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Case Study—Based Overview of Some Contemporary Challenges to Power Quality in Ship Systems

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Abstract: The content of this paper consists of a presentation and discussion on a case study-based overview of some selected challenges dealing with a problem of power quality on ships. As a consequence, the theoretical considerations are aided by experimental results based mainly on the author's research team experience and achievements. Two basic aspects, assessment and improvement of power quality are taken into account. In the process of power quality assessment, the existing ambiguities are analyzed and discussed, after that the undertaken measures and challenges to overcome them are presented. The ways of improving of power quality on ships are described and analyzed in two layers: technological solutions and the staff competences. Expectations and challenges for the future based on developments of both, legal and professional aspects are focused on the key question: how to reduce a risk of ship accidents. Finally, the future works as well as the concluding remarks are formulated and commented on.

Keywords: maritime power systems; power quality; assessment; improvement; case-study based analysis

1. Introduction

Core information of this paper is based on a recently published paper [1], describing the problem of electrical power quality and its influence on ship safety, which constantly remain vital and topical issues. Moreover, there has been a perceptible increase in the importance of power quality in recent years due to the introduction of new methods for electrical energy production and utilization in maritime power systems. An explanation of this increase results from peculiar and basic characteristics of maritime power systems. Conversely to overland the electrical power network, the marine electrical power network is an autonomous, flexible low capacity power system. Under dynamic conditions, the deviation of rms value of supply voltage and the frequency deviation always reaches high values when compared with their nominal values, especially when an electric propulsion ship is being considered. Due to a continuous increase in the number and power of electrical energy consumers installed and directly switched on to ship electrical power system, especially the impacting and fluctuant load, not only a large amount of harmonics have been brought on to the marine electrical power network, but also the problem of voltage fluctuations, including transient phenomena and 3-phase unbalance in a power network, has become more and more serious. Since the power of some switched-on heavy energy consumers is comparable to the one in the ship electrical power system, the switch of bulk load on always results in putting into parallel operation of one or more generators. The fact is that the generators start-up for parallel operation leads to the appearance of significant amount of harmonics (current transients) caused by subtransient reactance of generator. Furthermore, the application of large capacity-power electronic devices and systems also contributes to the power quality deterioration to a wide extension. Therefore, more and more attention has been paid to decreasing an adverse impact of power quality disturbances and the problem how to assess and improve electrical power quality has also become a hot topic in the field of marine electro-technology nowadays. As a result, new challenges for ship designers, crew members, and ship classification societies are looming. These challenges should be considered in the practice, and evaluated from the perspective: how to reduce a risk of ship accidents and related damages, and how to avoid catastrophic consequences of worsening of power quality? A graphical illustration of interactive relationships in the processes of assessment and improvement of power quality in maritime power system is shown in Figure 1.

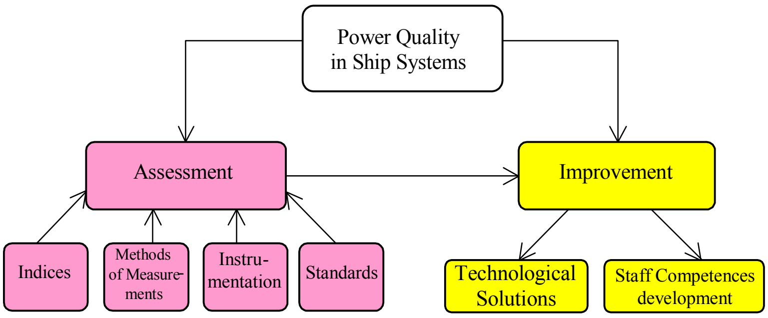


Figure 1. The concept of power quality assessment and improvement in maritime power systems; boxes marked with red color are referred to the process of power quality assessment and with yellow color—to power quality improvement, respectively.

This concept is built on the basis of the existing state of the art summarized by the conclusion, that processes of assessment and improvement of power quality are the integral parts of the maritime power system operation. The first of the aforementioned processes is a basic one: assessment. It usually precedes the improvement phase. However, an improvement may be initiated directly from the maritime power system, as an immanent part of the operations of the reconfiguration or modernization of the structure of the considered system. Improvement of power quality may be executed by the means of technological solutions or in result of the staff competences development. On the other hand, four components, that is: indices, methods of measurements, instrumentation and standards have a direct impact on assessment, as a fundamental process for evaluation of power quality in maritime power systems. This paper is organized in the following manner: firstly, after a short introduction, the maritime power system (Section 2) with regard to its basic characteristics, configuration and technology development is shortly presented. In the third section, a fundamental question on how to assess power quality on ships, is discussed and analyzed. In this key section, subheadings related to a formulation of the process of power quality assessment, power quality indices, measurement methods, instrumentation and legal instruments for power quality monitoring are described and discussed. Afterwards, in the fourth section, methods for improving power quality on ships are discussed, underlining technological solutions and crew competence-related measures. It is worth mentioning that in the third and the fourth section some case-studies documented the working hypothesis and formulated justifying conclusions are presented and commented on. The last section is devoted to a discussion of existing weaknesses, expectations and future challenges in the area of power quality in maritime power systems, with indications, how to overcome some existing ambiguities and inaccuracies, by undertaken ways for improving the current situation. Finally, the concluding remarks are formulated and commented on.

2. Maritime Power Systems

The ship electric power system (so-called in this paper maritime power system) consists of the devices for production, transmission and distribution of electric energy, as well as of its consumers. The main components of the ship electric power system are energy sources, main and emergency switchboard, power cable lines and electric consumers [2–6]. In the basic configuration as the energy sources the three electric generating sets are usually applied, [3,5–7] sometimes shaft generators as well as turbogenerators are also installed. The main switchboard (MSB) on board a ship is the central node of her electric power system. The MSB and ESB (emergency switchboard) are considered together with protective systems, switches as well as main busbars, measurement and control systems of the processes realized within the electric power system. The electric power consumers can be fed directly from the main switchboard or from auxiliary section switchboards and end switchboards by the appropriately designed power cable lines. Taking into account continuously running progress in marine electrical and electronic engineering many changes in configuration of ship electrical power systems are observed. Some of them are illustrated in Figures 2–4, where the main blocks responsible for power quality worsening are marked with the green color and for power quality improvement with the yellow color, respectively. These changes concern not only the new possibilities to apply the energy sources, e.g., additional gas turbines are also used, which are able to cooperate with a shaft generator, turbogenerator or free-standing generating sets [5,6], but first of all, a new philosophy concerning a main ship propulsion, it means electric propulsion is introduced. This concept is so-called all-electric ship (Figure 4).

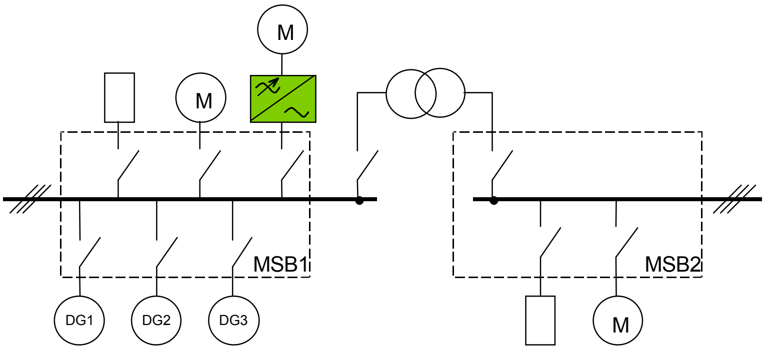


Figure 2. Traditional configuration of maritime power system, three electric generating sets of DG type, MSB1, main switchboard 3AC 380 V/50 Hz; MSB2, main switchboard 3AC 220 V/50 Hz; M—electric motor, box marked with green color is referred to worsening effect of power quality, in this case  means frequency converter.

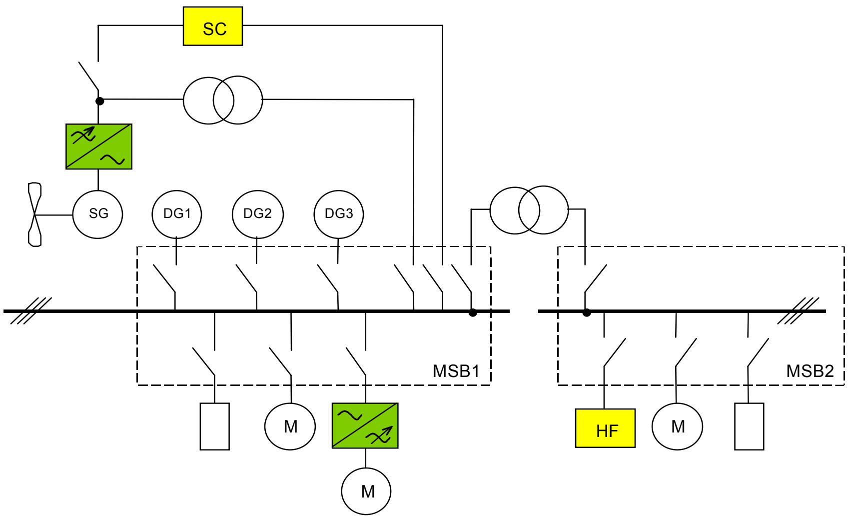


Figure 3. A configuration of maritime power system with, three generating sets of DG type together with shaft generator, MSB1, main switchboard 3AC 440 V/60 Hz; MSB2, main switchboard 3AC 220 V/60 Hz; SC, Synchronous compensator; HF, Harmonic filter; boxes marked with green color are referred to worsening effect of power quality and with yellow color—to power quality improvement, respectively, —frequency converter.

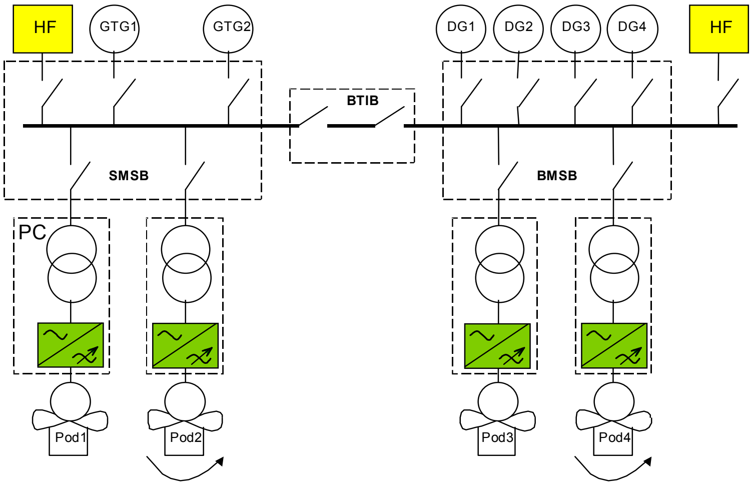


Figure 4. A configuration of all electric ship, BMSB, bow (forward) main switchboard 3AC 11 kV/60 Hz; SMSB, stern (aft) main switchboard 3AC 11 kV/60 Hz; BTIB, bus the interconnecting breaker; DGs, Diesel engine driven generators; GTGs, gas turbine driven generators; HF Aft and HF Fwd, harmonic filters, installed in aft and forward switchboards; respectively, PC, power converters; PODs, podded propulsion units of Mermaid azimuth thruster type; boxes marked with green color are referred to worsening effect of power quality and with yellow color—to power quality improvement, respectively, —frequency converter.

