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Voltage and Frequency Deviations in Exemplary Ship's Network—Research for Ship Owner

Janusz MINDYKOWSKI, Mariusz SZWEDA, Tomasz TARASIUK

Gdynia Maritime University, Poland

***Summary*: The paper is focused on a problem of electric power quality in ship electric power networks. Some current standards relevant to the discussed problem have been presented but the main part of the paper has described the research of voltage and frequency deviations on chosen ship. This research has been carried out on the ship owner request due to unusual steady-state frequency deviations from its rated value. Finally, the supply voltage parameters have been monitored during one exploitation trip and some conclusions for future undertakings have been drawn. This paper is based on original report for the ship owner and results of the research are given on the basis of the ship owner permission.**

Key words:
electric power quality factors and standards, ship's electric power networks, power quality assessment

1. INTRODUCTION

The phenomena of significant voltage and frequency deviations are typical for isolated power systems, including these on ships [5]. These deviations can be observed as long- and short-term phenomena. The reasons of the long-term deviations are usually on the supply side, but the load changes are mainly responsible for short-term deviations. In most cases these deviations are harmless but in some cases they can cause dire consequences for ship equipment. For example, the long-term voltage and frequency deviations can induce additional energy loss in electrical machines, their overheating and resulting decrease of their operational life [2, 3]. The short-term deviations can cause malfunction or failure of important electric energy receivers with potentially huge consequences for whole ship operation.

However, classical approach for voltage parameters control assumes a monitoring of deviations of voltage and frequency from their appropriate rated values respectively only over steady-state conditions due to limited capacity of measurement equipment. It means that short-term phenomena are omitted. That way the ship crew chances of diagnosis and neutralization of discussed phenomena consequences are strongly limited, lest to mention lack of expertise. Such situation has occurred on given ship. The long-term increase of frequency (approximately 4% of its rated value) has been found and reported by the crew-officers to ship owner. Further, the ship owner has requested help from Gdynia Maritime University due to lack of resources for coping with the problem. Situation has been obscured by the fact that nobody knows who, when and why had increased the frequency. The ship has not been brand new and has been bought from former owner. So, fundamentally there have been two questions laid by current ship owner: Firstly, what will be consequences of doing nothing? And secondly, taking into account the current level of voltage parameters in the system, is it safe to decrease frequency in this system? The responsible answer for these questions should rely on prior monitoring of the all voltage properties in discussed ship during steady-state and non-steady state conditions. Such research has been carried out and some conclusions have been drawn and presented to the ship owner. The results have been presented below on the basis of the owner permission.

2. RELEVANT STANDARDS

The standards relevant to power quality monitoring are connected with problems of permissible levels of defined power quality parameters (e.g. EN Std. 61000-2-4 [8]) as well as methods of their measurements (e.g. IEC Std. 61000-4-7 [9], IEC Std. 61000-4-30 [10]). However, there are only the former group of standards for the ship systems, namely rules of ship classification societies, which define permissible levels of many power quality parameters (e.g. rules of Lloyd's Register of Shipping [11]). Than, there is IEC standard 60092-101. *Electrical installations in ships. Definitions and general requirement* [12], which defines the very same permissible levels of power quality parameters for ship networks like in previously mentioned rules of ship classification societies. Among other parameters, these standards define the permissible levels of voltage and frequency

Table 1. Permissible levels of voltage and frequency deviations on ships

Parameter	Deviation from rated values		
	long duration	short duration	
	value [%]	value [%]	time [s]
voltage	+ 6.0 - 10.0	± 20.0	1.5
frequency	± 5.0	± 10.0	5.0

deviations in ship systems. According to most rules these deviations should not breach the values laid in Table 1[11, 12].

