# Contemporary challenges to power quality in ship systems - metrological perspective

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***Abstract* – This paper deals with some contemporary challenges to power quality in ship systems, observed from metrological perspective. Two basic aspects, assessment of power quality and improvement of safety of shipping are taken into account. In the process of power quality assessment, the existing ambiguities and gaps are shortly analyzed and discussed, with underlining the related metrological aspects. The ways of the safety improving related to power quality on ships are described and analyzed into two layers: technological solutions and staff competences, with appointing the metrological aspects of ship system design, development and exploitation. 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, or more widely, how to improve a safety of shipping. Concluding remarks are formulated in the wake of a role of measurement and related instrumentation in realization of analyzed challenges.**

***Keywords – power quality, ship systems, assessment, safety improvement, measurement, maritime education and training***

## I. INTRODUCTION

Core information of this paper is based on the recently published papers [1-3], describing the problem of electrical power quality and its influence on ship's safety. This problem constantly remains vital and topical issue. Also some ideas of the last author's paper [4], concerning the problem, how to reconcile technological advancement with training en route to improvement of safety, considered in the context of maritime education and training of Electro-Technical Officers are shortly presented. An added value of this paper consists in multi-aspect analysis of metrological components in the processes of power quality assessment and the related ship's safety improvement in the wake of legislative instruments, technological solutions and staff competences development.

### *A. Ship power system*

A perceptible increase in the importance of power quality in recent years has been observed due to the introduction of new methods for electrical energy production and utilization in ship power systems, An explanation of this increase results from peculiar and basic characteristics of these systems [1-3], [5], [6]. The ship electric 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 power system are energy sources, main and emergency switchboard, power cable lines and electric consumers [7-11]. They are shortly described on the basis of generic diagram of ship power plant in [1]. In the basic configuration as the energy sources the three electric generating sets are usually applied, [8], [10-12] sometimes shaft generators as well as turbogenerators are also installed. Presently, power systems' architectures [5] are organized as radial distribution system, ring distribution system, or zonal AC distribution system. Another kind of solution is DC shipboard electric power distribution system [13], [14], but author of this paper is of the opinion that this issue is beyond the scope of the presented subject. Taking into account continuously running progress in marine electrical and electronic engineering many changes in configuration of ship electrical power systems are observed. 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 [9], [10], but first of all, a new philosophy concerning a main ship propulsion, it means electric propulsion is introduced [15-17]. This concept is so-called 'all-electric ship'. Summing up, the ship electric power systems can be divided [3], [5] into systems with mechanical propulsion realized as conventional configuration (Fig. 1) and conventional with shaft generation (Fig. 2), and as integrated ship electric power system realized as all-electric ship (Fig. 3) or also as hybrid propulsion [5].

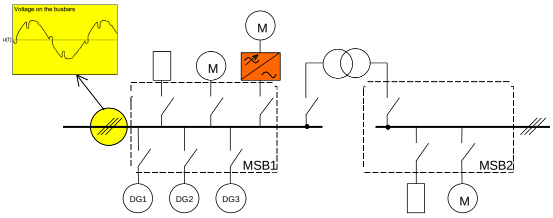



*Fig. 1. Traditional configuration of ship power system, three electric generating sets of Diesel-Generator (DG) type, MSB1, main switchboard 3AC 400 V/50 Hz; MSB2, main switchboard 3AC 230 V/50 Hz; M - electric motor, box marked with orange color is referred to worsening effect of power quality with yellow color - to power quality measurements, in this case means frequency converter [1], based on [12]*

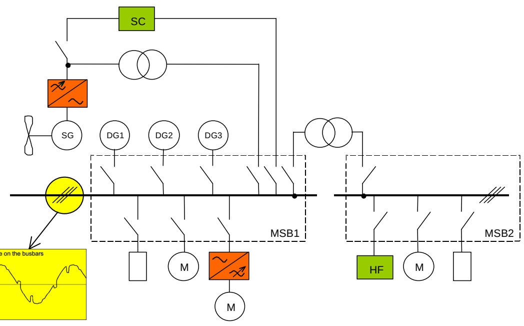



*Fig. 2. A configuration of ship power system with, three generating sets of DG type together with shaft generator, MSB1, main switchboard 3AC 440 V/60 Hz; MSB2, main switchboard 3AC 220 V/60 Hz; SC, Synchronous compensator; HF, Harmonic filter; boxes marked with orange color are referred to worsening effect of power quality, with yellow color - to power quality measurements and with green color - to power quality improvement, respectively, - frequency converter [1], based on [19]*

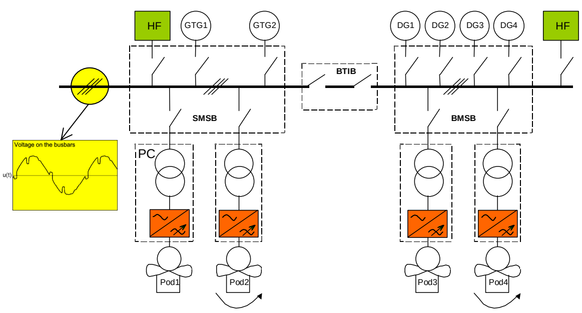



*Fig. 3. A configuration of all electric ship, BMSB, bow (forward) main switchboard 3AC 11 kV/60 Hz; SMSB, stern (aft) main switchboard 3AC 11 kV/60 Hz; BTIB, bus the interconnecting breaker; DGs, Diesel engine driven generators; GTGs, gas turbine driven generators; HF Aft and HF Fwd, harmonic filters, installed in aft and forward switchboards; respectively, PC, power converters; PODs, podded propulsion units of Mermaid azimuth thruster type; designations of colors are similar to those in Fig. 2, - frequency converter [1], based on [18]*

It is important to note that the latter case refers to a recent solution of ship electrical system with engine room of CODLAG (Combined Diesel Electric and Gas Turbine) type [3], [18]. The presented configuration (Figure 3) of ship electrical power system is limited to the high voltage electrical network, being in fact a vital part of the power system for the all-electric ships. The exemplary configurations presented in Figures 1-3 are based on power systems of research - training ship m/v "HORYZONT II" [12], on the chemical tanker m/s "Stolt Excellence" [19], and on the RMS "Queen Mary 2" [18], respectively. More detailed descriptions of these solutions and their main characteristics are presented in [1], [3], [12], [18], [19].

### *B. Basic characteristics of ship power system*

The common features of ship electric power systems [1], [3], [5], [6] could be characterized by ship network variations, particular properties of loads and generating sets, including relationships among their powers as well as constructional and marine environmental conditions and requirements. Conversely to the overland electrical power grid, the ship electrical power network is an autonomous and flexible power system. Its generating capacity is precisely determined and limited. Additionally, its short-circuit power is relatively smaller comparing with industrial grids. Often the power of singular loads installed in the system is comparable with the power of single generating set. In fact, the ship electrical power system must be considered as the variable frequency and voltage system, with short-term and long-term variations of these parameters. Those variations are closely related with the properties of loads and the time constant of generating sets. The chief electrical and mechanical time constants are in the same range of values, from hundreds milliseconds up to seconds for the ship generating sets (prime movers and generators). Aforementioned particular properties of loads concern their number, power and non-linear and non-stationary characteristics. With regard to operation of generating sets it is important to define their number, power, kind of prime mover and possibility for their parallel work. In consequence, for reliability reasons, the redundancy of generating sets and vital loads are required. Moreover, parallel operation of multiple power sources requires the load sharing control. It is also important, that the ship electrical power network is characterized by the short distances among its components, but at the same time this system operates in harsh environment. Such affecting factors like vibration, ship rolling and pitching, humidity, temperature, salinity must be taken into account. Finally, having in mind aforementioned features of ship power network, the application of large capacity-power electronic devices and systems also contributes to the power quality deterioration to a wide extension. This deterioration has a real influence on the ship and shipping safety.

### C. *Power quality on ships and related measurements*

On the basis of the real case studies, like the accidents of MS "Statendam" [20] or RMS "Queen Marry 2" [18], an apparently controversial thesis could be formulated: an impressive progress in marine technology is not always a guarantee for the ship and shipping safety [4]. To solve the power quality problem it is necessary, firstly, to appoint and discuss the existing gaps and weaknesses, and secondly, to indicate, how to overcome some presently observed ambiguities and inaccuracies. A solution of the problem under consideration in many aspects is closely connected with the area of metrology. In the considered case, is metrology applied to power quality assessment as well as to power quality - related ship safety improvement. This paper is organized in the following manner: firstly, after an introduction (Section I), including generic information about ship power system with regard to its basic characteristics, the challenges to power quality in ship systems (Section II) are shortly presented. In the third section, the metrological aspects of power quality assessment on ships, are discussed and analyzed. In this important section, the subsections related to 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 key section of this paper, the metrological aspects of PQ - related safety improvement are discussed, underlining technological solutions and crew competence-related measures. The last two sections are devoted to a discussion of expectations and future challenges in the area of power quality in ship power systems, with indications, how to overcome some existing ambiguities and inaccuracies by undertaking the adequate steps for improving the current situation.

## II. CHALLENGES TO POWER QUALITY IN SHIP SYSTEMS

As a result of the aforementioned problems related to power quality in ship systems, 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 power quality assessment and safety improvement in ship power systems is shown in Figure 4.

