# THE POWER QUALITY AND THE MEASUREMENT OF HARMONICS

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*This paper has a purpose to explain the concept of harmonics at Low Voltage Supply Systems, which are part of the Power Quality Measurements. The work describes the main sources of the harmonic voltages and currents, the effects of harmonics, and the objectives of power quality measurement. In this work are given also the values of individual harmonic voltages in percentage of the nominal voltage correspondent to EN50160. It is shown and described the block diagram of analog front end circuit for measuring the harmonics of three phase 4-wire power supply network. The results of all studies are explained and the conclusion is made at the end of the paper.*

**Keywords:** Power Quality, Harmonics, Total Harmonic Distortion

## 1. INTRODUCTION

Both electricity distribution networks and consumers' equipment are affected by harmonic distortion of the voltage waveform. Harmonic distortion levels have increased rapidly in electric power systems in recent years due primarily to the increasingly widespread application of non-linear semiconductor devices, which produce the majority of harmonic distortion.

In particular, switched-mode power supplies have over the last twenty years increasingly replaced transformer/rectifier power supplies in electronic equipment. These cause large 5th harmonic emissions, relative to the rated power consumption of the equipment, which are not randomly orientated in-phase and so are strongly additive.

## 2. DEFINITION OF HARMONICS

Harmonics are sinusoidal voltages or currents having frequencies that are multiples of the fundamental frequency - at which the supply system is designed to operate (e.g. 50 Hz in Europe).
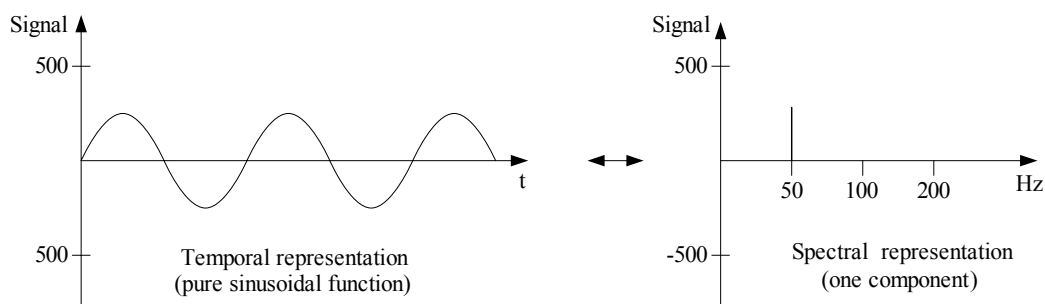


Fig. 1

An electric power supply system is inherently very passive and the generator outputs and voltages measured on the system would be nearly sinusoidal at the declared frequency if no load was connected to the system. For a pure sinusoidal voltage wave, with 50 Hz frequency and 230 V amplitude, the spectrum is equal to zero for all frequencies except 50 Hz, for which the value is 230 V.

For a distorted voltage wave, the spectrum contains harmonic frequencies which are characteristic of the nature of distortion. The fundamental is the component of the spectrum at which the network is designed to work. It is normally the first and greatest component of the spectrum. The term Total Harmonic Distortion (THD) is used to describe the r.m.s. sum of the voltages of all harmonic frequencies that are present relative to the fundamental.

All periodic functions (of frequency f) can be broken down into a sum of sinusoidal waves of frequency h x f (h > 1 is an integer of the harmonic order). The first order component is the fundamental component.
The mathematical expression of periodic function is:

$$y(t) = Y_0 + \sum_{h=1}^{\infty} Y_h \sqrt{2} \sin(2\pi hf + \varphi_h) \quad \text{Equation (1);}$$

The rms is:

$$Y_{eff} = \sum_{h=1}^{\infty} Y_h \sqrt{Y_0^2 + Y_1^2 + Y_2^2 + Y_h^2 + ...} \quad \text{Equation (2);}$$

The THD (Total Harmonic Distortion) factor measures the signal distortion:

$$THD = \sqrt{\sum_{h=2}^{\infty} \left( \frac{Y_h}{Y_1} \right)^2} \text{ , h=2 to 40, limited in EN50160;} \qquad \text{Equation (3).}$$

### 3. POWER QUALITY REQUIREMENTS TO THE HARMONICS VALUES PUBLISHED IN EN50160 STANDARD

The general approach of EN 50160 is to express all voltage characteristics by reference to the nominal voltage or declared voltage, as appropriate. However, it is typical for measurement instruments to reference harmonic measurements to the value of the fundamental voltage at the time of measurement.

Thus, although it defines harmonic voltages in relation to the fundamental voltage. It gives LV (Low Voltage) values (Table 1) in relation to the nominal voltage, and MV (Medium Voltage) values (not shown in this paper) in relation to the declared voltage. This deviates from the general practice (also followed by several standards) which is to express harmonic voltage components as percentage relative to the fundamental. It must also be mentioned that many instruments used for harmonic measurements of power supply systems express their output with reference to the fundamental component of the voltage, especially those indicating the THD factor. This may be covered by application of a conversion factor to any measurement of harmonics expressed as a percentage of the fundamental, before comparing it with the values in Table 1. In practice, however, this will not lead to significant differences since the scaling factor will be very close to unity. Harmonic values are specified

only up to order 25, for the practical reason that for higher orders the values are generally so small as to be impractical to measure and because of the difficulty of giving values which would be relevant to all networks.

| Odd harmonics | | | | Even harmonics | |
|---|---|---|---|---|---|
| Not multiples of 3 | | Multiples of 3 | | | |
| Order of harmonic [h] | Relative voltage [%] | Order of harmonic | Relative voltage | Order of harmonic | Relative voltage |
| 5 | 6.0 | 3 | 5.0% | 2 | 2.0% |
| 7 | 5.0 | 9 | 1.5% | 4 | 1.0% |
| 11 | 3.5 | 15 | 0.5% | 6…24 | 0.5% |
| 13 | 3.0 | 21 | 0.5% | | |
| 17 | 2.0 | | | | |
| 19 | 1.5 | | | | |
| 23 | 1.5 | | | | |

