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Total Harmonic Distortion Factor Evaluation in Shipboard Electrical Networks

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Abstract. Electric propulsion systems for modern civil and military ships, as well as the growing number of electric consumers on board, are a topical issue in terms of onboard electric power quality. In this respect, a growing number of high power static converters are used, which inevitably leads to the appearance, in the electricity distribution network, of voltage and current harmonics with very high weights.
Through this work, the authors made a study of these harmonics for two classical cases encountered aboard a ship, namely a nonlinear consumer and a consumer powered by a static six-pulse converter. Also, the highlight of these harmonics has been made in both shore and on-board power supplies. As a result of these measurements, some conclusions were drawn regarding the analysed situations.

Keywords: converter, waveform distortions, finite power source

1. Introduction

Total Harmonic Distortion (THD). The massive introduction of power electronics into electrical installations has made the study of harmonics taken seriously in all sectors of economic activity, especially since the most harmonic generating equipment is often of major importance for the economic activities.

The most frequently used harmonic and interharmonic indices are [1]:

- Harmonic Distortion (HD);
- Total Harmonic Distortion (THD)
- Total Interharmonic Distortion (THID);
- Total Demand Distortion (TDD);
- Distortion Band Factor (DBF).

THD - (Total Harmonic Distortion) characterized the type and weight of harmonics in a circuit and it is specific for both voltage and current harmonics:

$$THD(I) = \frac{\sqrt{\sum_{n=2}^{\infty} I_n^2}}{I_1} \times 100\% \quad (1)$$

$$THD(U) = \frac{\sqrt{\sum_{n=2}^{\infty} U_n^2}}{U_1} \times 100\% \quad (2)$$

Generally, THD ignores the phase angle information, and only considers a small range of frequency components, usually, fundamental and its integer multiples (not higher than 51th harmonic). In order to consider the impact of other frequency components or phase angles, new alternative indices have been defined: Crest Factor, *K*-factor, Telephone Inference Factor (TIF), and extended THD [2].

Total harmonic distortion is calculated in a range of 50-th harmonics. In this range, the total harmonic voltage distortion should be equal or less than 5% as measured at any point of common coupling (PCC) with any individual harmonic voltage distortion not exceeding 3% of the fundamental.[3]

On a dedicated system, higher level of harmonic distortion may be permissible as long as the equipment can operate safely at the higher limits.

Lately, there was an increase in the number and variety of electric propulsion ships being built around the world. This change has occurred, thanks to the development of electronic power control technology, which is used for the electric propulsion system. These units regulate the velocity of the propeller by modifying the supply voltage frequency, and this was made possible by developing high-power switching devices.

Regarding at harmonic standards for electric shipboard power systems, these have been adopted directly from the power utility standards. The characteristics of shipboard power systems regarding harmonic distortion have been defined by both commercial and military standards: IEEE Standard 519 [3], IEEE Standard 45 [4], and MIL-STD-1399 Section 300 [5].

Some studies indicate very little problems with harmonics on shipboard (only 10% of those surveyed indicated potential problems, others reported that values over 10% VTHD might create communication problems [6] [7].

Harmonic currents are generated by nonlinear loads. These include:

I. Single-phase loads, for example:

- Swiched mode power supplies (SMPS) used on TVs, computers, other office equipment (copiers, fax machines) and so on. The advantage for the equipment manufacturer is that the dimensions, cost and weight are significantly reduced and the energy unit can be made practically for any form factor required. The disadvantage - in addition to the other types - is that the power source absorbs a current in the form of pulses of current containing a large quantity of three or more harmonics.
- Electronic ballasts for fluorescent lamps - have become popular in recent years due to the need for increased efficiency. Generally, they are only slightly more efficient than the best magnetic ballasts, and in fact, the highest gain results in the fluorescent lamp, the level of illumination can be maintained for a longer lifetime by controlling the currents in the lamp. The main inconvenience is that it generates harmonics in the power supply.
- Uninterruptible power supplies (UPS) with similar operation to switching power sources.