In Figure 2, the very basic, traditional configuration of ship electrical power plant equipped with three free-standing generating sets, *i.e.*, three-phase synchronous generators driven by the auxiliary diesel engines (DG), is shown. In the presented example, based on the power system configuration of research—training ship m/v "HORYZONT II" [7], the generating sets supply two sections of the busbars of the different voltage values. The diesel engines are supplied with relatively expensive light fuel oil contrary to cheaper heavy fuel oil used to supply the main engine. For this reason, the shaft generators (SG) driven by the main propulsion shaft were introduced as additional energy sources to cooperate with free-standing generating sets (Figure 3) in ship power networks.

In the presented example, the power system configuration is based on the chemical tanker m/s "Stolt Excellence" [8], and a key issue concerns cooperation of shaft generator with the generating sets of DG type. Generally, in the case of a fixed propeller application, the shaft generators are used only during main engine work with constant speed, *i.e.*, in a sea voyage. In solutions with a controllable pitch propeller, it is possible to use a shaft generator also during the maneuvers. As a consequence, the shaft driven generators are sometimes provided, as they supply the vessel with electric power when underway while reducing fuel and decreasing operational costs in comparison with the classical configuration based on the generating sets only (Figure 2) [3,5,6]. Despite its obvious advantages, the system illustrated in Figure 3 has also important drawbacks. Some difficulties associated with using of shaft generator are caused by highly irregular work of the main engine as well as by the shaft generator's working in parallel with other generating sets. To overcome these difficulties there power converters consisting of controlled rectifiers and inverters are usually used. Their current and voltage waveforms are deformed at the converter's output. The inverter output voltage waveform consists of both harmonics and notching disturbances [3] and may not be of sufficient quality to supply the load and/or operate in parallel with diesel or other auxiliary generators. The harmonics produced by the inverter bridge are based on the "pulse number ± 1" format, which unfavorably impair quality of the electric power delivered to the ship electric network. Moreover, the electronic power converters have another important drawback—namely—the dependent thyristor converters with network commutation cannot serve as reactive power sources of inductive character, which makes it necessary to use an additional synchronous generator for producing such power (so-called synchronous compensator) [3,5,6]. On the other hand, in addition to providing the reactive power and commutation current, the synchronous compensator also provides a measure of harmonic filtering [4], supporting a process of power quality improvement, what will be discussed in Section 4 of this paper. Presently designed converters built of IGBT transistors do not have such drawbacks, they can work without consuming of reactive power and simultaneously without deformation of consumed current [3,5,6]. A new generation of ship electrical power systems, based on the electric main propulsion concept, is illustrated in Figure 4. Electric propulsion is an advanced solution among ship propulsion methods, and is increasingly popular in recent years. The advantages of application of electric propulsion in ships are: the energy saving and ocean environment protection, lower exhaust emission and vibration noise, higher efficiency of ship propulsion and flexible space configuration, as well as the ship mechanical operation properties.

A presented example is based on the RMS "Queen Mary 2" [9] and refers to a recent nowadays solution of high voltage part of ship electrical system with engine room of CODLAG (Combined Diesel Electric and Gas Turbine) type. The presented configurations (Figure 4) of ship electrical power systems are limited to the high voltage electrical network, being in fact a vital part of the system for the all-electric ships, where a dominant load of the system is represented by four main propulsion motors, each of power about 20 MW. The passenger ship Queen Mary 2 (Figure 4) [9] had a total production capacity of 135 MVA at 11 kV voltage of 60 Hz. Two gas turbine driven generators (GTG) supplied SMSB and four diesel engine driven generators (DGs) supplied the BMBS. In normal operation, the MSBs were always connected to each other through the two bus tie circuit breakers. The auxiliary machinery was supplied at 690 V, with the exception of the air conditioning compressors and bow thrusters, which were rated at 11 kV. In the case shown in Figure 4, the main propulsion motors were supplied through the step down transformers and power converters. Essential elements of the propulsion system are doubled because of the necessity to ensure the reliability of the system and improvement of related power quality. Some aspects closely concerning these issues will be described in Section 4, Case Study 4.

The aforementioned overview of some maritime power systems' configurations basically concerns AC distribution grids as a dominant tendency met on ships. However, a problem concerning AC *versus* DC shipboard electric power distribution has been discussed for many years [10], and a perspective for the future is rather promising for DC solutions, at least in the selected applications. It is noteworthy to mention that DC SCR drivers in spite of their constructional and power limitations, are still operating in older and in new specialized survey vessels, for example, where low noise and vibration levels are important [3]. On the other hand, the numerous analyses and researches on AC and DC power grids for naval electric ship are carried out [11,12]. They are focused on, among others, a survey of the influence on reliability, life cycle costs and technical consequences on applying power electronics in electrical energy in naval ship system's designs [11]. Another interesting area of onboard DC grid application is related to the enhancement of DP (Dynamic Positioning) operation in ships [13]. Summing up, it is expected that the DC grid technology onboard of ships will be significantly increased in the future. Nevertheless, the author of this paper is of the opinion that this issue is beyond the scope of the presented subject.

3. How to Assess Power Quality on Ships?

3.1. Electric Power Quality and Its Assessment in Ship Systems

Looking for a definition of power quality, one of the most comprehensive proposals is laid in the IEEE Std. 1159-1995 [14]. This standard issued by the IEEE Coordinating Committee, gives a description: "The term of power quality refers to a wide variety of electromagnetic phenomena that characterize the voltage and current at a given time and at a given location on the power system". According to the definition, the power quality is not simply a group of technical parameters (like in the standard IEC 61000-4-30) [15], but the outcome of interaction between numerous parameters. In this context, electric power quality in ship system is described by the set of parameters characterizing a process of generation, distribution and utilization of electrical energy in all operation states of the ship (maneuvering, sea voyage, stay in the port) and its impact on the operation and safety of the ship as a whole. This set of parameters under consideration covers two aspects:

- parameters describing a risk of loss of power supply continuity and
- parameters of voltage and currents in all the points of the analyzed system.

Parameters of the first group are essential, but the second group of parameters is significantly better recognized in the area under consideration. Nevertheless, electrical energy must first of all be delivered to the consumers, and then its parameters can be evaluated. Bearing in mind the aforementioned assumption, parameters of the first group are mainly related with correct distribution of active and reactive loads among generating sets working in parallel. A main goal of their control is to avoid the "black-out" phenomenon, resulting from apparent overloading of the ship power station. Technical realization of this task is usually supported by the Power Management System (PMS), it means one of the functions of the ship automation systems is dedicated to ensure the continuity of power supply of important receivers, maintaining the economical effectiveness of considered power system operation. The most frequently realized tasks of the PMS belong to the automatic start/stop procedure of auxiliary engines, and automatization of the electrical power generation system (control of generators and main switch board, frequency control in the ship network, and load control with automatic switch-off of less important receivers as well). It should be strongly stressed, that the experience, competences and operational skills of the watchkeeping engineers have a vital role to comply with discussed requirements [16,17]. Parameters of the second group are mainly expressed by the coefficients of rms voltage value and its frequency deviations, coefficients of voltage asymmetry and coefficients characterizing the shape of voltage and current waveforms, it means characterizing their distortion of supply voltage from the sinusoidal wave. Additionally, the parameters of related load current are also important, especially in the case of bulk non-linear loads, but their limit threshold values are not defined in main stream classification societies rules. Process of the power quality assessment fulfills a crucial role in the operation of the ship as a whole and is a basis for power quality improvement. The main components of this process are illustrated in Figure 5.

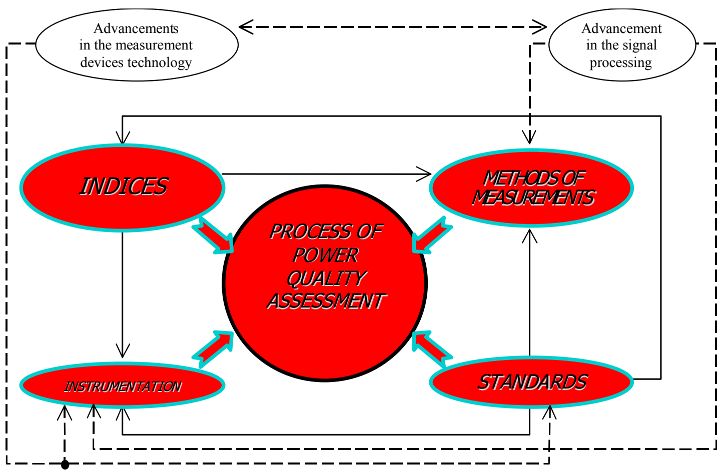


Figure 5. The main components of the process of power quality assessment in ship systems and interactions among them; the circles with red color are main components of the analyzed process, solid lines—interactions among main components of the process, dotted lines—additional interactions caused by continuously running advancements in the signal processing and in the measurements devices technology.

Presently existing main ambiguities of the power quality assessment process are:

- imprecise definitions of related power quality indices,
- a lack of unambiguous recommendations concerning application of adequate algorithms and measurements procedures,

- limited applicability of commercial solutions of power quality analyzers, hitherto available on the market (e.g., for varying frequency systems),
- standards and rules concerning a continuous monitoring of electric power quality are not exhaustive.

A possibility to compensate the appointed ambiguities and to comply all existing IMO recommendations is not easy because of numerous interactions among the main components of power quality assessment process in ship systems. In accordance to Figure 5, the standards in the area of power quality have an impact on indices, methods of measurements and instrumentation, respectively. On the other hand, indices have an influence on the methods of measurement and instrumentation. Finally, from the wider perspective, continuously running advancements in the signal processing, and in the measurement devices technology, have effect methods on measurements, standards and instrumentation accordingly to the interlinks marked by dashed lines in Figure 5. Anyway, some examples of the existing ambiguities and inaccuracies are shown on the basis of related case studies, mainly concerning the areas of indices and measurement methods. These case studies, previously announced in [18] and developed in [1], in this paper have been selected as the contemporary challenges in power quality in ship systems. Analysis and discussion of aforementioned case studies was a basis for building a conceptual model of power quality improvement presented and discussed in Section 4.

3.2. Power Quality Indices

Assessment of the ship electrical power systems, from a power quality point of view covers both supply and load side of the system, taking into account an influence of non-linear, asymmetrical receivers and in many cases the fluctuating loads. On the basis of a measurement of parameters characterizing the electric power quality (voltages, currents, powers) recorded in the selected points of the considered system, so-called points of common coupling (PCC), appropriate power quality indices, appointed by the user of the system have to be determined. With regard to two previously mentioned aspects of power quality, the basic power quality indices for ship systems together, with the recommended limit values, are laid in the related standards, described, among others, in [18,19]. Power quality indices concerning voltage and frequency deviations like δV, $\delta_{\text{per}}V$, δf and $\delta_{\text{per}} f$ are defined in [20,21]. If the indices δV and δf are well known as typical power quality indices, then the factors $\delta_{\text{per}} f$ and $\delta_{\text{per}} V$ have been defined in [20] and described in [1]. They are to show and limit the periodic variation of frequency and voltage during normal operation that might be induced by regularly or randomly repeated pulsing load. For purposes of the definition, the periodicity of the modulation should be recognized as not exceeding 10 s [20]. Such a situation is quite common in ship systems, especially during shaft generator direct operation [18]. Voltage asymmetry is usually defined by a quotient of symmetrical components of negative-sequence voltage, and positive-sequence voltage, respectively, expressed in percentages. The alternative possibility to define asymmetry is described by the formula [20,21]:

$$u_{L\_t\_L} = \frac{V_{\max\_L\_t\_L} - V_{\min\_L\_t\_L}}{V_n} \cdot 100 \tag{1}$$

where $V_{\max\_L\_t\_L}$, $V_{\min\_L\_t\_L}$ are maximal and minimal values of phase-to-phase voltage, V_n is rated value of rms voltage.

