Analysis of second order harmonic voltages in power systems

Julio Barros, Matilde de Apráiz and Ramón I. Diego

Department of Electronics and Computers
Escuela Técnica Superior de Náutica, University of Cantabria
Dique de Gamazo 1, 39004 Santander, Spain
Phone: (+34) 942201355, Fax: (+34) 942201303, email: barrosj@unican.es, apraizm@unican.es, diegori@unican.es

Abstract. Second order harmonic components, and in general even harmonics, produce asymmetries in voltage and current waveforms that can lead to undesirable effects on power system loads. Until now, the level of the second order voltage harmonic has not been investigated in depth in power systems. This paper reports the results of the monitoring of second order voltage harmonic group and subgroup, as defined in IEC harmonic measurement standards, in a low-voltage distribution systems and the effect on the asymmetry in voltage waveforms.

Keywords

Harmonics, Power distribution systems, Power quality

1. Introduction

Even order harmonic components are undesirable power system components that produce asymmetries between positive and negative half-waves in voltage and current waveforms. Nonlinear loads with asymmetrical i-v characteristics inject even harmonic currents that, when circulating through the power system, produce even harmonics in voltage waveforms. Half-wave rectifiers, half-controlled converters, arc furnaces or electrical discharge devices are examples of asymmetrical loads.

It is well known that even order harmonics produce higher detrimental effects in power system loads than odd order harmonics. For this reason international power quality standards define very strict limits for even order harmonic components. Thus, as an example, Table I shows the individual limits for even order harmonics in voltage supply defined in European Standard EN 50160 in public distribution systems [1].

Recent studies have shown that low levels of second order harmonics in voltage supply, as low as 1% of the fundamental component, may cause important effects in equipment, especially equipment sensitive to peak values, such as power control devices which regulate firing control based on zero crossing times or single phase rectifiers and elementary battery chargers that may produce high levels of direct current [2]. Due to these effects, it has been suggested that stricter limits for the second order harmonic voltages than the existing ones could be necessary.

TABLE I. Maximum values of individual even harmonic voltages at the supply terminal in public distribution networks according to EN50160

Even harmonics	
Harmonic order	% of nominal voltage
2	2 %
4	1 %
6..24	0.5 %

There are not many studies reporting the magnitude of second order harmonics and other even harmonics in distribution networks. As a general rule the magnitude of the second order voltage harmonic is lower than 0.2% of the nominal voltage, but in specific power networks higher magnitudes of this harmonic component can be found.

The purpose of this paper is to contribute to the knowledge of the existing levels of second order harmonic group and subgroup in voltage supply, reporting the results of several weeks monitoring of this harmonic component in a low voltage distribution systems, as well as an study of the asymmetry of the voltage waveform and its possible relation with the even order harmonic distortion.

2. Even order harmonics and asymmetry factor

As it was previously stated, the main effect that produces even harmonics is the asymmetry of voltage or current waveforms. The r.m.s. magnitude of the even harmonic components or their percentages with respect to the fundamental component do not give an exact representation of the asymmetry between the positive and negative half-cycles of voltage or current waveforms. To this purpose, the asymmetry factor (AF), as defined in [3], can be used to characterize the difference between the positive and negative peak values of a signal.

$$AF = \frac{V_{pp} - |V_{pn}|}{V_1} \quad (1)$$

where V_{pp} and V_{pn} are the positive and negative peak values of voltage waveform and V_1 is the nominal voltage.

The asymmetry factor is a function of the magnitude and phase angle of the even harmonic components. Figure 1 shows the asymmetry factor as a function of the magnitude and phase angle of the second order harmonic component. As can be seen, higher harmonic magnitude produces higher asymmetry in voltage waveform. Furthermore, for each magnitude of the second order harmonic, the AF value presents a maximum when the phase angle of the second harmonic is 90º or 270º and a minimum of 0% for 0º and 180º phase angles.

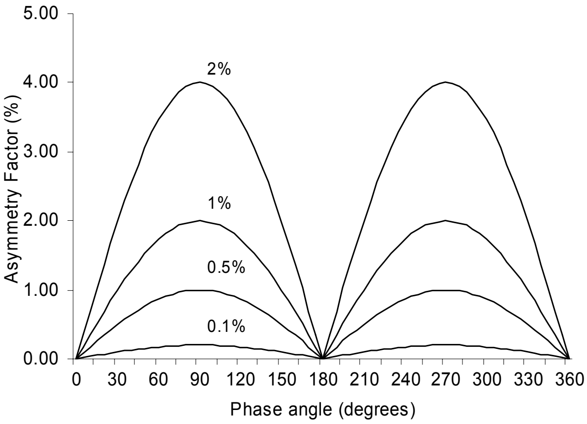


Figure 1. Asymmetry factor as a function of magnitude and phase angle of second order harmonic