Obviously there are other power quality parameters defined in relevant rules for ship use like in their land counterparts. However, one significant difference should be noted. There are not existing rules for method of power quality measurement in ship networks. Moreover, the existing rules for land systems can not be fully applicable for ship systems, especially for the frequency part. According to IEC Std. 61000-4-30 [9], the frequency reading shall be obtained every 10 s and it is the ratio of the number of cycles counted during 10 s time interval, divided by their cumulative duration. It is easy to observe that the method is of any use for evaluation of short-term frequency deviations, since their duration shall be not longer than 5 s, as mentioned in Table 1.

Finally, authors have decided to assume two basic time intervals of measurement. According to IEC Std. 61000-4-30 [10], the measurement of supply voltage magnitude shall be carried out over 10-cycle time interval for 50 Hz system or 12- cycle time interval for 60 Hz power system. Further the voltage calculated by this method will be described as U_{12}, since the nominal value of the frequency in the system under consideration has been equal to 60 Hz. Moreover, the basic measurement time interval for voltage dips and swells detection and evaluation shall equal to 1 cycle. However, the readings shall be refreshed every half-cycle and measurement shall be commencing at signal zero-crossing [9]. Further the voltage calculated by this method will be described as $U_{rms(1/2)}$. Taking into account the previously mentioned lack of relevant rules for frequency estimation in ship systems and irrelevance of the method laid in IEC Std. 61000-4-30 [10], authors decided to apply the very same methods for frequency estimation as for voltage measurement. Namely, frequency has been calculated as reciprocal of one cycle of measured voltage and refreshed every half-cycle $f_{(1/2)}$ as well as the ratio of twelve and duration of twelve cycles of measured voltage f_{12}. In all cases the measurement has been commenced at voltage zero-crossing (no multiple zero-crossings have been found in the system, which can potentially corrupt the results).

3. MEASUREMENT METHODS AND TOOLS

The authors have carried out the research of electric power quality in ship networks for quite a few years. The main aim of the research has been purely scientific. So, no real-time monitoring has been required. Nevertheless, in the case of considered aim a previously registered voltage post-processing has been allowed and advisable as well. Then, the simplest and reliable method has been done as the registering of voltage samples during chosen exploitation conditions and further processing of stored data by algorithms implemented in relevant mathematical environment, Mathcad software in the case. Such procedure has been previously used in authors other research. It enables the modification of used algorithm and implementation of different methods to the very same set of samples.

Finally, the measurement system (worked out in Department of Ship Electric Power Engineering of Gdynia Maritime University) contains two main parts: the hardware part and virtual part – software (recording, processing and graphical interface) as shown in Fig. 1.

The input signals for the above presented measurement system are three-phase voltage on bus bars of main switchboard as well as the currents of respective generators. These signals are adjusted to input range of A/D converters (layer of analog signal processing Fig. 1). Moreover, the isolation amplifiers ISO 124 of Burr Brown (voltages) and current probes flexRR3030 of LEM as well as antialiasing filters have been utilized. Further, the signals are sampled and digitized. In reality, the PC plug-in data acquisition board PCI703-16/A Eagle Technology has been used. It is fitted with 16 Channel Simultaneous Sample and Hold analog inputs and 14-bit A/D converter [4]. For the particular research the sampling frequency equal to 10504 Hz has been adopted, which ensures the analysis up to 50th harmonic.

However, the measurements have been carried out in network of relatively high voltage in the considered case. The rated voltage has

