Power Quality Assessment in the Wake of Ship Technology Development

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Abstract **–** This paper is focused on problems of power quality estimation in ships' electric power networks. The characteristic of electricity in the networks has been laid. Many examples of the original research have been presented. Some differences between the ship systems and land networks have been pointed out. The consequences of the differences for measurement methods and equipment have been described as well. Finally, the forthcoming trends in the ships' electric power engineering and metrology have been discussed.

I. Introduction

The ships' electric power networks have a few distinctive features which distinguishes the systems from their land brethrens. In particular, they are isolated small and medium power systems with enormous ratio of singular electric receiver power to source power. It results in notorious voltage and as well as all kinds of waveform distortions. The last phenomena are recently often noted in the wake of widely implementation of power converters in ships' systems. However, the frequency as well as spectrum fluctuations over time should be mentioned. The latter means the spread of signal spectral components over directly adjacent bins. The former means problem with proper spectral component estimation [1].

Moreover, the problems occurred in the systems need special approach. The paramount criterion in dealing with ships' electric power systems is ship safety. It influences all undertakings in the field of ships' electric power engineering, including electric power quality measurement and estimation. E.g. the voltage interruptions are not merely power quality disturbances, they could potentially lead to ship catastrophe and even one short interruption is unacceptable, because it means a lost of manoeuvrability of the ship. So, the estimation of interruption time is of less importance, if any. Finally, the paper exploits the problems of reliable estimation of electric power quality in ships' systems in all aspects: methods, software and hardware of measurement devices as well as some aspects of risk evaluation.

II. Power quality in ships' systems

Any approach to electric power quality measurement in ships' systems requires the prior evaluation of problem magnitude. The authors (together with other Department of Marine Electrical Power Engineering employees) have been carrying out the research of electric power quality in ships' systems from many years. The prominent part of the research has been measurement of voltage properties on different ships, as many as seven to the day of the paper preparation. The research allows determining of the characteristics of the systems, their similarities and differences. Additionally, basic requirements for measurement methods and devices have been specified. In shorthand, in all considered systems the enormous differences in power quality levels have been noticed due to frequently changes of system configurations. E.g. the THD factor in the very same point of the system could assume such a unlike values as 1.2% and 13.3%. This observation leads to conclusion that power quality should be monitored during whole time of ship exploitation, so dedicated measurement devices should be a part of ships' measurement equipment.

Finally, there have occurred all known power quality disturbances in ships' electric power systems. For this paper purpose, some of them have been carefully chosen and described.

A. Voltage and frequency deviations

The voltage and frequency deviations are notorious and the most recognised power quality disturbances in ships electric power networks. However, they can still cause problems during ship's exploitation. These phenomena can assume steady- as well as non-steady-state character and they have been registered in all ship's systems under investigation. The voltage and frequency deviations in ship's systems are mainly induced by switching large receivers on and off. Especially, the frequency

deviations are the very feature of the systems under consideration. They rarely occur in other systems with such high pitch. The frequency deviations assume extremely high values during ship manoeuvring due to influence of mooring winches operation. Such example has been depicted in Fig. 1 [2]. The example has been registered in system with rated frequency equal to 60 Hz. However, similar frequency deviations can be observed in another ships operation modes, they are not such frequent. The frequency for this paper purpose has been calculated for exactly twelve cycles measurement time interval. It is basic measurement time interval for many power quality parameters estimation according to IEC 61000-4-30 standard [3]. The relevant standards for ship systems e.g. classification societies rules do not impose any requirements in that matter.
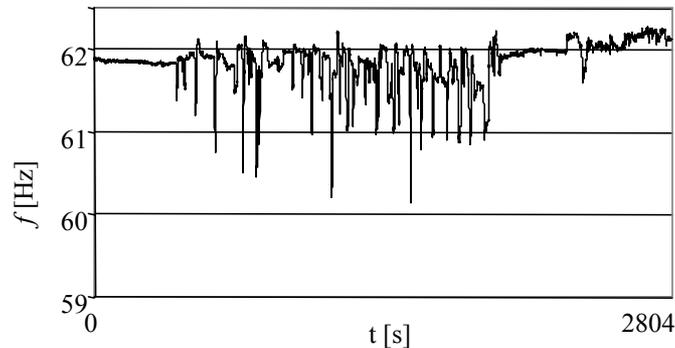

Fig. 1. Frequency deviations during manoeuvring of ferry ship

The significant short-term frequency deviations are easily discernible in Fig. 1. However, something more disturbing should be noticed. Namely, there has been enormous steady-state deviation of mean frequency of its rated value equal to 60 Hz in this system. The frequency registered on the ship usually has been above 3.5 % of its rated value. According to IEC [4] or Lloyd [5] standards, the electric power receivers should withstand such disturbance (up to ±5%), but the consequences could prove fatal in the long run, especially for electric machines. Furthermore, the frequency deviations can be augmented by voltage magnitude deviations, which often occur concurrently. In the considered case of ferry ship, the steady-state voltage deviation has been equal to -0.8% of rated voltage, which additionally augmented impact of frequency deviation on magnetic flux in electric machines. Moreover, it should be added that such short- and long-term frequency deviations have not been observed in land systems in normal operation conditions.

