} [V]	387.44	396.12
u_{-} [%]	1.74	0.06
THD	6.85	6.35
c_{vee}	1.081	1.047

It is also worth noting that according to the authors' experience, significant voltage unbalance in a ship microgrid often results from malfunctioning on-board equipment, such as breakdowns of harmonic filters or blown fuses. Typically, under normal operating conditions the power of single-phase loads onboard are many times lower than three-phase loads. Consequently, after discovering unbalance of supply, proper actions must be undertaken by crew or the technical service of a ship-owner, and the various components of the power system should be examined.

The results presented above show that an increase in frequency should be considered as especially detrimental from the point of view of energy-efficient operation of induction motors.

B. RESULTS OF INVESTIGATIONS ON BOARD VESSELS WITH SHAFT GENERATORS

Another particular case of maritime microgrids are power systems on board vessels with shaft generators, i.e. generators driven by the main engine as the prime movers of the generator. The solution increases overall efficiency of electrical energy generation but generally leads to worsening the electrical *PQ*. Simply put, the rotational speed of the main engine fluctuates because of wind and sea waves. As a result, the power frequency in the system fluctuates if the shaft generator is connected directly to the main bus bars. Therefore, in some ships, power converters are used for frequency stabilisation. A resulting side effect is an increase in the level of supply voltage distortions.

For the purpose of this paper, two cases of vessels with shaft generators were carefully selected and analysed. The first investigation was carried out on board the ro-ro ship shown in Fig. 6. This represents a ship with shaft generator working directly on main bus bars. The nominal voltage on the bus bars of the main switchboard was 400 V with a frequency equal to 50 Hz and a rated shaft generator power of 1500 kVA.

FIGURE 6. Ro-ro vessel with shaft generator [21].

The research on board the ro-ro vessel was carried out during shaft generator operation and under two sea states: rough sea and calm sea (in the narrow straits). For both states, the load remained the same and the only difference was in the level of frequency fluctuations shown in Fig. 7. The remaining *PQ* parameters were practically the same: $U = 399.4$ V, $THD = 1.8\%$ and negative-sequence voltage component $u_{-} = 0.9\%$.

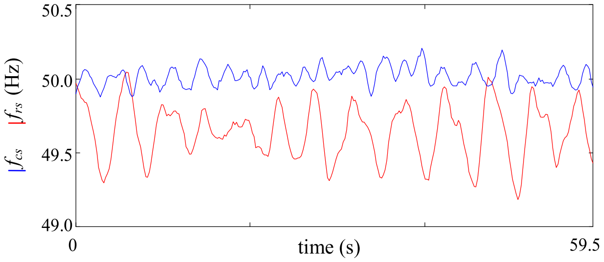

FIGURE 7. Frequency fluctuations on board the ro-ro vessel during shaft generator operation and rough seas ***rs*** (red line) as well as calm seas ***cs*** (blue line).

The impact of sea waves on the frequency is clearly visible. For rough seas, the mean value of frequency was 49.643 Hz and the standard deviation 0.187 Hz. For calm seas, the mean value of frequency was 50.017 Hz but the standard deviation equalled only 0.064 Hz. The phenomena presented above must lead to fluctuations of the calculated c_{vee} coefficients for both cases presented in Fig. 8.

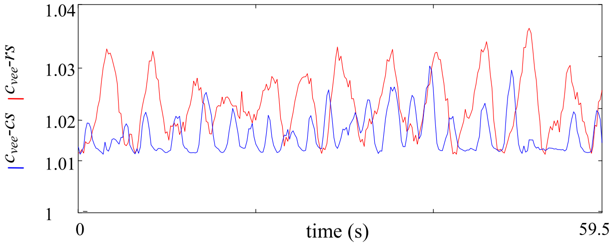

FIGURE 8. Fluctuations of c_{vee} coefficients during shaft generator operation and rough seas ***rs*** (red line) as well as calm seas ***cs*** (blue line).

As expected, the value of the c_{vee} coefficient changes was higher for rough seas. The mean value of the c_{vee} coefficient for rough seas was 1.021, whereas for calm seas it was 1.015.The values of the coefficients are rather low, but the impact of sea conditions is clear and the relative increase in the c_{vee} value is significant. The sea conditions also impact energy-efficient operation of marine induction motors. It must be stressed that similar frequency behaviour can be observed on board more and more popular ships with electric propulsion. In this case, the reason is load fluctuations produced by sea waves.

Another investigation was carried out on a chemical tanker with a shaft generator. The nominal voltage on the bus bars of the main switchboard was 440 V with frequency equal to 60 Hz and the rated shaft generator power 1187 kVA. In contrast to the ro-ro ship, the shaft generator supplied the network via a power converter, resulting in a significant level of voltage distortion ($THD = 11.44\%$). The actual voltage was practically constant and equalled 439.6 V and the voltage unbalance was very low, $u_{-} = 0.06\%$. During *PQ* monitoring, small regular load changes were observed, which led to the minor frequency changes shown in Fig. 9. The corresponding changes in the c_{vee} coefficient are shown in Fig. 10.