3. Harmonic and interharmonic groups and subgroups in voltage and current waveforms

IEC-61000-4-7 defines a harmonic group as the grouping of a harmonic component and the spectral lines adjacent to it within the time window according to equation (2), obtained applying the DFT analysis to the samples of voltage or current waveforms.

$$G_{g,n}^2 = \frac{C_{k-5}^2}{2} + \sum_{i=-4}^{4} C_{k+i}^2 + \frac{C_{k-5}^2}{2} \quad (2)$$

where $G_{g,n}$ is the r.m.s. value of a harmonic group of order n, C_k is the amplitude of the Fourier component of order k, being k= N*n (N=10, the time window width in a 50 Hz system).

The harmonic subgroup of order n is defined as the grouping of the harmonic component of order n and their two directly adjacent spectral components (equation 3).

$$G_{sg,n}^2 = \sum_{i=-1}^{1} C_{k+i}^2 \quad (3)$$

The first of the two definitions is used when only harmonics are evaluated, whereas the second definition is used when harmonics and interharmonics are evaluated separately, as is the case of assessment of interharmonics producing equipment.

According to this definition, the second order harmonic group covers the frequency bins from 75 to 125 Hz, whereas the second order harmonic subgroup only covers the frequency bins from 95 to 105 Hz. Figure 2 shows the grouping of spectral lines for the harmonic group and subgroup of order 2.

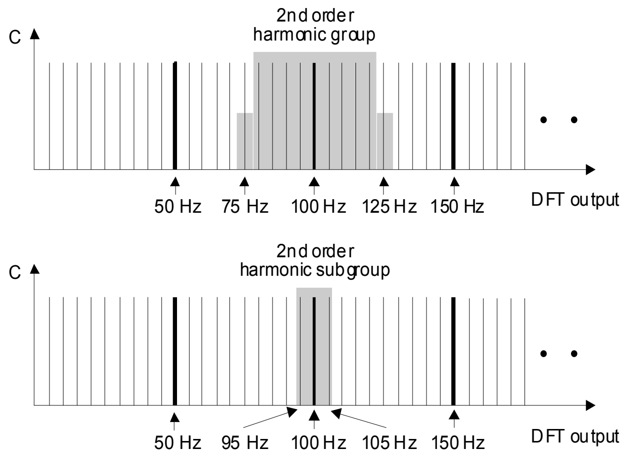


Figure 2. Grouping of output bins of the DFT analysis for harmonic group and subgroup of order 2

On the other hand, interharmonic groups and subgroups are defined as grouping of spectral lines using equations (4) and (5)

$$C_{ig,n}^2 = \sum_{i=1}^{9} C_{k+i}^2 \quad (4)$$

$$C_{isg,n}^2 = \sum_{i=2}^{8} C_{k+i}^2 \quad (5)$$

where $C_{ig,,n}$ and $C_{isg,,n}$ are the r.m.s. values of the interharmonic group and interharmonic subgroup of order n respectively.

4. Experimental results

A low-cost VI-based measurement equipment has been developed for the measurement of harmonics and interharmonics in voltage supply according to standard IEC-61000-4-7 [4].

The measurement equipment is made up of three Hall-effect voltage transducers, a USB data acquisition board, a phase locked loop and a labtop computer. A software module using the LabVIEW graphical programming environment has been developed for the measurement of harmonics and asymmetries in voltage supply waveform.

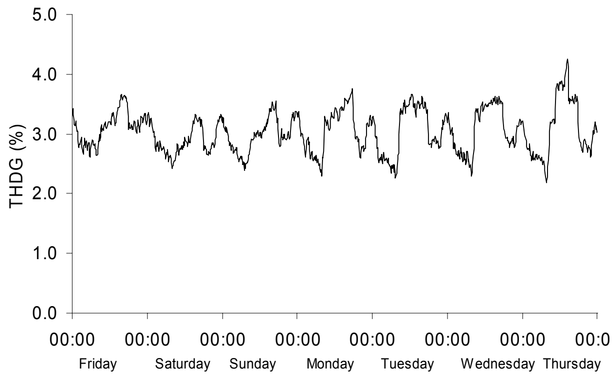
For analysis of harmonics, a 3.2 kHz sampling frequency has been selected, using synchronized rectangular sampling windows of ten cycle width of the fundamental frequency (200 milliseconds) and applying DFT analysis.

