

A short discussion about THD and its measurement in ship electric power systems

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Abstract- The paper is to investigate seemingly a simple problem of *THD* interpretation in the wake of standards' definitions and measurement methods, intended for ship use. The consequences of two various definitions of the factor are discussed. Further, the real examples of the *THD* measurements in ship systems are shown. Finally, the consequences for measurement methods and design of appropriate instrumentation are mentioned.

I. Introduction

The widely discussed and still hot topic in electrical engineering is power quality. According to IEC Standard 61000-4-7 the term power quality means "characteristic of the electricity at a given point on an electrical system, evaluated against a set of reference technical parameters" [1] and the term is chiefly related to voltage parameters [2]. The parameters are to describe rms value of voltage, its frequency, unbalance and waveform distortions. Particularly, waveform distortions assessment is arguably the most disputed topic in the area. There are numerous factors for estimation of waveform distortions. The appropriate definitions and framework for the factors measurement were laid in IEC Standard 61000-4-7 [3]. In this respect, chiefly total harmonic distortion (*THD*) factor is to be mentioned. Although, its value can not be related to any electric device operation, individual components content or other factors should be considered instead, but its popularity is due to simplicity and possibility of waveform rough assessment by simple one index. Obviously, if the *THD* assumes high value, the detailed analysis of actual distortions is necessary. Unfortunately, there are some slightly different definitions of *THD*. It can lead to misinterpretations and, since the limits for *THD* factor are laid in respective rules e.g. ship classification societies, it has a legal meaning. The problem will be discussed in the following section and existing ambiguities will be pointed out.

The waveform distortions of supply voltage can be extremely high in the isolated power systems due to the systems very features, especially limited electric power source capacity and its relatively high impedance [4] as well as an increasing usage of power converters [5]. As a result, *THD* factor, independently of details of its definition, sometimes assumes extremely high values above 10% [6] or even 20% [5], [7]. The chosen results of calculated *THD* values and related spectrum of voltage waveforms registered in ship systems will be presented in Section III. These examples are to underline the potential consequences of the above mentioned legal ambiguities.

II. Standard frameworks

The widely accepted and often used definition of *THD* is as follow [3], [8]:

$$THD = \frac{\sqrt{\sum_{h=2}^n V_h^2}}{V_1} \cdot 100 \quad (1)$$

where: V_h – rms value of harmonic of h-order, V_1 – rms value of fundamental component.

Taking into account the above definition, a main disadvantage of this approach is discernible. Namely, there is an ambiguity of the waveform distortion assessment by *THD*, it means many different curves can be characterized by the same value of *THD* coefficient. On the other hand, those curves may quite various affect the given electric devices operation. Therefore, *THD* is not sufficient for profound waveform assessment but it is an

convenient index for less experienced ship crew.

Another problem concerning the feasibility of assessment of waveform distortion by means of *THD* is covered frequency band. The number n usually assumes value 40 or 50 depending on specific rule requirement. It means that calculation should be carried out to 40th or 50th harmonic. The rules of some leading classification societies requires calculation up to 50th harmonic [9], [10]. Although, it has to be added that American Bureau of Shipping states that voltage *THD* factor should be measured up to 100th order if equipment with “active front ends” is installed [10].

In real power systems there are voltage magnitude fluctuations and its frequency changes. The impact of such a voltage parameters variations on results of harmonics measurements is hardly negligible. The problem of harmonics content assessment under such unfortunate conditions was profoundly investigated on the basis of a real signal and described in Ref. [11].

Finally, the concept of harmonic subgroups was introduced in IEC Standard 61000-4-7 [3]. This concept consists in calculation of square root of the sum of squares of harmonic component amplitude and amplitudes of two spectral components immediately adjacent to it. The result is considered as rms value of harmonic subgroup. Related total harmonic distortion factor (which incorporates harmonic subgroup concept) is designated as *THDS* [3] and defined as follow:

$$THDS = \frac{\sqrt{\sum_{h=2}^n G_h^2}}{G_1} \cdot 100 \quad (2)$$

where: G_h – rms value of harmonic subgroup of h-order, G_1 – rms value of subgroup of fundamental component.

In the authors’ opinion the latter definition, namely *THDS*, should is better than formula (1) for assessment of a waveform distortion in ship systems, although the concept has not been mentioned in respective rules for marine applications.

