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FUNDAMENTALS OF ELECTRICAL POWER QUALITY ASSESSMENT

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Abstract – The present paper deals with the selected problems of electrical energy quality assessment in the power system under non-sinusoidal conditions, i.e. the real power system. The principals are understood by the author as the three-segment block which consists of the basic definitions concerning power quality and its assessment, methods to determine electrical power quality indices by using the appropriate mathematical tools, as well as the related instrumentation for solving a problem of electrical power quality assessment. In the paper, these three fundamental parts for solving the electrical power quality assessment problem have been described and commented on. All analyses have been illustrated by the real data from ship electrical power systems.

Keywords: electrical power quality, measurement, digital signal processing, assessment

1. INTRODUCTION

Making an attempt to define: what is power quality in electrical networks, by which factors is it determined, and on the basis of which premises should it be assessed, it is necessary to clarify the actual meaning of the term power quality. This term is often used as synonymous with supply reliability [1,2] to indicate the existence of an adequate and secure power supply. Another, broader definition [2,3] has described service quality covering the three aspects of: reliability of supply, quality of power offered and provision of information. Taking into consideration the content of numerous contributions to the topic in recent years, the term power quality is generally used to express the quality of the voltage [2,4,5]. There is increasing acceptability of the latter interpretation with the expansion of power electronic control in the transmission and utilisation of electrical energy. At the same time many efforts in this area have been concerned with harmonics [5,6]. When harmonics distortion was an increasing quality problem, a wider power quality concept was needed which would include non-periodical and transient deviations from the ideal waveforms. Such deviations are used to assess Electromagnetic Compatibility (EMC), i.e. a subject concerned with the satisfactory operation of components and systems without interfering with or being interfered by other systems components [2,5]. Finally, taking into consideration the electrical power system, the power quality is usually defined by the following voltage or current parameters [2,4,5,7,8]:

- waveforms,
- frequency,
- magnitude,
- symmetry in three-phase systems

whose limits are appropriately standardised.

2. POWER QUALITY STANDARDS

As the power system is the conducting vehicle for possible interference between consumers, an important aspect of power system quality is the system ability to transmit and deliver electrical energy to the consumers within the limits specified by the EMC standards [2]. The two most widely referenced standards and guidelines are the IEC EMC series, including among others [9,10,11,12,13] and the IEEE 1159 [14].

The IEC series is published in separate parts covering the following elements [2,5]:

– General (IEC 61000-1-x): the overview of the series of standards and definitions,
– Environment (IEC 61000-2-x): a description of the characteristics of the environment and the compatibility levels for various disturbances.
– Limits (IEC 61000-3-x): a definition of emitted interference limits for voltage fluctuations, harmonics and flicker,
– Testing and Measurements Techniques (IEC 61000-4-x): a description of testing methods for emitted interference and interference immunity,
– Installation and Mitigation Guidelines (IEC 61000-5-x): a description of remedial measures,
– Generic Standards (IEC 61000-6-x): the interference immunity requirements and emitted interference limits

The IEEE 1159 standard contains several additional terms related to the IEC terminology. The IEEE categorisation of electromagnetic phenomena used for the power quality community is defined and explained in this standard [14].

3. ELECTRICAL POWER QUALITY PHENOMENA AND INDICES

The electromagnetic phenomena dealing with electrical power quality in engineering systems should be analysed in steady as well as non-steady states. The former has an effect mainly on the economic efficiency of the electrical power systems exploitation and due to its nature does not require fast measurements. The latter has a paramount importance for safety of the analysed systems exploitation in the meaning of jeopardising of human life or/and environment (dire economic effects are present as well).

Analysing the power quality problem in the light of accepted standards it is necessary to concentrate among others, on the commonly accepted indices for the characterisation of the disturbances. Commonly used indices may be discussed in relation to disturbances, waveform distortions, voltage unbalance and voltage fluctuation and flicker. However, electromagnetic phenomena should cover steady-states as well as non-steady-states of respective power systems [2,4,15].