The output bins of the DFT, with a resolution of 5 Hz, are grouped according to IEC 61000-4-7 to compute harmonic and interharmonic groups and subgroups in the input signal. Aggregation times of 3 seconds, 10 minutes and 2 hours, as proposed in IEC-61000-4-30 [5], have been used for assessment of voltage harmonics and interharmonics. In addition, individual frequency components from 75 to 125 Hz, in 5 Hz steps, are separately registered to the in-depth analysis of the second order harmonic group and subgroup.

On the other hand, for the analysis of the asymmetry in voltage waveform, the positive and negative peak values are registered in the ten consecutive cycles of the sampling window and the magnitude of AF is computed for this basic measurement interval. The same aggregation time intervals of 3 seconds, 10 minutes and 2 hours are used for the assessment of this factor.

The data reported have been taken in the low-voltage distribution network of a building located on our campus. The building is supplied by a 12 kV/380 V three-phase distribution transformer. A large percentage of the load consists of lighting, computers and other information technology equipment. There are also several laboratories in the building with rotating machines, electromechanical apparatus and also electrical welding installations.

As an example, Figure 3 shows the group total harmonic distortion (THDG), the r.m.s. magnitude of the second order harmonic group and subgroup and the asymmetry factor (AF), all expressed as a percentage of the fundamental component, measured during one week (from 8th to 14th December last year) and using 10-minute aggregation time interval.



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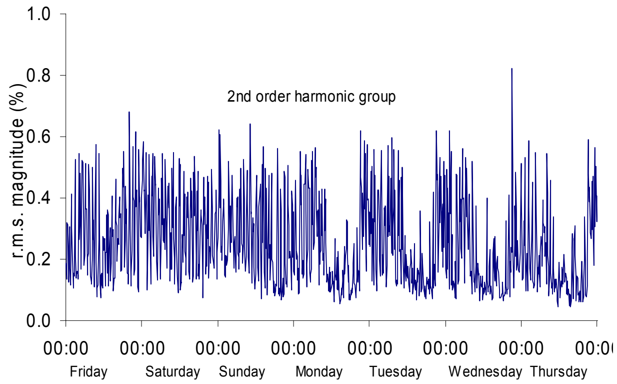

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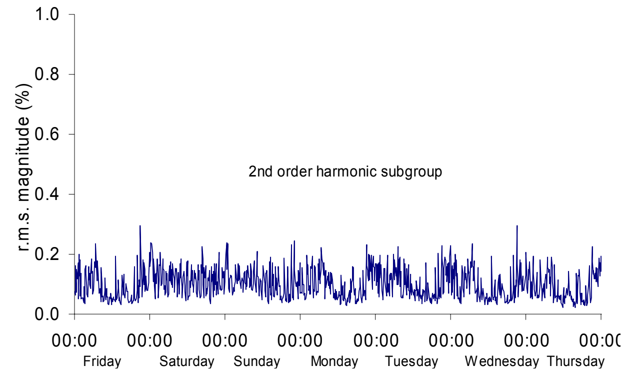

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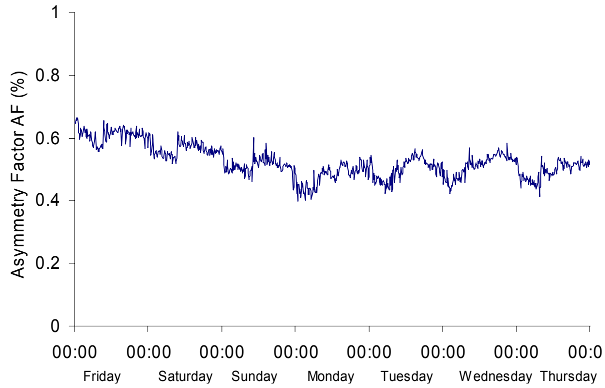


d)

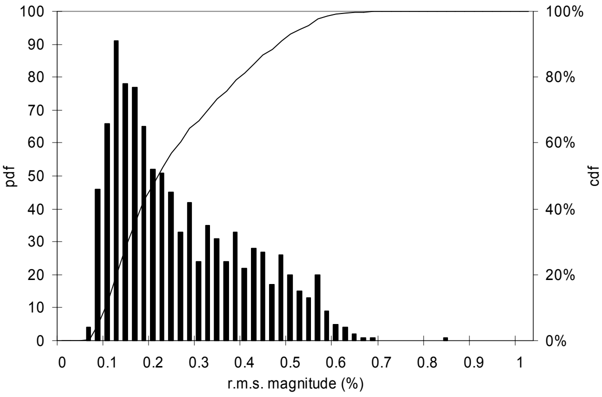
Figure 3. Weekly evolution of a) THDG, b) r.m.s. magnitude of second order harmonic group c) second order harmonic subgroup and d) asymmetry factor AF.

