TECHNICAL TRANSACTIONS 11/2018
ELECTRICAL ENGINEERING
DOI: 10.4467/2353737XCT.18.166.9422
SUBMISSION OF THE FINAL VERSION: 29/10/18

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Measurement and simulation testing of harmonics in the on-board power grid of traction vehicles

Pomiary i badania symulacyjne harmonicznych w napięciu pokładowej sieci zasilania w pojeździe trakcyjnym

Abstract

The requirements relating to the emission of auxiliary AC supply sockets in traction vehicles have been extended in standard PN-EN 50121-3-2:2015 by voltage harmonics measurement. This applies to the public on-board AC supply grid which is accessible to all passengers. It is concerned with providing the quality of power supply which is required by computer devices and mobile phone rechargers. This article presents the requirements and test methods resulting from extended standard scope. Normative factors, for which levels of permissible voltage harmonics in the public supply grid of traction vehicle have been defined are discussed. Examples of comparative results obtained from measurements and analyses of voltage harmonics within on-board supply grids are also presented. The presented results include extended calculations of distortion factors for groups and subgroups of supply voltage harmonics. In order to improve the quality of voltage within the on-board grid, which did not meet the requirements, simulation calculations were performed and an additional output sinusoidal filter was proposed.

Keywords: electromagnetic compatibility, power quality, voltage harmonics, total harmonic distortion

Streszczenie

Wymagania dotyczące emisji portów pomocniczego zasilania AC w pojazdach trakcyjnych zostały w normie PN-EN 50121-3-2 z 2015 roku rozszerzone o pomiar w zakresie harmonicznych napięcia. Dotyczy to publicznej sieci zasilania pokładowego ogólnie dostępnej dla pasażerów. Związane jest to z zapewnieniem jakości zasilania, która jest wymagana dla urządzeń komputerowych oraz zasilaczy telefonów komórkowych. W artykule przedstawiono wymagania oraz metody badań wynikające z rozszerzonego zakresu normy. Omówiono normatywne współczynniki, dla których określone są poziomy dopuszczalne emisji harmonicznych w napięciu publicznej sieci zasilania w pojeździe trakcyjnym. Przedstawiono również przykładowe wyniki porównawcze uzyskane na podstawie pomiarów i analiz harmonicznych w napięciu pokładowej sieci zasilania. Prezentowane wyniki obejmują rozszerzone obliczenia współczynników odkształceń dla grup i podgrup harmonicznych napięcia zasilania. W celu poprawy jakości napięcia w sieci pokładowej, która nie spełniała wymagań normatywnych wykonano obliczenia symulacyjne i zaproponowano dodatkowy wyjściowy filtr sinusoidalny.

Słowa kluczowe: Kompatybilność elektromagnetyczna, jakość energii, harmoniczne w napięciu

1. Introduction

The requirements relating to the emission of auxiliary AC supply sockets in traction vehicles have been extended in standard PN-EN 50121-3-2:2015 by voltage harmonics. This applies to the public on-board AC supply grid which is accessible to all passengers. It is concerned with providing the quality of power supply which is required by computer devices and mobile phone rechargers.

The requirements on emission limits are specified in detail in PN-EN 50121-3-2 [1]; specific guidelines for conducting tests of voltage harmonics are specified in detail in PN-EN 61000-4-30 [2]. The supplement referred to in standard [2] is a general guideline for harmonics and interharmonics measurement PN-EN 61000-4-7 [3]. The issue of harmonic emission in traction vehicles has been the subject of a number of publications; however, the vast majority of these refer to harmonic distortion in traction current [6]. This is directly related to traffic safety due to the possible negative effects of higher frequency current signals on railway traffic control circuits [5, 8]. Therefore, the results of tests and analytical calculations of harmonic distortions in power supply in traction vehicles have been widely presented in publications [4, 7].

This article presents requirements and test methods resulting from the extended scope of the referenced standard. The standard factors for which harmonic emission limits in the public supply grids of traction vehicles are specified are discussed herein. Examples of comparative results obtained from measurements and analyses of voltage harmonics within on-board supply grids are also presented. The presented results calculations of the distortion factor for groups and subgroups of supply voltage harmonics. In order to improve the quality of voltage within on-board grids which did not meet the requirements, simulation calculations were performed and an additional output sinusoidal filter was proposed.

2. Methods of measurement of harmonic distortion in the supply voltage

The guidelines for harmonics measurements in AC voltage on-board grids in traction vehicles are specified in standard [1]. Two main measurement classes (A and S) and an additional class (B) are specified therein. The scope of parameters which should be determined in the test varies depending on the class used in the measurements. The measurement tools used in tests can measure either individual or all the parameters required in the standard but within the same class for all parameters. An example of the standard measurement chain with signal indication is shown in Fig. 1.