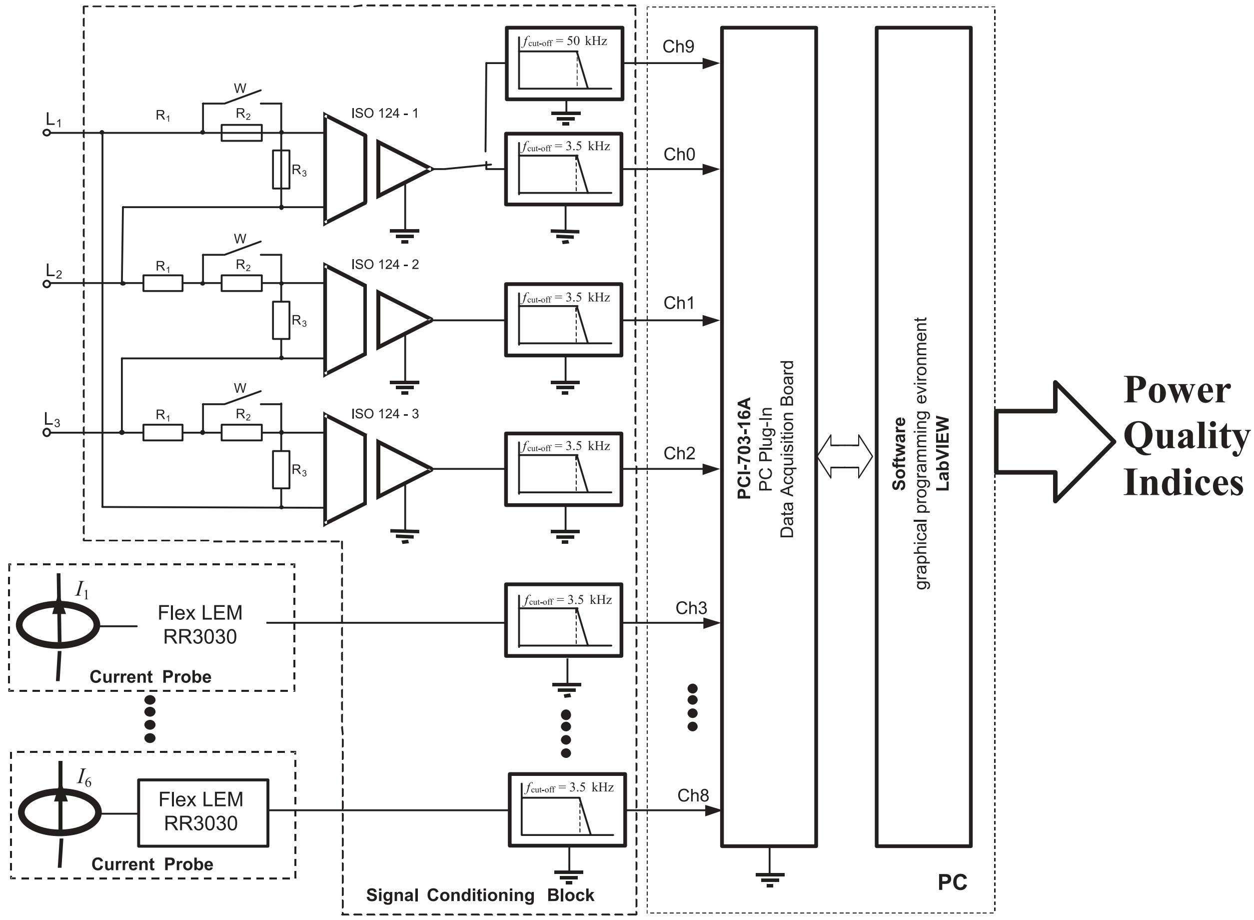


Fig. 1. The block diagram of measurement system for power quality indices estimation as carried out in Department of Ship Electrical Power Engineering of Gdynia Maritime University

been equal to 6.6 kV. So, the current channels have not been used due to the features of current probes. But it has not been necessary for the aim of the research.

4. RESULTS OF THE RESEARCH

The presented research has been carried out in the system with rated voltage 6.6 kV and rated frequency 60 Hz. The input signals have been obtained via voltage transformer 6.6kV/110V. But it should be stated that analyzed phenomena have passed to networks with other rated voltages because the sub-systems of different rated voltages have been interconnected. The ship has been equipped with two kinds of generators. High voltage generators (6.6 kV) with rated power equal to 2400 kW and low voltage generators (440 V) with rated power equal to 830 kW.