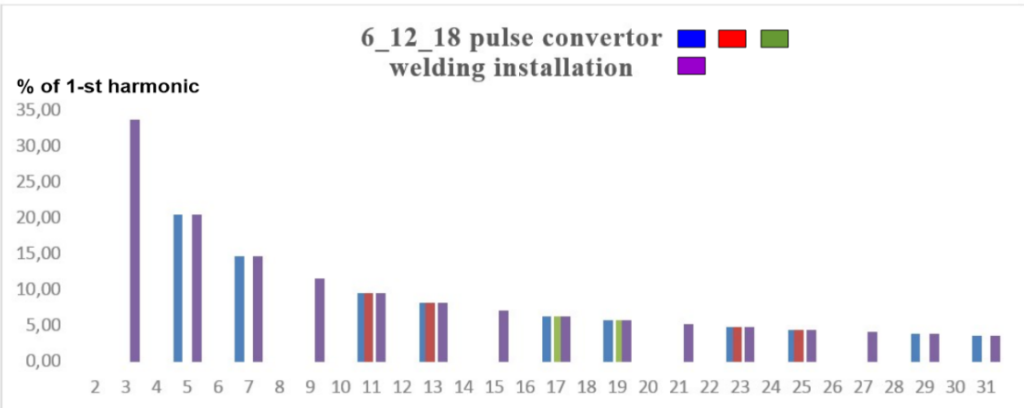

Figure 1. Ideal harmonic spectrum for 6, 12, 18 pulse convertor and welding installations

II. Three-phase loads, for example:

- Variable speed drives for asynchronous or DC motors;

- Large Uninterruptible Power Supplies (UPS);
- Industrial equipment (welding machines);
- Devices requiring electromagnetic saturation (transformers).

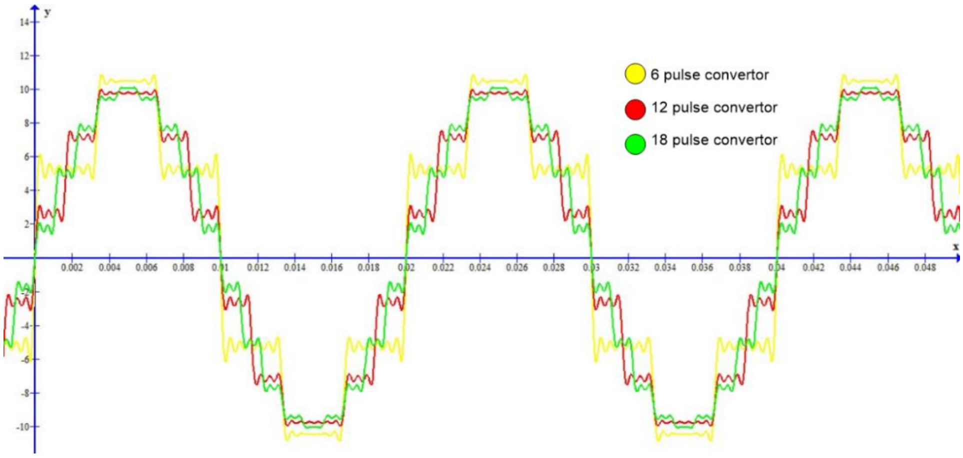

Figure 2. Voltage waveform for: 6, 12, 18 pulse convertor

It can be noticed that with the increase of the number of pulses in a converter there is an improvement of the shape of the voltage or current waveforms. This will occur in the decrease of the THD value due to the small weights of the constituent harmonics of the signal

For a 50 Hz fundamental harmonic frequency, the expression of voltage for 6, 12 or 18 pulse converters will look like this:

$$u_6(t) = 10\sin(314x) + \left(\frac{10}{5}\right)\cdot\sin(5\cdot 314x) + \left(\frac{10}{7}\right)\cdot\sin(7\cdot 314x) + \\ + \left(\frac{10}{11}\right)\cdot sin(11\cdot 314x) + \left(\frac{10}{13}\right)\cdot sin(13\cdot 314x) + \left(\frac{10}{17}\right)\cdot sin(17\cdot 314x) + \\ + \left(\frac{10}{19}\right)\cdot sin(19\cdot 314x) + \left(\frac{10}{23}\right)\cdot sin(23\cdot 314x) + \left(\frac{10}{25}\right)\cdot sin(25\cdot 314x) + \\ + \left(\frac{10}{29}\right)\cdot sin(29\cdot 314x) + \left(\frac{10}{31}\right)\cdot sin(31\cdot 314x) + \left(\frac{10}{35}\right)\cdot sin(35\cdot 314x) + \\ + \left(\frac{10}{37}\right)\cdot\sin(37\cdot 314x) \quad (3)$$

$$u_{12}(t) = 10sin(314x) + \left(\frac{10}{11}\right)\cdot sin(11\cdot 314x) + \left(\frac{10}{13}\right)\cdot sin(13\cdot 314x) + \\ + \left(\frac{10}{23}\right)\cdot sin(23\cdot 314x) + \left(\frac{10}{25}\right)\cdot sin(25\cdot 314x) + \left(\frac{10}{35}\right)\cdot sin(35\cdot 314x) + \\ + \left(\frac{10}{37}\right)\cdot sin(37\cdot 314x) \quad (4)$$

$$u_{18}(t) = 10sin(314x) + \left(\frac{10}{17}\right)\cdot sin(17\cdot 314x) + \left(\frac{10}{19}\right)\cdot sin(19\cdot 314x) + \\ + \left(\frac{10}{35}\right)\cdot sin(35\cdot 314x) + \left(\frac{10}{37}\right)\cdot sin(37\cdot 314x) \quad (5)$$