As can be seen, the THDG shows the typical daily variation with maximum magnitudes during the afternoon and minimum values at night, where the fifth order harmonic group is dominant. The maximum and minimum values recorded during the monitoring time were 4.24% and 2.19% respectively, with a mean value of 2.19% of the fundamental component.

On the other hand, the second order harmonic group in voltage waveform, which groups the spectral lines from 75 to 125 Hz, varies from a minimum of 0.044% to a maximum of 0.82%, with a mean value of 0.25% of the fundamental component, whereas the second order harmonic subgroup (spectral lines 95, 100 and 105 Hz), shows the same pattern as the harmonic group, with a range from a minimum of 0.023% to a maximum of 0.29%, and a mean value of 0.1%, approximately 50% of the harmonic group. This means that the contribution of the spectral lines included in the second order harmonic group, but outside of the range of the second order harmonic subgroup is of the same order.

Figure 3.d shows the weekly evolution of the asymmetry factor in voltage waveform, using 10-minute aggregation intervals. As can be seen, the AF magnitude shows similar time evolution to the THDG, with peak values corresponding approximately to peak magnitudes in the second order harmonic group and subgroup. The range of AF values during the monitoring period varies from 0.39% minimum to 0.66% maximum, with mean value of 0.52% of the fundamental component.

Figure 4 shows the probability density functions (pdf) and cumulative density functions (cdf) of the r.m.s. magnitude of the second order harmonic group and subgroup and the asymmetry factor AF of the data in Figure 3.



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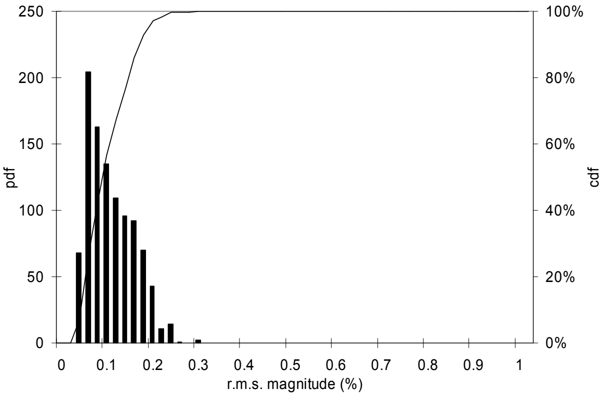

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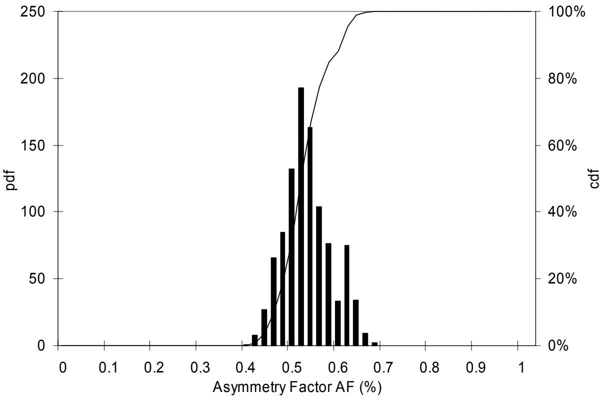

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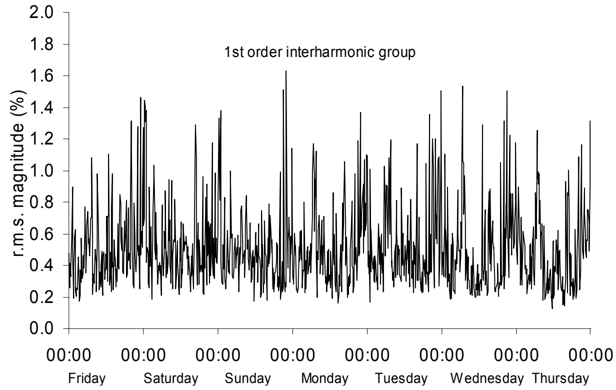
Figure 4. Probability and cumulative density functions of the data in Figure 3, a) second order harmonic group, b) second order harmonic subgroup, c) asymmetry factor

Finally, Figure 5 shows the weekly evolution of the r.m.s. magnitudes of the first order interharmonic group (frequency components from 55 to 95 Hz in 5 Hz steps), and the second order interharmonic group (frequency components from 105 to 145 Hz in 5 Hz steps) in voltage supply, measured using 10-minutes aggregation time interval and expressed as a percentage of the fundamental component, as well as the magnitude of the short-term flicker severity index P_{st}, simultaneously measured using a Fluke 435 Power Quality Analyzer, during the same monitoring period.