However, there have been short-term voltage deviations in the systems under consideration as well. The example of such phenomenon has been depicted in Fig. 2. The example has been registered in system with rated voltage equal to 6.6 kV [2]. For the short-term voltage analysis the results of voltage measurement $U_{rms(1/2)}$ over one period and refreshed each half cycle has been assumed [3].
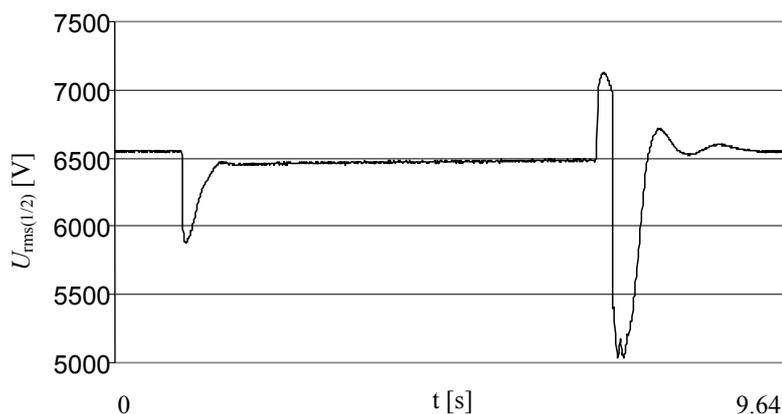

Fig. 2. Voltage $U_{rsm(1/2)}$ deviations during starting up of bow thrusters drive on ferry ship.

Analysis of the example presented in Fig. 2 has led to finding that the voltage minimum value has been below 80% of rated voltage, whereas the relevant rules requires the maximum short-term voltage deviations to be not greater than ±20% of rated voltage [4], [5]. Such high voltage deviations have been found during research only in quite a few cases, but their consequences can be fatal, since with bad luck it could lead directly to the ship's catastrophe.

B. Waveform distortions

The above mentioned voltage and frequency deviations are not the only phenomena connected with power quality, which occur in modern ships electric power networks. Nowadays, the power electronics devices are commonly used in ships systems. As a consequence, the voltages and currents distortions have being observed for quite a few years. For this paper two of such examples have been selected and depicted in Fig. 3.

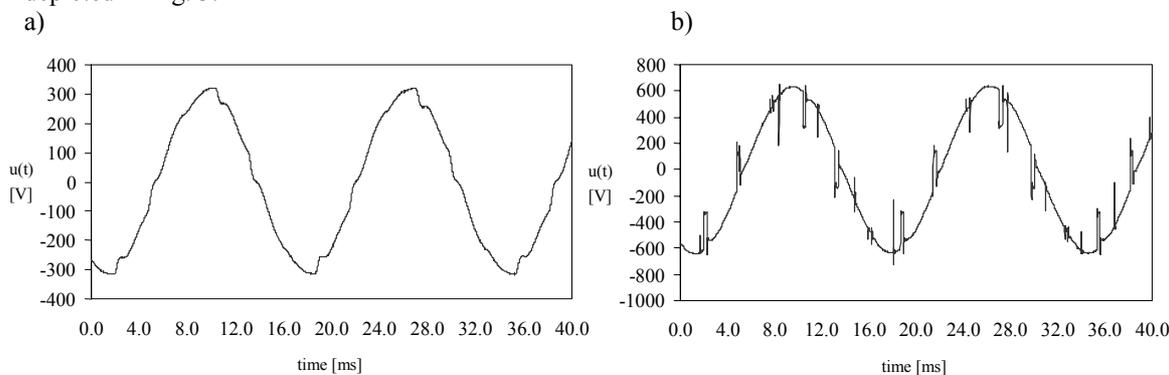a)   b)

Fig. 3. Exemplary voltage waveforms in ship systems of chemical tanker: a) harmonics in subsystem with rated voltage equal to 220 V, *THD* factor equal to 4.39%; b) notching in subsystem with rated voltage equal to 440 V, *THD* factor equal to 10.76%.

These voltages have been registered in ship's electric power system supplied via power converter [6]. But the lower voltage (220 V) has been obtained by means of transformer and the fifth harmonic filter has been applied as well.