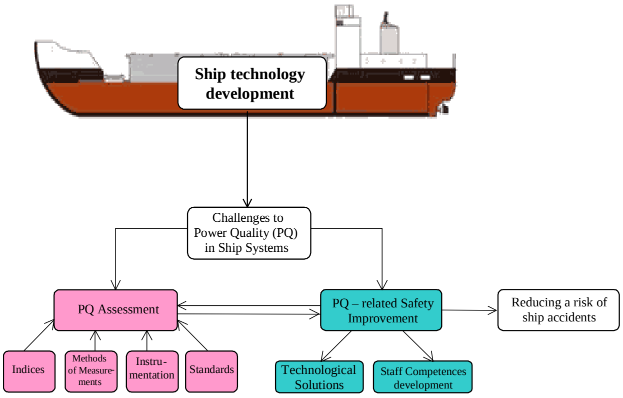



*Fig. 4. A concept of contemporary challenges to power quality in ship systems and their impact on shipping safety improvement; the boxes marked with red color are referred to power quality assessment, with blue color - to power quality - related safety improvement*

This concept is built on the basis of the existing state of the art summarized by the conclusion, that challenges to power quality, which mean its assessment and PQ - related safety improvement are the integral parts of the ship power system operation. The first of the aforementioned processes is a basic one: assessment. It usually precedes the PQ - related safety improvement phase. However, an improvement may be also initiated directly from the ship power system, as an immanent part of the operations caused by the reconfiguration or modernization of structure of the considered system. But it should be strongly underlined a mutual interaction between the aforementioned processes and the significant contribution of measurements in their realization.

## III. METROLOGICAL ASPECTS OF POWER QUALITY ASSESSMENT

### A. *Power quality on ships and related measurements*

Looking for a definition of power quality, two of the most comprehensive proposals are laid in the IEEE Std 1159-1995 [21] an in IEC Standard 61000-4-30 [22]. The first [21] document 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 this definition, the power quality is not simply a group of technical parameters, but the outcome of interaction between numerous parameters. The second definition [22] is: "Power quality - characteristics of the electricity at a given point on an electrical system, evaluated against a set of reference technical parameters". Directly from this last definition the term of power quality can be expressed by the set of inequalities:

$$Cpq_i \leq Cpqref_i \qquad (1)$$

where: $Cpq_i$ - the $i^{th}$ element of the ***Cpq*** vector of power quality coefficients, $Cpqref_i$ - the $i^{th}$ element of the *Cpqref* vector of power quality reference coefficients, $i = 1,2, \ldots k$.

The *k* value depends on the needs of electrical power system designers and users. In fact a question about *k* value means the choice of appropriate set of reference technical parameters of the system under consideration. 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 (manoeuvring, 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. 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. Taking into account ship technology needs, the legislative tools have been introduced, firstly, by the IEEE [23] and IEC [24] standards, and secondly, based on those, by the rules of classification societies. Generally accepted and well recognized classification society rules concern, among others, the IACS [25], ABS [26], DNVGL [27], Lloyd's [28], or PRS [29], [30]. It should be noted, that not all recommendations of IEEE and IEC authorities are transferred to and used within appropriate rules and requirements of classification societies. A short overview of the most commonly used power quality parameters, represented by corresponding with them the power quality indices is shown in Table 1. These indices cover the voltage and frequency deviations like $\delta V_p$, $\delta V_{tr}$, $\delta_{per}V$, $\delta f_p$, $\delta f_{tr}$, $\delta_{per}f$, the voltage asymmetry like $u_2$ and $u_{L\_t\_L}$, the waveform voltage distortions like THD, $V_{h\%}$ and transients $u_s$, and finally, indices characterizing a proportionality of the power distribution like δP and δQ. Aforementioned power quality indices are described and commented on, among others in [1-3]. Their listing together with the recommended limit reference values is collected in Table 1.

*Table 1. Limit values of electrical power quality indices in ship power systems [23], [24], [26], [29], [30].*

| $Cpq_i$ parameters | **Cpqref values** | | | |
|---|---|---|---|---|
| | IEEE 45 | PN-IEC6100 92-101 | ABS | PRS |
| $\delta f_p$ | ±3% | ±5% | ±5% | ±5% |
| $\delta f_{tr}$ a) value b) time | ±4% 2s | ±10% 5s | ±10% 5s | ±10% 5s |
| $\delta_{per}f$ | 0,5% | 0,5% | - | - |
| $\delta f_{max}$ | 5,5% | 12,5% | - | - |
| $\delta V_p$ | ±5% | +6%, –10% | +6%, –10% | +6%, –10% |
| $\delta V_{tr}$ a) value b) time | ±16% 2s | ±20% 1,5s | ±20% 1,5s | ±20% 1,5s |
| $\delta_{per}V$ | 5% | 2% | - | - |
| $\delta V_{max}$ | ±20% | ±20% | - | - |
| $U_{L\_t\_L}$ | 3% | 7% | - | - |
| $u_2$ | - | 3% | - | 3% |
| THD | 5% | 5% | 8% | 8%, |
| $V_{h\%}$ | 3% | 3% | 3% | 3%*, 6%** |
| δu | 5% | - | - | - |
| $u_s$ | 2500V ($V_n$=380-600V), 1000V ($V_n$=120-240V) | 5,5 $V_n$ 1,2µs/50 µs*** | - | - |
| δP | - | - | 15% | 15%, 25%**** |
| δQ | - | - | 10% | 10%, 25%**** |

where: *$V_{h\%}$ long-lasting aggregated values for the aggregation time 10 minutes in general purpose networks [30]; **$V_{h\%}$ long-lasting aggregated values for the aggregation time 10 minutes in networks for supplying of power converters [30]; *** rise / fall time - concerns only standard [24], **** - of the rated output kW of the individual generators, whichever is the less or of the smallest generator's rated reactive load, whichever is the less [26], [29].

Author of this paper is of the opinion, that having in mind two previously aforementioned basic aspects of power quality assessment [1-3] six principal components of the ***Cpq*** vector could be appointed:

$$\boldsymbol{Cpq} = \left[Cpq_1, Cpq_2 ... Cpq_6\right]^T \qquad (2)$$

Linking adequately the $Cpq_i$ components with the processes corresponding to continuity of power supply and assessment of its parameters in the analyzed electrical power system we obtain:

$$\boldsymbol{Cpq} = \left[\delta V, \delta f, u_2, THD, \delta P, \delta Q\right]^T \qquad (3)$$

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 fulfils a crucial role in the operation of the ship as a whole and is a basis for power quality improvement. It should be added, that process of power quality assessment is very important not only from exploitation point of view of ship systems, but also it plays a fundamental role for their design and development. Taking into account aforementioned approach, the author of this paper is aware, that power quality assessment process is closely related with measurement and modelling of these systems [1-3], [5], [18]. An effective realization of the measurements of power quality requires solving such tasks like choice of a set of reference technical parameters and defining related indices, a choice of their limit values and time of aggregation, if applicable, defining appropriate methods and instrumentation for measurement of these indices, conscious use and development of the power quality - related standards. Moreover, because of the assumed structure of the paper, issue of modelling is beyond the scope of the presented subject. Finally, the main components of power quality assessment process are illustrated in Figure 5.

Presently existing procedures and devices for realization of this process show some relevant ambiguities, concerning the related power quality indices, adequate algorithms and measurements methods, instrumentation and standards used in ship technology [1-3], [5]. A possibility to compensate the above mentioned 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 measuring devices technology, have effect on methods of measurements, standards and instrumentation accordingly to the interlinks marked by dashed lines in Figure 5.

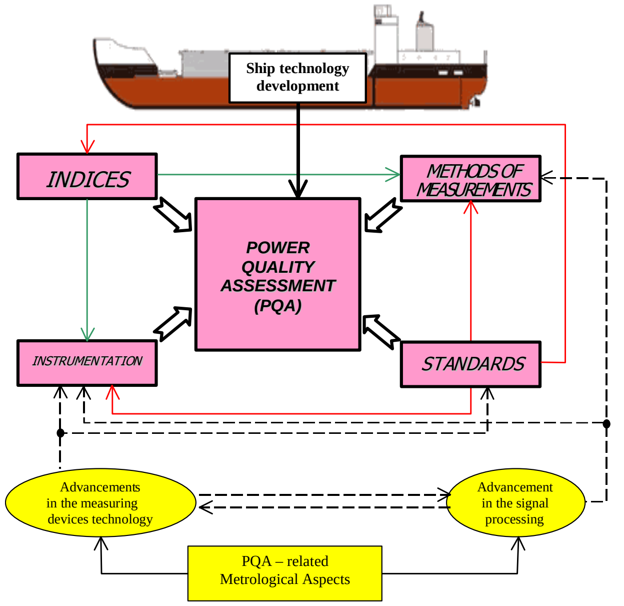



*Fig. 5. The main components of the process of power quality assessment in ship systems and interactions among them; the boxes marked with red color are referred to power quality assessment process, with yellow color - to metrological aspects of the analyzed process; solid lines - interactions among main components of the process, dotted lines - additional interactions caused by continuously running advancements in the signal processing and in the measuring devices technology*

### B. *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 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. The basic power quality indices for ship systems together, with the recommended limit values, are laid in the related standards, described, among others, in [2], [31]. In this subsection a main focus is concentrated on the indices described by the ***Cpq*** vector (3), with taking into account some characteristic peculiarities connected with the discussed systems. Power quality indices concerning the voltage and frequency deviations are defined as follows [23], [24]:

$$\delta f = \frac{f - f_n}{f_n} \cdot 100 \qquad (4)$$

$$\delta V = \frac{V - V_n}{V_n} \cdot 100 \quad (5)$$

where: $V$, $f$ are actual values of rms voltage or frequency, respectively, $V_n$, $f_n$ are rated values of rms voltage or frequency, respectively.

These indices are the basis for defining the voltage and frequency, $\delta V_p$ and $\delta f_p$ permanent variations, as well as the voltage and frequency $\delta V_{tr}$ and $\delta V_{tr}$ transient variations (including respective recovery time values), shown in Table 1. One of the most important peculiarities of ship system is its variable frequency. It was commented, e.g. in [6] "The frequency cannot be assumed to be constant aboard ship. The limited rotational inertia of prime movers and generators allows rapid accelerations and decelerations of the shaft and corresponding frequency fluctuations in response to load changes". An example concerning frequency and related parameters fluctuations is shown in Figure 6. For the analyzed case [2] the mean value of frequency during the ferry manoeuvring has been equal to 50.05 Hz but it has varied significantly between 48.97 Hz and 51.06 Hz.