The most commonly used measurement tool is a LEM voltage transducer with galvanic isolation of an input and output circuit. This is an important element of the measurement path, and its parameters should meet the requirements of standard [1] in the scope of frequency band and phase response. The measurement unit (Fig. 1) is usually an analogue-to-digital transducer with an option to record the measured signal. An advanced software program with the option for FFT analysis is the used for the verification of measurements and compliance with the standard.

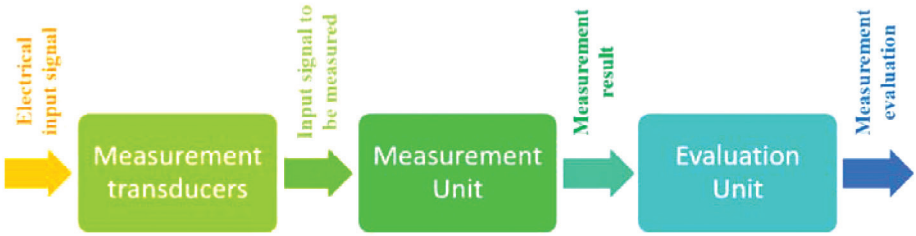

Fig. 1. Block diagram of measurement chain

Harmonic measurements can be made in single-phase or multi-phase power supply systems and, depending on the system and the needs, the following voltages can be determined: phase-neutral, phase-phase, phase-ground and neutral-ground. For traction vehicles, measurements are limited to a single-phase grid. Depending on the measurement class both in harmonic and interharmonic measurements, the standard specifies the maximum measurement order, the number of cycles included in the analysis, the required measurement uncertainty and the measurement range of the applied tools. Due to a huge number of measurement data items which require transmission recording, analysis and filing, data reduction is allowed using statistical methods or recording only the highest or average values.

3. Extended guidelines for the investigation of voltage harmonics in on-board supply grid

With regard to on-board AC supply grid in traction vehicle accessible to all passengers, the requirements relating to voltage harmonic emissions are included in PN-EN 50121-3-2. According to the standard, harmonic emission should be determined within the frequency range of 50 Hz to 2 kHz, whilst the indicator for the signal levels is total harmonic distortion (THD). The limit value of harmonic distortion is THD = 8%. The basic standard to carry out measurements in this scope is PN-EN 61000-4-30; however, the details are specified in PN-EN 61000-4-7.

THD is defined as:

$$THD = \sqrt{\sum_{n=2}^{H} \left(\frac{U_n}{U_1} \right)^2} \tag{1}$$

where:

- U_n – effective (r.m.s.) value of the n*th* harmonic,
- U_1 – effective (r.m.s.) value of fundamental harmonic,
- n – harmonic order,
- H – maximum harmonic order.

In addition to the basic definitions of harmonic and interharmonic effective (r.m.s.) values, PN-EN 61000-4-7 introduces the effective values of a harmonic group and subgroup, as well as the effective values of an interharmonic group and subgroup. The corresponding definitions of total distortion factors are also specified therein. The introduction of the effective value of a harmonic group and subgroup, which is calculated as a square root of the sum of squares of the harmonic value and its neighbouring spectral components, aims to improve the measurement accuracy in order that, for example, in the case of the effective value of the harmonic subgroup include the impact of fluctuations of values such as measured voltage.

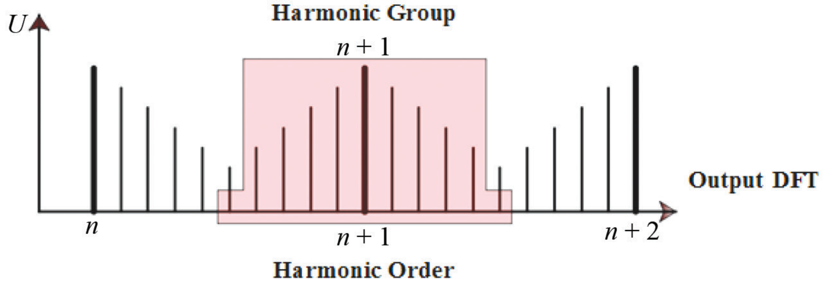

Fig. 2. Illustration of the harmonic group for a 50 Hz power supply network

The resultant r.m.s. value of the voltage harmonic group $U_{g,n}$ is defined as:

$$U_{g,n}^2 = \frac{U_{k-5}^2}{2} + \sum_{i=-4}^{4} U_{k+i}^2 + \frac{U_{k+5}^2}{2} \tag{2}$$

where:

U_{k+i} – r.m.s value of spectral component.