The waveform distortions analysis widely discussed in [1,18] defines firstly, a content of given higher harmonic component of h order in relation to fundamental component V_1:

$$C_f = V_{h\%} = \frac{V_h}{V_1} \cdot 100 \tag{2}$$

where both components are rms voltage values, and secondly appropriately defined indices of total distortions:

$$\mathrm{THD}_n = \frac{\sqrt{\sum\limits_{h=2}^{n} V_h^2}}{V_1} \cdot 100 \quad (3)$$

$$\mathrm{TWD}_n = \frac{\sqrt{V_{rms\_n}^2 - V_1^2}}{V_1} \cdot 100 \quad (4)$$

$$\mathrm{TWD}_{2.5-10\ \mathrm{kHz}} = \frac{\sqrt{V_{rms-2.5-10\ \mathrm{kHz}}^2 - V_1^2}}{V_1} \cdot 100 \quad (5)$$

In accordance with [20,21] "THD is the ratio of rms value of the residue (after elimination of the fundamental) to the rms value of the fundamental expressed in percentage". This approach is sometimes designated as TWD (Total Waveform Distortion) [22]. However, in the case of TWD the required frequency band for V_{rms} calculation has to be considered. This has to be above highest switching frequency of all AFE PWM drives. In fact, this influences a choice of sampling frequency of measurement device [23]. In this case, the operation of the input IGBT input bridge rectifier does significantly reduce low order harmonics compared to conventional AC PWM drives with 6-pulse diode bridges for $n < 50$, but at the same time a significant high order harmonic, above the 50th can be introduced [3,24]. It should be re-emphasized, that harmonic current magnitude interacts with the system impedances to produce the individual harmonic voltage drops at the harmonic frequencies, which result in the total harmonic distortion (in fact in TWD value) [3]. Based on the experimental results carried out by the GMU research team, with the author's contribution described in [18], it has been confirmed, that with respect to the isolated power systems, particularly belonging to the class "varying frequency systems", the hitherto adopted approach to waveform analysis based on the use of THD (Total Harmonic Distortion) expressed by Equation (3), leads to significant errors. Therefore, the application of TWD leads to more reliable results [23]. This position will be explained in the Case Study 1. The idea of $\mathrm{TWD}_{2.5\text{–}10\ \mathrm{kHz}}$ follows directly from the previous Equation (4), but is related to a limited frequency band, namely 2.5–10 kHz. The special kinds of waveform distortions are transients, which rather rarely appeared in the relevant regulations [18]. For example, according to [20] limit of voltage spikes is us = ±2500 V for 380–600 V systems. However, it has to be firmly stated that the phenomena are difficult to detect, and in consequence they are not monitored on an everyday basis. However, the current state of measurement techniques enables on-line monitoring and assessment a phenomenon under consideration [25]. A special attention should be paid to parameters describing the continuity of power supply delivery, like δP, δQ or δI, described, among others, in [1]. For ship systems the indices δP_i and δQ_i of proportionality of active and reactive power distribution for generating sets operating in parallel must be controlled. Monitoring of load distribution among generating sets operating in parallel is recommended by many ship classification societies, e.g., DNV, GL, LR or ABS, which rules impose acceptable levels δP_i and δQ_i indices. Appropriate indices characterizing a proportionality of the powers distribution of i-th generator are described by the formulae:

$$\delta P_i = \frac{P_i - \alpha_i \sum\limits_{i=1}^{k} P_i}{P_n} \cdot 100 \quad (6)$$

$$\delta Q_i = \frac{Q_i - \alpha_i \sum\limits_{i=1}^{k} Q_i}{Q_n} \cdot 100 \quad (7)$$

where P_i, Q_i are active and reactive load on the i-th—generator, respectively, P_n, Q_n—rated active or reactive load, respectively, on the largest output generator out of the generators running-in-parallel, or rated active or reactive load, respectively, on the smallest generator if its rated load is lower than 0.6 and its reactive load is lower than 0.4, respectively, of rated active load or reactive load on the largest output generator out of the generators running in parallel [26,27], k—number of generators running-in-parallel, α_i—coefficient of proportionality dependent on a number and output of running-in-parallel generating sets (α_i = 0.5, for k = 2, and the same output of the co-working generators).

Inappropriate values of these coefficients are the most frequent reason for blackouts in the ship's system and this is why the coefficients δP_i and δQ_i should be determined continuously during the ship operation. Another relevant parameter described also in [1], directly related to the active and reactive power distribution among generators working in parallel is coefficient of proportional current distribution of i-th generator:

$$\delta I_i = \frac{I_i - \alpha_i \cdot \sum_{i=1}^{k} I_i}{I_n} \cdot 100 \tag{8}$$

where I_n is rated current value on the largest output generator out of the generators running-in-parallel, k and α_i were defined above, I_i—effective value of equivalent current of the i-th generator [28]:

$$I_i = \sqrt{\frac{I_1^2 + I_2^2 + I_3^2}{3}}\ [A] \tag{9}$$

where I_1, I_2, I_3—effective values of phase currents, respectively.

To summarize a short overview of the most commonly used power quality indices, their listing together with the recommended limit values is shown in Table 1.

Table 1. Limit values of electrical power quality indices in ship power systems [20,21,26,27].

Parameter	**IEEE 45**	**PN-IEC610092-101**	**ABS**	**PRS**
δf_t	±3%	±5%	±5%	±5%
δf_{tr}	–	–	–	–
(a) value (b) time	±4% 2 s	±10% 5 s	±10% 5 s	±10% 5 s
$\delta_{\text{per}} f$	0.5%	0.5%	–	–
δf_{max}	5.5%	12.5%	–	–
δV_t	±5%	+6%, −10%	+6%, −10%	+6%, −10%
δV_{tr}	–	–	–	–
(a) value (b) time	±16% 2 s	±20% 1.5 s	±20% 1.5 s	±20% 1.5 s
$\delta_{\text{per}} V$	5%	2%	–	–
δV_{max}	±20%	±20%	–	–
$u_{L\_t\_L}$	3%	7%	–	–
u_2	–	3%	–	3%
THD	5%	5%	5%	5% *, 10% **
$V_{h\%}$	3%	3%	3%	3% *, 6% **
δu	5%	–	–	–
u_s	2500 V (V_n = 380–600 V) 1000 V (V_n = 120–240 V)	5.5 V_n 1.2/50 µs ***	–	–
δP	–	–	±15%	±15%
δQ	–	–	±10%	±10%

Where δV_t, δf_t, voltage and frequency tolerance, respectively; δV_{tr}, δf_{tr}, voltage and frequency transient component, respectively; u_s, voltage spikes; and * *THD* and V_h% long-lasting aggregated values for the aggregation time 10 min in electric power systems of general purpose; related instantaneous values (measuring window 200 ms) are equal 7.5% and 4.5%, respectively; ** *THD* and V_h% long-lasting aggregated values for the aggregation time 10 min in electric power systems designed to supply nonlinear consumers (*i.e.*, dedicated system); related instantaneous values (measuring window 200 ms) are equal 15% and 9%; respectively, *** rise/fall time—concerns only PN-IEC 610092-101 standard.

Overviewing the most important classification society rules, some ambiguities concerning imprecise definitions of related power quality indices may be formulated as follows [29]:

- a majority of existing rules concerning ship systems do not determine the aggregation times for particular indices of voltage waveform distortions,
- in the rules under discussion the same value of limit levels of particular harmonics is defined, what is a very controversial approach considering different effect on the given object of different orders harmonics,
- in the related standards for ship systems, the limit levels for interharmonics and subharmonics are not defined, whilst the disturbances of this kind occur frequently in ship networks fitted with electronic converter subsystems,
- similarly to previous objection, in the same standards, lack of limit contents of the disturbing components in the frequency band above usually accepted number of harmonics, *i.e.*, 40 or 50 is noted,
- and finally, a very imprecise definition of THD in accordance with traditional approach.

In many cases, THD evaluation is not effective, because the components above usually defined number of harmonics are simply avoided. This problem was preliminary indicated in [18] and developed in [1]. Moreover, traditional way of analysis considers only harmonics, avoiding other disturbances, like interharmonics, subharmonics or distortions, which are not related to fundamental component frequency. Two questions should be solved: which way and what kind of disturbances (not only harmonics in the limited frequency band) could be taken into account? In addition, which frequency band is to be considered?

Case Study 1. To clarify the consequences resulting from traditional approach (e.g., [30,31]) based on the rules which require measurement up to 50th harmonic, let's consider the example of voltage registered on terminal of navigation equipment at all-electric ship [18]. This has been shown in Figure 6 [18].

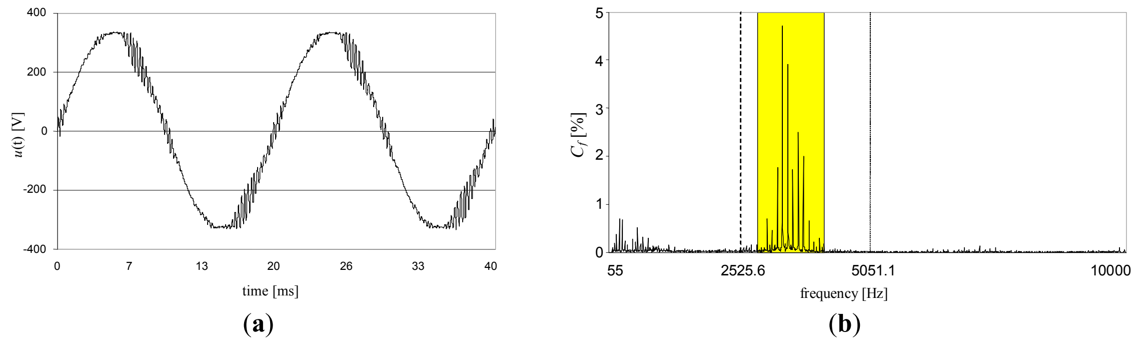


Figure 6. Exemplary waveform of supply voltage (**a**) on terminal of navigation equipment at all-electric ship and its spectrum (**b**) analyzed frequency sub-band is marked with yellow color; dashed line marks frequency of 50th harmonic whereas dotted line marks frequency of 100th harmonic. C_f, content of higher harmonic component with frequency f [14].

In the presented case, it is early visible that the components above 50th harmonic (marked with the yellow color) are dominant. The distortions are caused by operation of power converters with declared switching frequency 3.6 kHz. Therefore, the appropriate analysis of this case requires covering the frequencies above 50th harmonic. This problem has been recognized by some of ship classification societies. For example, the American Bureau of Shipping recommends calculation of THD factor (see Equation (3)) up to 100th for ship systems equipped with "active front ends" AFE PWM drives [26]. Apparently, the solutions should solve the problem in the example presented above, since the dominant components are located below 100th harmonic. Unfortunately, these distortions are not related to fundamental component frequency, namely they are not harmonics. It has been graphically shown in Figure 7.