First of all as was reported in a previous paper [6], the high magnitude of the P_{st} flicker severity index and the magnitude of the first and second order interharmonic groups in voltage supply, due to a 50 MVA arc furnace in an steel factory in the nearby area, as well as the close time relationship between them should be highlighted. The same time evolution can be seen in the r.m.s. magnitude of the second order harmonic group and subgroup in voltage supply as can be seen from the comparison of the results obtained.



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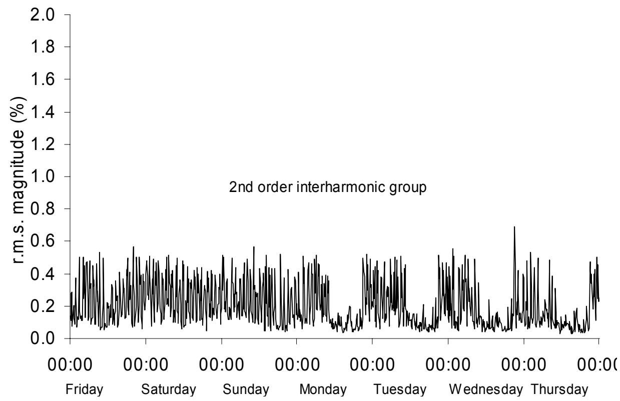

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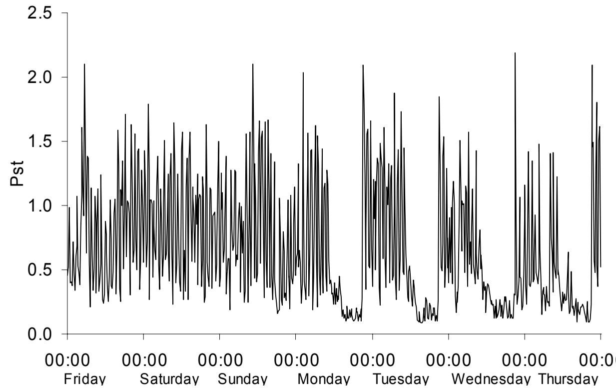

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Figure 5. Weekly evolution of the r.m.s. magnitude of the first order and second order harmonic groups and Pst flicker severity index

5. Conclusion

The paper presents the results obtained in the monitoring of the second order harmonic group and subgroup in voltage supply as well as the asymmetry in voltage waveform measured in a low-voltage distribution network. The r.m.s. magnitude of the second order harmonic group is the maximum range of 0.82% of the fundamental component, within the accepted range proposed in EN50160, but higher than the expected value, showing a close correlation with the flicker severity index and the r.m.s. magnitudes of the first order and second order interharmonic groups in voltage supply. On the other hand, the magnitude of the asymmetry factor in voltage waveform is less than 0.66% of the fundamental voltage during the time of monitoring, and shows similar patterns to the THDG, with peak values corresponding to peak magnitudes in the second order harmonic group and subgroup.

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References

[1] European Standard EN 50160, Voltage Characteristics of Electricity Supplied by Public Distribution Systems, 1999.

[2] J.A. Orr, A.E. Emanuel, "On the need for strict second harmonic limits", IEEE Transactions on Power Delivery, Vol. 15, No. 3, July 2000, pp. 967-971.

[3] G.T. Heydt, Y. Liu, "Second harmonic components in power system voltages and currents", IEEE Transactions on Power Delivery, Vol. 20, No. 1, January 2006, pp. 521-523.

[4] IEC Standard 61000-4-7. Electromagnetic compatibility (EMC), Part 4-7: Testing and measurement techniques - General guide on harmonics and interharmonics measurements and instrumentation, for power supply systems and equipment connected thereto. Second edition, 2002.

[5] IEC Standard 61000-4-30. Electromagnetic compatibility (EMC), Part 4-30: Testing and measurement techniques – Power quality measurement methods. First edition, 2003.

[6] J. Barros, E. Pérez A. Pigazo, R.I. Diego, "Simultaneous measurement of harmonics, interharmonics and flicker in a power system for power quality analysis", Fifth International Conference on Power System Management and Control (IEE Conf. Publ. No.488). IEE, London, UK, April 2002, pp. 100-105.