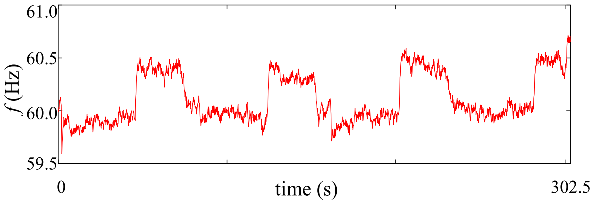

FIGURE 9. Frequency fluctuations on board a chemical tanker caused by regular load changes.

Analysis of results obtained on board the chemical tanker clearly indicates that energy-efficient operation of marine induction motors will depend on a combination of *PQ* factors. For the example presented, even a small increase in the frequency of approximately 0.5 Hz leads to an increase in the mean value of c_{vee} from 1.054 (related mainly to voltage distortion) to 1.072 (caused by both distortion and frequency deviation).

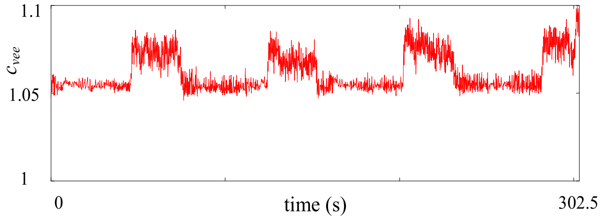

FIGURE 10. c_{vee} coefficient fluctuations on board a chemical tanker caused by regular load changes.

C. RESEARCH ON BOARD A SHIP WITH ELECTRICAL PROPULSION

A special and growing category of sea-going vessels are ships with electrical propulsion. This means that the propellers of the ship are usually driven by variable speed drives. Usually, six-, twelve-pulse or active front end (*AFE)* power converters are used for this goal. The electricity characteristics on board such ships are in some respects a combination of the characteristics on board ships with only free-standing generating sets and shaft generators working directly on main bus bars. The frequency sometimes shows a significant permanent deviation due to droop control completed by irregular frequency fluctuations due to rough seas, which cause propeller torque fluctuations.

The authors of the paper conducted research on board a dynamic positioning (*DP*) ship (shown in Fig. 11) with electrical propulsion during rough seas conditions. During the research, two propulsion *AFE* drives operated, both with rated power of 300 kW. The rated voltage of the electrical power system was 400 V with rated frequency 50 Hz. During the investigation, two diesel-driven generators worked in parallel, with rated powers 425 kVA and 200 kVA. For the purpose of this paper, the case of a step increase in the propulsion drive loads was selected for study.

FIGURE 11. DP ship with electrical propulsion [22].

The ship speed over ground during 26 minutes of sea going is shown in Fig. 12. The increase in speed was caused by a step increase in the load of the propulsion drives. The corresponding active power of the two generators working in parallel is shown in Fig. 13.

The small variations in speed observed from the 17th minute were caused by ship course changes and an increase in hydrodynamic resistance, despite the more or less constant propulsion power. Next, it can be noted that during the research, quasi-regular small load changes occurred, probably due to work of an auxiliary electrical receiver. Nevertheless, an increase in speed led to irregular variations in power visible after 13 minutes. Finally, the active power change resulted in a frequency step decrease by approximately 0.35 Hz. Small frequency variations were also visible. The frequency changes for the entire study period are presented in Fig. 14.

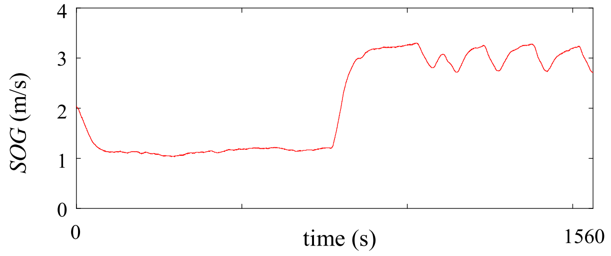

FIGURE 12. Speed over ground (*SOG*) of the DP ship.

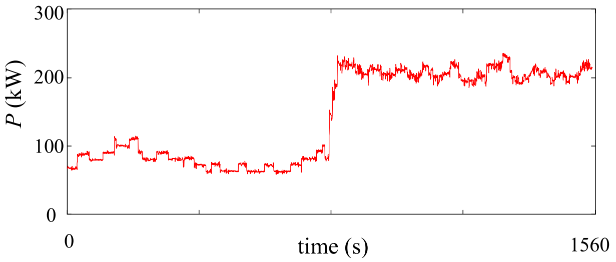

FIGURE 13. Active power of two generators working in parallel on board the DP ship.

