Electric Power Quality in Isolated Systems - Requirements and Examples of Analysis

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***Abstract* – The paper analyses power quality requirements for isolated systems. Standards used within this framework are taken from widely used classification societies rules, international standards applied to shore and off-shore units. The norms can be also divided into merchant and navy ships, both are analyzed. The requirements themselves are just a simple indication tool of the electric power quality. Hence, four real time examples are presented: 1) a navy ship with regular propeller, 2) an all electric ship with power network exceeded 1 MVA, 3) a passenger ship with 6.6 kV network and 4) equipment installed on shore, i.e. 120 kVA Uninterruptible Power Supply system. For some of the presented examples standards are not fulfilled, which is discussed and some remarks are given.**

***Index Terms* – Harmonic analysis, Harmonic distortion, Marine technology, Marine vehicles, Marine vehicle power systems, Power system harmonics, Power system measurements, Power system monitoring, Power quality, Uninterruptible Power Supply systems.**

1 Introduction

In the modern marine vehicles proportionally to the rank of their "intelligence" a number of power semiconductor devices is rising. These devices working at the defined electromagnetic environment should be compatible, i.e. immune to harmonic distortions defined in the international standards [8], [9], [10], [11]. On the other hand the devices should not generate distortions into power network above determined values.

The correct operation of devices exposed to the voltage distortions or magnetic fields is maintained by fulfilling the electromagnetic compatibility (EMC) standards related to permissible limits both, the emission and immunity in defined environments. These requirements are harmonized with some requirements concerning power installations and signal transfers.

For example, permissible levels of electromagnetic compatibility for human living spaces and industrial environment are quoted in norms [8], [9].

Equipment installed in isolated power systems is exposed to conducted disturbances of the wide band frequency, hence especially higher frequency requirements are expected. The disturbances may cause significant changes of the voltage waveform and unstable frequency.

On the one hand there are more strict requirements for equipment but on the other hand there are recommendations to keep appropriate electric power quality in isolated systems fitted with frequency converter subsystems. Such systems are common on ships.

2 Power quality standards

Nowadays, in the age of high saturation of the ship with electronics and power semiconductor devices, an electric energy is assessed by more complicated techniques and measuring methods. The indexes of power quality are defined in the following documents for ships:

- merchant: IEC 60092-101 *Electrical installations in ships - Part 101: Definitions and general requirements*,
- navy: STANAG 1008 *Characteristics of Shipboard Electrical Power Systems in Warships of the North Atlantic Treaty Navies,*

and standarisation for industrial plants

- EN 50160:2000 *Voltage characteristics of electricity supplied by public distribution systems,*
- IEC 61000, *Electromagnetic compatibility (EMC) – Part 2-4: Environment – Compatibility levels in industrial plants for low-frequency conducted disturbances.*

A considerable contribution in standardization was done by publication IEEE 1159, *Recommended Practice on monitoring Electric Power Quality.* The standard contains several additional terms related to the IEC terminology.

A. Waveform requirements

In table 1 requirements taken from the above listed standards are summarized. In the first two columns [10], [11] standards dealing with ships are presented while the remaining [8], [9] present standards for public distribution systems. Polish Register of Shipping, as a classification society, refers to standard EN 60092-101. However, for navy ships more adequate is a standard published by Military Agency Standardization presented in the second column. In brackets are given higher values allowed in some circumstances, more details are in the standard. In the case of parameters associated with voltage the differences between navy and merchant ships are not significant in comparison with frequency requirements.

In the third and fourth column requirements for isolated land systems are presented. They are applied to terminals, where power supplier and power consumers are meeting and also installations in heavy current industry. In standard EN 61000-2-4 are included requirements for the second class, it means equipment installed in main switchboards of an industrial plant. These values fundamentally differ in

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Table 1. Comparison of supply voltage requirements according to four various standards