However, there are standards, which define *THD* factor in other way. According to IEEE Standard 45-2002 [12] and IEC Standard 60092-101:2002 [13] *THD* is the ratio of rms value of the residue (after elimination of the fundamental) to the rms value of the fundamental expressed in percentage. It results in formula:

$$THD = \frac{\sqrt{V_{rms}^2 - V_1^2}}{V_1} \cdot 100 \quad (3)$$

where: V_{rms} – rms value of considered voltage.

The distortion index calculated according to formula (3) is sometimes designated as total waveform distortion *TWD* [8].

The numerical difference between *THD* calculated on the basis of formula (1) and (3) depends on frequency bandwidth of measurement instrument as well as width of measurement window. For the very same frequency bandwidth and one-cycle window results of calculation would be the same. Unfortunately, there is no mention about both in respective standards for marine use. It seems justified to assume that *THD* will be calculated on the basis of 10-cycle or 12-cycle measurement window, depending on rated system frequency 50 Hz or 60 Hz. It results directly from IEC Standard 61000-4-7 recommendations for methods of signal processing of harmonics and interharmonics [3]. Under this circumstance, results of calculation of *THD* factor depends on applied formula. If formula (1) is to be used, even rough waveform distortion assessment in ship systems would require complementary factor total interharmonic distortion *TIHD* or its equivalent calculated on the basis of interharmonic subgroups. But in the authors’ opinion it is not necessary for every-day exploitation of ship electric power systems and could make a confusion for non-experienced ship crew. Therefore, the better solution seems the application of the formula (3). It is what it should be, one and only one index for waveform distortions assessment. Moreover, it is simpler to determine. It does not require calculation of the whole spectrum but only rms value of the voltage and its fundamental component.

However, a general remark concerning an ambiguity of the waveform distortion assessment by *THD* is still valid. So, above mentioned problems have to be properly addressed in related rules and standards. First problem concerns the frequency bandwidth for measurement of rms value of whole voltage. In some respect, it is equivalent of assuming proper value of n in formula (1). Taking into account real signals investigation, e.g. presented in Ref. [6], it has to be extended beyond currently applied limit of 50th harmonic or better 2.5 kHz (for 50 Hz systems) or 3 kHz (for 60 Hz systems), when speaking about formula (3). Simply put, common usage of

active front end PWM drives in ship systems extended distortion bandwidth above 3 kHz. It seems that the simplest and consistent solution is to measure rms value of the whole voltage for the frequency bandwidth up to assumed limits of low frequency disturbances equal to 9 kHz [3] or 10 kHz [14]. The stance will be explained on the basis of research results presented in the following section.

Further, the methods of signal processing of *THD* by formula (3) has to be considered. There are numerous solutions, starting from high-pass or notch filtration up to Fourier transform. In the case of high-pass filtration analog, digital or mixed methods can be applied. However, in the most cases discrete Fourier transform DFT would be more convenient, especially if multi-parameter power quality analysers would be used. Authors are convinced that in this case concept of harmonic subgroups has to be used as well.

Summing up, for rough assessment of waveform distortions in ship systems, *THD* factor calculated for 10- or 12-cycles by DFT and frequency bandwidth up to 9 kHz by following formula is to be used:

$$THD = \frac{\sqrt{V_{rms}^2 - G_1^2}}{G_1} \cdot 100 \quad (4)$$

where: designations are the same like in formulas (2) and (3).

It is simple, easy to determine, unequivocal and covers most of disturbances registered by authors or reported in related documents in ship systems. It is worth adding that popular method of fast DFT calculation, namely fast Fourier transform FFT, is not to be used for the calculation, especially not the method recommended by IEC Standard 61000-4-7. For more details see Ref. [11].

III. Examples of real signals investigation

The research of real power quality disturbances in ship electric power systems has been carried out in Gdynia Maritime University for quite a few years. Among other parameters, supply voltage waveform spectra have been determined. For this paper purpose four examples were chosen and shown in Fig. 1. The designations: *THDS* is calculated according to formula (2) up to 50th harmonic and *THD* is calculated according to formula (4) and frequency bandwidth up to 9 kHz (except example of Fig. 1a, where the bandwidth equalled 6 kHz).