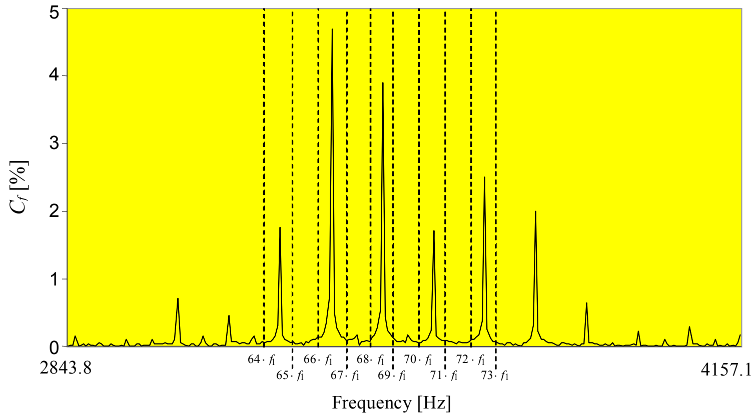


Figure 7. Example of spectrum of voltage on terminal of navigation equipment at all-electric ship for frequency sub-band 2843.8–4157.1 Hz marked with yellow color; dashed lines mark the harmonic frequencies as integer multiple of fundamental frequency equal to 50.51 Hz [18].

Finally, the basic distortion indices have been calculated by all above introduced Equations (3)–(5) and for various frequency bands. The results are laid in Table 2.

Table 2. Results of calculation of various distortion factors, designations [12].

THD_{50}	THD_{100}	$\mathrm{TWD}_{2.5\ \mathrm{kHz}}$	$\mathrm{TWD}_{10\ \mathrm{kHz}}$	$\mathrm{TWD}_{50\ \mathrm{kHz}}$
1.51%	1.61%	1.62%	7.83%	7.9%

The detailed analysis of results in Table 2 leads to the conclusions that dealing with waveform distortions at shipboard [18]:

- one must forget about all factors based on harmonics only, like THD_{50} calculated up to 50th harmonic or even THD_{100} calculated up to 100th harmonic,
- TWD factor is the only viable solution but proper frequency band of input signal has to be chosen carefully,
- the determining of only $\mathrm{TWD}_{10\ \mathrm{kHz}}$ and $\mathrm{TWD}_{2.5\text{–}10\ \mathrm{kHz}}$ factors would be enough for typical and less typical cases monitoring.

Next in [18], it was concluded that application of $\mathrm{TWD}_{10\ \mathrm{kHz}}$ and $\mathrm{TWD}_{2.5\text{–}10\ \mathrm{kHz}}$ factors for monitoring of waveform distortions of electrical signals at shipboard should be advised. It allows easy detection of the distortions and rough categorization, *i.e.*, low- or high-frequency phenomena or both. Taking into account of switching frequencies of typical large power AFE PWM drives, the 10 kHz limit of considered frequency band would be enough. This solution is consistent with the standard [32].

3.3. Measurement Methods of Power Quality Indices

Undoubtedly the standards concerning power quality assessment in industrial land networks should be considered as the primary standards, which constitute a state of the art in the question under discussion. They are a basis to form the standards addressed to power quality in ship systems. If we assumed, that power quality standards concern two aspects, firstly, they define a set of reference technical parameters, and their permissible limits, and secondly, they define methods of their measurement, we have easily indicate some similarities and common points in appropriate land and ship standards, e.g., [14,15,20,21,31], respectively, in relation to the first aspect. Additionally, there are rules of ship classification societies, e.g., [26,27,30,33], resulting from mentioned above standards. Generally, these rules are similar to the previously cited dominant standard [21] or even less precise, what was partly illustrated in Table 1 and discussed in Section 3.2. In respect to the second aspect, there are many rules concerning methods of respective parameters measurement in ship systems, and the key land network IEC standards [15,31] have not been mentioned in rules of ship classification societies or in IEC ship standard [21]. Under such conditions, the measurement methods of power quality indices are fundamentally based on signal processing methods described in the well-recognized standards [14,31]. Because the present commercial power quality analyzers implement the methods laid in these standards, it has been strongly recommended to analyze their applicability for ship systems [23,34,35]. According to considered standards, there are some recommendations for signal processing like [15,31]:

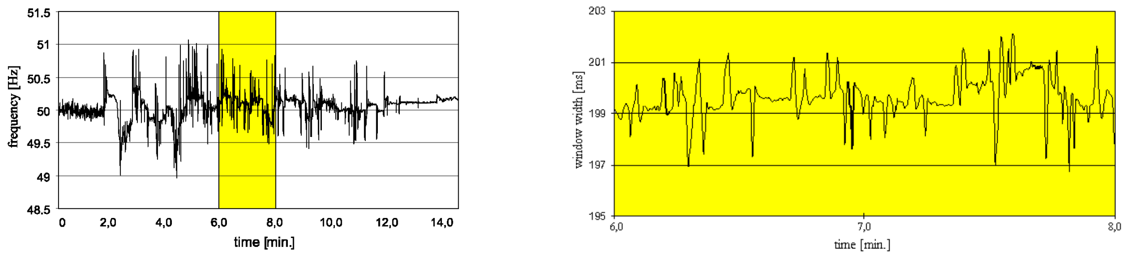
- window width equal to exactly 10 periods of the fundamental period for 50 Hz systems and 12 periods of the fundamental period for 60 Hz systems, corresponding roughly to 200 ms,
- rectangular window (Hanning weighting is allowed only in the case of a loss of synchronization),
- a Discrete Fourier Transform DFT,
- sampling frequency sufficient for the analysis of frequency components up to 9 Hz,
- the fundamental frequency should be calculated as the ratio of the number of integral cycles counted during the 10-s time clock interval, divided by the cumulative duration of the inter cycles,
- concept of voltage harmonic subgroups, where the Fourier transform analysis assumes that the signal is stationary. However, in reality, the voltage magnitude and frequency of the power system may fluctuate, spreading out the energy of harmonic components to adjacent interharmonic frequencies,
- time aggregation, combination of several sequential values of a given parameter (each determined over identical time intervals) to provide a value for a longer time interval.

Additionally, it has been predicted that new instruments are likely to use a Fast Fourier Transform FFT. A rough overview [29] of the commercial offer confirms the fact of application by world-wide producers of power quality analyzers the measurement methods of electrical power quality parameters based on the recommendations of the related IEC standards for land networks. A critical analysis of applicability of measurement methods described in the above mentioned standards leads to conclusion, that at least in the three cases these methods should not be applied to the signal analysis in ship networks, it means in the case of frequency measurement, a spectrum measurement and THD coefficient measurement [34]. The first exception concerns the method of frequency measurement. According to IEC 6100-4-30 standard "the fundamental frequency output is the ratio of the number of integral cycles counted during the 10-s time clock interval, divided by the cumulative duration of the intercycles". However, frequency values shall be obtained in relatively short periods of time in ship systems since its deviation from rated value shall be within the limit of $\pm$10% during the time not longer than 5-s (whereas the steady-state deviation should not exceed $\pm$5%). Taking into account these permissible limits for short-time frequency deviations in ship systems, it makes no sense to calculate the frequency on the basis of 10-s intervals. Finally, the method based on the basic measurement window duration has been proposed. For short-term frequency deviation analysis, a frequency calculation as reciprocal of one cycle refreshed each half cycle has been recommended, and for quasi steady-state frequency deviations a frequency calculation over basic measurement time interval equal to 10 cycles for systems with rated frequency equal to 50 Hz and 12 cycles for systems with rated frequency equal to 60 Hz has been used. This issue was discussed on the basis of real examples from ship systems in [36]. The second exception is connected with frequency spectrum analysis. Analysis of most important parameters of the selected and commonly used power quality analyzers show some discrepancies, incompleteness or a lack of data in the significant questions, for example concerning the measurements of higher harmonics and interharmonics, or the measurement within the range from 50th harmonic to 9 kHz. Measurement of higher harmonics and interharmonics in ship networks requires [37]:

- discarding FFT algorithm as a basic tool for spectrum estimation,
- implementing asynchronous (*i.e.*, non-coherent) sampling and next application of chirp *Z*-transform CZT or interpolation in the time-domain (*i.e.*, programmable re-sampling), and further Fast Fourier Transform FFT.

One of the fundamental questions is: why FFT algorithm cannot be used as a basic tool for spectrum analysis? On the one hand, FFT requires the particular number of samples, usually power of two, 2^N. In practical terms, this method does not allow taking into consideration a real number of samples, if different from 2^N, unlike in CZT. On the other hand, the input data set should contain integer number of cycles of all signal components in order to avoid consequences of spectrum leakage. It can be a problem in ship system due to, enormous long- and short-term frequency deviations and sometimes respective parameters fluctuations, like presented below, in Case Study 2.

Case Study 2. For the analyzed case [18] concerning frequency and related parameters fluctuations during all-electric ferry maneuvering (Figure 8) the mean value of frequency during the ferry maneuvering has been equal to 50.05 Hz but it has varied significantly between 48.97 and 51.06 Hz.



(**a**) (**b**)

Figure 8. Frequency (**a**) and basic measurement window width (**b**) fluctuations during all-electric ferry maneuvering; analyzed frequency sub-band is marked with yellow color.

In the author's opinion expressed in [1,18] the consequences of the phenomena, like in Figure 8 for power quality assessment are underestimated, and even worse, only a few are fully understood. Moreover, in [18] it was commented on that "reliable measurement of most of the power quality indices requires prior information about actual fundamental frequency. One can even state that determining frequency of fundamental component is must-be for most of other components determining, with only a few exceptions. In fact, this means necessity of estimation of the measurement window width understood as duration of integer number of fundamental component cycles. The required accuracy of the width determining can even reach 0.03%, like in the case of harmonics and interharmonics assessment [31]". Having this in mind, it is necessary to underline that in accordance with IEC 61000-4-7 standard recommendations, manufacturers of related measurement instruments usually synchronize sampling frequency with the actual frequency of voltage with only short delay (a few hundred milliseconds at most) [38], in order to meet the requirement and perform typical fast Fourier transform (FFT) on integer number of cycles (10 or 12 cycles depending on system rated frequency 50 or 60 Hz [31]). In the previously cited [18] it was explained: "However, one cannot conclude on the actual width of measurement window on the basis of previous ones at systems with such an enormous and frequent frequency fluctuations like ship systems. Therefore, this approach can be misleading [37]. For presented example (Figure 1) in [18], duration of as many as 50.5% of adjacent measurement windows differs more than 0.03%. Therefore, another approach is necessary and instruments based solely on FFT algorithm for distortion analysis must not be used on shipboard [34]. Unfortunately, it seems that only a few are aware of this fact and this is completely absent at related rules, recommendations and practice. This is despite the hitherto progress in digital signal processors (DSPs) technology, which enables online application of asynchronous sampling frequency and more complex methods of signal processing like software re-sampling [37,39,40] or chirp z-transform (CZT) [37,41,42]".

The third exception concerns a problem of THD coefficient measurement, including an extended interpretation of this coefficient and consequences resulting from their implementation have been discussed in Section 3.2, Case Study 1. To complete this problem, it is worthy to add the definition proposed by the author's research team [23]: "Total Harmonic Distortion (THD) is the ratio of rms value of residue in the frequency band up to 9 kHz after elimination of fundamental to the rms value of fundamental, expressed in percentage, where rms value of fundamental subgroup calculated for approximately 200 ms window in accordance with IEC Std. 61000-4-7". In further works the related frequency band has been extended from 9 kHz to 10 kHz [18]. Additionally, on the basis of many-year research of ship networks for different kinds of ships as a more adequate definition is a formula with using of harmonic subgroup concept, it means G_1 instead V_1 in Equation (4). This approach significantly minimize an influence of fluctuations of input signal parameters [23].