Parameter	60092-101 [10]	STANAG 1008 [11]	EN 50160 [8]	EN 61000-2-4 class 2 [9]
	ships		land	
Steady-state voltage deviations	+6, -10%	±5% (±6%)	±10%	±10%
Phase to phase voltage unbalance (continuous)	3%	2%	2%	2%
Voltage momentary deviation	±20%	±16% (±20%)	±40%	±90%
Voltage transients recovery time	1,5 s	2 s	1s	3s
Total harmonic distortion THD	5%	5%	8%	8%
A single distortion (any harmonic greater than)	3%	3%	even s.h. up to 1% odd s.h. up to 6%	even s.h. up to 1% odd s.h. up to 6%
Steady-state frequency deviations	±5%	±3%	±2%	±4%
Frequency momentary deviations	±10%	±4% (±5,5%)	±15%	to be agreed
Frequency transients recovery time	5 s	2 s	not specified	2 s

the high voltage drops and with stricter frequency tolerance with respect to requirements of maritime regulations. Standard EN 61000-2-4 in the case of requirements for class 1, i.e. equipment supplied by Uninterruptible Power Supply (UPS), tighten requirements with respect to class 2 as well as regulations EN 50160. For example, it increases a permissible voltage tolerance up to 8%, voltage transients recovery time only up to 10 ms, THD coefficient up to 5% and single odd harmonics up to 3% depending on a harmonic, like in [8], [9].

B. Power distribution

In table 2 the permissible load distribution parameters are presented. The table was elaborated on the same requirements given in different classification societies rules for merchant and navy ships, [13], [15].

Table 2. Load distribution requirements

Parameter	permissible value
Active load distribution	15%
Reactive load distribution	10%
Current distribution	15%

Gdynia Maritime University in cooperation with the Polish Register of Shipping is working on establishing dedicated measurements equipment for ship use, which allows detailed power quality assessment and eliminates possible hazards. Within the carried out measurements on a few new-built ships, navy as well as civilian, it was found that significant breaching of permissible values are not common although measurements may positively influence on not discernible, however important details.

Together with the growth of high power non-linear applications such as electrical drives and bow thrusters, the importance of appropriate power quality is growing as a basic factor for safety of a ship.

3 ELECTRIC POWER QUALITY ISSUE OF THE SAFETY NOT ONLY ON SHIPS

A. Distortions cause failures in power networks

Harmonic distortions may result in failure and/or malfunction of important components within:

a. sources of electric power:

- overheating insulation, coils, which result in aging of electrical insulation materials and damage of bearings,

b. consumers:

- overheating of stator and rotor of electric motors with fixed speed, hazard of bearings damage depends on overheating rotor, additional temperature increase of insulation and in fact, faster aging. Especially dangerous to electric motors installed in hazardous areas.
- not intended deenergizing switches, distortions of equipment installed on board such as navigation equipment, personal computers, as well as in industry.

c. electrical network:

- both, ship network as well as industry network, are exposed to cables overheating due to resonance phenomena, reduced current-carrying capacities in wiring system due to “skin effect”, so the current density near the surface of the conductor is greater than that at its core.
- overheating and faster aging of transformers [2].

B. Synergy effect

Mutually dependent distortions may enhance level of disturbance in power network. In this field it is worth to consider the following disturbances, especially in present power network systems:

- voltage waveform distortions,
- voltage deviation from its root mean squared value,
- voltage asymmetry.

Significantly higher level of disturbances directly brings about degradation of equipment insulation, which in turn causes mentioned faster aging. It results in failure and/or malfunction [2]. Research carried out in the Department of Marine Electrical Power Engineering proved that worsened power quality, according to the maximum permissible values for ships shown in Table 1, may cause failure of a motor in relatively short time. For example, in the case when power quality is reduced such way, that: f=51,85Hz (103,7% of the rated frequency), U_{rms}=377 V (99,2% of the rated voltage) and THD_U=12,45% (prevailing even harmonics not divided by 3, especially 5^{th}) additional temperature increase is equal to 11 K [3], whereas for insulation F class additional increase 9.3 K could shorten insulation life time two times [1]. It is worth to point out that such distortions were observed in power networks.

C. From distortions to losses

Disturbances have an effect on failure or malfunction of numerous devices. Break-down of essential consumers at the sea in a simply way may lead to a shipwreck, what is shown at the diagram below.