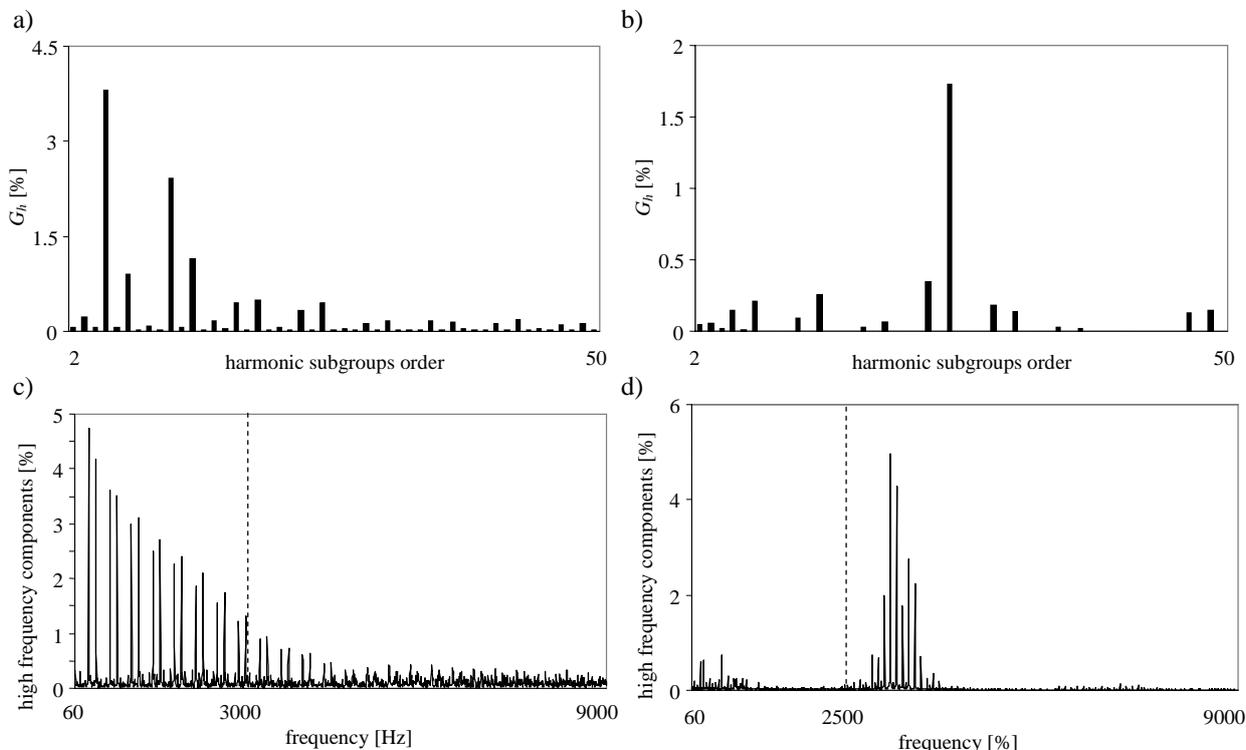


Fig. 1. Exemplary spectra of supply voltages registered on busbars of main switchboard: (a) training ship *THD*=4.82% and *THDS*=4.78% [15], (b) ro-ro ship *THD*=1.91% and *THDS*=1.83%, (c) chemical tanker *THD*=13.90% and *THDS*=11.26% [6], (d) research all-electric ship *THD*=8.31% and 1.38% - dashed line marks 50th harmonic

Fig. 1a and Fig. 1b represents harmonic subgroups depicted up to 50th harmonic, whereas Fig. 1c and 1d represent spectra depicted with 5 Hz resolution up to 9 Hz. This was presented in such a way because waveform distortions in ro-ro and training ship were limited practically to low frequencies. Further, in the case of chemical tanker and research ship, there were high frequency distortions above 50th harmonic. It should be added that distortions in the latter frequency band can be unrelated to fundamental frequency, like in the case of research ship. In this ship significant distortion in proximity of 3.6 kHz (switching frequency of power converter) were detected. It should be added that in numerous standards intended for ships, the THDS or THD values are not to exceed 5% [9], [10], [12], [13].

The above presented results reveals that there is not common characteristic of waveform distortions of voltage in ship systems. The fact can not be neglected when considering definition *THD* coefficient. The differences between formula (2) and (4) are negligible for training ship (Fig. 1a) and acceptable for ro-ro ship (Fig. 1b). But this must not be ignored in the cases of chemical tanker and particularly research ship. Especially, the latter ship has to be underlined, since using the formula (2) would be completely misleading.

It is worth noticing that ro-ro is nonetheless interesting case, because the significant value of 25th harmonic has been observed. It seems rather uncommon situation and it was probably caused by gear of shaft generator.

Summing up, the impact of choice of appropriate *THD* definitions and precise description of measurement conditions can not be omitted. These results justify above described authors' stance, regarding superiority of formula (2) for rough assessment of waveform distortions in ship systems, obviously completed by unambiguous determination of covered frequency band and measurement method of respective components.