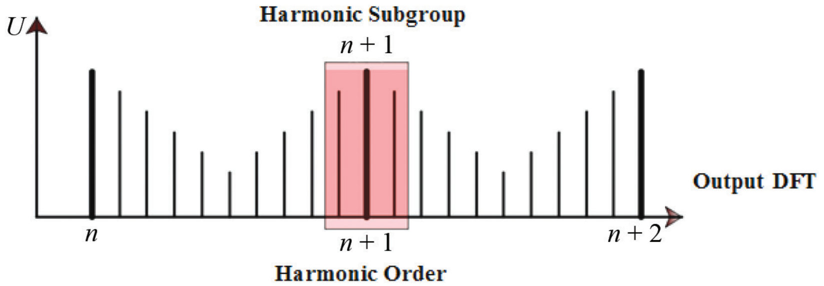

Fig. 3. Illustration of the harmonic subgroup for a 50 Hz power supply network

The resultant r.m.s. value of the voltage harmonic subgroup $U_{sg,n}$ is defined as:

$$U_{s,g,n}^2 = \sum_{i=-1}^{1} U_{k+i}^2 \tag{3}$$

where:

U_{k+i} – r.m.s. value of spectral component.

The group total harmonic distortion THDG is:

$$THDG = \sqrt{\sum_{n=2}^{H} \left(\frac{U_{gn}}{U_{g1}} \right)^2} \tag{4}$$

where:

U_{gn} – effective (r.m.s.) value of the n*th* harmonic group,
U_{g1} – effective (r.m.s.) value of the group fundamental,
n – harmonic order,
H – maximum harmonic order.

The subgroup total harmonic distortion THDS is:

$$THDS = \sqrt{\sum_{n=2}^{H} \left(\frac{U_{sgn}}{U_{sg1}} \right)^2} \tag{5}$$

where:

U_{sgn} – effective (r.m.s.) value of the n*th* harmonic group,
U_{sg1} – effective (r.m.s.) value of subgroup fundamental,
n – harmonic order,
H – maximum harmonic order.

4. Test results of supply voltage harmonic distortion in on-board grid

The presented measurement results derive from the tests which have been carried out for several selected on-board power supply grids in traction vehicles. The measuring setup consisted of a LEM voltage transducer with galvanic isolation, a DEWE43 analogue-to-digital transducer with the option to continuously record signals on an external computer and an autonomous power supply system. The obtained results of voltage measurements to determine the harmonics were subjected to FFT analysis in Matlab software and compiled on charts for the purpose of comparison. Calculations included 10 cycles of voltage signal using a rectangular-shaped window and the maximum harmonic order was 40. The indicators for determining the compliance of power supply parameters with standard [1] were calculated.

Time waveform and voltage supply harmonic distortion (Us1) in the 230 V AC on-board grid in the traction vehicle, in which the sinusoidal wave-forming methods were not applied are shown in Fig. 4. The results for on-board grids (Us2 and Us3) in which output filtering systems were applied are shown in Figs. 5 & 6. To compare time waveforms and on-board voltage supply harmonic distortions; Figs. 7 & 8 show the results obtained for typical power supply (Us4) and uninterruptible power supply UPS (Us5), respectively.

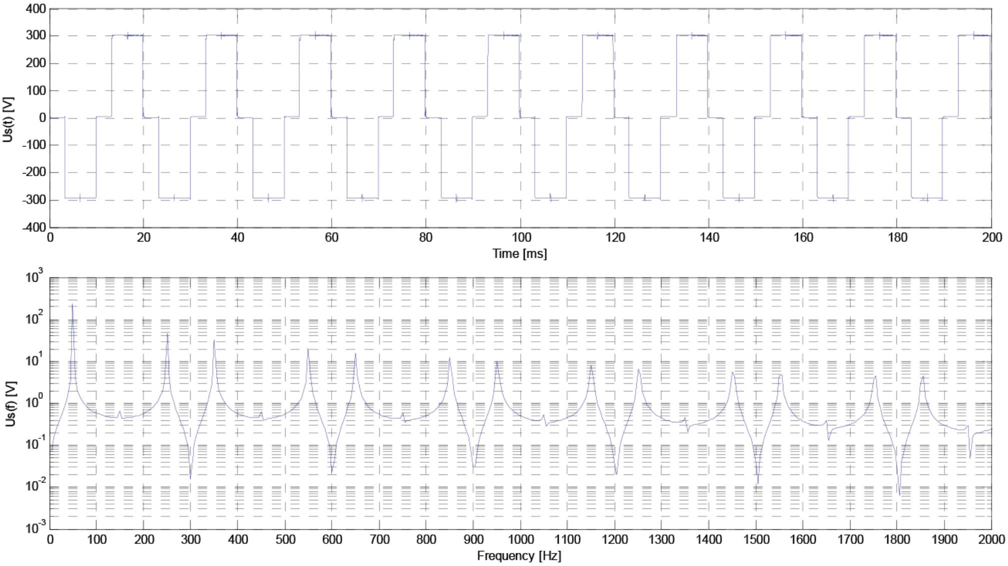

Fig. 4. Variable component of voltage supply and voltage harmonic spectrum (Us1)