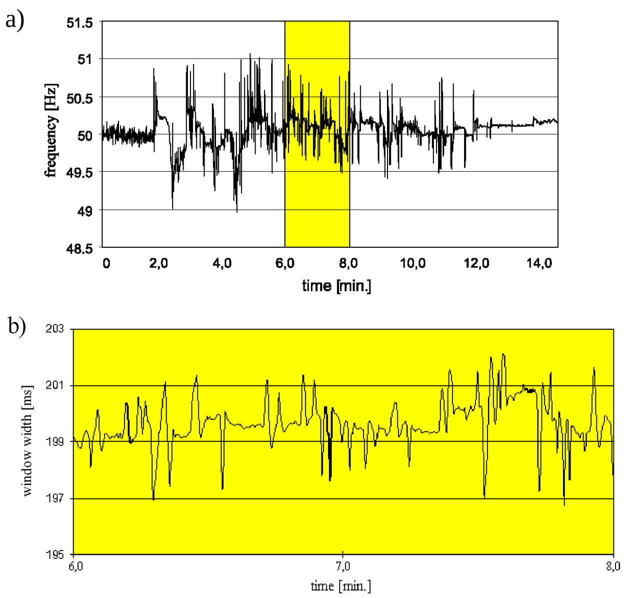



*Fig. 6. Frequency a) and basic measurement window width b) fluctuations during all-electric ferry manoeuvring; analyzed frequency band is marked with yellow color*

These changes must be analyzed in the context, that the reliable measurement of most of the power quality indices, requires prior information about the actual fundamental frequency. Among others, frequency fluctuations affect on basic measurement window width, understood as a duration of an integer number of fundamental component cycles, and next, on the process of synchronization of the sampling frequency with the actual frequency of voltage [2]. In consequence, some recommendations concerning the choice of appropriate method for distortion analysis, meaning synchronous sampling frequency and the FFT algorithm or asynchronous sampling frequency and more complex methods of signal processing such as software re-sampling [32-34], or chirp z-transform (CZT) [34-36], have to be formulated. In accordance with the IEC Standard [37] the window duration should be 10 periods for 50Hz systems or 12 periods for 60Hz systems with a rectangular weighting. Moreover, the maximum permissible error of the measuring window synchronization with the actual duration of recommended rectangular window width should not exceed ± 0,03%. For the presented example (Fig. 6), a duration of as many as 50,5% of the adjacent measurement windows differs more than 0,03%. Therefore another approach than FFT algorithm must be used [2], [34]. It is worth adding, that frequency fluctuations in ship systems are caused not only by specific characteristics of these systems, but also by impact of environmental conditions, like different states of sea or operation states of the ship. Some in-depth analyses defining the angular frequency variations as a key feature of electricity characteristic in ship systems and analyzing their impact on power quality measurements, may be found in [5], [38].

Voltage asymmetry is described by the formula [23], [24]:

$$u_{L\_t\_L} = \frac{V_{max\_L\_t\_L} - V_{min\_L\_t\_L}}{V_n} \cdot 100 \quad (6)$$

where: $V_{max\_L\_t\_L}$, $V_{min\_L\_t\_L}$ are maximal and minimal values of phase-to-phase voltage, $V_n$ was defined above.

Alternative possibility to define asymmetry is described in [24]:

$$u_2 = \frac{V_-}{V_+} \cdot 100 \quad (7)$$

where: $V_-$ and $V_+$ indicate symmetrical components of negative - sequence voltage or positive - sequence voltage, respectively.

The waveform distortions analysis widely discussed in [1-3] defines firstly, a content $V_h$ of given higher harmonic component of $h$ order in relation to fundamental component $V_1$:

$$C_f = V_{h\%} = \frac{V_h}{V_1} \cdot 100 \quad (8)$$

where: both components are rms voltage values, and secondly appropriately defined indices of total distortions [2], [28], [37], [39]:

$$THD_n = \frac{\sqrt{\sum_{h=2}^{n} V_h^2}}{V_1} \cdot 100 \quad (9)$$

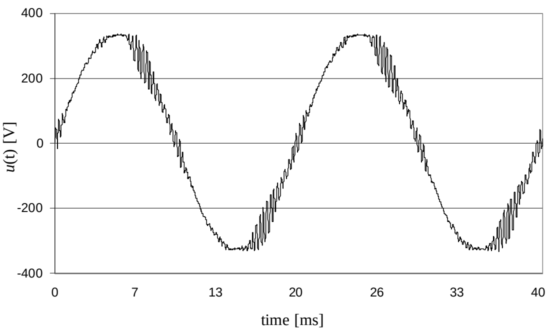
$$TWD_n = \frac{\sqrt{V_{rms\_n}^2 - V_1^2}}{V_1} \cdot 100 \quad (10)$$

$$TWD_{2.5-10kHz} = \frac{V_{rms-2,5-10kHz}}{V_1} \cdot 100 \quad (11)$$

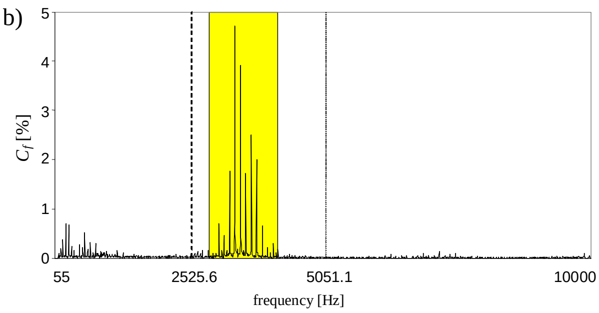
In many cases, THD evaluation expressed by the formula (9) is not effective, because the components above usually defined number of harmonics are simply avoided. This problem was discussed in [40]. Moreover, traditional way of analysis (9) considers only harmonics, avoiding other disturbances, like interharmonics, subharmonics or distortions, which are not related to fundamental component frequency [2]. 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?

To clarify the consequences resulting from traditional approach (e.g. [28], [37]) based on the rules which require measurement up to 50th harmonic, let's consider a case study analyzed and commented on in [2], [40]. This example concerns voltage registered on terminal of navigation equipment at all-electric ship [2] and has been shown in Figure 7.

a)




b)




c)

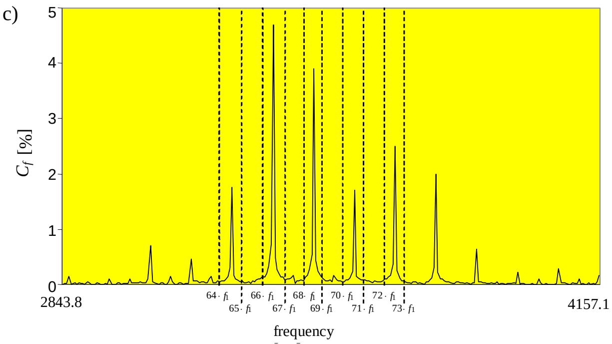



*Fig. 7. Exemplary waveform of supply voltage (a) on terminal of navigation equipment at all-electric ship and its spectrum (b) analyzed frequency sub-band is marked with yellow color; dashed line marks frequency of 50th harmonic whereas dotted line marks frequency of 100th harmonic (c) extended frequency 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 [2]*

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 (9)) up to 100th for ship systems equipped with "active front end" AFE PWM drives [8], [41], [42]. In this case, the operation of the 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 harmonics, above the 50th can be introduced [8], [41]. Apparently, the approach proposed by ABS 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 7c. Finally, the basic distortion indices have been calculated by all above introduced Equations (9) - (11) and for various frequency bands. The results are laid in Table 2.

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

| THD 50 | THD 100 | TWD 2.5kHz | TWD 10kHz | TWD 50kHz | TWD 2,5-10kHz |
|---|---|---|---|---|---|
| 1.51 % | 1.61 % | 1.62% | 7.83% | 7.9% | 7.66% |

The first observation is, that the approach to waveform analysis based on the use of THD (Total

Harmonic Distortion) expressed by Equation (9), leads to significant errors, and the application of TWD ((10) and (11)) leads to more reliable results. The detailed analysis of results in Table II presented in [2] leads to the conclusion, that application of $TWD_{10kHz}$ and $TWD_{2.5\text{-}10kHz}$ 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 10kHz limit of considered frequency band would be enough. This solution is consistent with the standard [43]. To complete this problem, it is worthy to add the THD definition proposed by the author's research team [40] and developed more precisely as TWDS in [5] is: "Total Waveform Distortion (TWDS) 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 is value of fundamental subgroup measured for approximately 200 ms window in accordance with IEC Std. 61000-4-7".

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 $\delta P_i$ and $\delta Q_i$ 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, eg. DNV-GL, LR or ABS, which rules impose acceptable levels $\delta P_i$ and $\delta Q_i$ indices. Appropriate indices characterizing a proportionality of the powers distribution of i-th generator are described by the formulae, adopted on the basis of ship classification societies' provisions:

$$\delta P_i = \frac{P_i - \alpha_i \sum_{i=1}^{k} P_i}{P_n} \cdot 100 \qquad (12)$$

$$\delta Q_i = \frac{Q_i - \alpha_i \sum_{i=1}^{k} Q_i}{Q_n} \cdot 100 \qquad (13)$$

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], [29], $k$ - number of generators running-in-parallel, $\alpha_i$ - coefficient of proportionality dependent on a number and output of running-in-parallel generating sets ($\alpha_i$=0,5, for $k$=2, and the same output of the co-working generators). Inappropriate values of these coefficients is the most frequent reason of the blackout in ship system and this is why, the coefficients $\delta P_i$ and $\delta Q_i$ should be determined continuously during the ship operation. An example of active powers distribution between two generators working in parallel during the ship manoeuvring, based on experimental results carried out by Gdynia Maritime University research team [44] is illustrated in Figure 8.

a)

b)

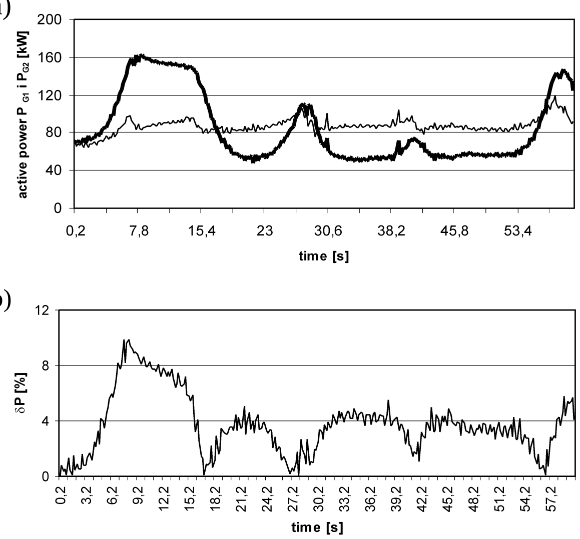



*Fig. 8. Distribution of active powers between two generators working in parallel during sip maneuvering (a) active powers of two generators working in parallel during ship maneuvering (b) proportionality indices characterizing distribution of active powers between two generators working in parallel*

More information concerning load sharing in ship power systems can be found, among others, in [5], [45].