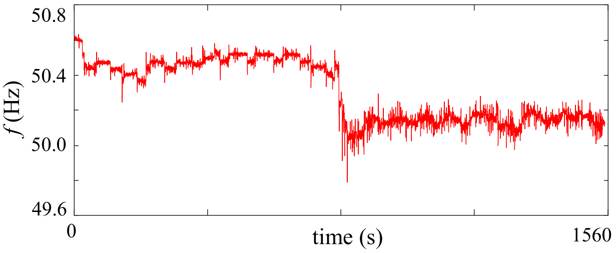

FIGURE 14. Frequency changes on board the DP ship during the considered process of step propulsion load changes.

In some respects, frequency changes mimic the active power changes. Namely, an increase in ship speed caused an increase in frequency fluctuations. Obviously, the phenomenon was due to increased impact of sea waves on load fluctuations for higher speeds.

Finally, the c_{vee} coefficient was not constant but varied in a pattern similar to the frequency changes, which is shown in Fig. 15. For the this example the mean values of the c_{vee} coefficient were calculated before and after the speed increase. For low speed, it was 1.038 and at medium speed it was 1.012. Clearly, the decrease was related to frequency drop, which was not compensated by a small increase in voltage *THD* from 1.3% to 1.9%.

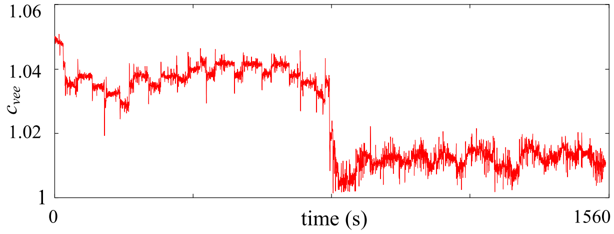

FIGURE 15. c_{vee} **coefficient changes on board the DP ship during step speed increase in rough seas.**

The analysis of all the examples presented leads to the conclusion that the chief impact on the energy-efficient operation in maritime microgrids is exerted by frequency, sometimes leading to a c_{vee} coefficient equal to 1.14, which is hardly acceptable from the points of view of both energy efficiency and thermal ageing of the insulation of electric motors. The authors registered such a mean c_{vee} value on board one of the investigated ferry during normal operation (*PQ* parameters: $U = 435.4$ V, $f = 61.8$ Hz, $u_- = 0.1\%$, $THD = 1.15\%$) Unfortunately, frequency changes in ship power systems are a key feature and cannot be avoided altogether. The distortion of supply voltage observed in ship systems is particularly harmful, above its limit value 8%. Similarly for unbalance, this would exert an onerous impact above 2%. But particularly the combination of all the phenomena considered in this paper would lead to unacceptable energy losses in electrical motors. Consequently, there is a need for *PQ* monitoring from the point of view of energy-efficient operation of induction motors. An appropriate tool for *PQ* assessment could be the *coefficient of voltage energy efficiency*. Recommendations concerning its application are formulated in the next section.

III. RECOMMENDATIONS CONCERNING APPLICATION OF THE COEFFICIENT OF VOLTAGE ENERGY EFFICIENCY

A. PRELIMINARY REMARKS

Practical implementation of the coefficient of voltage energy efficiency requires determination of its threshold values. The values can be indicated on the basis of analysis of requirements included in standards IEC-EN 60034-30-1 Rotating electrical machines - Part 30-1: Efficiency classes of line operated AC motors (IE code) [23], IEC 60092-101 Electrical installations in ships – Part 101: Definitions and general requirements [9], IEEE Std. 45-2002 IEEE Recommended practice for electrical installations on shipboard [24], as well as in IEC 60034-1 Rotating electrical machines - Part 1: Rating and performance [25]. In addition, an increase in input power could be taken into consideration.

B. CHOSEN REQUIREMENTS INCLUDED IN THE STANDARD IEC-EN 60034-30-1

The standard IEC-EN 60034-30-1 Rotating electrical machines - Part 30-1: Efficiency classes of line operated AC motors (IE code) [23] provides requirements concerning efficiency classes IE1–IE4. The analysis of threshold values for each efficiency class shows that an increase in power losses of 20–21% (depending on the rated power of the machines) may result in movement from efficiency class IE3 to efficiency class IE1. At the same time, according to various international and national regulations, new motors are required to be of at least efficiency class IE3. Further, many modern induction motors have efficiency corresponding to the threshold value of class IE3 (based on an analysis of catalogues of induction motors). Consequently, an increase in power losses above 20% should be found inadmissible from the point of view of energy-efficient operation of induction motors.

C. CHOSEN REQUIREMENTS INCLUDED IN IEC 60092-101

As was mentioned above, the present power quality rules of ship classification societies are generally in accordance with the requirements of the standards IEC 60092-101 Electrical installations in ships – Part 101: Definitions and general requirements [9]. The standards and rules [10]–[12] usually permit among other things ±5% frequency deviation and voltage deviation 10%, +6%. For combinations of voltage and frequency admitted by [9]-12], the value of the coefficient of voltage energy efficiency, c_{vee}, even reaches 1.43. However, for a constant ratio U/f, the value of the c_{vee} coefficient does not exceed about 1.17.