The registration of voltage parameters has been carried out during one case of pulling in and harbour and two cases of pulling out of harbour. These cases of ship maneuvering have been particularly interesting due to significant and sudden load changes. So, there have been observed significant voltage and frequency deviations as well. Moreover, the process of starting-up large motor has been observed prior to maneuvering (drive of thruster). Furthermore, the case of no load changes has been observed as well for evaluation of long-term voltage and frequency deviations.

4.1. Long-term voltage and frequency deviations

The first task for achieving assumed aim has been to estimate the scope of reported problem. Namely, the long-term frequency deviations should be analyzed, together with other steady-state power quality disturbances due to obvious synergy effect of discussed phenomena for operation of many electric power quality receivers [2]. Basically, the first question should be addressed: What will consequences be of doing nothing?

The analysis of power quality parameters during steady-state conditions has been carried out for two cases: sea voyage and staying at port. There have been different configurations of ship power plant for these considered cases. During sea voyage one high voltage generator (load equal to 900 kW) and one low voltage

Table 2. Mean values of voltage and frequency under steady-state conditions.

	f_{12} [Hz]	$U_{L1\text{-}L2}$ [V]	$U_{L2\text{-}L3}$ [V]	$U_{L3\text{-}L1}$ [V]
Sea voyage	61.89	6514	6536	6544
Stay at port	62.18	6549	6570	6582

generator (load equal to 320 kW) have been working but during stay at port as many as two high voltage generators (load equal to 380 kW each) and two low voltage generators (load equal to 120 kW and 130 kW respectively) has been working on ship electric power system. Such surplus of power supply has been required due to preparation for maneuvering and safety reasons. The measurement has been carried out for three phases concurrently for checking possibility of unbalance. The results of the U_{12} and f_{12} measurement have been laid in Table 2.

Taking into account results laid in Table 2, it is easy to notice the utmost problem—frequency steady-state deviation, which reaches 3.6%. Fortunately, no other power quality disturbances have been found. The THD value has rarely exceeded 1.2% and voltage unbalance has been practically absent. Only small voltage deviation has been noticed, in some cases above 1%. However, sub-

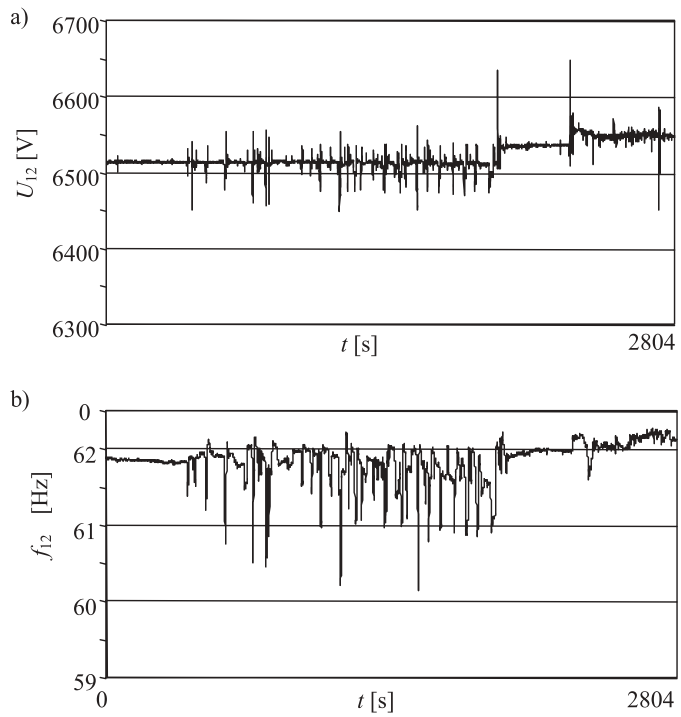


Fig. 2. The voltage (a) and frequency (b) changes during pulling in port

systems with rated voltage equal to 440 V have not been controlled. Ship owner has not requested such analysis.