Overviewing the most important classification society rules, some ambiguities concerning imprecise definitions of related power quality indices may be formulated as follows [46], and discussed in [1], [3], [5]: - 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 differentorders 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.

### C. Measurement methods of power quality indices

An issue of measurement methods of power quality indices requires answering the question, what signal processing tools are to be used and how? An answer for this question in majority of measurements' results from the existing power quality standards for industrial land systems. Undoubtedly, these standards should be considered as primary standards, which constitute a state of the art in the question under discussion. They are a the basis to form the standards addressed to power quality in ship systems. They define not only a set of reference technical parameters and their permissible limits, but also the methods of their measurement. Some similarities and common points in appropriate land and ship standards, e.g. [21], [22], [37] and [23], [24] can be easily indicated. Additionally, there are rules of ship classification societies, e.g. [26-29], resulting from the mentioned above standards. Generally, these rules are similar to the previously cited dominant standard [24] or even less precise, what was partly illustrated in Table 1. According to considered standards like [22], [37], there are some recommendations for signal processing concerning the window width, window type, DFT transform, sampling frequency, fundamental frequency calculation, concept of voltage harmonic subgroups, and time aggregation, respectively. 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 [47].

With regard to first exception, method of frequency measurement recommended by the IEC Standard [22] cannot be accepted because of its discrepancy with ship system requirements for frequency value control. In [22] the number of integral cycles is counted during the 10-s time clock interval, whereas the 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 ±10% during the time not longer than 5-s. The second exception is connected with the frequency spectrum analysis. Because of the relevant frequency fluctuations observed in ship networks, mentioned in subsection III.B, the measurement of higher harmonics and interharmonics in ship networks requires [34]: a discarding FFT algorithm as a basic tool for spectrum estimation, as well as implementing asynchronous sampling and next application of chirp Z-transform (CZT) or interpolation in the time-domain. The third exception concerns a problem of THD coefficient measurement, including an extended interpretation of this coefficient and consequences resulting from their implementation which have been discussed in subsection III.B. Additional comments concerning the three aforementioned cases have been also presented in [1-3].

Taking into account continuously running advancements in signal processing, and having in mind recommendations for signal processing in standard for industrial land networks [22], [37], as well as the presented exceptions for ship networks, a package of adopted recommendations for ship measurement technique is proposed [5] and [34]: - asynchronous sampling with frequency at least 18,34 kHz and adjustment number of considered samples to the duration of 10/12 cycles, - rectangular weighting, - signal processing, dependently to the needs and requirements of application: Chirp Z-transform for both, on line and, off-line analysis, DFT for off-line analysis, FFT with the interpolation in time-domain.

Alternative solution, for simple analysis of signal distortion, is signal low-pass filtration [48]. Assuming, that an appropriate signal processing tool has been chosen, a next question is: how to aggregate measurement results? This question is very important for the operators of power systems, including ship systems. They need a clear indication, which values of distortion factor should be considered in decision making processes? A comprehensive background of this problem and examples of research results recorded on all-electric ship is presented in [47]. It was confirmed by research carried out on board all-electric ferry presented in [2]. 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 [49]. Therefore, in the case of time-varying waveforms, the relaxed thresholds of waveform distortion indices should be adopted. The arduous analysis of real ship examples leads to a conclusion that the aggregated 150 cycles values for systems with rated frequency equal to 50Hz 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 [47]. 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 [1-3]. 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 [50] and this should concern other power quality indices as well. Unfortunately, except the UK Defence Standard [51], and Polish Register of Shipping [30] 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 [39] and also not to increase the number of some hard-to-interpret data for ship crew.

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 [46] and discussed in [1], [3]: - 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.

### D. *Instrumentation for power quality assessment on ships*

Looking at the state of the art in the field of instrumentation for power quality assessment on ships, two cases can be considered: the first, for the existing and now operating ships and the second one, for the newly built ships. The first case, related to day-to-day onboard watchkeeping duties, is based on use of the main switchboard standard equipment (Fig. 9). This measurement and control equipment usually consists of a set of one-parameter measuring instruments to control such electric quantities of ship power systems like currents, voltages, powers, load character, frequency and network's insulation resistance.

The readings from those instruments can be applied for indirect determining of power quality indices, by means of calculations. The selected power quality indices values are described in subsection III.B. Additionally, in the measurement field of each generator the SYNPOL®D unit [11], [52] (or similar) is installed. This unit, in fact, is the multi-parameter instrument of aforementioned quantities characterizing ship power plant and, at the same time, operates as the compact device used for controlling and safeguarding of generating set. Each SYNPOL®D device incorporates all important functions necessary for Power Management in ship network. However, it should be stressed very clearly that the instrument functions do not comprise the assessment of most important power quality parameters, e.g. voltage or current waveform distortions.

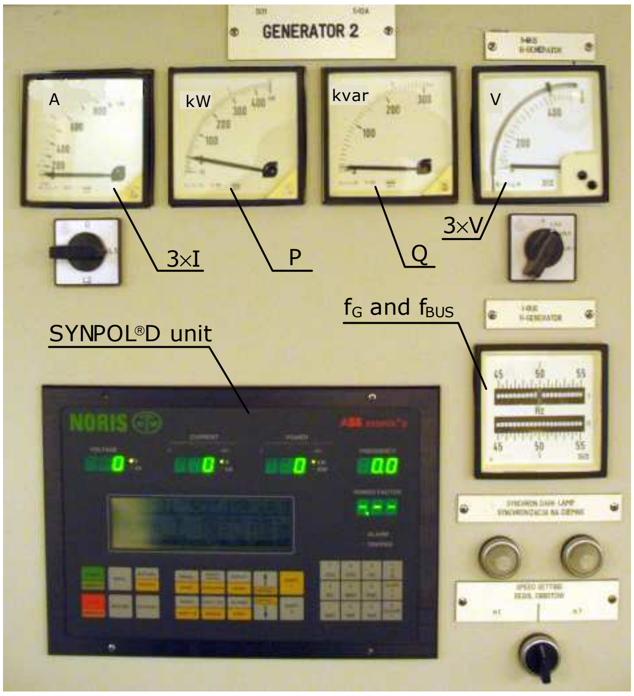



*Fig. 9. An exemplary arrangement of the measurement and control instruments in the generator field of the main switchboard of the existing ship [based on author's resources]*

The second case concerning the instrumentation for power quality assessment on ships is related to newly built ships and directed to the nearest future. In accordance with the lately updated IACS requirements [25], "(…) ships are to be fitted with facilities to continuously monitor the levels of harmonic distortion experienced on the main busbar …" and "(…) As a minimum, harmonic distortion levels of main busbar on board such existing ships are to be measured annually under sea going conditions". Former provision of those unified IACS requirements concern the ships built after July 1st, 2017. Aforementioned requirements are strongly linked with and dependent on the undoubtful coincidence between the observed number of ship accidents and technological solutions development (e.g. harmonic filters application) for power quality improvement [1-3], [18], [20]. Assuming, that the application of power quality analyzers in ship technology will be wider than in past, a necessity to propose and introduce to ship practice an adequate solution for isolated ship power networks is obvious and justified. Looking for the suitable proposal for ship electrical power networks, firstly, the well known and generally available solutions of power quality analyzers designed for industrial, land networks have been considered. A rough overview [46] of selected solutions, i.e., Fluke 435, Hioki 3196 and PowerVisaTM of Drantez BMI belonging to the best measurement class

A in accordance with [22] show some advantages, commented on, among others in [1], [3]. In contrary, the main disadvantages (from isolated networks point of view) of presented solutions are: use of inappropriate measurement methods, based of FFT, due to varying frequency in those systems, next a lack of sufficient number of current channels and a lack of relevant measurement modules, e.g., addressed to proper active and reactive power distribution, in consequence the limited possibilities of measurement of power distribution coefficients and, finally, a lack of possibilities of measurement of steady-state disturbances in the band above 50th harmonics up to 9 kHz. In addition, the all disturbances registered in ship systems 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 [50], [53]. 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 [35], [36], [55], [56].

In the device under consideration (Fig. 10), addressed mainly to voltage quality monitoring, two modes of operation were introduced [35], [36], [47], [55]: - 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.