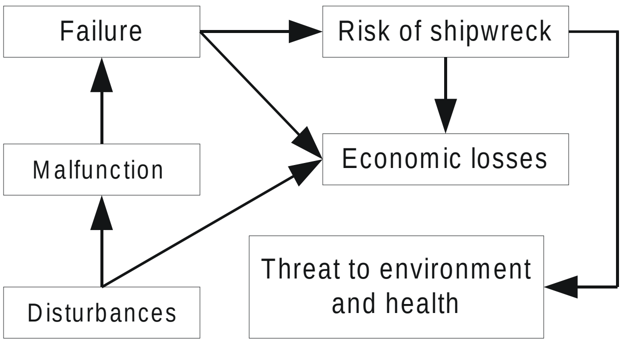

Fig. 1. The algorithm showing a way from disturbances to a shipwreck.

4 Examples of isolated systems

During several years of cooperation with universities and the classification societies, researches carried out a great number of power quality measurements on ships supervised by PRS and other classification societies. This chapter shows selected results of power quality measurements on three ships including two of them under the PRS class and an example taken from industrial practice.

A. Warship "Kontradmirał X. Czernicki"

The first examined ship was a Polish navy warship "Kontradmirał X. Czernicki". She did not have any significant non-linear consumers. Power distortions were in permissible limits. The most significant RMS voltage deviation was observed during maneuvering, what illustrates an example shown in Fig. 2, when she was leaving the port (first 470 s.) and sea-going (last 230 s.).

Voltage deviations were in permissible limits for a navy ships, which in fact are more strict for navy than merchant ships. In addition, voltage unbalance was not observed in network of the 220 V and the 380 V as well. The voltage unbalance factor, C_{va}, describing maximum deviation phase to phase voltage with average phase to phase voltage was higher in network of the 220 V than the 380 V. An example of the C_{va} changes is shown in Fig. 3.

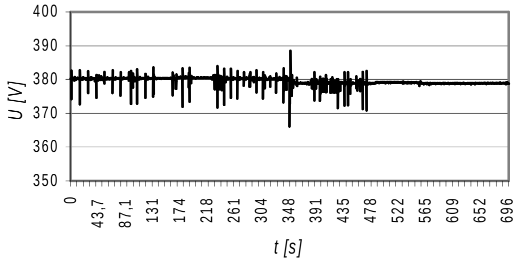

Fig. 2. Voltage U variation during maneuvers when arriving into the port.

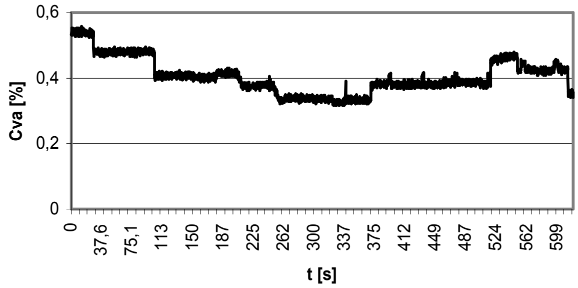

Fig. 3. A voltage unbalance coefficient for load changes in network of the 220 V.

Voltage THD values and harmonics and components interharmonic were measured in frequency band up to 3.5 kHz, however significant voltage waveform distortions were not observed in network of the 220 V and the 380 V. Analysis in network of the 220 V shown similar level of distortions, varied from 1.45 up to 1.9%, which depends on load. An example of THD changes depends on load illustrates Fig. 4.

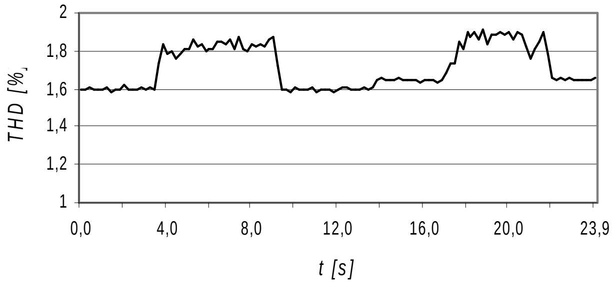

Fig. 4.THD coefficient values during load changes in network of the 220V.

Average frequency on the ship was around 50.2 Hz. Frequency changes were only observed during load changes. Different power network configurations had a negligible influence on average frequency value.

The highest frequency variations were observed during load change over from an emergency generator through stand alone generator, Fig. 5. Then the average frequency was established 50.88 Hz in 5 seconds, likewise the appropriate standards permit.