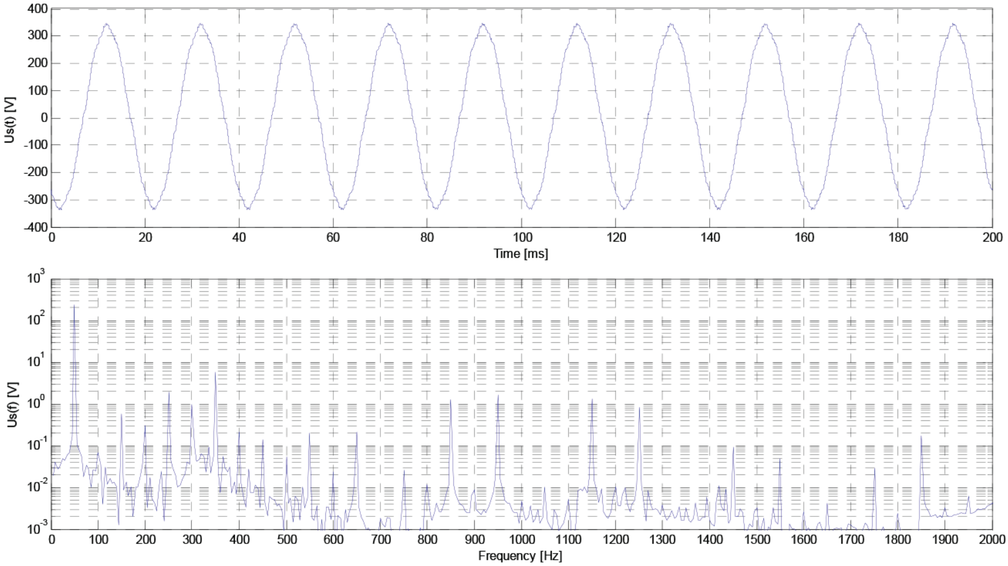

Fig. 5. Variable component of voltage supply and voltage harmonic spectrum (Us2)

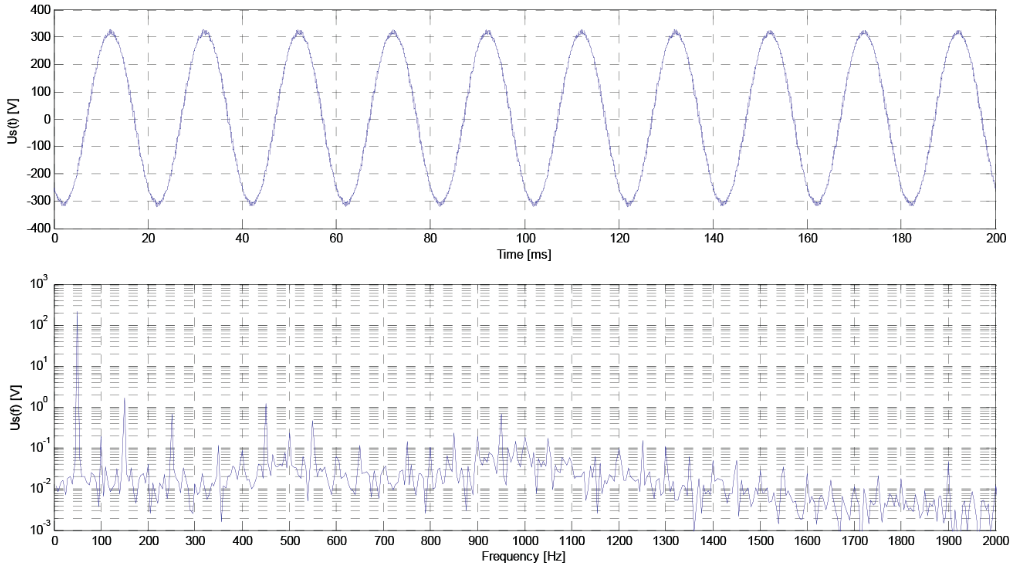

Fig. 6. Variable component of voltage supply and voltage harmonic spectrum (Us3)