D. CHOSEN REQUIREMENTS INCLUDED IN THE STANDARD IEEE STD. 45-2002

The standard IEEE Std. 45-2002 IEEE Recommended practice for electrical installations on shipboard [24] (present status – in reserve) imposes strict requirements concerning *PQ* in the ship power systems. Among other things, it allows a ±3% frequency deviation and a ±5% voltage deviation. For the worst frequency and voltage combinations, that is $f = 103\%$ of f_{rat}, $U = 95\%\ U_{rat}$ and $f = 97\%$ of f_{rat}, $U = 105\%\ U_{rat}$, the values of the c_{vee} coefficient are equal to 1.178 and 1.222, respectively.

E. REQUIREMENTS CONCERNING VOLTAGE UNBALANCE AND VOLTAGE WAVEFORM INCLUDED IN IEC 60034-1

According to the standard IEC 60034-1 Rotating electrical machines - Part 1: Rating and performance [25], the value of a harmonic voltage factor (*HVF*), understood as

$$HVF = \sqrt{\sum_{n=2}^{k} \frac{u_h^2}{h}}, \tag{1}$$

where u_h is the ratio of the voltage harmonic and the rated voltage, h is harmonic order, $k = 13$; should not exceed 0.02 or 0.03 (depending on machine properties). The factor $HFV = 0.02$ corresponds to the 5th harmonic equal to $u_5 = 4.5\%\ U_{rat}$, while $HFV = 0.03$ – to simultaneous occurrence of 5th and 7th voltage harmonics, equal to $u_5 = 5\%\ U_{rat}$ and $u_7 = 5\%\ U_{rat}$.

Further, ‘three-phase a.c. motors should be suitable for operation on a three-phase voltage system having a negative-sequence component not exceeding 1% of the positive-sequence component over a long period (...) Should the limited values of the HFV and of the negative-sequence (...) components occur simultaneously in service at the rated load, this shall not lead to any harmful temperature in the motor...’ For such specified PQ disturbances, the value $c_{vee} = 1.04$ for $HFV = 0.02$ and $c_{vee} = 1.063$ for $HFV = 0.03$.

F. REQUIREMENTS CONCERNING FREQUENCY AND VOLTAGE VALUE ACCORDING TO IEC 60034-1

The standard [25] also specifies the limited values of voltage and frequency deviation that a motor should be capable of long-term operation. For the limited values, the coefficient c_{vee} is up to 1.13. It should be noted that the mathematical description of the coefficient considers an increase in the load torque due to an increment in the rotational speed [16]. At the same time, the requirements given in [25] concern motors working with constant torque. So, after modifications of the mathematical description of the coefficient (removing expressions describing the increase in the rotational torque), its value is up to 1.10.

G. INCREASE IN INPUT POWER

As was mentioned in the previous sections, for a fan-type load, variation in the rotational speed due to power quality disturbances may result in an increase in the power on the shaft and consequently in an additional increase in the input motor power. The proportion of the consumed power to the value of the c_{vee} coefficient is especially high for the ratio $U/f = \text{const}$. In practice, for this ratio the input power is approximately proportional to the value of the coefficient of voltage energy efficiency. For the coefficient $c_{vee} = 1.05$, an increase in the input power can be expected of about 5% (in comparison to the nominal supply), and for $c_{vee} = 1.1$, of about 10%. At the same time the PQ disturbances should not lead to a large increase in the power consumed by induction motors.

H. PERMISSIBLE AND RECOMMENDED VALUES OF THE COEFFICIENT OF VOLTAGE ENERGY EFFICIENCY

Taking into account the considerations in subsections B–G, the permitted value of the coefficient of voltage energy efficiency should be $c_{vee} = 1.2$, which more or less reasonably covers the above-mentioned requirements and is directly related to IEC-EN 60034-30-1 provisions [23]. This value is recommended to be implemented in the standard [9], and rules of ship classification societies concerning PQ. The maximal permissible value $c_{vee} = 1.2$ can also be required to be achieved on new ships, in the same way that Energy Efficiency Design Index [3], [17] is.

The rules of ship classification societies aside, strict requirements also contain various recommendations. Such a recommendation could be the value of the coefficient of voltage energy efficiency $c_{vee} \leq 1.05$. Further, for values c_{vee} greater than 1.05, analysis of the effect of PQ disturbances on heating of induction motors could be recommended, for example with the method presented in [13], [15].