Finally, it should be stated that the voltage parameters during steady-state conditions have fulfilled relevant standards (see Table 1). But is it acceptable anyway? Firstly, it seems that the operation of electric motors should be considered. Obviously, the changes of their rotational speed have been observed, with possible minor consequences for some processes (changes in pump delivery, pressures etc.). However, the effect for the very motors should be considered as well. Please, look at the results once again. The frequency has been above its rated value but the voltage has been slightly below its nominal value. So, the voltage to frequency ratio has assumed significantly lower value than under rated conditions. It can induce the additional thermal loss in electrical motors and cause the temperature rise of the motors elements, including insulation materials [2, 3]. The experiment has been carried out for rough assessment of such voltage and frequency deviations impact on additional temperature rise of motor windings. The motor under research has nominal voltage equal to 380 V, nominal frequency equal to 50 Hz and rated power equal to 5.5 kW. Then, its parameters have not exactly corresponded with respective rated voltage and frequency in low voltage subsystems of considered ship. Nevertheless, its behavior under similar relative voltage and frequency deviations (in relation to rated values) should be advice of possible consequences. The experiment has been worked out for the rated load torque [3]. As a result, the temperature-rise in the hottest measured point was 6.3K higher than for the rated work conditions. But it should be noted that the research does not deal with the worst work conditions of ships motors, which appear for pump and ventilator drives. For such kind of load the rotational torque is proportional to the squared rotational speed. As a result, an increase in the frequency causes an excess in the load torque and consequently—extra heating of induction machine [3].

Finally, it has been stated that such supply conditions like observed in the ship under investigation are hardly acceptable for electrical motors in the long run. It causes additional energy loss as well as increases temperature of insulation materials, with resulting significant shortening their operational life [3]. So, it is at least advisable to lower the value of frequency in the system under investigation.

Table 3. Maximum and minimum voltage and frequency deviations during three cases of ship maneuvering

	ΔU_{12} [V]	δU_{12} [%]	$\Delta U_{rms(1/2)}$ [V]	$\delta U_{rms(1/2)}$ [%]	Δf_{12} [Hz]	δf_{12} [%]	$\Delta f_{(1/2)}$ [Hz]	$\delta f_{(1/2)}$ [%]
Case 1 – pulling out port	+365	+5.53	+457	+6.92	+2.26	+3.77	+2.28	+3.80
	-1195	-18.11	-1302	-19.73	+0.81	+1.35	-0.67	+1.12
Case 2 – pulling out port	+513	+7.77	+560	+8.48	+2.63	+4.38	+2.69	+4.48
	-1274	-19.30	-1568	-23.76	+1.05	+1.75	+0.96	+1.6
Case 3 – pulling in port	+76	+1.15	+115	+1.74	+2.26	+3.77	+2.31	+3.85
	-152	-2.30	-196	-2.97	+0.14	+0.23	+0.11	+0.18

4.2. Short-term voltage and frequency deviations

Before decreasing frequency in the ship network under investigation, one should answer on the second of previously mentioned questions: Is it safe to decrease frequency in this system? The reliable answer on this question has required analysis of system behavior under dynamic conditions. Then, the three cases of ship maneuvering have been considered, because of frequent load changes due to thrusters and mooring winches operation. Additionally, the case of switching motor of thruster on has been registered and carefully analyzed due to great start-up current. The motor rated voltage has been equal to 6.6 kV and rated power has been equal to 1720 W. The sudden changes of active power demand like during maneuvering have enormous impact on both voltage and frequency but a start-up of electric motor influences disproportionably the voltage value due to relatively low power factor during the process.

The exemplary changes of U_{12} voltage and f_{12} frequency during puling in harbor have been depicted in Fig. 2.

It is easily discernible in Fig. 2b that during the whole process of maneuvering, the frequency f_{12} do not fall below its rated value, namely 60 Hz. Although frequent and significant frequency changes have occurred during the process the difference between frequency f_{12} maximum and minimum values has hardly exceeded 2% of frequency rated value. The detailed results of analysis for all three cases of maneuvering have been laid in Table 3.