To complete a version 1.0 to monitor power/current distribution, among generating sets working in parallel, the expanded version of Estimator-Analyzer of power quality 2.0 was realized. More information about design 2.0 version, functions, modifications in both, hardware and software layers, can be found in [54-56] 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). The presented device was called "estimator-analyzer of power quality" to emphasize its relevant distinctness from the solutions available on the power quality analyzers market.

a)

b)

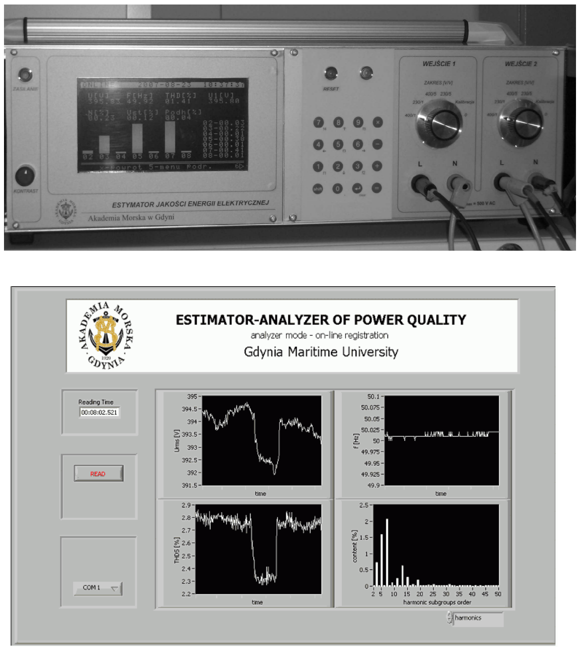



*Fig. 10. The estimator-analyzer 1.0: (a) front panel; (b) example of user interface of PC for communication with estimator - analyzer of power quality [35], [36], [47]*

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 [35], [36], [54-56]. 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.

Taking into consideration a continuously running advancements in measuring devices technology and having in mind recommendations for ship measurement technique described in subsection III.C, the chief requirements concerning the measuring instruments for ship technology applications have been formulated, among others in: - the measurement channel structure of the main instrument contains the following: an input circuit with anti-aliasing filters, sample-and-hold and an A/D converter, synchronization and window-shaping unit, if necessary, DFT processor providing the Fourier coefficients, - the window duration should be 10 periods for 50Hz systems or 12 periods for 60Hz systems with a rectangular weighting, - synchronization conditions: the maximum permissible error of the measuring window synchronization with the recommended window width should not exceed ±0,03%, synchronization with the required accuracy should be possible within a range of at least ±5% of the nominal frequency.

Aforementioned requirements basically result from the existing power quality standards IEC 61000-4-7 [37].

### E. Legal instruments for power quality monitoring

There are many standards dealing with the problem of electric power quality. As it was mentioned in subsection 3.3, the standards concerning power quality issues in the land, industrial grids had to be considered as the primary standards. Among the standards for ship networks, there is a group of standards established and continuously updated by the classification societies. The group of leading classification societies has established the International Association of Classification Societies (IACS). The IACS consists of the following members: American Bureau of Shipping (ABS), Bureau Veritas (BV), China Classification Society (CCS), Croatian Register of Shipping (CRS), Det Norske Veritas Germanischer Lloyd (DNVGL), Indian Register of Shipping (IRS), Korean Register (KR), Lloyd's Register (LR), Nippon Kaiji Kyokai (Class NK or NK), Polish Register of Shipping (PRS), The Royal Institution of Naval Architects (RINA) and Russian Maritime Register of Shipping (RS). These societies play a vital role in ship industry, what results directly from the documented IACS strategy defined as: "The objective of ship classification is to verify (…) the reliability and function of the propulsion and steering systems, power generation and those other features and auxiliary systems witch have been build into the ship in order to maintain essential services on board." For this reason, the classification societies' standards are basic point of reference for designers, shipowners, crew members and users of ship systems. The lists and short description of most important standards concerning the issues of power quality assessment in the land and in ship networks, were shown, among others, [1-3], [5]. It is worth to underline, that some of the standards (IACS, 2016; ABS, 2016; DNVGL, 2016; LR, 2016; PRS, 2017) were lately updated as the result of the wide discussion after some accidents on ships [18], [20]. Aforementioned standards 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 [31] was that of LR [28], where in case of naval ships it makes reference to STANAG 1008 [57]. Other new trends were observed after the accident of RMS Queen Mary 2, when some requirements concerning the procedures for power quality assessment in ship systems have been slightly updated in appropriate standards and rules. For example, the role and requirements for the system integrator of the distribution system, when the electrical distribution system on board a ship includes harmonic filters have been precisely defined [25]. Also, the requirements and recommendations concerning the level of total harmonic distortion (THD) and harmonic distortion calculation have been placed in the standards [25], [27]. Observing positively those efforts, the still existing main ambiguities of discussed standards and rules, have been formulated and discussed in the subsections III.C and III.D, respectively. It is a consequence of the simultaneous impact of the related standards on indices, methods of measurements and instrumentation shown in Figure 5.

Summing up, the metrological aspects of power quality assessment defined on the basis of the ***Cpq*** (1), are closely related with four components, i.e.: indices, methods of measurements, instrumentation, and standards. Presently existing ambiguities of the power quality assessment process, appointed and discussed in [1-3], [5], 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 yet exhaustive, although the last proposals are going in the right direction.

Some recommendations concerning the power quality indices should be addressed to their exact definitions, especially waveform distortion indices, and defining limiting values of respective parameters, depending on the parameter magnitude and time of exposure. Next, the detailed recommendation concerning the measurement methods and instrumentation dedicated to power quality have been presented in subsections III.C and III.D, respectively.

## IV. METROLOGICAL ASPECTS OF POWER QUALITY-RELATED SHIP SAFETY IMPROVEMENT

Power Quality - related safety improvement may be executed by the means of technological solutions or in result of the staff competences development. A graphical illustration of the ways of power quality-related safety improvement en route to reduce ship accidents based on the concept presented in [4], is shown in Fig. 11.

Taking into account author's team research experience and numerous case studies described in the related references [8], [18], [20], the most frequent reasons of power quality disturbances, often leading to increase a risk of ship accidents, are: influence of the power electronic devices installed in the considered system, switching processes and overvoltages provoked by them in distribution switchgears and electrical consumers, failures of important elements of the system (e.g., harmonic filters cooperating with shaft generators or main electric propulsion), carelessness in design, carrying out, maintenance and diagnostics of the system, human errors in the system operation.

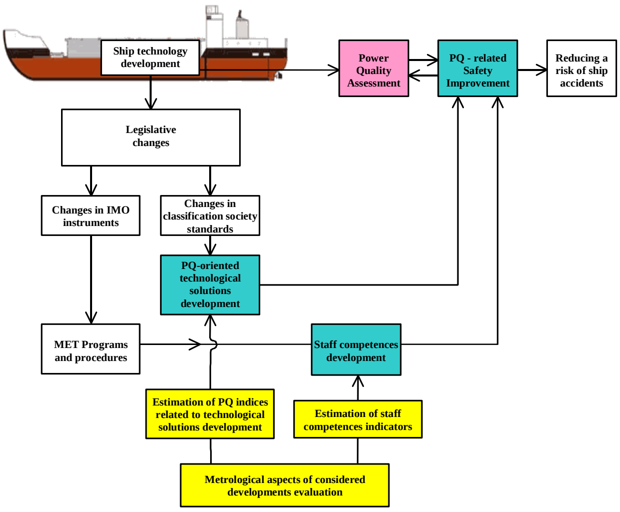



*Fig. 11. The ways of the safety improvement related to power quality on ships en route to reducing of ship accidents, the boxes marked with blue color are refered to PQ-related safety improvement resulting from technological solutions and staff competences developments, respectively; with yellow color - to metrological aspects of the analyzed problem*

The last one, is a dominant cause of the accidents at sea according to the International Maritime Organization statistics. To keep power quality in accordance with ship industry standards, and to reduce a risk of ship accidents it requires performing of the appropriate measures. An improvement of power quality - related ship safety can be achieved in the two parallel ways: by means of using appropriate technological solutions, connected with the three first of the five aforementioned reasons and by increasing of the staff competencies and skills, related to the two last, remaining reasons. The first option, an improvement resulting from appropriate technological solutions is usually connected with the design and development stage of the ship systems, the latter one - an increasing of the staff competencies and skills with exploitation stage of these systems. Adequately, a role of the measurements consists in assessment of power quality parameters in the ship systems in the first stage, and in estimation of the staff competencies and skills for ensuring the exploitation safety of the systems under consideration - in the second one. This last aspect is immanently connected with diagnostic measurements, being a basis for correct and safe control, maintenance, and diagnostics and repair of electrical and electronic installations on shipboard.

### A. *Power quality - oriented technological solutions' development*

Having in mind, previously described features of ship power network (Subsection I.B) a serious problem of power quality deterioration appears. Because of the relevant influence of this deterioration on ship and shipping safety, expressed by the observed during last years increasing number of ship accidents dependent, among others, on power quality problems [1-3], [18], [20], the problem of power quality - related improvement (Fig. 11), in both, technological solutions and staff competences must be solved. Firstly, a short overview of power quality - oriented technological solutions with paying attention to the related metrological aspects is presented below. This overview is based mainly on the works [1-3] and [5]. Technological solutions are the subject of activities and cooperation of the shipowners, designers and users of the ship systems. They can be considered and undertaken at the design stage and the exploitation stage of the considered ship, respectively. At the design stage some recommendations concerning the related solutions should be considered, like generator and receiver construction, a separation of disturbing or susceptible loads and the technical tools, like filters for mitigation of harmonic distortion in the analyzed systems. The exploitation stage is usually connected with power quality management, it means the reconfiguration of ship power plant and load sharing control, including switching on and off harmonic filters. 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 [58]. 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 [8], [12], [18]. Taking into account above mentioned effect an important recommendation for designers is to install generators with a large sub-transient reactance [18]. An illustration of this phenomenon, based on the experimental study results [12] is shown in Fig. 12.

The experimental study was based on the electric power plant configuration of the ship m/v "Horyzont II", roughly presented in subsection I.A, Figure 1. Three configurations of the ship power plant have been considered [12]: 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 [12]. The registered power quality parameters were measured on the busbars of the ship's main switchboard and they covered, among others, THD, TWD and TWD2.5–10 kHz; previously defined in subsection III.B, by Equations (9)-(11). 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.