One should note especially the second example (Fig. 3b). The analysis of such frequency phenomena requires covering of relatively broad frequency bands. The analysis of this voltage has led to conclusions that the analysis up to 35 kHz has been at least advisable [6]. The considered case has been registered by data acquisition board with sampling frequency equal to 163934 Hz. The cut-off frequency of antialiasing filter has been equal to 50 kHz.

However, the requirement of high sampling frequencies is not a main problem in dealing with signals waveform distortion in the systems under consideration. There have been observed the continuous frequency changes in these systems, especially in the case of the considered chemical tanker in extremely high level. These frequency changes has impact on the methods of waveform analysis and estimation, because even in basic measurement window equal to 10 or 12 fundamental periods there are frequency fluctuations with consequences to spectrum leakage presented in Fig. 4. However, it should be mentioned that some short-term quasi-periodic harmonic components values fluctuations have been observed as well. This phenomenon has enormous impact on harmonic components as well as subgroups estimation, if non-overlapping Hanning window for harmonics analysis is to be applied [7].
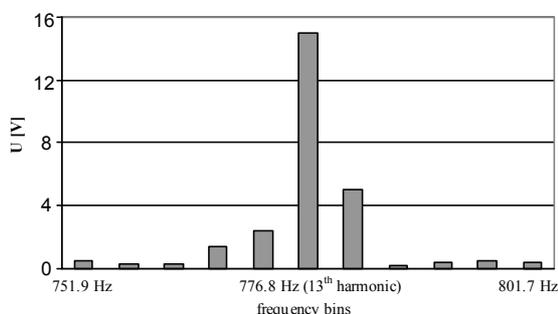

Fig.4 Voltage spectrum (13th harmonic and adjacent frequencies) of exemplary voltage in ship system

It seems that for the ships systems the lately introduced in IEC 61000-4-7 standard [8] a concept of harmonic subgroups is of the greatest relevance. The idea consists in calculating the square root of the sum of squares of harmonic component amplitude and amplitudes of two spectral components directly adjacent to it. The result is considered as rms value of given harmonic subgroup. The appropriate

formula to calculate the sum of squares of the previously mentioned amplitudes has been shown as (for rated frequency 60 Hz) [8]:

$$C_{n-200-ms}^2 = \sum_{k=-1}^{1} C_{12n+k}^2 \qquad (1)$$

where: C_{12n} – n-order harmonic component,
$C_{n-200-ms}$ – amplitude of nth harmonic subgroup.

The comparison of chosen harmonic components and corresponding harmonic subgroups for voltage depicted in Fig. 3b. has been laid in Table 1. The results in this table are mean values of appropriate analysis carried out for 200 measurement intervals during steady-state conditions.

Table 1. Results of harmonic components and subgroups analysis.

	Harmonic component and subgroup order						
	1st	5th	7th	11th	13th	17th	19th
Harmonic component [V]	435.98	20.59	18.35	15.71	15.39	13.0	13.29
Harmonic subgroup [V]	436.04	20.73	18.56	15.95	15.75	13.48	13.93

Taking into account the results in Table 1, one can discern that the impact of discussed phenomena of spectrum leakage to adjacent bins relatively increases for harmonics of greater order. However, the method based on harmonic subgroups for waveform disturbance estimation seems the most useful in ship systems.

Finally, the impact of the observed notching (Fig. 3b) for measurement window width estimation should be noted, since the inaccurate measurement window width estimation affects results of measurement of many power quality parameters [1], [9]. This impact reveals as multiple zero-crossings of analysed voltage. Such a phenomenon has been presented in Fig. 2.
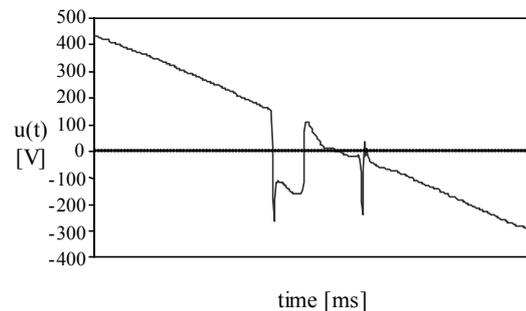

Fig. 2. Notching with multiple zero-crossings in ship electric power system

So, there should been some precautions against the multiple zero-crossings, especially if simplest method of window width estimation is to apply. The method consists in analysing samples polarisation changes and determining fundamental frequency. The solution can be filtering out higher frequency components. It can be easily done by application digital wavelet transform, if the tool is implemented for transient and notching detection and evaluation concurrently [9].