The designations in Table 3 have been as follow:

ΔU_{12}, Δf_{12} – absolute value of voltage U_{12} or frequency f_{12} deviation,

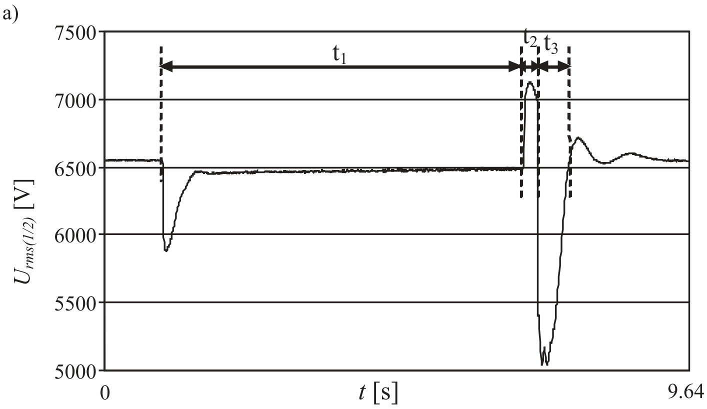
δU_{12}, δf_{12} – relative value of voltage U_{12} or frequency f_{12} deviation (in relation to their rated values, respectively),

$\Delta U_{rms(1/2)}$, $\Delta f_{(1/2)}$ – absolute value of voltage $U_{rms(1/2)}$ or frequency $f_{(1/2)}$ deviation,

$\delta U_{rms(1/2)}$, $\delta f_{(1/2)}$ – relative value of voltage $U_{rms(1/2)}$ or frequency $f_{(1/2)}$ deviation (in relation to their rated values, respectively).

Analysis of the measurement results laid in Table 3 leads to conclusion that basically there is no problem with the dynamic frequency changes in the system. The decrease of the mean value of the frequency to its rated value should not cause an adversely effects during non-steady-states. However, something troubling has been noted as well. Eventually, a new question emerged: what does happen with voltage under dynamic conditions? The question is connected with significant voltage dips during pulling out port. In case 2 the voltage $U_{rms(1/2)}$ dips even below permissible level laid in relevant standards (Table 1 – although standards for ship networks do not directly describe a method of voltage measurement, it seems justified to apply the method assigned for voltage dip estimation in land systems). The culprit of such situation has been easy to detect. It has been the process of start-up of electric motor for thruster propulsion. The maximum voltage deviation in the Case 3 (see Table 3) has been much lower than in other two cases because the process has not been registered. Nevertheless, the voltage $U_{rms(1/2)}$ and frequency $f_{(1/2)}$ during the start-up the thruster motor has been depicted in Fig. 3 (maximum observed value of voltage deviation for case 2 from Table 3).

a)



b)

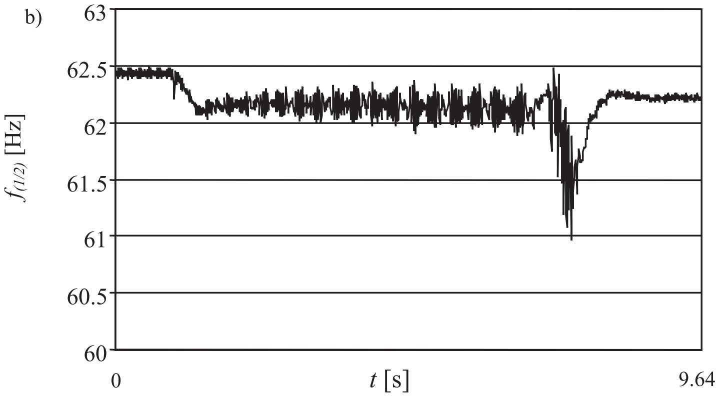


Fig. 3. Voltage $U_{rms(1/2)}$ (a) and frequency $f_{(1/2)}$ (b) deviations during chosen process of switching motor of thruster on; t_1 = 5970 ms, t_2 = 225 ms, t_3 = 542 ms.