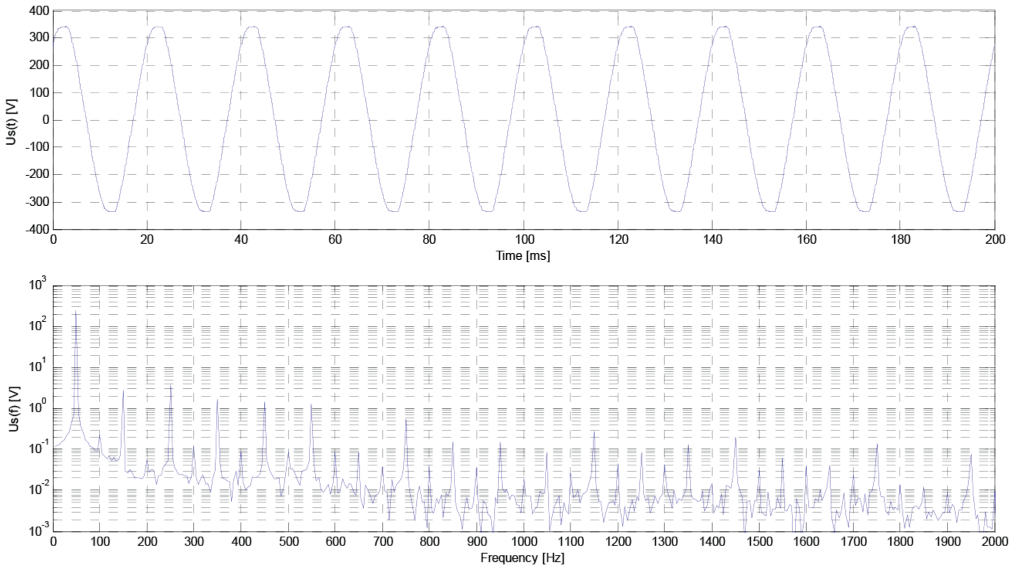

Fig. 7. Variable component of voltage supply and voltage harmonic spectrum (Us4)

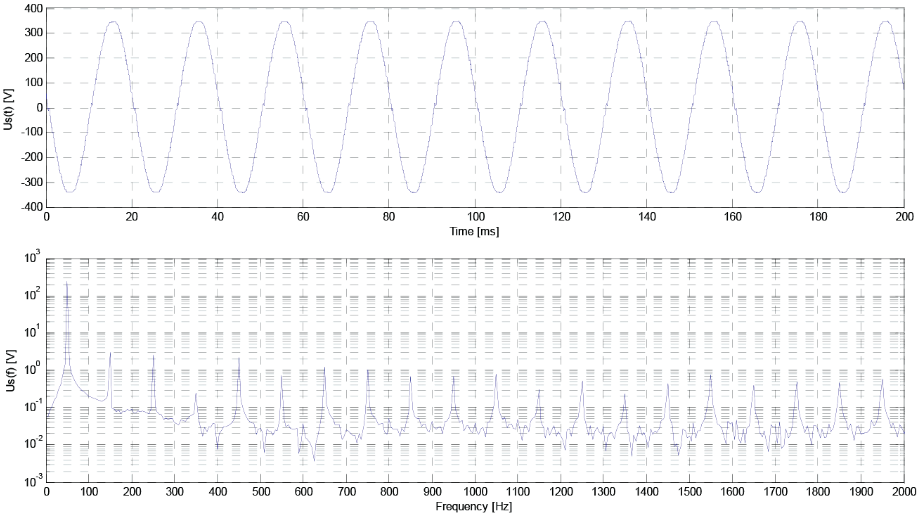

Fig. 8. Variable component of voltage supply and voltage harmonic spectrum (Us5)

A summary of the results of the individual harmonics for the three selected on-board power supply grids in traction vehicles is shown in Fig. 9. The comparison refers only to odd harmonics due to their dominant share in the spectrum.

Based on the determined levels of individual harmonics, the factors characteristic of total harmonic distortion in the 230 V AC supply in traction vehicles were calculated and are shown in Table 1. In addition to the basic THD factor, the group total harmonic distortion (THDG) and subgroup total harmonic distortion (THDSG) factors were also determined. For the purpose of comparison, the table also includes the total harmonic distortion for a typical power supply and an uninterruptible power supply.