3.1. Disturbances

Disturbance has been understood as a temporary deviation from the steady-state waveform, being in fact a short-term phenomenon. This concept is often used to refer to a non-repetitive change in the amplitude of the system voltage at the fundamental frequency for a short period of time [2].This deviation can be a high-frequency phenomenon (impulsive, oscillatory and periodic transients) or a low-frequency phenomenon (voltage dips, interruptions and swells). Examples of voltage disturbances are illustrated in Fig.1 [2].

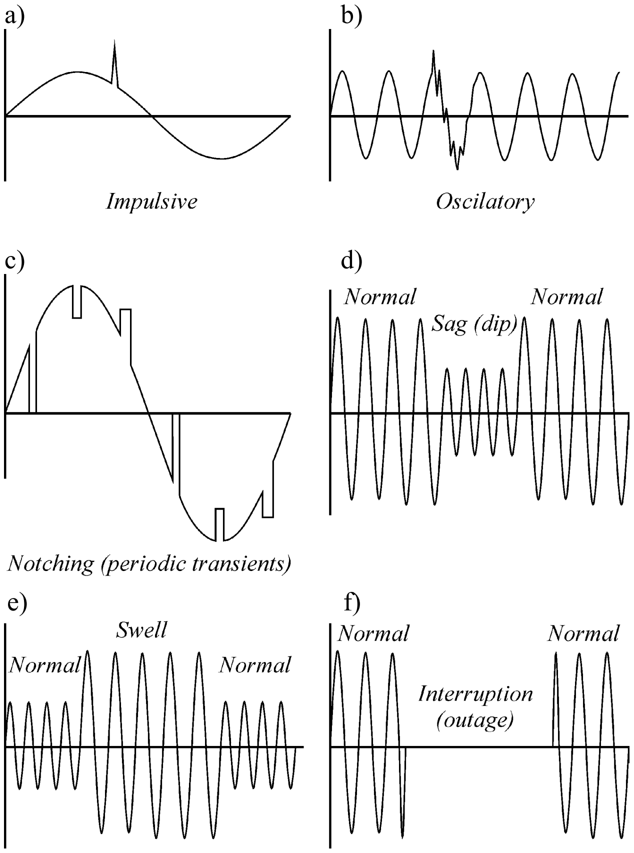

Fig.1. Voltage disturbances: a), b), c) high-frequency, d), e) and f) low-frequency

The main attributes for characterising these kinds of disturbances are the change in the amplitude and duration of the occurrence.

In some regulations [2,5,8] permissible voltage deviations are defined dependently on a voltage level as voltage range for a time period: steady state, less than 1min, less than 10s and impulse voltage respectively. In practice, recorded parameters dependently on the needs can be averaged by the day, week or month.

3.2. Waveform Distortion

This area covers harmonics, interharmonics, harmonics phase-angle, harmonic symmetrical components and notching.

The most frequently used harmonic and interharmonic indices are [2,4,5,6,7]:

– Harmonic Distortion (HD)
– Total Harmonic Distortion (THD)
– Total Interharmonic Distortion (TIHD)
– Total Demand Distortion (TDD)
and Distortion Band Factor (DBF)

The THD, HD and TIHD indices are defined as the rms of the harmonics or interharmonics respectively expressed as a percentage of the fundamental or the original distorted signal [2,5,16]. The TDD is similar to the THD concept except that the distortion is expressed as a percentage of some rated or maximum load current magnitude, rather than as a percentage of the fundamental current. Using the THD or HD indices, the lack of information about the value of respective harmonics may be observed. It is very important if detection of higher order harmonic is considered. The problem may be eliminated by estimation of waveform distortion caused by the frequency component of a respective frequency band. It can be done by estimation of waveform distortion as distortion band factors DBF [7]:

$$DBF_{f_1-f_2} = \frac{U_{rms(f_1-f_2)}}{U_{rms}} \qquad (1)$$

where: $U_{rms(f_1-f_2)}$ - rms value of voltage components of (f_1-f_2) frequency band

Only if respective DBF factor has relatively great value, the measurement of harmonics content of the band is needed.