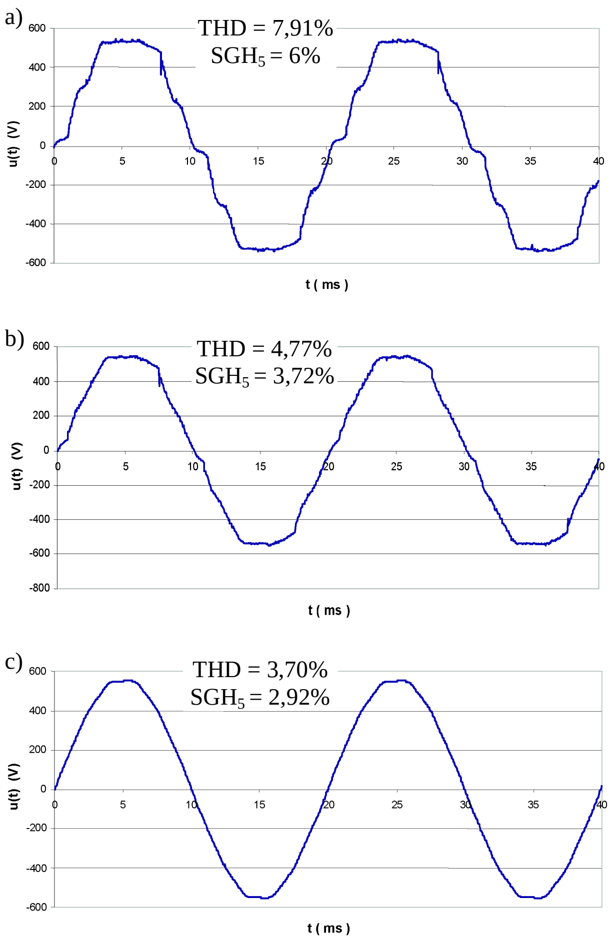



*Fig. 12. Exemplary voltage waveforms recorded on bus bars of main switchboard during bow thruster operation for: one generator working (a); two generators working in parallel (b); and three generators working in parallel (c); THD, $SGW_n$ - mean values of parameters of power quality measured on the busbars of the main switchboard, $SGH_n$ - content of harmonic subgroup of n order, based on [12]*

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 detailed research results are presented in [12], and additionally commented on in [1], [3] and [5]. A very similar effect based on the additional reactance of the synchronous compensator (Figure 2) occurs in the power system aided by shaft generator. 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 [8].

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 3). Under these conditions the SOLAS convention [59] 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. Metrological aspects related to power quality - oriented technological solutions at the design and development stages of the ship systems are mainly concentrated on assessment of power quality indices (mainly waveform distortion indices) resulting from the reconfiguration of ship power plant, including load sharing control, and the switching on and off harmonic filters. Procedures of their defining and determining were previously described in subsection I.C, and illustrated by the example shown in Fig. 12. Some valuable information concerning these metrological aspects may be achieved in the way of the ship system modeling [5], [18].

Continuing a discussion on possibilities to improve power quality - related ship safety 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 [2], used to mitigate the effect of harmonic distortion in the systems under consideration, including, among others [8], [42], [58], [60-62]: 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. 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. In many cases, to increase effectiveness and reliability of harmonic distortion mitigation the multi-step solutions, e.g. based on passive harmonic filters, supported by multi - pulsed systems and multiple phase shifted secondary windings in propulsion motor supply transformers are used (Fig. 13), based on [18].

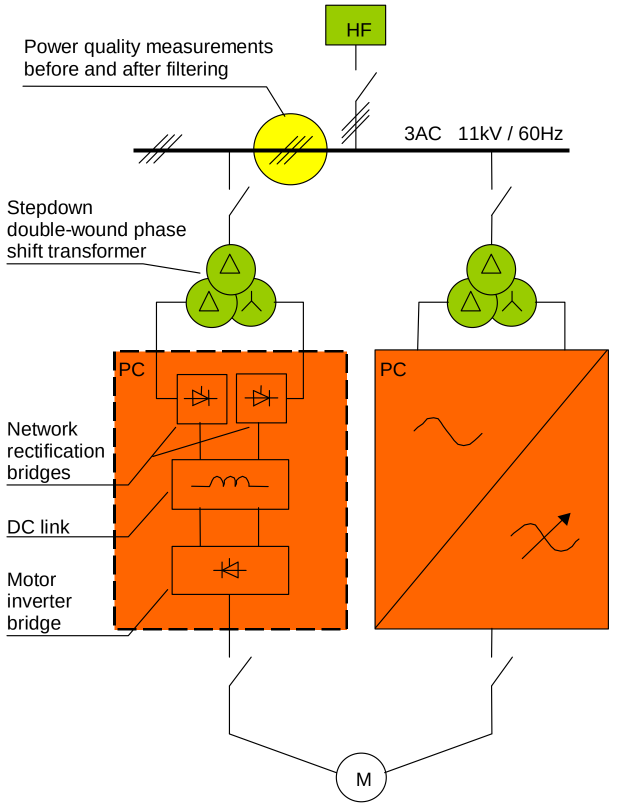



*Fig. 13. The example of power converters for propulsion motors based on the Figure 13. The example of power converters for propulsion motors based on the RMS "Queen Mary 2" [18]. PC, power converters; M, main propulsion motor; boxes marked with orange color (PC) are referred to worsening effect of power quality; and boxes with green color - to improve power quality based on harmonic filters (HF) and multi-pulsed systems and multi-phase shifted secondary windings in supply transformers, boxes marked with yellow color are referred to power quality measurements*

A presented example is based on the configuration illustrated in Fig. 3 and concerns high voltage network, where a dominant load of the system is represented by four main propulsion motors, each of power about 20MW. The main propulsion motors were supplied through step down double - wound phase shift transformers and power converters. In [18] one can find more detailed description of the power converter modules: "…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". For the 12-pulse converters fitted on QM2 [18] 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% [28], the harmonic filters were installed. Each HF consisted of two sub-sections tuned to resonant frequencies equivalent to the 11.3$^{rd}$ and 4$^{th}$ harmonics, and referred to on board the considered vessel as rank 11.3 and rank 4, respectively [18]. However, even this multi-step mitigation harmonic solution, could not protect the system against previously described technical failure and main consequence, marine casualty [2, 18].

Another kind of power quality correction system is based on the active power filters [61], [62]. Active filters treat harmonics by measuring the level of harmonic current present in the system and injecting currents of opposite polarity to cancel them.

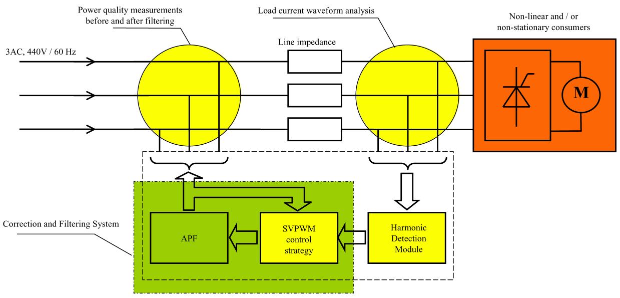



*Fig. 14. Ship electrical power network with shunt APF as power quality correction system, designations of colors are similar to those in Fig. 13, based on [65]*

An example of ship electric power system equipped with the power quality improvement modules is shown in Fig. 14 [63],[64]. In the presented network, the non-linear loads, like AC PWM drives, cause distorted line load currents, which through the voltage drop on the generator and line impedances are subsequently transferred into the distorted voltage supply on the busbars of main and auxiliary switchboard in the ship electrical power systems. To counteract this adverse phenomena results in necessity of, firstly, fast and adequate detection of analyzed, usually significantly distorted load current waveforms [63], and, secondly, a precise control of active power filter with the use of appropriate algorithms for compensating current generation [64]. The first task is usually based on the use of instantaneous reactive power theory of a 3-phase circuit ($i_p - i_q$ method) [65] and their developments, e.g. [63], [66], [67]. The second one is mostly solved by the use of tracking PWM control algorithms and their modifications, among others Space Vector Pulse Width Modulation (SVPWM) [64], [68], [69]. Analyzing the metrological aspects of passive and active power filters implementation, the passive power filtering is mainly oriented to the designing of filters with appropriate resonant frequencies, and next, with checking the required harmonic distortion level on the busbars. In other words, an effect of harmonic mitigation. Active power filtering is basically related to control the level of harmonic line load current, and finally, the level of distorted voltage supply on the main bus bars. A solution of this problem mainly consist in appropriate algorithmization of the processes of harmonic detection and compensating current generation, it means, a key point is focused on elaboration of the procedures of measurements, adoption of the suitable signal processing methods and adequate algorithmization of the analyzed processes. But finally, the effects of the active filtering are evaluated with a use of the power quality indices concerning the waveform distortion (Subsection III.B), but related not only to the voltage, (like in the case of passive filters), but to the line load current first of all.

The last group of methods for mitigation of harmonic distortion is connected with other, than previously analyzed, specialized constructional and technological solutions. This group covers, among others, the power factor corrected power supplies, reactors and chokes. Some information concerning these solutions can be found in [8], [42], [60].

### B. *Staff competences development*

Looking at Fig. 11 and appreciating a significant role of technological solutions development, we cannot forget about the "human factor", as one of dominant reasons of power quality problems in recent years. Bearing in mind, that the human error can be caused by different reasons, for the need of this paper a notion of human error (human factor) is understood as a personal, individual attribute of the crew member, depended mainly on his adequate qualification, confirmed by certificate of competences [4]. Human factor is very strongly and inseparably connected with the staff competences, understood and interpretated in the International Maritime Organization meaning [70] as: "Competence is the possession of the skills required for the award of Certificate of Competency", commented on in [71]: "… at sea, competencies more likely to be defined as a capacity to do a job efficiently in any circumstances likely to arise". In this context, a working hypothesis is formulated in the way [4], that "… a rapid and substantial technological progress in electrical and electronic engineering on ships causes a competence gap of watchkeeping officers responsible for control, maintenance, diagnostics and repair of electrical and electronic installations on board of ships". It should be expressed very clearly, that aforementioned technological progress 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 [4], [18], [20]. In result, the competence gap documented by the recorded in several last years accidents and their consequences [1-3], [18], [20], [72], creates a real threat for safety of shipping. A short overview of those accidents [18], [20] allow to appoint some categories related to the capacitor failures in different circuits and arrangements, to the arc-flash accidents or to the erroneous operation of the protection relay systems, respectively. The analysed situations, led to the explosion, fire or loss of main propulsion and abilities of manoeuvring, in consequence, at least to economical losses. 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 [18], [72], in other cases they concluded about undoubted ambiguities within KUP competences (knowledge, understanding and proficiency) of watchkeeping officers [18], [20] in IMO meaning [70]. Sometimes, two components, technical and competence - related occur together [18]. With regard to the first case, concerning the catastrophic failure of a capacitor in the aft harmonic filter (HF) room on board RMS Queen Mary 2 [18], the report under consideration concluded, that HF 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 [18]. A current imbalance alarm detection system consisted of the current transformer, which primary winding was connected to the capacitor circuit. Secondary winding of the current transformer is linked to a current imbalance detection relay [18]. Under normal conditions, little or no current should have flowed through the transformer (Fig. 15). When a capacitor degraded, the current flow across the circuit became unbalanced and induced a current in the transformer's secondary winding.