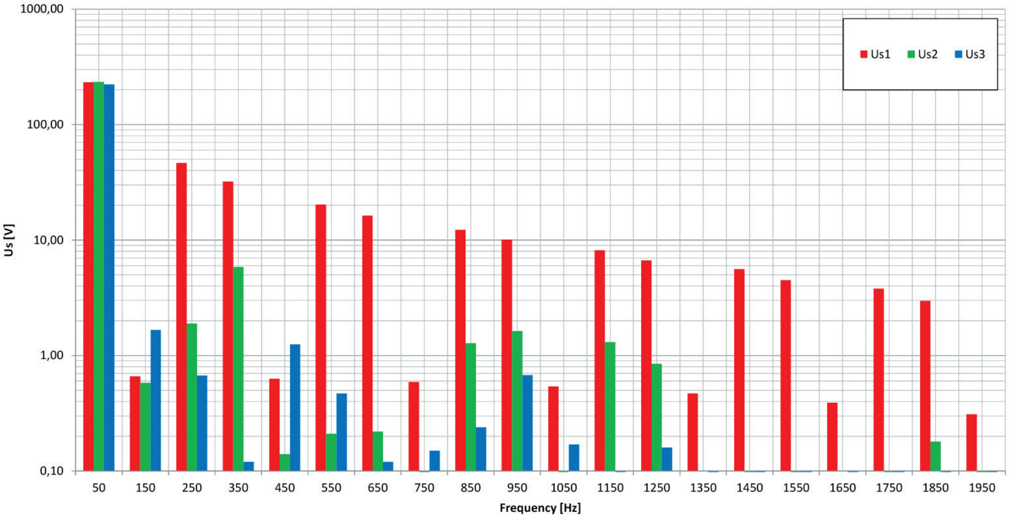

Fig. 9. Comparison of harmonic distortion in the on-board supply voltage

Table 1. Factors characteristic of harmonic distortion in selected grids

Factor	Us1	Us2	Us3	Us4	Us5
THD [%]	28.22	2.89	1.09	2.25	2.15
THDG [%]	29.66	2.89	1.11	2.25	2.21
THDSG [%]	29.23	2.89	1.09	2.25	2.17

The determined harmonic distortion factors in the investigated 230 V AC on-board grid in traction vehicles (Us1, Us2, Us3) show significant variation. Odd harmonics have a key impact on the value of this factor for all tested grids. The collation of THD for on-board supply with THD for the typical power supply (Us4) and the uninterruptible power supply UPS (Us5) shows that the THD for on-board supply grid in which output waveforming systems are applied (Us2 and Us3) is comparable to the THD for a typical power supply. In one case, for grid Us3 the THD is even better than the THD for a typical power supply. The results for on-board grids with output filtering systems meet the requirements of PN-EN 50121-3-2, as the determined THD factors are less than 8%. Further calculations of THDG for group harmonic distortion and THDSG for subgroup harmonic distortion have confirmed that in a properly conducted FFT analysis, no significant differences are observed. It does not mean, however, that the methods of harmonic grouping presented herein, and detailed in PN-EN 61000-4-7, cannot be useful for improving the accuracy of determining both voltage harmonics as well as harmonic distortion. The impact of the methods on the result is dependent upon the type of supply grid, its parameters and the applied FFT analysis.

5. Simulation testing of an additional input filter

As part of the tests a solution was proposed to improve the quality of the on-board voltage of the traction vehicle. The 230 V AC on-board voltage is obtained from the three-phase 3 × 400/230 V output of the auxiliary converter powered by full-line overhead contactors. This converter supplies the three-phase voltage primarily to the main drive cooling fan motors and to the heating system blower motors. Due to the high harmonic content of the 230 V AC on-board power grid and the THD value of 28.22%, which does not meet the requirements of PN-EN 50121-3-2 (THD < 8%), the output filter was proposed. The output sinusoidal filter is an example of a passive low pass second order LC filter. The filter shapes the sinusoidal voltage by suppressing the higher harmonics in the on-board grid. The resonance frequency of the filter falls between the primary supply frequency and the lowest harmonic frequency resulting from the control algorithm. The capacity of the filter capacitor should compensate for the reactive power of the engine connected to this power supply grid and for the fall in voltage in the filter inductance. In addition to a smoothed sinusoidal waveform, this filter protects both the engine and engine cable against high du/dt values and overvoltage by limiting further losses in the engine. This generally improves the reliability of the converter drive system. Due to the electrical structure of the on-board grid subjected to testing, in which a three-phase isolation transformer at the output of the inverter was applied, the selection of the filter had to take into account the influence of the parameters of this transformer. Converter loads are inductive engines operating in variable configurations that have been replaced in the simulation by one substitute. A flowchart of the converter system modelled in Matlab Simulink is shown in Fig. 10. In order to represent the actual shape of the voltage obtained from the measurements for grid 1 (Fig. 4), the waveform (Fig. 11) was outlined in the simulation, the parameters of which reflect the actual waveform. After the selection and activation of the sinusoidal filter to the system shown in Fig. 10, a sinusoidal phase voltage waveform was generated as shown in Fig. 12. The analysis of the obtained waveform showed a significant decrease in the level of higher harmonics (Fig. 13) and the THD factor (Table 2). The results of the simulations show that the use of a properly selected output sinusoidal filter enabled sinusoidal shaping of voltage in the 230 V AC on-board network as well as reducing the THD = 2.73% to a level acceptable by PN-EN 50121-3-2.