The appropriate curves $c_{vee} = 1.05$ and $c_{vee} = 1.2$ are shown in Fig. 16 for a range of voltage and frequency deviations. It should be noted that occurrence of voltage unbalance and/or voltage waveform distortions will significantly reduce the zone limited by these curves, which Figs. 17 and 18 illustrate. They show analogous curves as in Fig. 16, but determined for a 2% voltage unbalance ($u_{-} = 2\%$ of U_{rat}) and for a 2% voltage unbalance combined with voltage waveform distortions. The values of the voltage harmonics are: $U_5 = 5\%$ of U_{rat}, $U_7 = 4\%$ of U_{rat}, $U_{11} = 3.5\%$ of U_{rat}, and $U_{13} = 3.5\%$ of U_{rat}. It worth mentioning that they are based on the voltage waveform recorded on board the chemical tanker considered in Section II. For simultaneous occurrence of voltage deviation, frequency deviation and voltage unbalance (Fig. 17), the zone limited by the curve $c_{vee} = 1.05$ practically disappears. For all the considered PQ disturbances (Fig. 18), the area limited by the curve $c_{vee} = 1.2$ is much smaller than for the other considered cases (Figs. 16, 17) and the maximal permitted frequency is merely about 103% of f_{rat}.

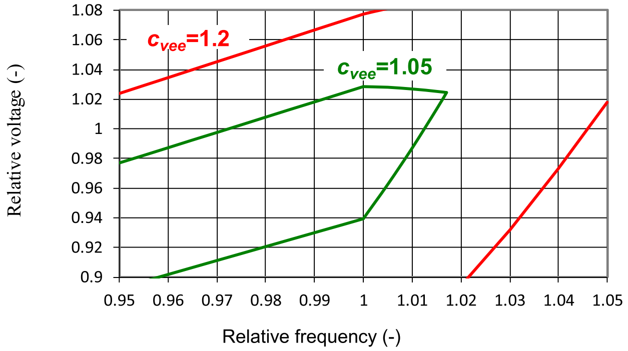

FIGURE 16. The curves $c_{vee} = 1.05$ and $c_{vee} = 1.2$ versus relative frequency and relative fundamental voltage component, for the purely sinusoidal, balanced voltage.

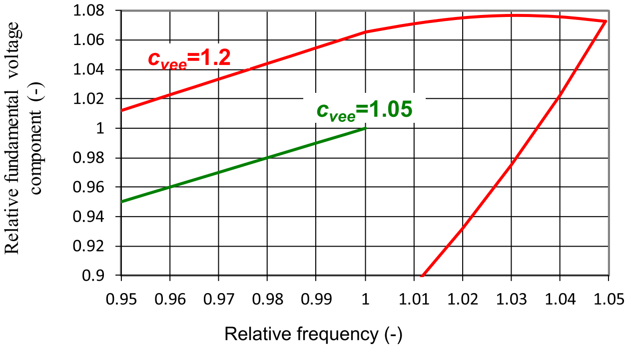

FIGURE 17. The curves $c_{vee} = 1.05$ and $c_{vee} = 1.2$ versus relative frequency and relative fundamental voltage component, for 2% voltage unbalance.

It is also worth mentioning that in previous works [13], [14], [15], the authors formulated a proposal for limitation of

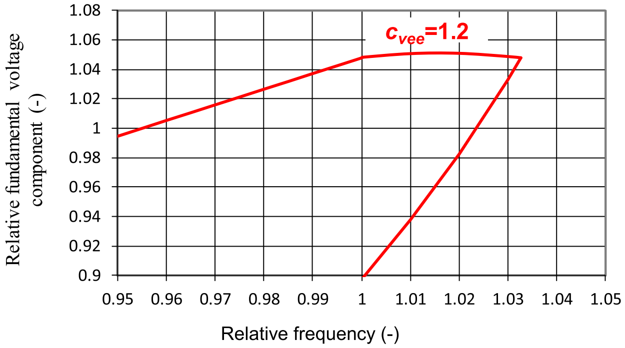

FIGURE 18. **The curve $c_{vee} = 1.2$ versus relative frequency and relative fundamental voltage component, for 2% voltage unbalance and the following voltage harmonics: $U_5 = 5\%$ of U_{rat}, $U_7 = 4\%$ of U_{rat}, $U_{11} = 3.5\%$ of U_{rat} and $U_{13} = 3.5\%$ of U_{rat}.**

PQ disturbances to protect induction motors against excessive heating. The proposal is based on a synthetic power quality factor—a temperature coefficient of power quality (c_{pqs}) [15]. For a general case, the permissible value of the c_{pqs} coefficient is 1.13 [13]. For ships with motors with a higher class of insulation than resulting from windings temperature rise (*SMHCI*), it rises to 1.46 [14], while for ships with motors working with less load than the rated one, c_{pqs} can be even higher [14], [15]. In Fig. 19, the limited curves $c_{pqs} = 1.13$ and $c_{pqs} = 1.46$ are presented for a range of voltage and frequency deviations. Collation of Figs. 16 and 19 shows that both the *PQ* factors complement each other. For the general case, the permissible levels of *PQ* disturbances are limited by the value $c_{pqs} = 1.13$ (excessive rate of insulation systems thermal ageing) and for *SMHCI* by $c_{vee} = 1.2$ (decrease in energy efficiency).