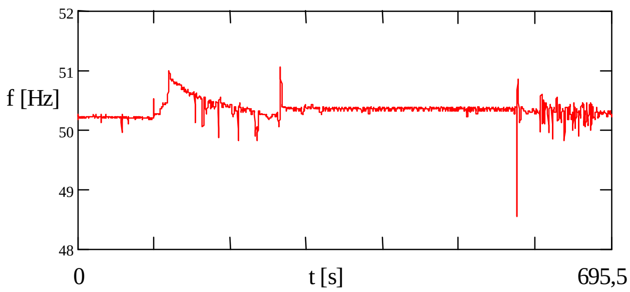

Fig. 5. Frequency f variation during power network configuration changes

It appears that electric power quality on the examined navy ship is quite good. However, some problems were observed in power distribution between generating-sets working in parallel. The power distribution was close to permissible value, i.e. 10%; whereas noticeable problem

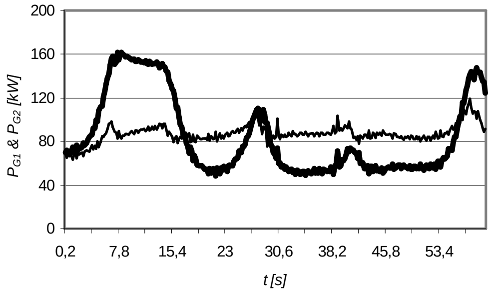

Fig. 6. Active power changes of generating-sets no 1 and 2 during coming into port.

was in active power unbalance in dynamic states, especially in initial stage. During sudden loads, changes response is significantly different for each generating-set working in parallel. The process is illustrated in Fig. 6, bolded line shows active power P_{G2} of generating-set no 2. Finally, it was recommended to check engine governors of the generators [7].

B. *All-electric ship "IMOR"*

Next examined ship was a research vessel so called *all electric ship* – "IMOR" of Maritime Institute in Gdansk. She has two main electric propellers connected to *VACON* converters CXI with rating power of the 315 kW each. These motors are fitted at the stern and denoted in Fig. 7 as MPS for port side main propeller and MSB for starboard main propeller. A single block denotes system: converter – azi-pod.

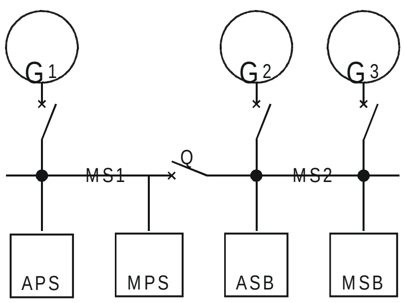

Fig. 7. Schematic diagram of electric network of IMOR

Maneuvering was enhanced by additional two auxiliary propellers fitted in fore in each hull. The power of the auxiliary propellers is the 72 kW each and they are described as APS and ASB in Fig. 7. The main sources of power are three generators, two of them are of the 425 kVA (G_1 and G_3) and the remaining of the 200 kVA (G_2). The catamaran has two floats with two main switchboards, MS1 and MS2, connected via switch Q. This solution increases a robustness, because if one of the floats was flooded the catamaran is still maneuverable.

It was expected to obtain interesting measurements results due to nonlinear consumers, which entail distortions in electric power network. During measurements it turned out that in general electric power quality on the examined vessel was correct. The most significant voltage and frequency variations were noted on the network of the 400 V, during sea-going when speed of the ship was changing, see Fig. 8.

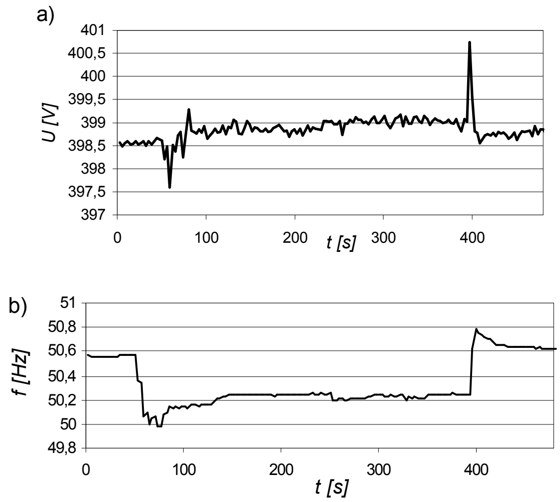

Fig. 8. Voltage U and frequency f variations in network of the 400 V.