As it is discernible in Fig. 3 the start-up method star-delta has been implemented in the case of considered motor. But something is wrong with the process and significant voltage dip has occurred. It is worth to observe that the $U_{rms(1/2)}$ voltage deviation assumes value above permissible limit equal to 20% of its rated value but in the case of U_{12} voltage its value do not reach 20%. However, nobody suspects such enormous dip prior to described research. The ship crew simply has lacked the appropriate measurement equipment for voltage dips evaluation.

Such enormous voltage dip can cause the malfunction and/or failure of important receivers, possibly following by lost of ship ability to maneuvering. Then, the start-up of considered motor typically occurs immediately before maneuvering, so the risk for ship safety is simply unacceptable. Moreover, there is possibility that the problem had been a reason of increase of the frequency in the ship. Sometimes a ship crew tries such a strange solution as precautionary measure against consequences of voltage and frequency deviations during dynamic conditions. In this case the advice for ship owner can be only one. It seems necessary to analyze the whole process of thruster motor start-up in order to avoid likely consequences for the remaining parts of the ship electric power system operation.

Finally, it should be added that periodic frequency and voltage fluctuations have been analyzed in considered ship. These periodic fluctuations should be understood as periodic voltage or frequency deviations, as it might be caused by regularly load changes [12]. But their value has assumed negligible values, hardly exceeding 0.1%, whereas permissible values are 0.5% for frequency and 2% for voltage [12].

5. FINAL CONCLUSIONS

Obviously, the paramount purpose of this research has been to carry out an advice for ship owner. This advice seems to be simple. Such enormous voltage dip during switching a thruster on is unacceptable. The fixing of the problem is required by analysis and correction of process of the start-up of the thruster motor. Firstly, the duration of respective start-up phases should be analyzed. After fixing the problem it is strongly advised to decrease frequency to its rated value. Although the frequency fulfils requirement laid in relevant standards, it can cause some adversely effects, chiefly additional energy losses and increase of risk of electric motor failure.

However, some general conclusions result from this research as well. These conclusions relate to relevant standards for estimation of electric power quality in ship systems as well as widespread practice in monitoring power quality parameters in ship networks. One of the purposes of this paper has been to show that even such widely recognized and notorious power quality disturbances like voltage and frequency deviations can still cause problems during exploitation of modern ships. Moreover, the ship crew lacks resources for coping with the problem. So, even the basic diagnosis is hard to achieve. Eventually, it is practically necessary to provide ship with appropriate measurement equipment. In practical terms, the dedicated electric power quality analyzers should become standard devices in ship networks. Furthermore, the analyzers enable coping with broad range of other power quality disturbances, foremost harmonic distortion. The waveform distortions can be real problem in ship networks and values of THD factor exceeding 10% have been often noted in other ship systems [1, 6, 7].

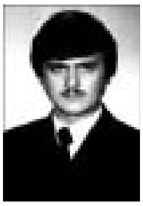
Finally, last but not least, some improvement in rules of ship classification societies and other relevant standards should be needed for avoiding present ambiguities. The method of power quality parameters measurement in ship systems should be precisely defined or their relevance in other similar standards should be pointed out. Especially, the problem of frequency measurement method should be properly addressed, since the present situation leads to some confusion. The definition laid in IEC 61000-4-30 [10] seems useless in ship networks. In this paper, authors have proposed two simple methods of frequency measurement under dynamic conditions. The difference is in the duration of observation interval (one or ten/ twelve cycles). These methods are consistent with relevant method of voltage analysis. However taking into account the permissible duration of frequency deviation under dynamic conditions (5s – see Table 1), it seems advisable to apply the method based on reciprocal of one cycle refreshed each half cycle, previously described as $f_{(1/2)}$.