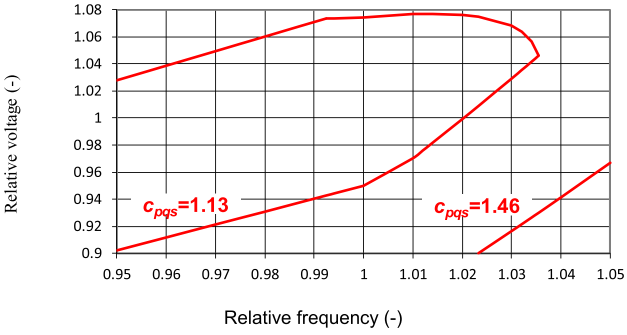

FIGURE 19. **The curves $c_{pqs} = 1.13$ [13] and $c_{pqs} = 1.46$ versus relative frequency and relative fundamental voltage component, for the purely sinusoidal, balanced voltage.**

In summary, the values $c_{vee} = 1.05$ and $c_{vee} = 1.2$ are advised for implementation into *PQ* standards, rules and recommendations.

IV. CONCLUSION

The coefficient of voltage energy efficiency (c_{vee}) is a synthetic power quality factor, whose value is proportional to power losses occurring in induction motors under power quality disturbances. The concept of c_{vee} coefficient is a supplementary tool to *EEDI* and complements the existing gap concerning power quality assessment from the point of view of energy-efficient operation of marine induction motors. In the authors' opinion, the described phenomena and their expression in the form of the coefficient of voltage energy efficiency should be considered during ship operation as well as during the ship design stage, particularly given the more common usage of modelling and simulation tools during this stage. According to standard [26], modelling and simulation 'plays a key role throughout all aspects of systems integration and should be used extensively throughout all phases of the design'. Taking into account the above considerations, the assessed value of the coefficient of voltage energy efficiency will result in better design for ship electric power systems, including choice of electrical equipment and control settings.

The results of experimental investigations carried out on board selected vessels point to factors affecting energy-efficient operation of induction motors on board sea-going vessels. The especially harmful factor is an increase in frequency in a ship's microgrid. The highest values of the c_{vee} coefficient were observed for the increased power frequency combined with other power quality disturbances. The actual value of the coefficient can also be affected by such agents as sea state, vessel speed and switched-on loads. For this reason, measurements of the c_{vee} coefficient for the purposes of certification should be performed in a similar way to the mandatory annual monitoring of harmonic distortion [10], that is 'under sea-going conditions (...) when the greatest amount of distortion is indicated by the measuring equipment'.

Further, on the basis of an analysis of IEC, IEEE standards and an increase in power consumption, the maximal permissible value $c_{vee} = 1.2$ and the recommended value $c_{vee} = 1.05$ are determined. The experimental research presented clearly indicates that the latter value in particular can be easily exceeded in the ship power systems under normal operating conditions. In addition, the coefficient of voltage energy efficiency and the temperature coefficient of power quality are complement each other. Implementation of these coefficients in power quality standards and rules may contribute to more energy-efficient and safer ship operation.

APPENDIX

Mathematical description of the *coefficient of voltage energy efficiency* [16]:

$$c_{vee} = p_{fund} + p_{har} + p_{unbal} \tag{2}$$

where p_{fund} represents the relative power losses occurring in an induction motor (related to its value under the nominal supply), caused by fundamental current and voltage harmonics, p_{har} indicates the relative power losses due to the voltage harmonics, and p_{unbal} represents the relative power losses due to the voltage unbalance:

$$p_{fund} = \max\left(p_{fund1}, p_{fund2}\right) \tag{3}$$

$$p_{fund1} = f_*^{2.9}\left(c_1 u_*^{-3} \Delta u_*^3 + c_2 u_*^{-3} + c_3 u_*^{-1}\right) \tag{4}$$

$$p_{fund2} = f_*^{2.9}\left(c_4 \Delta u_*^2 + u_*^{0.7}\right) \quad \text{for } \Delta u_* \geq 0 \tag{5a}$$

$$p_{fund2} = f_*^{2.9}\left(-c_4 \Delta u_*^2 + u_*^{0.7}\right) \quad \text{for } \Delta u_* < 0 \tag{5b}$$

$$f_* = f \quad \text{for } f > 1 \tag{6a}$$

$$f_* = 1 \quad \text{for } f \leq 1 \tag{6b}$$

$$u_* = f^{1.45} u_1^{-1} \quad \text{for } f > 1 \tag{7a}$$

$$u_* = f u_1^{-1} \quad \text{for } f \leq 1 \tag{7b}$$

$$\Delta u_* = u_* - 1 \tag{8}$$

$$p_{har} = \sum_{h=2,5,11\ldots}^{hmax} u_h^2\left(c_{h1} f_h^{-1.2} + c_{h2} f_h^{-1.7}\right) + \sum_{h=4,7,13\ldots}^{hmax} u_h^2\left(c_{h3} f_h^{-1.2} + c_{h4} f_h^{-1.7}\right) \tag{9}$$

$$p_{unbal} = c_- u_-^2 \tag{10}$$

where u_1 is the fundamental voltage component, u_- is the negative sequence voltage component, u_h, f_h are the voltage and the frequency of a harmonic of the h^{th} order, $c_1 = -150$, $c_2 = 0.3$, $c_3 = 0.7$, $c_4 = 1.3$, $c_{h1} = 7000$, $c_{h2} = 50000$, $c_{h3} = 7000$, $c_{h4} = 15000$, and $c_- = 125$.