III. Equipment for power quality estimation in ships' systems

The careful analysis of ships' electric power characteristics and measurement needs leads to determining the mot desirable features of measurement equipment for electric power quality estimation in ships' networks. The equipment should be reliable and capable of coping with electric power quality disturbances shown in previous paragraph. The former requirement can be ensured by proper hardware structure. Especially, its distributed structure with some degree of hardware redundancy has been proposed. The hardware should consist of few independent, unified and interconnected measurement modules [10].

However, the solution for problem of proper measurement of above presented power quality phenomena seems the more complicated. It should handle as many as possible input signals with broad

frequency range in real time by as simple as possible methods, for the cost of whole solution should be minimised. It requires some optimising of measurement algorithms for different phenomena analysis. Such methods have been proposed especially complementary implementation of discrete Fourier transform and discrete wavelet transform has been introduced and tested. In shorthand, the method consists in a few simple assumptions [9],[11]:

♦ wavelet coefficients for each decomposition layer contain relevant frequency information,
♦ number of wavelet coefficients for each consecutive decomposition layer is divided by factor of 2,
♦ wavelet coefficients of low-pass filters of analysis filter bank are smoothed version of original signal.

As a result the huge decreasing of required mathematical operation needed for spectrum analysis is noted, in practical terms by factor 2^4 or more [11]. Additionally, the higher frequency components can be filtered out and the measurement window width estimation should be improved [9]. Further considered methods improvement is possible by introducing a new easily measured distortion band factors DBF. These factors can be measured on the basis of wavelet coefficients as follow [11]:

$$DBF_{f_{j-i} - f_{j-(i+1)}} = \frac{S_{rms(f_{j-i} - f_{j-(i+1)})}}{S_1} \tag{2}$$

where: $S_{rms(f_{j-i} - f_{j-(i+1)})}$ - rms value of signal components of $(f_{j-i} - f_{j-(i+1)})$ frequency band, S_1 – rms value of fundamental harmonic.

The rms value of signal components for each frequency band can be calculated by means of wavelet coefficients for respective layers of analysis filter bank as follows [11]:

$$S_{rms(f_{j-i} - f_{j-(i+1)})} = \sqrt{\frac{1}{2^i \cdot n} \sum_{k=0}^{N-1} (d_{j-i,k})^2} \tag{3}$$

where: $d_{j-i,k}$ – wavelet coefficients for respective frequency bands, N – number of wavelet coefficients calculated for integer number of periods of original signal, n – relative (non-integer) number of wavelet coefficient in an analysed window, i – calculation order of respective decomposition layer ($i \in 1..j$).

The continuous monitoring of these factors enables further decreasing of mathematical operation needed for harmonics evaluation, since only the frequency bands affected by harmonics are to be considered [11].

And last but not least, the all registered disturbances registered in ships system occurred concurrently, with obvious negative synergy effect. It should be taken into account when evaluating electric power quality. For example, the temperature rise of electric motor winding caused by voltage and frequency deviations has been significantly increased if supply voltage waveform has been corrupted concurrently [12]. Moreover, the current standards in the field should be amended to cope with the problem of disturbances synergy. For example, long-life operation of electrical machines installed in ship systems may be considerably reduced despite the fact that the voltage quality fulfils the standards [12]. So, some kind of risk assessment of malfunction or/and failure of receivers important for ship safety should be introduced as well. It should be done during designing a specific ship system as well as during the system exploitation. In the case of mentioned electrical machines it can be predicting the remaining operational life of these devices.

III. Conclusions

The described work is any but finished. The current undertakings are focused on three areas. These are: working out prototypes of measurement equipment for evaluation of power quality in ships, carrying out new methods of power quality assessment as well as providing some guidance for amendment of ships' classification societies standards. There has been a significant progress in all three above-mentioned areas. Especially, some new methods of electric power quality estimation have been proposed. These methods are based mainly on complementary application of Fourier as well as wavelet transforms. The result should be the more effective (time consuming) algorithms of analysis of signals in ship's systems. They are to cope with required high sampling frequencies and the very features of these signals like frequency and harmonic content short-time fluctuations, notching, multiple-zero crossings. Furthermore, it has been noted that not only estimation of power quality parameters but some elements of risk assessment should be taken into account, because of obvious synergy effect of different power quality disturbances.

Finally, it seems worth to mention once again importance of the method based on harmonic subgroups analysis in dealing with signals distortions in ship networks. Authors are convinced that the harmonic subgroups permissible limits should be included in relevant standards for ships, even instead of harmonic components content.

Nevertheless, the paramount conclusion seems obvious at this moment, the special solution of electric power quality problem for ships' networks are necessary and possible to ensure ship safety and provide reliable as well as simple information for ship crew. The additional effect will be improvement of economical aspects of ships exploitation.

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