REFERENCES

1. Evans Ian C.: *Mitigation of harmonics for AC electric drives of thrusters and small ship's propellers*. The Harmonic Solutions Co.Uk
2. Gnaciński P., Mindykowski J., Tarasiuk T.: *Influence of electrical power quality on induction cage machine durability.* 7th International Conference "Electrical Power Quality and Utilization" Cracow September 17-19,2003, pp. 455-462.
3. Gnaciński P., Mindykowski J., Tarasiuk T.: *Thermal phenomena in electric machines in the wake of electric power quality in ships' networks.* 8th International Conference "Electrical Power Quality and Utilization" Cracow 21–23 September 2005.
4. Mindykowski J., Szweda M., Tarasiuk T.: *Comprehensive Solution of Power Quality Evaluation in Ships' Networks.* Journal of Shanghai Maritime University. Vol. 25 Oct. 2004, Supplement 2004.11, pp. 86-95.
5. Mindykowski J., Tarasiuk T.: *Measurement of supply voltage properties in ships' electrical power systems*. Metrology and Measurement Systems. Polish Scientific Publishers PWN, vol. IX, No. 1/2002 Warszawa 2002, pp. 19-30.
6. Reinecke H., Schild W.: *Harmonics in main electric supply systems with semiconductor rectifiers and subsequent methods of compensation*. IMECE'91 China, s. 1-10.
7. Tarasiuk T., Szweda M., *A few remarks about notching analysis - case study.* Proceedings of 13th IMEKO TC4 International Symposium, Greece 2004, pp. 504-509.
8. EN 61000-2-4 Std. 1994. *Compatibility levels in industrial plants for low-frequency conducted disturbances.*
9. IEC, Std. 61000-4-7.*General Guide on Harmonics and Interharmonics Measurements for Power Supply Systems and Equipment Connected Thereto.*
10. IEC, Std. 61000-4-30. *Testing and Measurement Techniques – Power Quality Measurement Methods.*
11. Lloyd's Register of Shipping 1996, part 6, Electrical Engineering. *Rules and Regulations for the Classification of Ships.*
12. IEC 60092-101:2001. *Electrical installations in ships. Definitions and general requirements.*

Prof. Janusz Mindykowski
was born in 1950 in Gdańsk, Poland. He graduated from Gdańsk University of Technology in 1974, obtaining M.Sc. degree in automatics. In 1981 he gained Ph.D. degree in electrical metrology and in 1993 D.Sc. degree from the same specialization. Full professor from 2002. Since 1993 professor of the Gdynia Maritime University. Dean of Marine Electrical Engineering Faculty and Head of Marine Electrical Power Engineering Department. Janusz Mindykowski is the Member of the Institution of Electrical and Electronic Engineers (IEEE), the Fellow of the Institution of Electrical Engineers (IEE), the member of IMEKO Technical Committee on Measurement of Electrical Quantities (TC4), the Vice-President of the Polish Association of Measurements, Automatics and Robotics and Metrology Committee Chairman of the same Association and the member of Committee of Measurement and Scientific Instrumentation, Polish Academy of Sciences.
e-mail: janmind@am.gdynia.pl

Mariusz Szweda M.Sc.
was born in 1972 Złotów, Poland. He received M.Sc. degree in Marine Electrical Engineering from the Gdynia Maritime University in 1998. He has been employed in numerous foreign ship owners as electro-automation officer and in Gdynia Maritime University as assistant in Department of Ship Electric Power Engineering from 2000. His research is focused on problems of electrical power quality measurement and assessment, mainly in ship networks.



Dr. Tomasz Tarasiuk
was born in 1964 Gdynia, Poland. He received MSc degree in Marine Electrical Engineering from the Gdynia Maritime University in 1989 and Ph.D. degree from the Electrical and Control Faculty of Technical University of Gdansk in 2001. He has been employed in Polish Steamship Company since 1989 and in Gdynia Maritime University since 1994. His research is focused on problems of electrical power quality estimation. Tomasz Tarasiuk is the Member of the Institution of Electrical and Electronic Engineers (IEEE) and member of the Polish Association of Measurements, Automatics and Robotics and Secretary of Metrology Committee of the latter organisation.