All voltage parameters in the above expressions are per unit, relative to the rated voltage and frequency.

ACKNOWLEDGMENT

The authors would like to thank Mariusz Szweda for providing the voltage samples from the chemical tanker.

REFERENCES

[1] J. Barros and R. I. Diego, “A review of measurement and analysis of electric power quality on shipboard power system networks,” *Renew. Sustain. Energy Rev.*, vol. 62, pp. 665–672, Sep. 2016.

[2] R. D. Geertsma, R. R. Negenborn, K. Visser, and J. J. Hopman, “Design and control of hybrid power and propulsion systems for smart ships: A review of developments,” *Appl. Energy*, vol. 194, pp. 30–54, May 2017.

[3] D. Kumar and F. Zare, “A comprehensive review of maritime microgrids: System architectures, energy efficiency, power quality, and regulations,” *IEEE Access*, vol. 7, pp. 67249–67277, 2019.

[4] J. Mindykowski, “Contemporary challenges to power quality in ship systems-metrological perspective,” in *Proc. 22nd IMEKO TC4 Int. Symp. 20th Int. Workshop ADC Modeling Test.*, Iasi, Romania, 2017, pp. 536–558.

[5] T. A. Rodrigues, G. S. Neves, L. C. S. Gouveia, M. A. Abi-Ramia, M. Z. Fortes, and S. Gomes, “Impact of electric propulsion on the electric power quality of vessels,” *Electr. Power Syst. Res.*, vol. 155, pp. 350–362, Feb. 2018.

[6] 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 Trans. Transport. Electrific.*, vol. 2, no. 4, pp. 522–537, Dec. 2016.

[7] Y. Terriche, M. U. Mutarraf, S. Golestan, C.-L. Su, J. M. Guerrero, J. C. Vasquez, and D. Kerdoun, “A hybrid compensator configuration for VAR control and harmonic suppression in all-electric shipboard power systems,” *IEEE Trans. Power Del.*, vol. 35, no. 3, pp. 1379–1389, Jun. 2020.

[8] T. Tarasiuk, “Angular frequency variations at microgrids and its impact on measuring instruments performance,” *IET Gener., Transmiss. Distrib.*, vol. 10, no. 13, pp. 3234–3240, Oct. 2016.

[9] *Electrical Installations in Ships—Part 101: Definitions And General Requirements*, IEC Standard 60092-101, 2018.

[10] *Requirements Concerning Electrical and Electronic Installations*, Int. Assoc. Classification Societies, London, U.K., 2019.

[11] *Rules for Building and Classing Steel Vessels, Part 4 Vessel Systems and Machinery*, Amer. Bureau Shipping, Houston, TX, USA, 2019.

[12] *Rules for Classification Ships, Part 4 Systems and Components, Chapter 8 Electrical Installations*, DNV GL, Hamburg, Germany, Edition Jul. 2019, Amended, October 2019.

[13] P. Gnacinski, J. Mindykowski, and T. Tarasiuk, “Effect of power quality on windings temperature of marine induction motors. Part II: Results of investigations and recommendations for related regulations,” *Energy Convers. Manage.*, vol. 50, no. 10, pp. 2477–2485, Oct. 2009.

[14] P. Gnacinski, “Power quality and marine induction motors with higher class of insulation than resulting from windings temperature rise,” in *Proc. 22nd Int. Conf. Electr. Mach. (ICEM)*, Lausanne, Switzerland, Sep. 2016, pp. 2002–2008.

[15] P. Gnacinski, “Thermal loss of life and load-carrying capacity of marine induction motors,” *Energy Convers. Manage.*, vol. 78, pp. 574–583, Feb. 2014.

[16] P. Gnacinski, J. Mindykowski, M. Peplinski, T. Tarasiuk, J. D. Costa, M. Assuncao, L. Silveira, V. Zakharchenko, A. Drankova, M. Mukha, and X.-Y. Xu, “Coefficient of voltage energy efficiency,” *IEEE Access*, vol. 8, pp. 75043–75059, 2020.

[17] *2012 Guidelines on Survey and Certification of the Energy Efficiency Design Index (EEDI)*, dcoument Resolution MEPC.214(63), International Maritime Organization, 2012. [Online]. Available: http://www.imo.org

[18] *Interim Guidelines on the Method of Calculation of the Energy Efficiency Design Index for New Ships*, document MEPC.1/Circ.681, Aug. 2009.