The presence of harmonics in naval distribution networks degrades the quality of electricity. This phenomenon can have many negative effects, the most common being: overloads in distribution networks caused by increasing the efective current value; premature aging of capacitors used to compensate the reactive energy; disturbances in communications networks; damage of conductor insulation due to the appearance of the skin effect (for harmonics exceeding 350 Hz).

The presence over a certain limit of the harmonics in the power supply networks has major negative economic effects, producing: premature aging of the equipment (which requires premature replacement if it has not been oversized since the beginning, oversize also costly) estimated from about 5% for transformers, 18% for three-phase motors, up to 32.5% for single-phase motors; overload distribution network that required higher generated power due to increased losses; distortion of the current waveform that may cause unexpected triggering of the protection relays, resulting in losses by stopping machinery, equipment or production processes.

Another important issue in terms of the quality of electricity is represented by the presence of interharmonics and other associated components. Harmonics are sinewaves voltages or currents whose frequency is a multiple of the fundamental frequency of the source. A rigorous analysis of voltage and current should take into account the following components:

- harmonics - $f = nf_1$, where n is an integer greater than zero;
- DC component - $f = nf_1$ for $n = 0$;
- interharmonics - $f \neq nf_1$, where n is an integer greater than zero;
- subharmonics - $f > 0$ Hz, and $f < f_1$.

Where: f_1- fundamental harmonic of the voltage or current.

Regarding voltage or current interharmonics, these have a sinusoidal variation with a frequency that is not an entire multiple of the source frequency, although they have always been present in power systems. The interest in interharmonics has increased with the increase in their amplitude due to the widespread of power electronics in electrical installations.

Generally, two basic mechanisms that generate interharmonics are considered:

- The first is the generation of components in the lateral bands of the fundamental frequency as a result of amplitude and phase variation due to the disturbances caused by electrical loads in long or short-term transient modes or. These disturbances are largely random, depending on the electrical load variation, during different technological processes;
- The second mechanism is the asynchronous switching (not synchronized with the supply voltage frequency) of the semiconductor elements in the static converters. A typical example is offered by pulse width modulation (PWM) converters.

As a results, interharmonics can be generated at any voltage level and can be transferred to a different voltage level, for example, interharmonics generated in high-voltage and medium voltage networks can be injected into low voltage networks and vice versa.

2. Experimental set-up and results

The power source on board was a Diesel Generator with the following characteristics:

- Three phase voltage - U = 400V/230V;
- Frequency –f=50Hz;
- Apparent power S=15KVA;
- Maximum single phase I=23A

The experimental determinations were performed for different operating regimes and will primarily aim to highlight the waveform distortions of the voltages and currents.

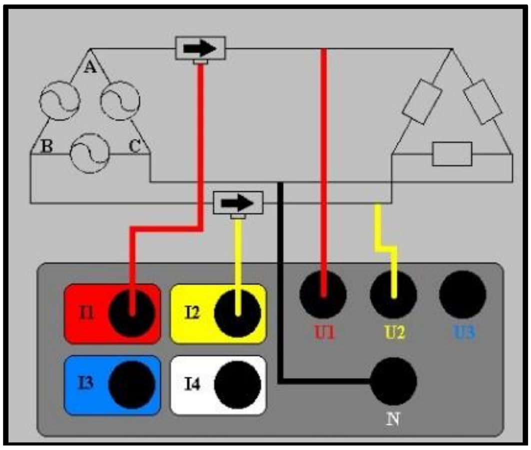

Figure 3. Type of connection 3P3W2M

Measuring instruments used for data acquisition were : AMPROBE PQ55A power analyzer and RIGOL DS-1052E digital oscilloscope. In this instance, they were able to perform a FFT (Fast Fourier Transformation) analysis, up to the 31st harmonic.

The frequency measuring devices provide correct information when the measured signal consists only of harmonics. These instruments use a phase sync circuit to synchronize the measurement with the fundamental frequency component and to sample the signal for one or more periods in order to apply the analysis using FFT (Fast Fourier Transformation). Due to phase synchronization, samples acquired over a period can give a fair representation of the curve spectrum only if it does not contain interharmonics. If non-harmonic frequencies are present in relation to the measurement period and the sample curve is not periodic, difficulties may arise during this time to interpret the results.