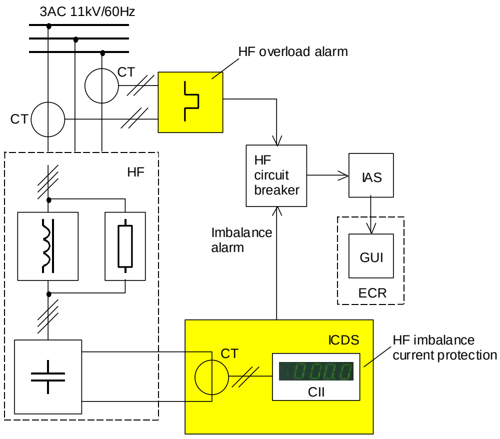



*Fig. 15. Block diagram of the monitoring of harmonic filter operating parameters; ICDS – imbalance current detection system, CII – current imbalance indicator, CT – current transformer, IAS – integrated automation system, GUI – graphical user interface, ECR – engine control room, boxes marked with yellow color are referred to power quality measurements, including a monitoring of vital parameters*

The detailed description of the threshold values for imbalance alarm and triggering processes can be found in [18]. A block diagram of the monitoring of harmonic filter operating parameters based on [18] and developed by the author, is illustrated in Fig. 15.

It is important, that a current imbalance detection system and the overload current sensors in the HF itself have been linked to circuit breakers of HFs, and finally, to integrated automation system (IAS). The idea of combined monitoring of harmonic filter operating parameters with a use of engine control room display is described in [18]: "When the IAS received an imbalance or overload alarm from an HF, the duty engineer could interrogate the graphical user interface (GUI) in the ECR, which indicated the rank of the HF which was in alarm. The GUI display for both the overload and the imbalance alarm was combined, and read "OVERLOAD / UNBALANCE (…) as a one indication at the display". After the accident, the transformer's windings were found to have failed. This caused the alarm display to read 0mA (Fig. 15) giving a false indication that the capacitors were in good condition. And finally, although detection of an unbalanced current was the only protection system for harmonic filters, it had no backup and did not fail safe. Routine tests of the system were by the secondary current injection method, and by-passed the transformer. In other words, the only means to warn against capacitor deterioration 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. Moreover, in the previously cited report [18], 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. This case confirms objections concerning the lack of appropriate qualifications and competences of crew members, especially within the power quality measurements, including the monitoring of vital parameters. The analyzed example, based on monitoring of the harmonic filters operating parameters, being in fact a kind of the diagnostic measurements, leads to finding some ambiguities and inaccuracies in both, human errors and present design, testing and maintenance procedures. The most of them has been appointed in the related reports [18], [72]. With regard to the described and analyzed situation the main discrepancies concern: insufficient knowledge about protection systems of critical devices for ship power plant operation, harmonic filter protection system had no backup and did not fail safe, erroneous approach to current transformers design and testing, hard-to-interpret data and difficult use of the monitoring equipment of harmonic filter operating parameters, human errors in ship tests, day-to-day routine and periodical service and operation.

Another well documented [20] situation is presented and commented on in [2]. 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 [20]. 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. Commenting this accident, the same report [20] concludes: "… several opportunities to determine the problem with DG2 were missed". But the 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" [20]. In other words, the indirect reasons of the damage was a lack of sufficient qualifications of marine engineers and simultaneously, lack of electrical engineers on board of the ship. Presently, the situation is much better after the introduction to the current version of the STCW Convention and Code [70] 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 [73].

Overviewing aforementioned cases from the metrological perspective of power quality - related ship safety improvement the two components should be taken into account. Firstly, the diagnostic measurements for critical equipment, like the main circuit breakers and protection devices, and secondly, a human factor. Those diagnostic measurements are inseparably connected with the harmonic filters operation, which are not only the basic technical solution for harmonic mitigation in ship systems, but also one of the most frequently failing protection devices. For this reason, the measurements addressed to monitor of harmonic filter operating parameters belong to the basic and vital measurements in the considered systems. Assuming, that the technical layer of these measurements, concerning in fact the adequate indices and methods, is defined and implemented into practice (e.g. Fig. 15), only some aspects of the ergonomy, user friendly readings and their interpretation as well as the measurement data transfer inside the monitoring system of harmonic filter operating parameters could be considered as a subject to facilitate appointed components. The latter component - a human factor - in author's opinion, is critical and fundamental. This component concerns not only the processes of diagnostic measurement, but first of all, the ship tests, day-to-day service onboard of the vessel, as well as the operation and maintenance of the electronic and electrical installations on shipboard. In consequence, the staff competences development appears as a key problem, including an issue of estimation of these competences with a use of commonly accepted indicators. Therefore many studies have been provided [71], [74], in order to improve staff competencies, as well as to evaluate the processes connected with the staff competences development. A discussed problem of the staff competences development, and next, the evaluation of this process, should be considered in two layers: quantitative and qualitative. The first aspect results from the state of the art in the analyzed field of research, which shows that worldwide shortage of qualified seafarers has been caused due to rapidly increasing world merchant fleet on one hand, and the difficulty of attracting and retaining people in the shipping industry on the other [4], [75], [76]. It is obvious, that a quality of seafarers' preparation to the profession depends not only on the offered lecturing labs and simulator facilities but also on the study competitiveness. This competitiveness is directly connected with the number of applicants and students who follow the study programmes, dedicated to future ship officers. So, an increase of the number of candidates to seafarers' profession, and next, an increase of the number of watchkeeping officers confirmed by adequate certificate of competency (in the discussed case, the Electro-Technical Officer (ETO) Certificate) are a primary, for basic question, how to solve a problem of appropriate, high qualifications of the crew members. Quantitative measures of the discussed problem depend on many factors, among others, on changes in IMO instruments, organizational evolution of the MET, qualitative improvement of the new ETO's certificate, demographic trends and education conditions in the given country, etc. Some analyses, concerning the influence of the change of IMO legislation on the increase of the quantity of ETO's certificates and students, based on the Polish case study, are presented and discussed in [4]. The second aspect, qualitative one, is a very sensitive point of the staff competences development. A need to develop a highly qualified staff, results directly from the lack of good practice related to ship operation safety appointed before, and described in [18] with clear suggestion formulated by competent national bodies, that measures should be undertaken to overcome existing drawbacks and future threats. Taking into account an undoubted fact, that highly qualified staff fulfills better its onboard, watchkeeping duties, the power quality - related safety improvement of ship operation will be achieved. Author is aware that the power quality - related safety improvement is a specific part of ship safety as a whole, and the staff competences described in IMO documents by means a specification of minimum standard of competence for Electro-Technical Officer (ETO) [4], [70] (the example in Table 3) covers not only the requirements related to power quality, but also to other fields of watchkeeping officers duties.

*Table 3. Specification of minimum standard of competence for Electro-Technical Officers. Function: electrical, electronic and control engineering at the operational level.*

| **Column1** | **Column2** | **Column3** | **Column4** |
|---|---|---|---|
| **Competence** | **Knowledge, understanding and proficiency** | **Methods for demonstrating competence** | **Criteria for evaluating competence** |
| ⋮ | ⋮ | ⋮ | ⋮ |
| Operate and maintain power systems in excess of 1000 volts | ***Theoretical knowledge***<br>High-voltage technologySafety precautions and proceduresElectrical propulsion of the ships, electrical motors and control systems<br><br>***Practical knowle***<br>dgeSafe operation and maintenance of high-voltage systems, including knowledge of the special technical type of high-voltage systems and the danger resulting from operational voltage of more than 1000 volts | Examination and assessment of evidence obtained from one or more of the following:<br>1 - approved in-service experience,<br>2 - approved training ship experience,<br>3 - approved simulator training, where appropriate<br>4 - approved laboratory equipment training | Operations are planned and carried out in accordance with operating manuals, established rules and procedures to ensure safety of operations |
| ⋮ | ⋮ | ⋮ | ⋮ |

Looking at the Table 3, it can be summarized that the four-column specification of minimum standard of competence [4], [70], covers the list of tasks, duties and responsibilities (column 1), the list describing minimum theoretical and practical knowledge, understanding and proficiency (KUP) required for certification (column 2) and the list of evidence, of having achieved the required standard of competence (column 3 and column 4). The example presents the description of competence dedicated to power systems in excess of 1000V, being one of the most important competences in the discussed field of power quality in ship networks. This specification is the basis on maritime training and education (MET) for Electro-Technical Officers. A complete specification includes 16 competences aggregated in three functions [4], [70]: Electrical, electronic and control engineering; Maintenance and repair, and Controlling the operation of the ship and care for persons on board, all functions considered at the operational level. It is worth adding, that in the IMO International Convention on Standards of Training, Certification and Watchkeeping for Seafarers [70], in Section A-I/6 dedicated to training and assessment, one can find a very clear explanation, that "Each Party shall ensure that all training and assessment of seafarers for certification under the convention is: (1) structured in accordance with written programmes, including such methods and media of delivery, procedures and course material as are necessary to achieved the prescribed standard of competence; and (2) conducted, monitored, evaluated and supported by persons qualified in accordance with paragraphs (…)". A question is, why numerous cases of the gap in staff competences were noted, although the IMO requirements in this matter are clear and unambiguous? There are some reasons of such situation.