On the examined ship voltage unbalance was satisfactory on both the 400 V and the 230 V systems. In the case of network of the 230 V, voltage unbalance index, C_{va}, was changing in range 0.15-0.48 depending on load, see Fig. 9, whereas in network of the 400 V the index was similar, i.e. 0.21-0.42.

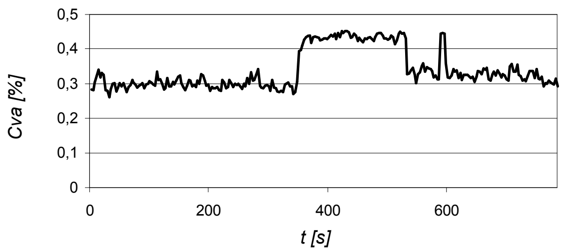

Fig. 9. Voltage unbalance coefficient depending on loads in network of the 230 V.

Taking into account type of consumers the most interesting for researchers were voltage and current distortions evaluation. Power of the converters was slightly smaller than total available power installed on board. Evaluation of the distortion was done in accordance with IEC60533 [12], a frequency of the 10 kHz has been accepted as the upper limit of the scope of low frequencies. Measurements were carried out during switching drives for networks of the 400 V and the 230 V measured at the main switchboard and the 230 V measured on the bridge, because of the highest risk of distortions.

As it was mentioned before, the main source of distortions were frequency converters supplying the main propellers. Fig. 10 shows voltage waveform when the main propeller at the port side was switched on. It is easy noticeable influence of the frequency converter on voltage waveform in the considered example. The propeller was not loaded when was switched on.

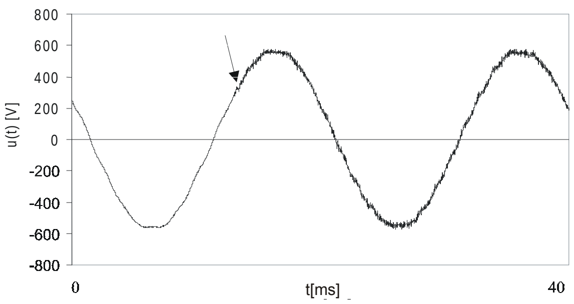

Fig. 10. Example of the 400V voltage waveform when starting up the aft propeller drive (the moment of start was marked with the arrow).

Some difficulties are related to the component contents in the band of the 3.2-3.7 kHz and some of the bands above 10 kHz, however, disturbances are asymmetrical. The changes of the component with the frequency ca the 3463 Hz are shown in Fig. 11.

It can be concluded that contents of components in frequency band from 50th up to 10 kHz are relatively high. The maximum contents of 3463 Hz component (leading in this range) is 5.03 % measured for time range equal to 10 cycles of analyzed voltage and 4.85 for 3 seconds. However, large amount of variation of the contents (as well as others in this range) caused maximum value of the component, noticed for 10 minutes equal to 2.54%, hence was smaller than instantaneous maximum values.

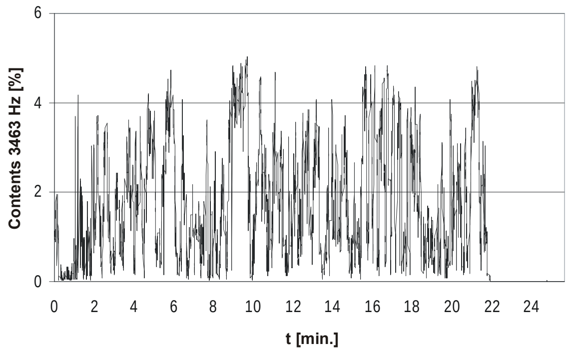

Fig. 11. Variation of the component contents for frequency of the 3463 Hz in the supply voltage of devices fitted on the bridge during sea voyage.

Finally, it was recommended to install marine RFI filters (for component contents above 10 kHz), at least for main propellers [6].