Measurements were made for two cases: 6-pulse converter and welding machine powered from a 400V three-phase network in a triangle connection. Measurement was made for an Aron connection – Measurement type 3P3W2M of connection mode.

To carry out our study aboard a ship, the measurements have been achieved for two distinct power supply cases, namely: from an infinite power source (connection to shore electricity network) and from a finite power source (the onboard generators).

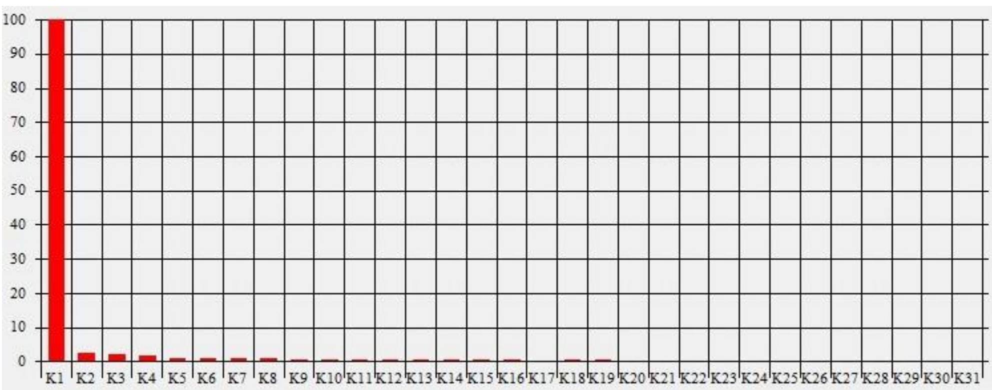

Figure 4. Case of inite power source (connection to shore electricity network)

For the case of infinite power source (connection to shore electricity network), in both situations, the weight of current and voltage harmonics was insignificant. Along with switching to the the onboard generator the weight of harmonics has increased.

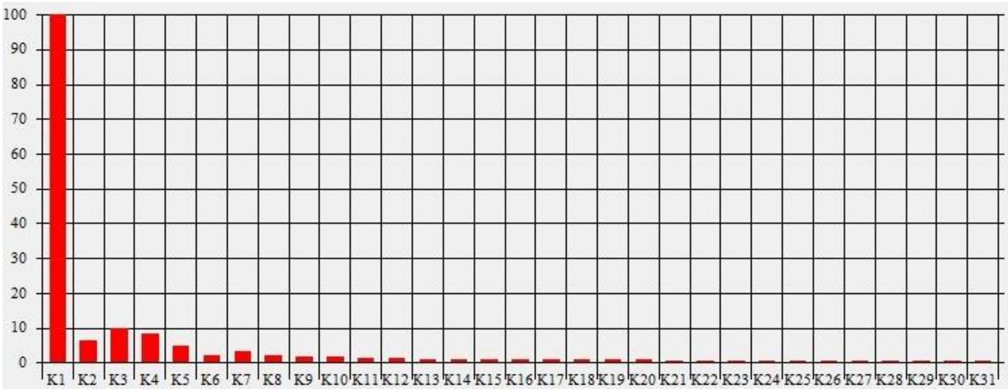

Figure 4. Case of finite power source (the onboard generators)

The weights in the signals for current and voltage harmonics, up to the harmonics no. 31, were obtained with FFT analyzes The harmonics weights allowed the automatic calculation of THD, and its values were:

• For 6-pulse converter:

- finite power source (the onboard generators):THD_I = 9.92% and THD_U = 4.54%;
- infinite power source (connection to shore electricity network): THD_I = 2,19% and THD_U = 1,73%;

• For welding machine case:

-finite power source (the onboard generators):THD_I = 10.37% and THD_U = 7.61%;
- infinite power source (connection to shore electricity network): THD_I = 3,14% and THD_U = 2,12%;

From the obtained values we could see a higher THD for the current harmonics in both situations.

3. Conclusion

The two analyzed cases highlighted the importance of monitoring the power system in terms of THD values. By determining the weight of each constituent harmonic of the signal it can be determined the most important contributors to the distortion of the useful signals, thus limiting their influence on the electric power system by installing filters with punctual action.

Under these circumstances many of equipment manufacturers (especially three-phase converters) take some measures to reduce the amplitude of harmonic currents, some of them declaring that their equipment is in compliance with G5/4-1 normative, although it is applicable to a complete installation not for each constituent equipment.

Under these conditions, by limiting the harmonics, there is the certainty that the power system will work properly, keeping the harmonic levels within the limits set by the regulation.

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