Firstly, a problem of general knowledge of the crew members responsible for Electrical, Electronic and Control Engineering tasks realization. So, it is really difficult to state that the graduate from usual university course, such as Electrical Engineering with a Basic Training for Seafarers could be automatically granted the relevant Certificate of Competency (CoC). It depends on the programme of the university course (or other appropriate educational institution) in comparison with the mandatory minimum standards established under the STCW convention for a given certificate of competency. Basic Training for Seafarers as per STCW [70] is the necessary condition for obtaining the relevant CoC (in this case ETO certificate), but is not sufficient. The programme of the Electrical Engineering university course must comply with the mandatory minimum requirements for ETO. The simplest way of such comparison is to confront the considered programme of the usual university / appropriate education institution with a Model Course: Electro - Technical Officer [73]. In the forward of this Model Course, published and circulated by the IMO Publishing, it is stated: "This model course aims to meet the mandatory minimum requirements for knowledge, understanding and proficiency in Table A-III/6, of STCW Code for the function of Electrical, Electronic and Control Engineering at the Operational Level, for the function Maintenance and repair at the Operational Level and the background knowledge to support Controlling the Operation of Ship and Care for Persons on Board at the Operational Level". If the results of the comparison show the important differences, the gap must be compensated in the way indicated by the relevant National Maritime Administration.

Secondly, continuously running progress in ship technology requires not only some changes and completions of the teaching and training programmes of the STCW Convention signatories, but also creation of a new and modernization of the existing laboratories, with a use of simulator technology [4]. To face this situation, it is necessary to change our approach to the crew training, which is all the time underestimated by the main players at the shipping market. This observation can be found in [74], where the authors concluded: "There should be a decisive reverse in financial outlays for technology development and crew training i.e. 80% of finances should be devoted for in depth training and less for continuous development in technology with the crew cannot catch up". More information concerning this issue are presented and commented on in [4].

Thirdly, the aforementioned examples of the lack of good practice related to ship operation safety should be comprehensively described, analyzed and used as an important tool for seafarers education. This idea is discussed at the IMO forum [77-79], in related IMO documents accompanying the 4th session of the Sub-Committee on Human Element, Training and Watchkeeping (HTW), where some very important proposals have been included, among others: "… illustrate marine casualties as detailed as possible in order to facilitate maritime lectures to replay or simulate them more precisely and to help seafarers to better understand the causes of and lesson learned from casualties through training and education …".

Discussion about the staff competences development in the wake of the previously appointed threats and proposals which leads to solving the considered problem, cannot avoid a question concerning the estimation of this development. Some existing conditions and related circumstances must be taken into account. With regard to the maritime education and training processes in many countries the different forms of the measurable indicators are generally accepted and used, like the numerical final grades, weighted grade average, grading scales, qualitative scales, the minimum marks required for approval, etc, presented and discussed, among others in [80]. Although these indicators are often based on the European Credit Transfer and Accumulation System (ECTS), it is very difficult to compare those systems and to find a "common denominator", because of the differences and customs in different countries, even in the commonly declared community, like European Union. This evaluation, and later, comparison, is especially difficult in the part of education and training concerning the practical skills, which play a decisive and crucial role in forming the manual excellence of the crew members. Remembering, that "… at sea, competences more likely to be defined as a capacity to do a job efficiently in any circumstances likely to arise", there is a question, how to evaluate the crew member's readiness for and behavior and reaction in unpredictable situation? The latter observation is not only a fundamental one, but it also creates a challenge on how to measure the non - measurable psychological and behavioral phenomena? Perhaps, one of the possible ways to evaluate a human reaction and behavior "in any circumstances likely to arise" will be the "Emotion Detector" concept [81], as a one of the future measuring tools for assessment of the crew members professional competences potential.

## V. CONCLUDING REMARKS AND FUTURE CHALLENGES

A presently existing problem how to harmonize a technological advancement and maritime education and training en route to improving safety of shipping, in last years is closely related with the relationship between ship accidents and power quality issues. To face the main challenges concerning the power quality assessment and related ship safety improvement it is necessary to continuously develop technological solutions and staff competences, as well as to update the legislative instruments in the maritime sector. This development must be well balanced and aided by the adequate tools and procedures for measurement of appropriately defined power quality parameters and for evaluation of power quality related processes, including sociolegal phenomena.

Metrological aspects of power quality assessment, defined on the basis of the ***Cpq*** vector components (1), are closely related with four elements, that is: indices of power quality, methods and instrumentation for their measurements and related standards. Presently existing ambiguities and inaccuracies, concern all aforementioned components, but future challenges and expectations are connected with the advancements in signal processing (subsection III.C) and in measuring devices technology (subsection III.D). These advancements are resulting not only from the fact, that power quality measurements in ship networks are executed in a different way that in land industrial networks, because of the very different characteristics of both systems (subsection II), but they are also stipulated by updating the related standards and requirements of classification societies. For example, in result of the post-accident analyses and reports of the competent bodies, concerning the case of Queen Mary 2, some important power quality - related regulations concerning harmonic distortion for ship electrical distribution system, including harmonic filters (subsection III.E), have been placed in the Unified Requirements of International Association of Classification societies. These regulations define that “the total harmonic distortion (THD) of electrical distribution system is not to exceed 8%”, next, “the ships [ … ] are to be fitted with facilities to continuously monitor the levels of harmonic distortion experienced on the main busbar as well as altering the crew [ … ]”, and finally, “as a minimum, harmonic distortion levels of main busbar on board such existing ships are to be measured annually under seagoing conditions”. Those newly implemented regulations correspond well to safety lessons included in Marine Accident Investigation Branch report [18]: “… Regular monitoring of electrical networks should be undertaken to provide early warning of deterioration. Monitoring equipment should be capable of detecting transient voltage spikes, resonances, and excessive harmonic distortion levels (either continuously or periodically)”. In this context, the future challenges and expectations concern the implementation of the newly designed, and commonly accepted power quality module, installed in main switchboard for continuous monitoring the level of harmonic distortion and the implementation of the portable measuring instrument for the realization of the same task. The former, stationary option is generally dedicated to the current detection of power quality deterioration and looming the corresponding threats. This option should be linked with the ship alarm system. The latter, portable option is planned to the control of routine power quality troubleshooting, as well as to the periodical realization of continuous monitoring of the harmonic distortion level, like stationary version. A design of the new measuring devices will be good opportunity to cover some other power quality measurements, for example hitherto avoided by the classification societies a detection of transient disturbances.

Metrological aspects of power quality - related improvement, concern the estimation of PQ indices related to technological solutions development and the estimation of staff competences.

PQ-oriented technological solutions development improves the power quality - related safety in the way of technological progress confronted to and accompanied with PQ measurement indices checked before and after reconfiguration of ship power plant (including control of a number of generators working in parallel and load sharing control), as well as checked together with a use of the considered and described technological solutions (subsection IV.A) at the design and exploitation stage, respectively. Analyzing the metrological aspects of passive and active power filters implementation, the passive power filtering is mainly oriented to the designing of the filters with appropriate resonant frequencies, and next, with checking the required harmonic distortion level on the busbars. Active power filtering is basically related with control the level of harmonic line load current, and finally, the level of distorted voltage supply on the main busbars. A solution of this problem mainly consist in appropriate algorithmization of the processes of harmonic detection and compensating current generation, i.e. a metrological component which is focused on elaboration of the procedures of measurements, adoption of the suitable signal processing methods and adequate algorithmization of the analyzed processes. The effects of active filtering are evaluated with the use of power quality indices concerning the waveform distortion analysis (subsection III.C), but related not only to the voltage, (like in the case of passive filters), but firstly to the line load current.

Next, PQ - related staff competencies development and its estimation (subsection IV.B) is determined by the two components: diagnostic measurements and maritime education and training programmes and procedures. Diagnostic measurements fulfil a crucial and vital role for the ship operation safety, and, as it was showed by the examples of a lack of good practice and the reports of the analyzed accidents prepared by the competent, well internationally recognized bodies. The recommendations called “safety lessons” for the previously mentioned report [18] include, among others, the recommendations: “Protection systems for critical equipment must ‘fail safe’, and should be thoroughly tested at regular intervals to prove that all sub-components are functioning correctly. In particular harmonic filters with current imbalance protection systems should be thoroughly checked by a competent person at the earliest opportunity”. Also in the synopsis of the report [18] some important recommendations like, to develop requirements to detect and mitigate against the failure of high-energy storage devices, to ensure that protection devices of critical items are fail safe, and to provide related data to crew are included. Author of this paper is of the opinion, that in the aforementioned documents a main focus is concentrated firstly on competent person and flow of the related data about the protection systems to crew members, and secondly, on the technical equipment for mitigation of power quality disturbances, in the meaning of critical devices for the ship power plant operation. In this context, staff competency development depends on an effectiveness of maritime education and training system. This system, based on three pillars [76]: theoretical education, practical skill training and assessment and examination is discussed in subsection IV.B. Assuming, that all necessary conditions to comply the IMO requirements for obtaining the certificate of competency are exactly and precisely defined and explained in the IMO legislative instruments [70], the only question is to respect them and implement in practice. This implementation requires the continuous updating the MET programmes and training scenarios, being in accordance with the technological progress in ship technology and our knowledge about the reasons and courses of the analyzed ship accidents [72-74]. So far, the trials undertaken to formally describe, by means of appropriate indicators, the evaluation process of professional skills of the crew members had no complete solution. Taking into account present state of the art, it is the open challenge, how to find an adequate procedure and the related measurable factors, for, in fact, non-measurable human behavior, often in unpredictable situation? But first of all, one should look for and expect to meet the substantial realization of the STCW requirements, not only the formal ones. Because of the complexity of the power quality - related issues, an improvement of professional skills, and finally, development of staff competences require the closer than before cooperation of ship designers, crew members and ship classification societies under the umbrella of the IMO legislative instruments.

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