C. Ferry "Wavel", 6kV

The third examined isolated network is a motor ferry *Wawel* with network of 6.6 kV and rated frequency 60 Hz. The most significant voltage and frequency variations were during start up bow thrusters when she was maneuvering into a port. The worst case, U_{rms}, is shown in Fig. 12.

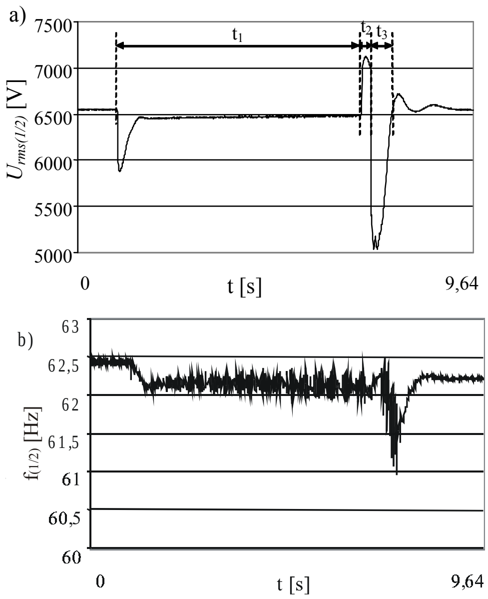

Fig. 12. Voltage and frequency deviations during start up a large electric motor on, t_1 = 5970 ms, t_2 = 225 ms, t_3 = 542 ms

Voltage transient variations were above permissible value in marine standards (see table 1) and exceed 23 %. It was determined that start up analysis is necessary, especially time of particular stages of starting up process needs to be correctly chosen [7].

D. UPS, 120 kVA

The above discussed examples of isolated networks were on boards. In order of comparison them with an industry example, measurements were carried out in a system of three UPS of the 40 kVA each. The results were compared with permissible values given in table 1. First column of table 3 gives list of parameters in accordance with [9]. Measured values on in the network satisfy both marine and land standards, shown in table 1.

Table 3. Electric power quality indexes for UPS, permissible values are given for class 1 in accordance with [9]

	Limit	**L1**	**L2/tot**	**L3**
Voltage Variations 95%	230 V ± 10%			
Max [%] Un	8	0	0	0
Min [%] Un	-8	-3,34	-2,32	-2,48
Interruptions		0	0	0
Events		0	0	0
Frequency 95%	50 Hz ± 4%			
Max [%]	4		0,18	
Min [%]	-4		-0,15	
Imbalance [%]	2		0,19	
Harmonics				
THD [%]	5	2,03	2,3	2,32
2. Harm. [%]	2	0	0	0
3. Harm. [%]	3	0,4	1,2	1,2
5. Harm. [%]	3	1,6	1,4	1,5
7. Harm. [%]	3	0	0	0
9. Harm. [%]	1,5	0,4	0,5	0,5

Applied measurement instruments had an ability to measure the average, maximum and minimum values, which in turn allowed transient states analysis in a full period of 20 ms. Fig. 13 shows voltage variations registered on the UPS in a week. The recorded small voltage changes of maximum and minimum values subject to average value did not indicate transient states.

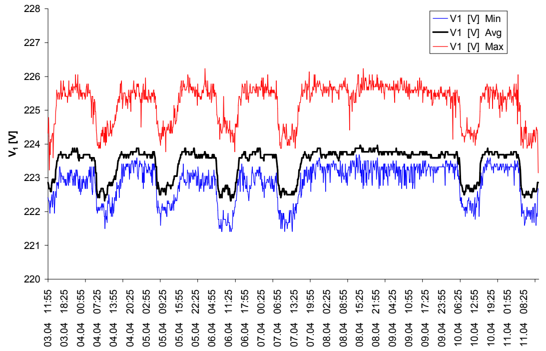

Fig. 13. Supply voltage variations registered on the UPS

(where: V1Min – minimum values of the voltage variation, and so on)

In transient states the frequency level changes was in the range of ±0,2 Hz, what in fact is at least twice as high as for non-isolated (land power) networks.

Average total harmonic distortion was about 2 %, while maximum level measured for window width equal to 160 ms did not exceed 4 %, see Fig. 14. Particular harmonics contents were in accepted limit, i.e. 1.6 %. Odd harmonics, such as 7th, 11th, were not observed.