A question, how to aggregate measurement results is very important for the operators of power systems, including ship systems. From their point of view, a principal question is: which values of distortion factor should be considered? A comprehensive background of this problem and examples of research results recorded on all-electric ship is presented in [34]. It was confirmed by research carried out on board all-electric ferry presented in [18]. Some conditions concerning the discussed problem are illustrated and commented on in [1]. Considering the fact that the overall level of distortions significantly varies during ship maneuverings, it seems reasonable to assume various permissible limits of distortion factors depending on the time of occurrence [43]. Therefore, in the case of time-varying waveforms, the relaxed thresholds of waveform distortion indices should be adopted. To some extent, the concept of measurement results aggregation laid in [15] is simplified version of this idea. Unfortunately, except the UK Defence Standard [44], the concept has not entered into related standards for power quality assessment on ships. The assumed aggregation intervals for the assessment of waveform distortions impact on ship electrical equipment should take into consideration the receivers thermal time constants [22] and also not to increase the number of some hard-to-interpret data for ship crew. There are two aggregation intervals that have been introduced in [15]. First aggregation interval is equal to 150 cycles for systems with rated frequency equal to 50 Hz and 180 cycles for systems with rated frequency equal to 60 Hz. In both cases it is equal to approximately 3 s. Second time interval is equal to 10 min. The arduous analysis of real ship examples leads to a conclusion that the aggregated 150 cycles values changed in similar pattern like values measured on the basis of 10 cycles window, with only slightly lower maximal values. However, this is quite different for 10-min aggregate values [34]. Some experimental results concerning the selected distortion factors of all-electric ferry manoeuvring considered in the context of the aggregation time are analyzed and discussed in [1,18]. It was shown, that taking into account two various limit values for both: momentary 200-ms aggregated values and aggregated 10-min values of distortion factors are reasonable. The second aggregation time would be appropriate for assessment of waveform distortions impact on heating of electric motors [45] and this should concern other power quality indices as well. The main ambiguities related to the measurement methods of quantities characterizing electrical power quality in the wake of appropriate ship standards and rules, can be formulated as follows [29]:

- there are no rules concerning methods of respective parameters measurement in ship systems and the relevant IEC standards related to land power systems have not been mentioned neither in rules of ship classification societies, nor in IEC 60092-101 ship standard,
- generally, lack of threshold value of power quality indices and adequate aggregation times in standards and rules of ship classification societies, besides of the Polish Register of Shipping rules and UK Defense Standards, where these kind of data in selected areas are included,

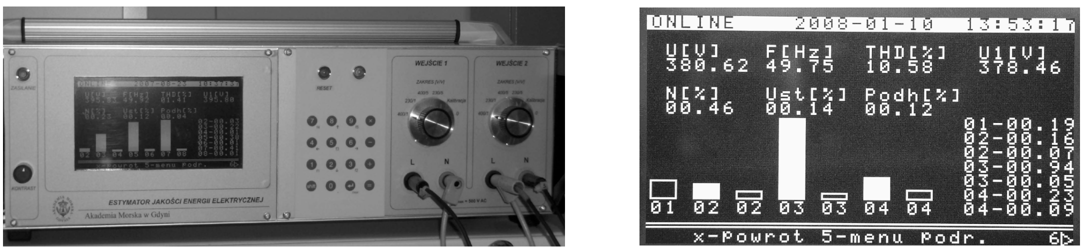
- moreover, lack of recommendations addressed to assessment of harmonic components in the frequency band above 50th harmonic in ship systems, only two exceptions are noted: Polish Register of Shipping requires this kind of assessment in frequency band above 50th harmonic up to 10 kHz, and American Bureau of Shipping has recommended the measurement of harmonic components above 50th harmonic up to 100th harmonic on ships equipped with Active Front End (AFE) drives.

3.4. Instrumentation for Power Quality Assessment on Ships

Nowadays solutions used in electrical power quality analyzers, in relation to the isolated electrical power networks application, show some significant disadvantages, mainly caused by varying frequency in those systems (fluctuations of electrical power energy parameters and lack of sampling frequency synchronization), a lack of relevant measurement modules, e.g., addressed to sufficient proper active and reactive power distribution and a lack of sufficient number of current channels. A rough overview [29] of selected solutions, *i.e.*, Fluke 435, Hioki 3196 and PowerVisa™ of Drantez BMI (Edison, NJ, USA) show, that all these commercial analyzers belong to the measurement class A in accordance with [15]. In considered solutions it is possible automatically compare results of measurements with their threshold values included in related standards. The main disadvantages (from isolated networks point of view) of presented solutions are: use of inappropriate measurement methods, limited possibilities of measurement of power distribution coefficients and a lack of possibilities of disturbances measurement in the band above 50th harmonics up to 9 kHz. In addition, last but not least, the all registered disturbances registered in ships system usually has been observed concurrently, with obvious negative synergy effect. It should be taken into account when evaluating electric power quality. For example, the temperature rises of electric motor winding caused by voltage and frequency deviations have been significantly increased if supply voltage waveform and/or unbalance have occurred concurrently [45,46]. Taking into account present state of the art, to overcome the above appointed disadvantages concerning the applied methods of signal processing and hardware structure of existing solutions, some research oriented to dedicated devices complying with marine environment requirements and needs have been undertaken, among others, at Gdynia Maritime University [41,42,47,48].

In the device under consideration (Figure 9) two modes of operation were introduced [41]:

- operation mode "Analyzer", when all parameters of electrical power quality were determined and a constant algorithm of signal processing was used,
- operation mode "Estimator", when those parameters are determined, whose current values exceed the limit threshold values, based on the original concept of multi-stage signal processing and changeable algorithms of signal processing, for decreasing in computational complexity.



(**a**) (**b**)

Figure 9. The estimator-analyzer 1.0: (**a**) front panel; (**b**) an example of screen: analyser mode and display of harmonic (marked with white color) and interharmonics (marked with transparent color) subgroups up to 4th harmonic [41,42].

To complete a version 1.0 and overcame some previously appointed disadvantages, mainly in hardware structure, the expanded version of Estimator-Analyzer of power quality 2.0 (Figure 10) was realized [35,47,48].

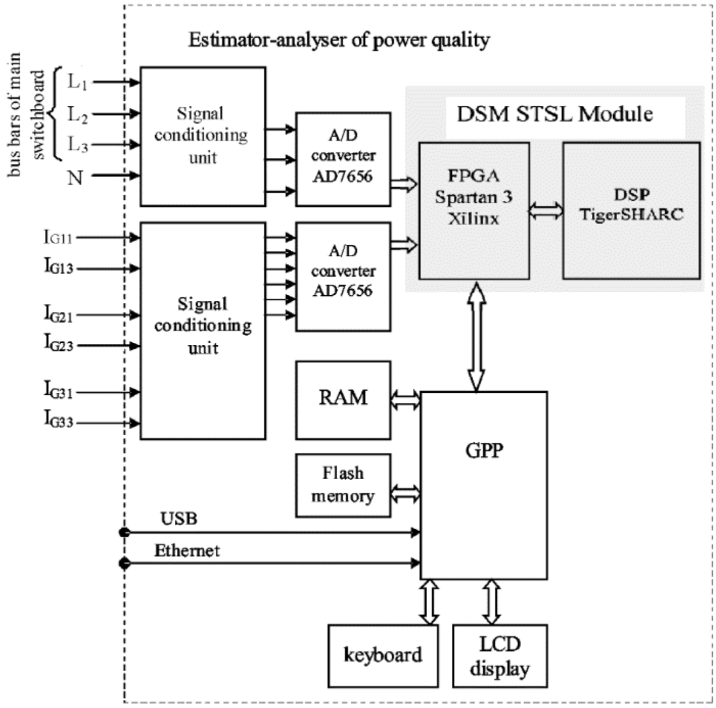


Figure 10. Simplified hardware structure of the new version of estimator-analyser of power quality; DSP, digital signal processor; GPP, general purpose processor [35,47,48]; the part with grey background is referred to DSM STSL Module.

The developed estimator/analyzer of electric power quality gives some options of the device for choice by the user. These options [35] concern a kind of analysis (voltage quality monitoring or monitoring of power/current distribution), mode of operation (estimator/analyzer), and also a kind of power system and number of generators working in parallel. During realization of the instruments some original ideas have been used in the layer of the methods and algorithms (Estimator and Analyzer modes, monitoring of voltage parameters and monitoring of powers and currents distribution), in the hardware (configuration of current and voltage measurement channels, two-processor structure of the device) as well as in the software (complementary application of different transforms). The carried out device has not the main disadvantages commercially available power quality analyzers, it means, its algorithms are not based on the typical FFT algorithm, which cannot guarantee of correct assessment of power quality under conditions of great changes of inputs parameters, mainly frequency. Further monitoring of currents and powers in the case of parallel work of three generating sets is now possible, contrary than in hitherto available solutions. The proposed, newly designed and tested solution is characterized by the following properties: measurement of voltage, current and power parameters; broad spectrum of measured disturbances approximately up to 100 kHz, calculation of temperature factor of electrical power quality, assessment of load distribution among generating sets working in parallel, correct operation under of great changeability of input signal parameters, additional option-continuous monitoring of electrical energy quality parameters and its conformity with respective standards (new operation mode—estimator). Designed, carried out and tested device was called "estimator-analyzer of power quality" to emphasize its relevant distinctness from the solutions available on the power quality analyzers market. The carried out tests [42,47,48] confirmed a correctness of the used algorithms and procedures applied in the DSP and FPGA devices, as well in the estimator-analyzer as a whole. The accuracy of determining the related coefficients is satisfactory from a practical point of view. More detailed description and analysis of the measurement tests of the designed power quality estimator/analyzer have been behind the concept and scope of the presented paper, but more information can be found in related papers [1,35,41,42,47,48]. The presented example of power quality estimator/analyzer is an attempt to confront existing state of the art in the considered area with the isolated power network's needs. Author is aware, that presented example is only one of many different, independently elaborated, solutions of the problem described above.

3.5. Legal Instruments for Power Quality Monitoring

There are many standards dealing with the problem of electric power quality. As it was mentioned in Section 3.3, the standards concerning power quality issues in the land, industrial grids had to be considered as the primary standards. There was a basis to form the standards for ship networks. The lists of most important standards concerning the issues of power quality assessment in the land and in ship networks, are shown in Tables 3 and 4, respectively. The standards of the most significant meaning in ship technology are marked in the grey color.

Table 3. Most important standards concerning the issues of electric power quality assessment in the land systems.

No.	Symbol of the Standard	Range of the Standard
1	IEEE 1159-1995	IEEE Recommended Practice for Monitoring Electric Power Quality
2	IEC 61000-4-15:1997/A1:12003	Electromagnetic Compatibility (EMC), Part 4: Testing and Measurement Techniques—Section 15: Flickermeter—Functional and design specification
3	IEC 61000-4-30-2003	Testing and Measurement Techniques—Power Quality Measurement Methods
4	IEC 61000-4-7-2007	General Guide on Harmonics and lnterharmonics Measurement for Power Supply Systems and Equipment Connected Thereto
5	EN-50160-2007	Voltage characteristics of electricity supplied by public distribution network
6	IEEE 1459-2010	IEEE Standards Definitions for the measurement of electric power quantities under sinusoidal, nonsinusoidal, balanced or unbalanced conditions

Table 4. Most important standards concerning the issues of electric power quality assessment in ship networks.