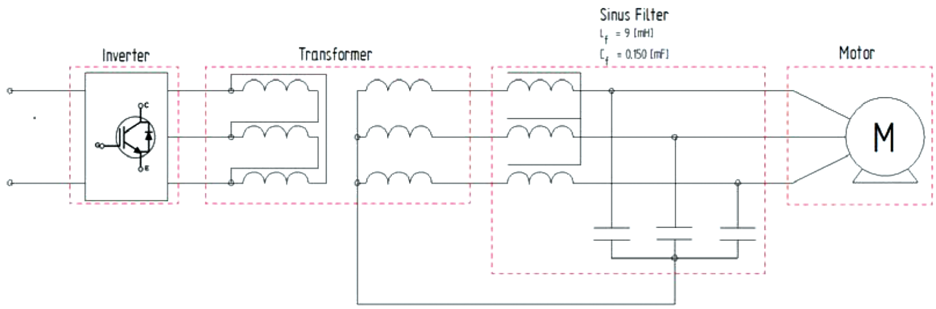

Fig. 10. Flowchart of the converter system modelled in Matlab Simulink

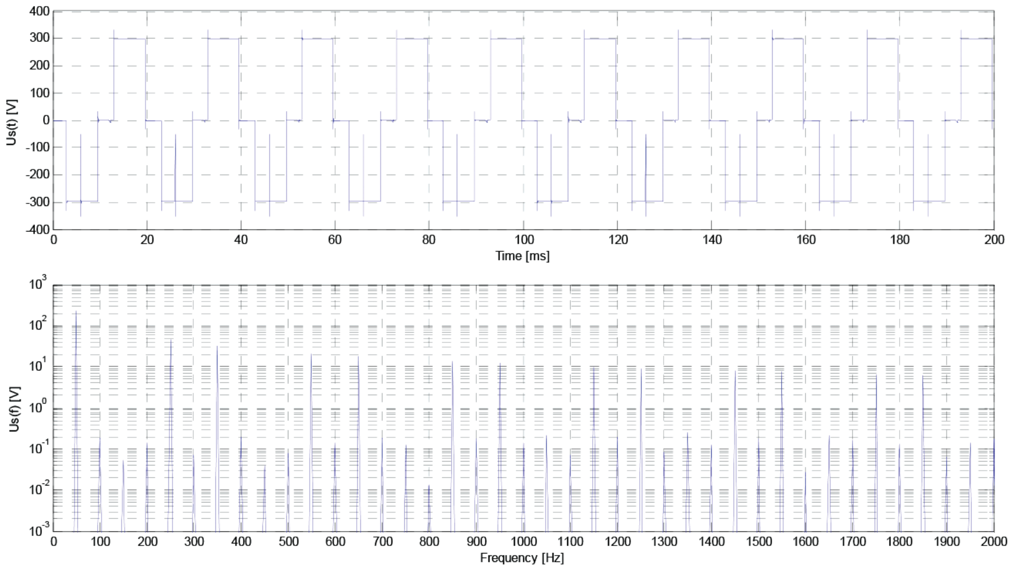

Fig. 11. Variable component of voltage supply and voltage harmonic spectrum – simulation without filter