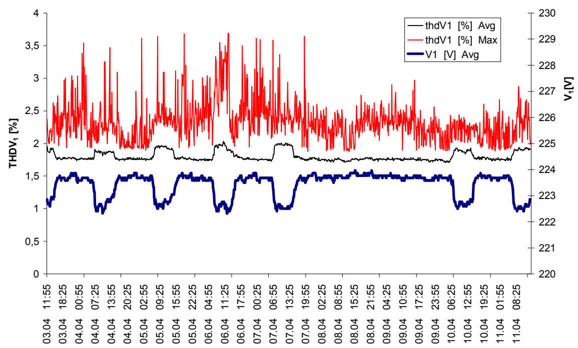

Fig. 14. Maximum, average and minimum of THD measured values on UPS.

5 Summary

Electrical and Automation Department of Polish Register of Shipping in co-operation with Department of Marine Electrical Power Engineering of Gdynia Maritime Academy is going to introduce obligation to monitor of electrical power quality on all electric ships [13]. It will certainly increase a robustness of power supply. Analysis of electric power quality may prevent failures, simplify a schedule of repairs and in addition save fuel.

At the same time development of new measurement techniques and accessibility of more advanced measurements tools cause this monitoring possible and relatively cheap. In land power networks similar phenomena as on ships occur, however standards give slightly different limits.

References

Periodicals & Papers Presented at Conferences:

[1] E. L. Brancato, "Estimation of lifetime expectationcies of motor", *IEEE Electrical Insulation Magazine*, May/June 1992, Vol 8 no 3, p. 5-13.

[2] E. Szmit, J. Mindykowski, T. Tarasiuk. *Power quality on ships as common problem shipowners, shipyards, maritime academies and classification societies* (In Polish: Jakość energii elektrycznej na statkach wspólnym problemem armatorów, stoczni, uczelni morskich i towarzystw klasyfikacyjnych), Power quality, SEP, Gdańsk 2004, p. 23-30

[3] J. Mindykowski, E. Szmit, T. Tarasiuk, Electric Power Quality and Ship's Safety; Polish Academy of Sciences, Branch in Gdańsk "Marine Technology Transactions", Vol. 15, Gdańsk 2004, p. 351-360.

[4] P. Gnaciński, J. Mindykowski, T. Tarasiuk, Thermal Phenomena in Electric Machines in the Wake of Electric Power Quality in Ships' Networks. 8th International Conference „Electrical Power Quality and Utilization", Cracow September 21-23, 2005, p. 399-404.

Technical Reports:

[5] J. Mindykowski, T. Tarasiuk, M. Szweda, E. Szmit, *Power quality on a selected ship*, PRS Technical Report No 48, Gdańsk 2004.

[6] J. Mindykowski, T. Tarasiuk, M. Szweda: *Report on Power quality on motor ship IMOR*, Gdynia Maritime University, Gdańsk 2005.

[7] J. Mindykowski, T. Tarasiuk, M. Szweda: *Analysis of voltage and frequency variations on motor ship WAWEL*; Gdynia Maritime University, Gdynia 2005.

Standards and Rules:

[8] EN 50160:2002, Voltage characteristics of electricity supplied by public distribution systems

[9] IEC 61000-2-4:2003, Electromagnetic compatibility (EMC) - Part 2-4: Environment - Compatibility levels in industrial plants for low-frequency conducted disturbances.

[10] IEC 60092-101:1995 Electrical installations in ships Part 101: Definitions and general requirements.

[11] Standarization agreement, STANAG 1008 Characteristics of Shipboard Electrical Power Systems in Warships of the North Atlantic Treaty Navies, 1994.

[12] IEC 60533:1999 Electrical installations in ships – Electromagnetic compatibility.

[13] Publication 25/P, Technical requirements for shipboard power electronic systems, 2006, Polski Rejestr Statków S.A.

[14] Rules for the Classification and Construction of Sea-going Ships, Part VIII, Electrical Equipment and Automation, PRS S.A. Gdańsk 2002.

[15] Rules for the Classification and Construction of Navy Ships, Part VIII, Electrical Equipment and Automation, Ministry of National Defence, Warsaw 2006.