No.	Symbol of the Standward	Range of the Standard
1	IEEE Std. 45:2002	IEEE Recommended Practice for Electrical Installations on Shipboard
2	IEC 60092-101:2002	Electrical installations in ships. Definitions and general requirements
3	STANAG 1008:2004	Characteristics of Shipboard Electrical Power Systems in Warships of the North Atlantic Treaty Navies, NATO, Edition 9, 2004
4	American Bureau of Shipping, ABS, 2008	Rules of building and classing, steel vessels
5	Rules of international ship classification societies, e.g., PRS/25/P/2006	Technical Requirements for Shipboard Power Electronic Systems

A short description of these standards content is presented, among others, in [1]. It is worth mentioning the universal character of the standard EN-50160-2007 [49], where the definitions of voltage characteristics of electricity by the public distribution network are presented and discussed.

Going to the issues addressed to the power quality assessment in ship networks, first of all two standards: IEEE 45:2002 [20] and IEC 60092-101:2002 [21] should be taken into account. In both standards, the requirements set for the electrical installations in commercial ships also cover the permissible values of particular parameters characterizing power quality in ship networks. The related requirements concerning navy ships of the NATO countries are included in the standard STANAG 1008 [50]. Two last of the norms cited in Table 4, *i.e.*, ABS 2008 [26] and PRS/25/9/2006 [27] are the examples of the legal instruments of ship classification societies, responsible for a technical state of ships during their construction and periodically, during their exploitation. Classification society rules mainly refer to normal operation of electric networks of commercial ships. These rules, in general, have not taken into account the significant upcoming changes in the network field and are rather poor in stipulating standardized terminology and limitations. A worth mentioning exception noted in [19] is that of LRS, where in case of naval ships it makes reference to STANAG 1008. Supervision of classification institutions (American Bureau of Shipping, Lloyds Register of Shipping, Det Norske Veritas, Chinese Classification Society, Polish Register of Shipping and others) covers also a control of the most important factors (indices of electrical power quality). Much interesting data concerning an overview of electrical power quality requirements in the wake of the most important international standards may be found in [19]. The main ambiguities of existing standards and rules for ship networks concerning the imprecise definitions of related power quality indices and related to the measurement methods of quantities characterizing electrical power quality in the system under consideration, have been formulated and discussed in the Sections 3.2 and 3.3, respectively. It is a consequence of the simultaneous impact of the related standards on indices, methods of measurements and instrumentation shown in Figure 5.

4. How to Improve Power Quality on Ships?

4.1. Sources and Reasons of Lowered Power Quality on Ships

Nowadays, many of the new-technology based sophisticated ships, like passenger ships, large ferries, chemical and gas tankers, container vessels, oil rigs suppliers and large offshore structures are all-electric ships. In many cases, they are ships equipped with dynamic positioning system or ships with main engine without camshaft with electronic control injection—common rail system. On some electrically propelled vessels (all-electric ships), the propulsion motors consume more than 70% of the total generated power and the resulting voltage distortion is more significant. On many kinds of vessels, including previously mentioned, numerous electronic power converters are applied both to the main propulsion motors and auxiliary drives. These electronic power converters frequently regarding high-power devices deal with drives of deck cranes, mooring-anchoring winches, thrusters, cooling water pumps of diesel engines cargo pumps on tankers, fans, refrigerating medium compressors on refrigerated ships usually belong to the class of non-linear and variable-energy consumers. It is worthy to add that presently not only the number of power converters in ship systems increases, but also power of a single electrical motor rises, which together with converter system used in main propulsion systems often exceeds 20 MW. At the same time, total power of electrical energy receivers installed in these systems in many cases reaches the values up to 80–100 MW. Such a great values of power cause a necessity to use high voltage solutions, and level of applied voltages reaches even 11 kV. Under such conditions, the new competences for highly qualified staff, dedicated mainly to electrical, electronic and control engineering issues are required [18]. A necessity of usage of many non-linear and variable-energy consumers on ships causes a problem of appropriate power quality in ship networks. Beyond traditional voltage dips or voltage and frequency fluctuations, a waveform distortion problem including transient and notching phenomena is more and more visible. However, we also cannot forget about the "human factor", as a one of dominant reasons of power quality problems in recent years. Taking into account author's team research experience and numerous case studies describes in the related references [3,9,51], the most frequent reasons of power quality disturbances are:

- carelessness in design and carrying out of the system,
- errors in the system operation ("human error" is a dominant cause of the accidents at sea in accordance with the International Maritime Organization statistics),
- influence of the power electronic devices installed in the considered system,
- switching processes and over voltages provoked by them in distribution switchgears and electrical consumers,
- failures of the important elements of the system (e.g., harmonic filters cooperating with shaft generators or main electric propulsion).

Summing up, to keep power quality in accordance with the adequate for ship industry standards, it requires of undertaking of the appropriate measures. An improvement of power quality can be achieved on the two parallel ways: by means of using appropriate technological solutions and by increasing of the staff competencies and skills. The first option is usually connected with the design stage of the ship system, the latter one—with exploitation stage. However, a ship is reality more complex with numerous aspects. This should be taken into account when building a conceptual model for solving the central problem, *i.e.*, a problem of power quality improvement, or in the wider perspective, the problem of reducing a risk of accidents and ship safety improvement.

4.2. Conceptual Model for Solving the Central Problem

To solve the central, previously formulated problem concerning the power quality improvement en route to reducing a risk of accidents and improving a ship safety a relevant conceptual model is presented in Figure 11 and described below. An idea of the presented approach is taken from [52].

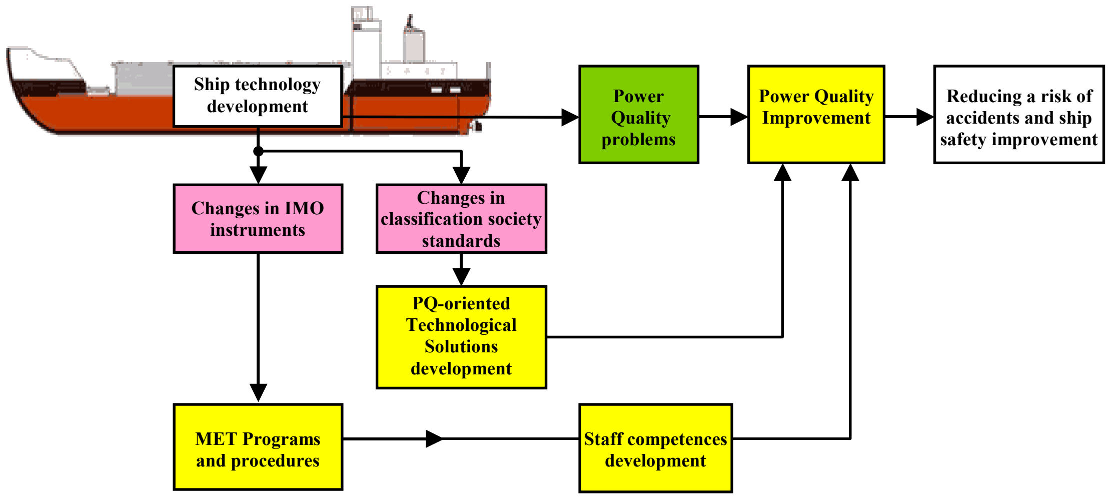


Figure 11. Conceptual model for solving the problem of power quality improvement en route to reducing a risk of accidents and improving a ship safety the boxes marked with red color are referred to necessary changes resulting from ship technology development, with green color—to new power quality problems occurring, and with yellow color—to ways of power quality improvement, respectively.

This model is built on the basis of the existing state of the art, summarized by the conclusion, that ship technology development creates power quality problems. To overcome these problems, some measures concerning power quality improvement should be undertaken. These measures are referred to two layers: technical—expressed by power quality technological solutions development, and socio-technical, strictly linked with crew-competence related matters and expressed by continuously running staff competences development (Figure 11). However, it is important, that these two components are of complementary character and both are provoked initially by ship technology development. This development has a fundamental impact on changes made in two parallel tracks: in IMO instruments changes, and in classification society standards changes. If the IMO instruments (understood as the appropriate conventions and protocols ratified by the world maritime community), change, they will affect the maritime education and training (MET) programmes and procedures, and later the staff competencies development. Simultaneously the changes in classification society standards are the basis to the power quality oriented technological solutions development. At the same time, both paths lead in consequence to power quality improvement. The author of this paper is of the opinion that this latter observation concerning the link between staff competences development and power quality improvement is significantly underestimated, and this will be developed and documented in Section 4.4 and in further discussions. Summing up, a key point presented in Figure 11's conceptual model is a final aim of the undertaken actions: how to reduce a risk of ship accident and related changes, in other words—ship safety?

4.3. Technological Solutions

Technological solutions are based on the activities and cooperation of the shipowners, designers and users of the ship systems. They may be undertaken at the design stage and the exploitation stage of the considered ship. At the ship system design stage, it should be taken into account that the impedance of a marine generator is also normally quite high compared to that of the utility's transformer [53]. This results in a larger voltage distortion at the source when harmonic currents are drawn by substantial non-linear loads such as the main propulsion motor power converters. As more generators are added to increase the power generated, they also have the effect of lowering the overall impedance, reducing the amount of harmonic distortion [3,7,9]. Taking into account above mentioned effect an important recommendation for designers is to install generators with a large sub-transient reactance [9]. An illustration of this phenomenon, based on the experimental study results [7] is shown in Case Study 3. A very similar effect based on the additional reactance of the synchronous compensator (Figure 3) occurs in the power system aided by shaft generator. In addition to providing reactive power and commutation current, the synchronous compensator also provides a measure of harmonic filtering [3]. The low harmonic reactance of the compensator attracts a relatively large degree of harmonic currents, which would otherwise be injected into the load. The induced voltages in the compensator are essentially sinusoidal, therefore the output voltage will also be relatively sinusoidal [3]. In addition, at design stage, we have considered a division of the power system into independent subsystems with individual power supply sources for a ship power station with total power upper 3 MW (Figure 4). Under these conditions the SOLAS convention [54] recommends, the main switchboard should be divided into Sections. Another recommendation for designers is that loads with increased sensitivity for changes of voltage supply parameters and devices with special significance for ship safety should be supplied from the separated sub-system. Alternatively, disturbing loads can be supplied from dedicated generators, if their combined power is relatively small.

Case Study 3. In [7] authors carried out research on impact of ship electric power plant configuration on power quality in the ship power system. The experimental study was based on the electric power plant configuration of the ship m/v "Horyzont II", roughly presented in Section 2, Figure 2. The registered power quality parameters were measured on the busbars of the ship's main switchboard and they covered, among others, THD, TWD and $TWD_{2.5\text{–}10\,\text{kHz}}$; previously defined in Section 3.2, by Equations (3)–(5). The THD values have been calculated on the basis of harmonics subgroups, up to the frequency of the 50th harmonic, but TWD has been determined up to 10 kHz. The instantaneous values of the above-mentioned indices (including also content of respective harmonics subgroups, SGH) have to be determined. Three configurations of the ship power plant have been considered [7]: one generator working alone and two or three generators working in parallel. In all considered cases the load has remained the very same, with bow thruster as dominant component. The exemplary voltage waveforms recorded for bow thruster full load and various power plant configurations are depicted in Figure 12 based on [7]. Mean values of related parameters of power quality are illustrated in Table 5.