[19] *Requirements Concerning Electrical and Electronic Installations, Harmonic Distortion for Ship Electrical Distribution System Including Harmonic Filters*, document UR E24, International Association of Classification Societies, 2016.

[20] Uniwersytet Morski w Gdyni. *Zdjecia*. Accessed: Apr. 9, 2020. [Online]. Available: https://umg.edu.pl/zdjecia

[21] *Statek Tychy*. Accessed: May 7, 2020. [Online]. Available: https://umtychy.pl/artykul/112/statek-tychy

[22] Instytut Morski Uniwersytetu Morskiego w Gdyni. *Statek badawczy Instytutu Morskiego r/v IMOR*. Accessed: May 7, 2020. [Online]. Available: http://im.umg.edu.pl/statek

[23] *Rotating Electrical Machines—Part 30-1: Efficiency Classes of Line Operated AC Motors (IE code)*, IEC-EN Standard 60034-30-1, 2014.

[24] *IEEE Recommended Practice for Electrical Installations on Shipboard*, IEEE Standard 45, Oct. 2002.

[25] *Rotating Electrical Machines—Part 1: Rating And Performance*, IEC Standard 60034-1, 2017.

[26] *IEEE Recommended Practice for Shipboard Electrical Installations-Systems Engineering*, IEEE Standard 45.3, Jul. 2015.

PIOTR GNACIŃSKI (Member, IEEE) received the M.Sc., Ph.D., and D.Sc. degrees in electrical engineering from the Gdańsk University of Technology, Poland, in 1993, 2000, and 2011, respectively. Since 1993, he has been on the Staff of Gdynia Maritime University, Poland, where he is currently an Associate Professor. His research and teaching interests include power quality and electrical machines. From 2008 to 2012, he was the Chapter Treasurer/Secretary of the Polish Section of the IEEE Instrumentation and Measurement Society.

TOMASZ TARASIUK (Member, IEEE) received the M.Sc. degree in marine electrical engineering from Gdynia Maritime University, Gdynia, Poland, in 1989, the Ph.D. degree in electrical engineering from the Gdansk University of Technology, Gdańsk, Poland, in 2001, and the D.Sc. degree in electrical engineering (metrology and signal processing) from the Warsaw University of Technology, Warsaw, Poland, in 2010. Since 1994, he has been with Gdynia Maritime University. Since 2019, he has also been the Head of the Research and Development Department, Remontowa Electrical Solutions. His research interests include marine microgrids and power quality assessment.

JANUSZ MINDYKOWSKI (Senior Member, IEEE) received the M.Sc. and Ph.D. degrees in electrical engineering from the Gdansk University of Technology, Poland, in 1974 and 1981, respectively, and the D.Sc. degree from the Warsaw University of Technology, Poland, in 1993. Since 1994, he has been the Head of the Marine Electrical Power Engineering Department, Gdynia Maritime University, where he has been a Full Professor, since 2002. His research interests include measurement aspects of technical systems operation and diagnosis, mainly ship's systems, power quality problems, and analysis of measurement and monitoring systems in ship technology. From 2008 to 2012, he was the Chapter Chairman of the Polish Section of the IEEE Instrumentation and Measurement Society.

MARCIN PEPLIŃSKI (Member, IEEE) received the B.Sc., M.Sc., and Ph.D. degrees in electrical engineering from the Gdynia Maritime Academy (presently Gdynia Maritime University), Poland, in 1998, 1999, and 2015, respectively. From 1999 to 2001, he worked as a Telecommunication Engineer. From 2002 to 2003, he was worked on ships as an Electric Assistant. He was the Diploma of Ship Electric Officer, in 2003. Since 2003, he has been on the Staff of Gdynia Maritime University, where he is currently an Assistant Professor. His research and teaching interest includes electrical machines.

MARIUSZ GÓRNIAK was born in Gdynia, Poland, in 1976. He received the M.Sc. degree in electrical engineering from Maritime University, Gdynia, in 2001. Since 2002, he has been on the Staff of Gdynia Maritime University, Poland. His research interests include power quality measurements and analyses with digital signal processing in marine microgrids, design of power management systems for ships, and modeling of power systems of ships.

DAMIAN HALLMANN received the B.Sc., M.Sc., and Ph.D. degrees in electrical engineering from Gdynia Maritime University, Poland, in 2011, 2012, and 2020, respectively. Since 2011, he has been on the Staff of Gdynia Maritime University, where he is currently an Assistant. His research interest includes electrical machines.

ANDRZEJ PIŁAT received the master's degree in electrical engineering from Gdynia Maritime University, in 2008. He currently works with the Department of Marine Electrical Power Engineering, Gdynia Maritime University. His research interests include modeling of marine power electrical systems and measurements of power quality on marine vessels. He received the certificate of the Marine Electro Automation Officer, in 2013, and worked on sea ships as an Electro Automatic.

• • •