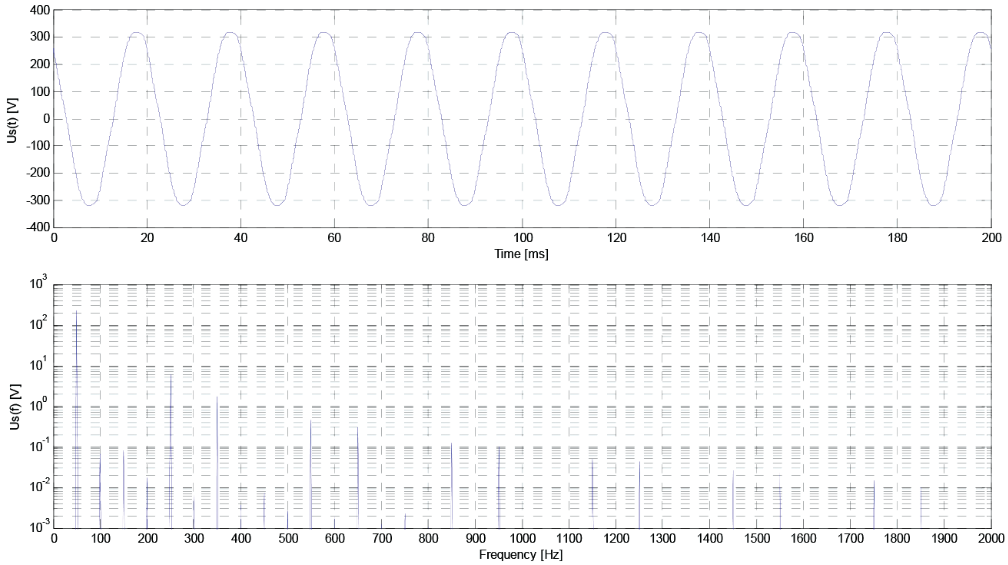

Fig. 12. Variable component of voltage supply and voltage harmonic spectrum – simulation with filter

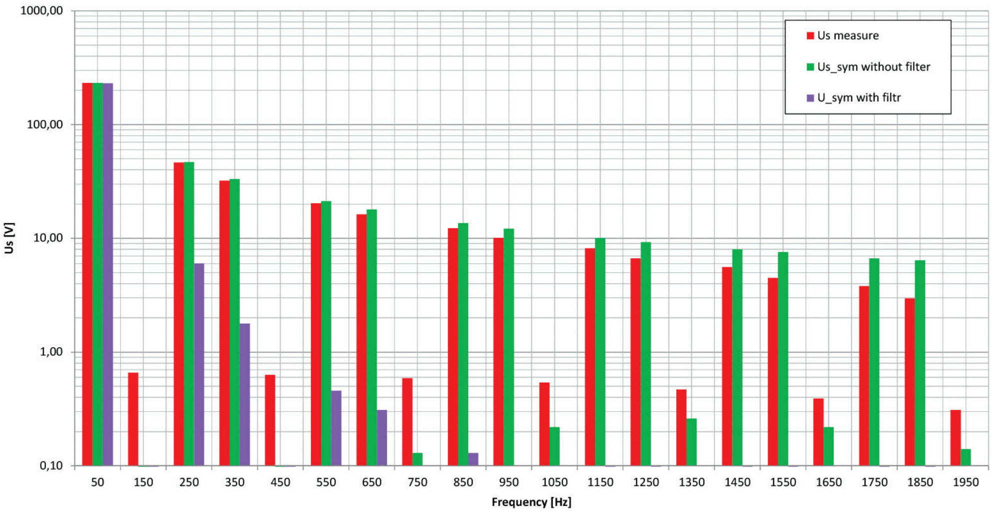

Fig. 13. Comparison of harmonic content in on-board power supply – measurement, simulation without filter, simulation with filter

Table 2. Factors characteristic to harmonic distortion – measurement, simulation without filter, simulation with filter

Factor	Us1	Us without filter	Us with filter
THD [%]	28.22	29.76	2.73
THDG [%]	29.66	29.76	2.73
THDSG [%]	29.23	29.76	2.73

6. Summary

The guidelines outlined in this article for testing the quality of an on-board 230 V AC grid and the results of the measurements conducted for the selected grids provide an overview of the need to ensure the required quality of power supply. The tests performed for selected on-board grids in traction vehicles in which sinusoidal output voltage waveforming methods were applied meet the requirements of PN-EN 50121-3-2. The results of the calculation of the total harmonic distortion for these grids show a comparable quality of voltage for both a typical power supply and an uninterruptible power supply. Further calculations for group harmonic distortion and subgroup harmonic distortion have shown that in properly conducted FFT analysis, no significant differences are observed. The harmonic grouping methods presented herein and detailed in PN-EN 61000-4-7 may, however, be useful for improving the accuracy of the determination of both voltage harmonics and harmonic distortion. The results of the simulations show that the use of a properly selected output sinusoidal filter enabled sinusoidal shaping of voltage in the 230 V AC on-board network as well as reducing the THD to the level acceptable by PN-EN 50121-3-2.

The results presented in the article, carried out within the project ref. E4/511/2016/DS., were financed by the grant awarded by the Ministry of Science and Higher Education.

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If you want to quote this article, its proper bibliographic entry is as follow: Czuchra W., Woszczyna B., *Measurement and simulation testing of harmonics in the on-board power grid of traction vehicles*, Technical Transactions, Vol. 11/2018, pp. 105–118.