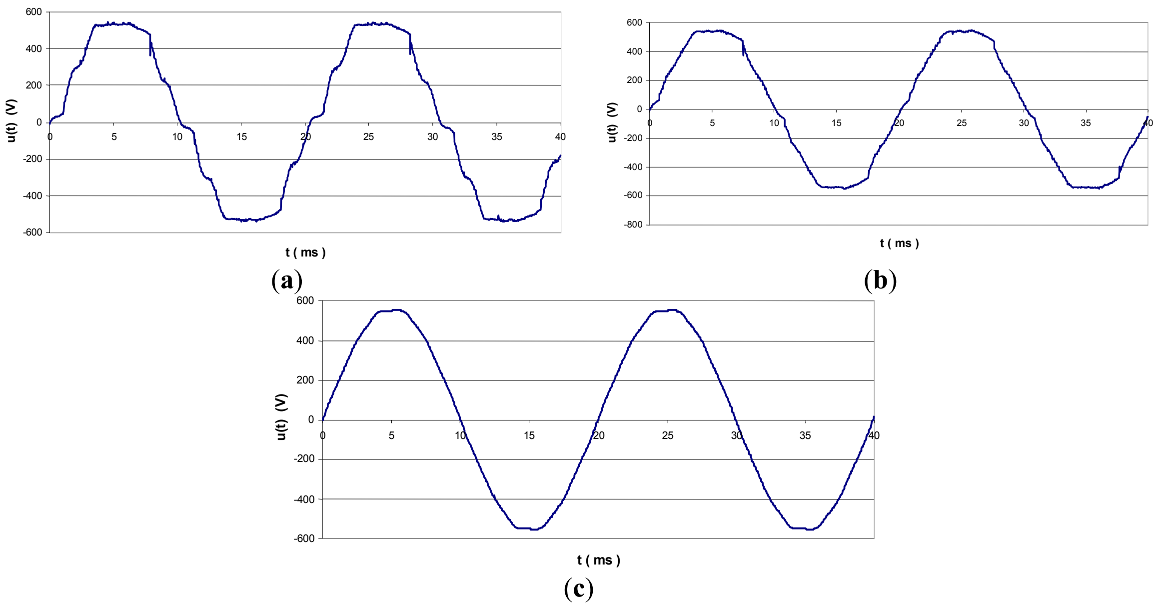


Figure 12. Exemplary voltage waveforms recorded on bus bars of main switchboard during bow thruster operation for: one generator working (**a**); two generators working in parallel (**b**); and three generators working in parallel (**c**), [7].

Table 5. Mean values of parameters of power quality measured on bus bars of the main switchboard, based on [7].

Analyzed Parameters	Number of Working Generators		
	1	**2**	**3**
$U_{\rm rms}$ (V)	385.5	384.2	383.4
TWD	7.92	4.79	3.73
THD	7.91	4.77	3.70
$\rm TWD_{2.5–10\ kHz}$	0.97	0.89	0.93
$\rm SGH_5$	6.00	3.72	2.92
$\rm SGH_7$	0.87	1.36	1.38
$\rm SGH_{11}$	4.05	2.07	1.30
$\rm SGH_{13}$	2.62	0.89	0.53

Designations: $U_{\rm rms}$, rms values of phase-to-phase voltages; $\rm SGH_n$ content of harmonic subgroup of n order.

The studies have shown significant changes of the level of voltage distortions which depends on the electric power plan configuration with a single rule: fewer generators, more distortions. The instantaneous values of the THD and TWD coefficients have been from 3.70% to 7.92%, the $\rm SGH_n$ from 0.53% to 6.00%, dependently on their order. This rule covers all kinds of voltage distortion indices, shown in Table 5. The profound analysis of the cases under consideration in [7] leads to conclusion, that the character of the distortion has varied depending not only on electric power plant configurations, but also on the actual bow thruster load. Continuing a discussion on possibilities to improve power quality on ship on the basis of technological solutions, it should be noted, that even complying with all recommendations concerning the effective configuration of ship power system, finally harmonics and other disturbances in marine systems cannot be omitted altogether. In fact, there are several methods, shortly described in [18], used to mitigate the effect of harmonic distortion in the systems under consideration, including, among others [3,53,55,56]:

- passive or active filters,
- increasing the number of pulses in power converters, by using multiple phase shifted secondary windings in propulsion motor supply transformers,
- using other specialized constructional and technological solution.

The predominant harmonics that are expected to occur in the electrical power conversion system are calculated at the design stage. Usually, harmonics filters of the passive filters type, consisting of a tunnel circuit of capacitors and inductors provide a low impedance path to the predominant harmonics, in the electric networks. Their operation relies on the resonance phenomenon which occurs due to variations in frequency in inductors and capacitors. The series passive filters, usually connected in parallel with nonlinear load are "tuned" to offer very low impedance to the harmonic frequency to be mitigated [3]. Resonant L-C filters have a relatively high cost, poor effectiveness in low voltage systems and the tendency to cause the system to operate with a leading power factor [56]. More information about other passive or active filters solutions to mitigate the effect of harmonic distortion, like conventional tunnel or trap filters, broad-band filters, active filters, the LINEATOR™ type filter [53] can be found in [3,55–57]. "Phase shifting" techniques have been commonly employed to reduce the input harmonics current. In this solution the multiple input converter bridges are necessary, connected such, that the harmonics produced by one bridge(s) cancels certain harmonics produced by other(s). Therefore, certain harmonics, as determined by the number of converters bridges in the system, are eliminated at the input, *i.e.*, primary side of the phase shift transformer [3]. In multi-pulsed systems, the drive manufacturer will phase shift between multiple front-end rectifiers to cancel harmonics. More information is available among others, in [55,56]. Phase shifting transformers can be a very cost effective method of harmonics treatment but require multiple 6-pulse rectifier loads operating simultaneously, and at the same time phase shifting systems are typically limited in the number of harmonic orders which can be mitigated and the degree of harmonic mitigation depends upon the extent to which harmonics produced by the various harmonic sources are identical and depends upon their phase shift angles [53]. In general terms, there are two main types of phase shift transformer used for drive harmonic mitigation [3]: double-wound isolating transformer and polygonal non-isolating transformers. Some characteristics of the first solution, based on the case of the RMS "Queen Mary 2" [9], is illustrated in Case Study 4. Finally, power factor corrected power supplies, reactors and chokes belong to the other specialized technological and constructional solutions proposed for mitigation harmonic current. Some information concerning this solution can be found in [3,55,56].

Case Study 4. In the QM 2 case a solution to mitigate harmonic distortion was based on passive filters, supported by multi-pulsed systems and multi-phase shifted secondary windings in propulsion motor supply transformers [9] (Figure 13).

Each of the four main propulsion motors (Figure 4) is supplied through step down transformers and power converters [9]. Each motor consisted of two independent sets of windings (half motors), because of a reliability reasons. It was explained in [9], that the used transformers had a delta connected primary winding and two secondary windings: one star wound and the other delta wound. The delta and star connections generated a phase difference between their voltage outputs of 30 electrical degrees. There were eight power converters, one for each half motor, with one connected to the output of each secondary coil of the transformer. In [9] we can find more detailed description of the power converter blocks: "Each converter consisted of a network bridge, which rectified the 1510 V AC to a direct current (DC); a DC link, which included an inductor coil of 5.5 mH designed to damp surges and eliminate current transients; and a motor bridge which inverted the DC supply into an AC waveform of variable frequency and voltage. Both the network and motor bridges were thyristor controlled and supplied the synchronous motor at a frequency to provide the required propeller speed. The electrical phase shifting achieved by the delta-star transformer secondary winding output, combined with the full wave rectification process resulted in 4 pulses per phase and 12 pulses for the 3 phase supply to the motor, this way a 12 pulse converter was selected because of its level of harmonic distortion compared with other types of converters”. In the same report [9] it was also commented on that “power converters produce harmonics at frequencies according to the relationships np ± 1, where n is a positive integer and p represents the number of pulses in the power converter. Therefore, for the 12-pulse converters fitted on QM2 the predominant harmonics were at the multiples 11, 13, 23, 25, 35, 37 and so on of the fundamental frequency 60 Hz”. To mitigate these harmonics and to keep the harmonic distortion level under 8% [30], the harmonic filters were installed. Each HF consisted of two sub-sections tuned to appropriately chosen resonant frequencies. A configuration of each filter [9] included a group of capacitors connected in a double star termination, a group of inductors, and a resistor bank connected in parallel to the inductors to limit the amount of in-rush current into capacitors when HF was started up. However, even this multi-step mitigation harmonic solution, based on passive harmonic filters, supported by multi-pulsed systems and multiple phase shifted secondary windings in propulsion motor supply transformers, could not protect the system against previously described technical failure and main consequence, marine casualty [9,18].

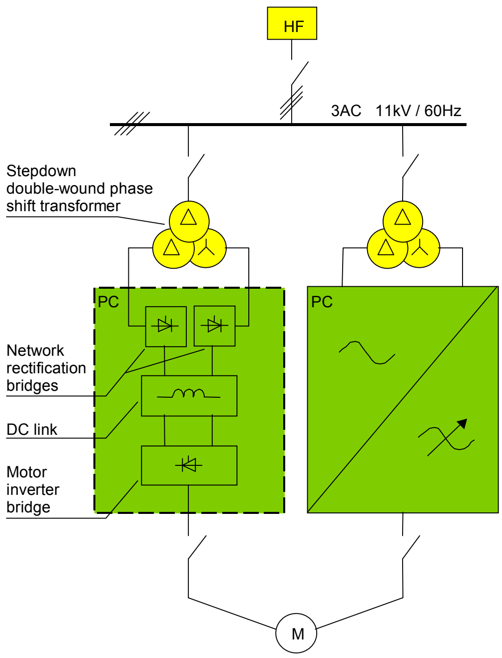


Figure 13. The example of power converters for propulsion motors based on the RMS “Queen Mary 2” [9]. PC, power converters; M, main propulsion motor; boxes marked with green color (PC) are referred to worsening effect of power quality; and boxes with yellow color—to improve power quality based on harmonic filters (HF) and multi-pulsed systems and multi-phase shifted secondary windings in supply transformers.