IV. Conclusions

The current standards concerning power quality in ship systems define at least two different *THD* factors. Both are used in the very same manner, namely for rough assessment of waveform distortions. The first definition, namely formula (1) or after modification formula (2) is rather precise and unambiguous. The harmonics up to 50th are to be considered. (There is one above mentioned exception.) Unfortunately, this coefficient is inappropriate for assessment of signals with components above 50th harmonic or interharmonics. The distinct example is research all-electric ship. The value of *THDS* is safely below 5% limit, but distortions in the frequency band up to 9 kHz are significantly above the 5%, reaching 8,31%. Therefore, the second definition (formulae (3) or (4)) seems better solution, but some unifications amendments of existing rules is necessary. Finally, authors propose to define *THD* coefficients for ship applications as follow:

Total Harmonic Distortion (THD) is the ratio of rms value of residue in the frequency band up to 9 kHz after elimination of fundamental to the rms value of fundamental, expressed in percentage, where rms value of fundamental is value of fundamental subgroup calculated for approximately 200 ms window in accordance with IEC Standard 61000-4-7.

The above definition is unambiguous and can not be misleading. It covers frequency band affected by operations of nowadays power converters installed in the systems under considerations. Moreover, the recommended signal processing method is included as well.

The open question is the appropriate aggregation time of results of *THD* measurement or other power quality parameters in ship systems. The problem was preliminary discussed in Ref. [16]. In shorthand, the aggregation time equal to 10 minutes was chosen, apart from instantaneous values, calculated over basic 200-ms measurement window. Its trial solution may be found in Ref. [17].

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References

- [1] IEC Std. 61000-4-30, 2003. *Testing and Measurement Techniques – Power Quality Measurement Methods*.
- [2] R. Dugan, M. McGranaghan, H. Beaty, *Electrical power systems quality*, McGraw-Hill Companies, 2002.
- [3] IEC Std. 61000-4-7, 2002. *General guide on harmonics and interharmonics measurements for power supply systems and equipment connected thereto*.

- [4] J.P. De Abreu, J.S. De Sa, C.C. Prado, "Harmonic voltage distortion in isolated electric systems". 7th International Conference „Electrical Power Quality and Utilization” Cracow, September 17-19,2003, pp. 469-472.
- [5] I. Evans, H. Hoevenaars, "Meeting harmonic limits on marine vessels", *IEEE Electric Ship Technologies Symposium, ESTS '07*, 2007, pp. 115 – 121.
- [6] T. Tarasiuk, "The Method Based on Original DBFs for Fast Estimation of Waveform Distortions in Ship Systems – Case Study", *IEEE Transactions on Instrumentation & Measurement* vol. 57 no. 5, 2008, pp. 1041-1050.
- [7] C.G. Hodge, D.J. Mattick: The electric Warship (Parts I-VI), *Trans. IMarE*, vol. 108, 109, 110, 111, 112, 113, The Institute of Marine Engineers, UK, 1996-2001.
- [8] Bollen M., Gu I.: *Signal processing of power quality disturbances*, Wiley-Interscience 2006.
- [9] Lloyds Register of Shipping, *Rules and regulations for the classification of naval ships – electrical engineering*, LRS, vol 2, part 10, charter 1, 2001.
- [10] American Bureau of Shipping, *Guidance notes on control of harmonics in electrical power systems*. ABS 2006.
- [11] T. Tarasiuk, "Comparative study of various methods of DFT calculation in the wake of IEC Standard 61000-4-7", *IEEE Transactions on Instrumentation and Measurement* vol. 58 no. 10, 2009, pp. 3666-3677.
- [12] IEEE Std. 45:2002, *IEEE Recommended Practice for Electrical Installations on Shipboard*.
- [13] IEC 60092-101:2002. *Electrical installations in ships. Definitions and general requirement*.
- [14] IEC 60533:2002. *Electrical installations in ships. Electromagnetic compatibility*.
- [15] T. Tarasiuk, *Estimation of power quality in ships' electric power systems with use of digital signal processors*, Publishing House of Gdynia Maritime University, 2009 (in Polish).
- [16] T. Tarasiuk, J. Mindykowski, "In the Search of the Effective Assessment Method of Electric Power Quality on Ships". Proceedings of XVIII IMEKO World Congress, September 22-27, 2006, Rio de Janeiro, Brazil, (CD-ROM).
- [17] Polish Register of Shipping, *Technical requirements for shipboard power electronic systems*. PRS 2006.