3.3. Voltage unbalance

Unbalance describes a situation, in which either the voltages of a three-phase voltage source are not identical in magnitude, or the phase differences between them are not 120 electrical degrees, or both [2,5]. The degree of unbalance is usually defined by the proportion of negative and zero sequence components.

The simplest method of expressing voltage unbalance is to measure the voltage deviation Δu at each of the three phases, and compare it to the average phase voltage U_a:

$$C_{vu} = \frac{\Delta u}{U_a} \qquad (2)$$

where: C_{vu} - the voltage unbalance coefficient

According the IEC settlements (IEC Report 892/1987) if the voltage unbalance exceeds 5%, the work of the electrical motor should be analysed with regard to negative - sequence voltage. At smaller voltage unbalance load limitation to a degree dependent on this unbalance is recommended.

3.4. Voltage fluctuations and flicker

Voltage fluctuations are described as the cyclical variations of the voltage envelope or a series of random voltage changes, the magnitude of which does not exceed the range of permissible operational voltage changes mentioned in IEC 38 (i.e. up to ±10%) [2].
Fluctuations in the system voltage (concerning its rms value) can cause perceptible, low frequency light flicker depending on the magnitude and frequency of the variations [2,5].
A common method of analysing the severity of a flicker disturbance is to measure the fluctuation of light luminosity of an incandescent lamp. [11,13]. This assessment of flicker can be broadly divided into two parts: measurement of instantaneous flicker sensation as perceived by human eyes, and statistical evaluation of this severity level. Two severity indices short-term flicker severity (P_{st}) and long term flicker severity (P_{lt}) have been proposed for flicker evaluation [2,12,13].

4. METHODS AND TOOLS

The proper analysis of electrical energy quality requires measurement of quite a deal of different parameters. Usually the measurements for electrical power quality assessment are carried out with the use of digital signal processing algorithms. But it is worth underlining that the harmonic and transient analysis (waveform analysis) requires indeed much more computational power than determining the remaining power quality indices.

Traditionally, the Fourier Transform has almost exclusively been used in power engineering for higher frequency components extraction. Nevertheless, in recent literature with reference to the potential power systems applications, three principal alternative have been discussed [7,15,17,18,19]. These are the Walsh, Hartley and Wavelet Transform. Especially the latter one is worth recommending. The Wavelet Transform (WT) provides a fast and effective way of analysing non-stationary voltage and current waveforms. So, it could be stated that this tool becomes paramount for transients detection and analysis. Similarly to the Fourier case, the WT decomposes a signal into its frequency components, but unlike the Fourier transform, the Wavelet can tailor the frequency resolution [2]. The WT has a digitally implementable version, the Discret Wavelet Transform. In this kind of transformation, the scale and translation variables are discretised [2].

5. INSTRUMENTATION

In an existing power system the waveform can be obtained from measurements at points of common coupling (PCC) and their frequency components are then derived using signal processing. This process is at the case of quality assessment, realised by means of power quality monitoring devices and systems.
Appropriate instrumentation for solving a problem of electrical power quality assessment usually consists of multifunctional microprocessor instruments, namely the specialised analysers of electrical power quality. The key problem of those measuring devices is included in measurement algorithms and the software very often elaborated and addressed to well-defined concrete needs.
Power quality monitoring involves the capturing and processing of voltage and current signals at various points of the system. The signals to be captured are normally of high voltage and current levels and this use of the current and voltage transformers is necessary before they can be processed by the instruments [2].
Two general concepts may be considered: conventional centralised processing architecture and distributed processing architecture illustrated in Fig.2.