4.4. Staff Competences Development

Rapid progress in electrical and electronic engineering on ships does not only guarantee full ship safety, but inversely, can even cause additional hazards because of the technical complexity of new solutions, their hardly predictable interactions and a need for better trained and qualified crew onboard [9,15,51]. These situations have been appointed in some publications, among others in [18,51,58]. It is worth mentioning that in the report on is catastrophic failure of a capacitor in the aft harmonic filter room on board RMS Queen Mary 2 [9] some other similar accidents have also been mentioned. In that report, in subsection concerning the capacitor failures, three cases on board offshore support vessels were shortly described. The first of them concerned an explosion and related consequences provoked by a smoothing capacitor failure fitted in the rectifier circuit. The second—failure of a capacitor in phase harmonic filter, resulting in the disruption of variable speed sea water cooling pumps for the low temperature cooling system. In addition, in the third incident, the harmonic filter enclosure panel was blown out when capacitor exploded [9]. In the same report [9], in subsection related to the arc-flash accidents, a series of arc-flash faults with their consequences like fire, explosion and a loss of vessel propulsion were identified: a passenger vessel "Regent Star" (in 1990), the ro-ro vessel "Union Rotorua" (in 1993), the passenger vessel "Celebration" (in 1995), the passenger ferry "Columbia" (in 2000) and the passenger vessel "Statendam" (in 2002). In some well documented cases, the competent bodies to investigate the circumstances and reasons of ship accidents could only indicate hypothetical technical reasons for failures [9,58], in others they concluded about undoubted ambiguities within KUP competences (knowledge, understanding and proficiency) of watchkeeping officers [51] in IMO meaning [16]. With regard the first case, the report under consideration [9] concluded that harmonic filter capacitor degradation was probably caused by a combination of transient high voltage spikes due to frequent switching operation and occasional network overvoltage fluctuations. However, the most important observation is, that the only protection against catastrophic failure of the capacitors was a current imbalance detection system. It consisted of a current transformer, which was connected to the capacitor circuit [9]. After the accident, the transformer's windings were found to have failed. There had not been any alarms on this part of the system for several years and it was likely that the imbalance detection system had not worked for some time [9]. In other words, the only means to warn against capacitor determination was found to be inoperable, and it was evident that it had not worked for several years. It means that indirect reasons for this accident were a lack of continuous monitoring of electric power quality as well as shortcomings in ship tests, service and operation. The second above mentioned case concerns appropriate qualifications and competences of crew members. In the previously cited report [9], we can find another observation, which concerns the fact, that harmonic distortion was not routinely measured in service as the crew were not aware that they had supposedly the appropriate measuring equipment on board. Another well documented [51] situation is presented and commented on in [18]. This case concerns a dead short caused by the failure of a generating set's circuit breaker, in the ship power system at 6.6 kV voltage. This happened during a passenger ship voyage m/s STATENDAM and it has been described in [51]. A lack of adequate analysis of protection relay operation was the reason for a serious fire and loss of main propulsion. The vessel was subsequently towed back to port. Most intriguing were the statements formulated by the Transport Safety Board of Canada: firstly, "None of the senior engineers onboard had theoretical or practical education in 6.6 kV generation, distribution and troubleshooting" and secondly, "The seafarers Training, Certification and Watchkeeping (STCW) code however, does not identify electricians as a seafaring profession and does not specify a minimum internationally applicable standard for their education training and competence" [51]. Presently, the situation is much better after the introduction to the current version of the STCW Convention and Code [16] of the international qualification for Marine Electro-Technical Officers (ETO). Afterward, the new Model Course for Electro-Technical Officers, as a new tool supporting ETO's standard implementation was created and accepted by IMO [59]. Summing up this paragraph, the staff competences development is one of the necessary actions towards the improvement of power quality on ships.

5. Discussion

The accidents statistics of the last several years show that even technologically developed ships operated by experienced and well recognized ship-owners are not free form unexpected events and their consequences. In the paper [18] it was stressed, that reviewing power quality standards and related technical and organizational tools lead to finding out some ambiguities and inaccuracies in present procedures, which were presented and developed in Sections 3 and 4. This situation should not be tolerated anymore and it implies requirement for undertaking some measures in advance to improve the current situation. These measures should concern two layers: presented below (Section 5.1) legal aspects, like e.g., continuous monitoring of power quality, transient control, unification of indices and methods of their measurements and other discussed professional aspects in Section 4.4, related to appropriate qualifications and competencies of the crew members and correct operation, maintenance and testing. Some questions related to the possibilities of power quality control and necessary condition for realization of this aim are discussed in Section 5.2. Another important future challenge is connected with the new ideas concerning power quality in the wake of ship energy efficiency from global point of view (Section 5.3).

5.1. Legal Aspects

Post-accident recommendations based on in-depth current state analysis of the international legislation in the considered field of knowledge showed some ambiguities or even contradictions in the rules under discussion. Above mentioned situation may lead to the use of commercial solutions of power quality analyzers, hitherto available on the market and an inadequate for ship applications. In consequence, in many cases, the result will be skewed by great errors and correct power quality assessment will be impossible. A lack of adequate diagnosis in the collision situations or during the ship maneuvering can lead to the non-predictable consequences for safety of crew members and passengers, ship and sea environment. To improve present situation, the International Association of Classification Societies (IACS) has undertaken some activities, e.g., cooperation among IACS-PRS (Polish Register of Shipping) Department of Ship Electrical Power Engineering, Gdynia Maritime University, which concerns the new proposals of legislative solutions within:

- design of unambiguous definitions of measured indices of electric power quality,
- design and implementation of the "Continuous power quality monitoring" procedure, and
- design of procedure standards within "transient disturbances in ship networks".

Continuously running progress in electric and electronic devices construction and control imposed the new requirements for watchkeeping officers, responsible for control, maintenance diagnostics and repair of electrical and electronic installations on shipboard. These requirements first all concern ship power systems [16] and in natural way are connected with power quality aspects. On the other hand, the STCW 2010 Convention, with inclusion of ETO (Electro-Technical Officers) as well as by introducing of new KUPs (knowledge, understanding, proficiency) for marine officers, significantly improve international standards.

5.2. Power Quality Control

In the context of power quality issue, a question is: is it possible to control (in the meaning to improve) electric power quality? It should be clearly stressed, that control of electric power quality is a challenge for the designers and operators (crew members) of ship electric power systems [1]. This process can be considered as a passive and active control of electric of electric power quality. Under the term of passive control, we understand an application of such technological and constructional solutions prepared during the design stage of ship system, like described in Section 4.3 (appropriate configuration of main switchboard, filtering circuits, harmonic mitigation devices and techniques). Contrary, active control of electric power quality is based on a "smart grid" concept, or widely, active networks. Presently, in ship electric power systems the smart grid elements, like various energy sources (Section 2) cooperating each other (combinations of turbogenerators, diesel generators, shaft generators and experimentally photovoltaic cells), optional compensative devices (reactive power compensators and harmonic filters) and energy storage devices (batteries, fuel cells, experimentally super capacitors) and finally Power Management System, dedicated to ensure the continuity of power supply of important receivers are frequently met and used. A necessary condition for active control of electric power quality is continuous measurement information [18], which could be obtained by means of appropriate dedicated to power quality analysis devices, e.g., estimator/analyzer of power quality [35,37]. Estimator/analyzer or its equivalent device (Section 3.4) is treated as a module installed in automatic control systems of electric power quality, in which measurement information concerning power quality parameters would be processed into control signals, governing the voltage and frequency control systems and also the circuit breakers of particular generating sets. Independently on the accepted measuring solution, continuous power monitoring procedure is a key point for improving power quality on ships in wide meaning (Section 5.1). Anyway, the designers and operators (crew members) of ship electric power systems must be aware that perturbations and EMC disturbances cannot be completely eliminated, it is possible only to reduce the reasons of their occurring and mitigate the consequences of their negative influence.

5.3. Power Quality and Green Ship Technology

It is worthy to note that one of the dominant tendencies in the nowadays shipbuilding is "Green Ship Technology" [1,60,61], *i.e.*, trend in the design, construction and exploitation of modern ships. This trend covers numerous links to SMART GRIDS idea, like 3R Green Design concept: reduce, recycle, reuse. In fact, the considered concept supports the promotion of safe-energy and environmentally friendly solutions, improves a comfort of passengers and crew members during a voyage as well as ensures a safety of transported goods. Summing up, Green Ship Technology's idea develops a care of protection of seas and oceans. To support the above aforementioned ideas, in the context of ship's energy efficiency, The Marine Environment Protection Committee of the International Maritime Organization adopted to related resolutions, *i.e.*, 2012 Guidelines for the development of a ship energy efficiency management plan (SEEMP) [62] and Guidelines for calculations of reference lines for use with the energy efficiency design index (EEDI) [63] The first document is addressed to the existing ships, the second one—to the newly built ships. A SEEMP provides a possible approach for monitoring ship and fleet efficiency performance over time and some options to be considered when seeking to optimize the performance of the ship. In global terms it should be recognized that operational efficiencies delivered by a large number of ship operators will make an invaluable contribution to reducing global carbon emissions. The purpose of a SEEMP [62] is to establish a mechanism for a company and/or a ship to improve the energy efficiency of a ship's operation. The ship-specific SEEMP is linked to a boarded corporate energy management policy for the company that owns, operates or controls the ship. The SEEMP seeks to improve a ship's energy efficiency through four steps: planning, implementation, monitoring, and self-evaluation and improvement [62]. There are a variety of options to improve efficiency, like speed optimization, weather routing and hull maintenance and the best package of specific for given ship measures, depending upon ship type, cargoes, routes and other factors, should be identified and implemented. Some specific measures, for example, speed optimization and optimized shaft power, propulsion system and its maintenance or energy management are closely related to power quality aspects. The purpose of the EEDI [63] is to provide a fair basis for comparison, to stimulate the development of more efficient ships in general and establish the minimum efficiency of new ships depending on ship type and size. Taking into account a consequence and effectiveness of IMO activity and its leading role in promoting and stimulating the important trends in global shipping, author of this paper is convinced, that some power quality aspects resulting from optimization of shaft power and propulsion system will be implemented, improving the energy efficiency of a ship's operation.

6. Conclusions

All general conclusions formulated below should be considered as a completion and summing up of the detailed recommendations and observations presented inside the Sections 3–5, respectively. In addition, the conclusions accompanying all case studies presented in the aforementioned sections should be treated as a documentation of described and analyzed phenomena. Under this assumption the four main conclusions may be expressed in the following manner:

1. Assessment and improvement of the power quality in ship systems constantly remain vital and topical issues, because of their influence on ship and shipping safety.
2. The presented case-study based analysis of the state of the art in the area of power quality assessment confirmed some relevant existing ambiguities and inaccuracies, illustrated in Case Studies 1 and 2. Moreover, a deep analysis of the main components of the process of power quality assessment in ship systems and interactions, among them those illustrated in Figure 5, leads to the conclusion that it is rather impossible to compensate for appointed lacks and weaknesses "just now" because of the continuously running processes of advancement in the signal process and in the measurement devices technology as well as a mutual interfering of aforementioned components of the power quality assessment. It is would be more reasonable to consider a continuous development of related procedures following adaptively with the progress in the considered area. Nevertheless, some given actions, for example concerning more precise description of power quality definitions or methods of measurements are possible and expected, among others, due to the IACS (International Association of Classification Societies) activity.
3. Improvement of the power quality is a key point of the considered matter, because of its direct influence for reducing a risk of accidents and ship safety improvement, what was illustrated in Figure 11 by means of conceptual model for solving the central problem. It was widely discussed in Section 4 and shown on the basis of Case Studies 3 and 4, that power quality improvement is depending on the two important factors: development of power quality—oriented technological solutions and development of staff competences. A presented analysis showed (Case Study 4) that even in the case of a technologically advanced real object, like RMS Queen Mary 2, and applied multi-step mitigation of power quality disturbances, expressed, among others, in harmonic mitigation solutions, it was impossible to protect the system against previously described technical failure and main consequence, marine casualty. However, in-depth analysis the case under consideration, as well some other cases known from the numerous papers, lead to conclusion that more and more influential factor on appropriate power quality, or widely—ship safety, are the adequate staff competences. Author of the paper is absolutely convinced, that this aspect is all the time underestimated and without staff competency development, even assuming a progress in the domain of technical solutions, the effective solutions for power quality improvement in maritime power systems are not possible.
4. Finally, a synergy of the legal aspects improvement, technical solutions oriented to power quality control development and continuous efforts of IMO, shipowners, designers and users of maritime power systems may significantly support the effective operation of ships and reduce a risk of accidents caused by power quality problems onboard of ships.

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