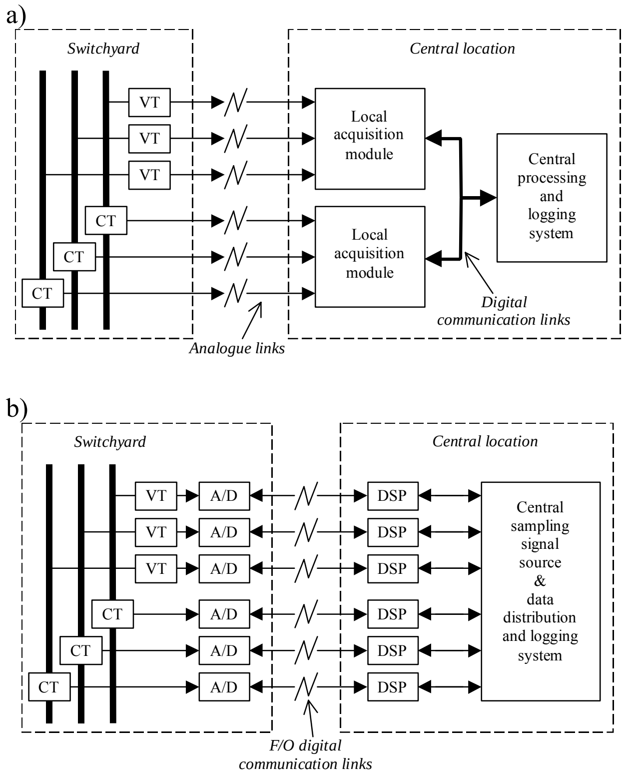

Fig.2. Power Quality Instrumentation-Structure Designs [2]: a) Conventional centralised processing architecture, b) A possible distributed processing architecture; CT - current transformer, VT - voltage transformer, A/D - analog-to-digital converter, DSP - digital signal processor

An in-depth analysis of both above illustrated versions in the light of their advantages and disadvantages may be found in [2].

Many concrete solutions for the quality analysis of power systems - as power quality analysers, digital instruments for harmonic monitoring, transient monitoring, interharmonics measurement, flicker monitoring or event recording, were described in innumerable contributions related to the topic in recent years for example in [2,5,7,16,20].

6. IMPLEMENTATION - CASE STUDY

This part of the paper covers a case study: a problem of estimation of electrical energy quality in ships electric power systems. First of all, it is worth mentioning that the discussed matter should not be limited to ships systems. It is rather an example of the operation description of autonomous, flexible power systems, like systems applied in aircraft or in banks and hospitals.

6.1. Main features of the evaluated system

The main task of ship electrical power system is to deliver and process electrical energy. The system contains autonomous free standing generating sets (typically synchronous generator coupled to distinct internal combustion engine), cable lines, switchboards and different kinds of loads, often heavy and non-linear consumers. Sometimes a shaft generator or/and turbogenerator are present for the sake of energy savings. A sketchy arrangement of a ship electrical power system with shaft generator is depicted in Fig.3.

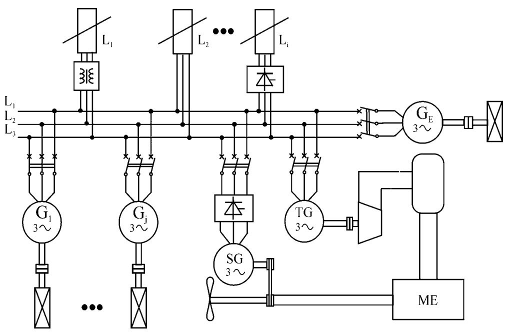

Fig.3. Exemplary arrangement of ship electrical power system with shaft generator

The characteristic attribute of a ship electrical power system is an enormous ratio of nominal power of singular energy receiver to one generating set. In many cases, the nominal power of odd load exceeds the nominal power of each generator. So, it causes flexibility of ship electrical network. It creates a great sensitivity to load changes, which evoke notorious voltage and its frequency deviations from their nominal values. In ship electrical power plants there is often a necessity for free standing generating sets to work in parallel. The importance of proportionate active and reactive power distribution plays a vital role just in manoeuvring or in difficult weather and navigational conditions. For safety reasons it is necessary to maintain power surplus; as a rule, it is about 20% power of single generator at sea or more while manoeuvring. Reassuming, the power quality in ship systems can be described by parameters of three-phase supply voltage on the bus bars of the main switchboard (rms value, frequency, unbalance, waveform distortion and proportionality of active and reactive power distribution) [15].

6.2. Power quality standards and indices for ship electrical power systems

The following indices are used by classification societies for characterising power quality on ships systems:

– $\delta U(\delta U_d)$ and $\delta f(\delta f_d)$ - coefficients of voltage and frequency deviations from their nominal values in static and (dynamic) conditions [15],
– THD - total harmonic distortion coefficient, defined with N=40 or 50, where N is number of harmonics taken into consideration [15,21,22],
– C_{vu} - voltage unbalance coefficient (not applicable on ships yet) [2,5,15],
– C_{tvd} - coefficient characterising the voltage distortion by means Δu_{max} maximal transient voltage deviation from the first harmonic value in relation to the maximal value of the fundamental [15],
– $\delta L_i(\delta P_i$ and $\delta Q_i)$ - coefficients characterising the proportionality of distribution of active and reactive powers between generating sets working in parallel [15].

6.3. Estimation of power quality on ships

Considering the standard version of measuring equipment of the main switchboard (voltage, frequency, current, active and/or reactive power measurement during steady state conditions) [15,23,24] it may be stated, that hitherto used instrumentation is practically not useful for direct estimation of power quality. At the same time, we need proper information about the parameters characterising electrical energy [25]. Some exemplary records of voltage's rms value and frequency [26] as well as distorted waveform [27] registered on the bus bars of ships power station are illustrated in Fig.4 and Fig.5, respectively.

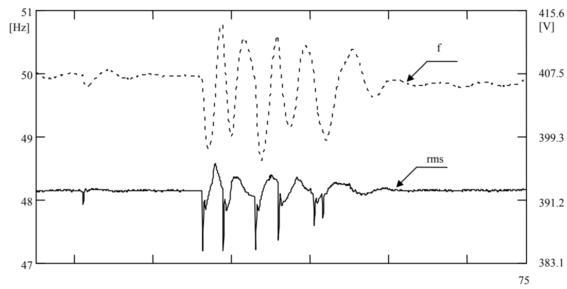

Fig.4. Exemplary deviations of voltage's rms value and frequency over switching on large loads

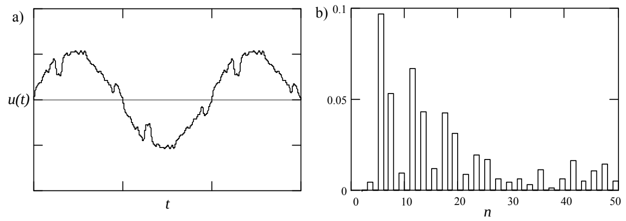

Fig.5. Exemplary distorted voltage waveform, on the main bus bars of a ship's power station loaded with six-pulse semiconductor converter: (a) u(t) signal waveform; (b) discrete amplitude spectrum of the u(t) analysed signal for h≥2 [27]

These waveforms are characterised by a wide range of distortion, including in general case harmonics and transient/notching [7,15,22,27], the low-as well as high-frequency components. It is worth mentioning that although most classification societies require the THD value less than 10%, however, the distortions exceeded by 20% may be noted [15,27]. The voltage unbalance is also often observed. In this context, lack of classification societies requirement concerning the supply voltage symmetry should be underlined. Moreover, the level of distortions is practically recorded neither or - non off-line.

6.4. Specialised analyser for ships' applications

The power quality analyser for ship use should convey at least information of voltage quality required by rules of respective ship classification societies with respect to safety of its own operation. Then, the proposed analyser consists of a few autonomous units. Each unit has identical but autonomous hardware structure. It ensures maximum reliability of the device and decreases number of required spare parts.

The model of this kind of measurement system has been carried out in Department of Ship Electrical Power Engineering of Gdynia Maritime University. It has been based on the Digital Signal Processors ADSP 21061 of the Sharc family. It consists of a few independent blocks, as has been shown in Fig.6 [26].

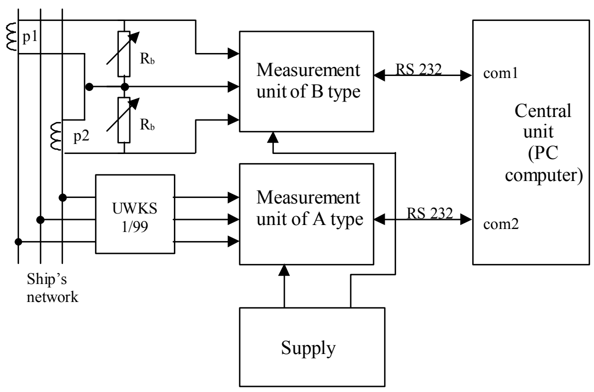

Fig.6. Model of measurement-diagnosis system of electrical energy quality in ships' electrical power system

The measurement unit of the A type is to determine all voltage parameters included in relevant rules of ship classification societies, like: voltage and frequency deviations, THD factor, harmonics and interharmonic content as well as unbalance of voltage. The measurement unit of the B type is to analyse the current of large and important receivers.

The above-depicted model has been positively tested on Gdynia Maritime University training ship m/v "Horyzont II" [7]. The examples of its user interface for measurement unit of the A type and registered disturbances have been shown in Fig.7.

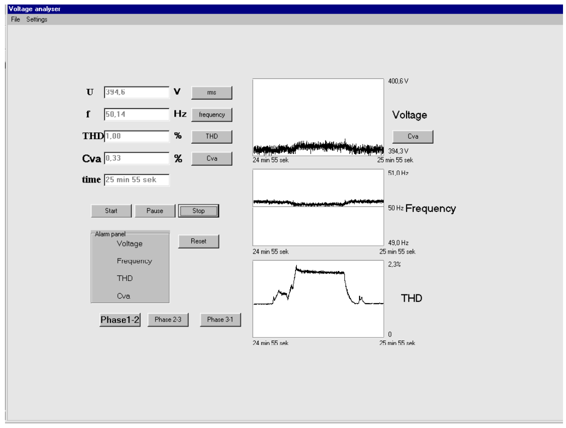

Fig.7. User interface for measurement unit of the A type.

The most important parts of information about voltage parameters are presented graphically. All information is also registered on hard drive of the central unit. The situation depicted in Fig.7 concerns the manoeuvring of m/v "Horyzont II" with the use of bow thruster. It is worth mentioning that a whole program consists of a few similar interfaces [7,15,26].

7. CONCLUDING REMARKS

Grappling the problem of electrical power quality assessment one could ask why is a measurement of electrical power quality so distinctive. The answer lies in the terminal aim of this quality assessment. The aim of the assessment of electrical power quality concerns safety and economic efficiency of the exploitation of electrical power systems as a whole. So, it has to cover a wide range of parameters and it also induces implementing multi-parameters measurement devices, practically all based on digital signals processing. This way, the problem of different parameters measurement should be taken on as one task, in the meaning of intersecting and connecting all the mathematical tools used as well as hardware in one powerful efficient device or system.

Generally, power quality assessment is not carried out regularly and systematically in the meaning of global assessment of the system under consideration. Instead, ad hoc measurement procedures are used to ensure that the PPC voltage waveform meets the specified distortion levels. A local solution, however, affects the rest of the system to some degree and in a positive or negative way, but usually is not so easy to take into account consequences. It is therefore far from ideal, both in terms of overall cost and performance. A very characteristic example of this problem is the ship electrical power system, where casual surveys do not provide full information. The occurrence of various kinds of interference is strictly related to different stages of ship exploitation. So, it is necessary to carry out research over a relatively long period of ship exploitation under conditions of different electric power plant configurations. The eventual combination of local monitoring and global assessment should provide cost-effective and better technical solutions.

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