Table 1 - Harmonic values specified by EN50160 Standard

## 4. SOURCES OF HARMONICS

Harmonics are mainly produced by non-linear loads which draw current of a different wave form from the supply voltage (see Fig. 2). The spectrum of the harmonics depends on the nature of the load. Harmonic voltages occur across network impedances resulting distorted voltages which can disturb the operation of other users connected to the same supply. The value of the supply impedance at different harmonic frequencies thus has a vital role in limiting the voltage distortion. Note that if the source impedance is low (Scc is high), voltage distortion is low.
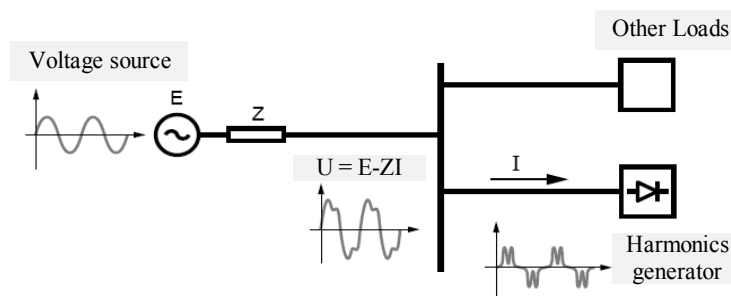


Fig. 2

The origin of harmonic distortion is mainly given by:

4.1. Harmonic currents injected by industrial and commercial installations. In general, the harmonic currents produced by industrial installations are high, and very often, for mitigation purposes, a filter is needed to get installed. High levels of harmonic currents stemming from commercial areas are usually associated with large installations of ITE.

4.2. Harmonic currents injected by residential equipment connected to LV public network as for example TVs, PCs, self-ballast lamps, and air conditioners. In general, the single equipment has a low rated power and produces only a low harmonic current, but because they are very often applied at the same time by customers and

because there is no self-cancelling effect, the cumulative effect of all these small contributions of harmonic emission is not insignificant.

### 5. EFFECTS OF HARMONICS

**5.1. Destruction of capacitors in consumers' installations due to the amplification of the normal operating current, by resonance.** This effect has been observed in

- Industrial installations containing static converters;
- Commercial areas with large amounts of fluorescent lighting equipment comprising power factor capacitors;
- Areas with significant computer load.

| Equipment | Effects | Limits |
|---|---|---|
| Power Capacitors | Overheating, premature ageing (breakdown), resonance | I < 1.3 In, (THD < 83 %) or U < 1.1 Un for 12 hrs/days at MV or 8 hrs/days at LV |
| Motors | Losses and excessive overheating. Reduction of capacity for use at full load. Pulse torque (vibrations, mechanical stress). Noise pollution. | HVF ≤ 2 % for usual asynchronous motors |
| Transformers | Losses (ohmic-iron) and excessive overheating. Mechanical vibrations. Noise pollution. | |
| Circuit breakers | Additional dielectric and ohmic losses (especially in the neutral conductor if third harmonic currents present). | THD ≤ 10 % Uh / U1 ≤ 7 % |
| Computers | Operating problems. | Uh / U1 ≤ 5 % |
| Power Electronics | Problems related to waveform (commutation, synchronisation). | |

Table 2 - Major effects of the harmonics on the equipment and the practical limits

$$HVF = \sqrt{\sum_{h=2}^{13} \frac{U_h^2}{h}} \text{, Harmonic Variation Factor according to IEC892}$$

**5.2. Increasingly, overheating of transformers and neutral conductors caused by harmonic currents, particularly of the third order.** Fires may result from excessive third order harmonic currents because these harmonic currents add in the neutral whereas the fundamental frequency currents cancel each other out so that neutral conductors in three-phase circuits have not in the past needed to be separately protected against overload.

Consumers and distribution systems are sometimes forced to derate their transformers because of the heating effects of harmonic currents. Transformer manufacturers recommend derating by 10 % when a transformer supplies more than 30 % of its nominal capacity to non-linear load, and the same recommendation applies to generating plant.

**5.3. Poor power factors associated with non-linear loads are responsible for a substantial increase in the currents flowing in power supply systems and consumer installations, and hence in the cost of losses.**

Harmonic voltages in excess of the compatibility levels would cause distributors to replace their transformers, switchgear and lines at prohibitive cost. The resulting networks would be inefficient as harmonic distortion represents reactive power flow. There is no doubt that at such levels many consumers would begin to experience significant difficulties and early failure of components and machines could be expected to increase.

## 6. OBJECTIVES OF POWER QUALITY MEASUREMENT

### 6.1. Corrective maintenance

Even where best practice is observed (singleline diagram, choice of protective devices and neutral point connection, application of appropriate solutions) right from the design phase, malfunctions may occur during operation:
- Disturbances may have been ignored or under-estimated.
- The installation may have changed (new loads and/or modification).

Troubleshooting is generally required as a consequence of problems of this nature. The aim is frequently to get results as quickly as possible, which may lead to premature or unfounded conclusions.

### 6.2. Optimising the operation of electrical installations

To achieve productivity gains (operational economies and/or reduction of operating costs) correct operation of processes and sound energy management are required, both of which are factors dependent on PQ. Operating, maintenance and management personnel of service sector and industrial sites all aim for a PQ which matches their requirements. Complementary software tools to ensure control-command and continuous monitoring of the installation are thus required.

### 6.3. Statistical surveys

Such research requires a statistical approach on the basis of wide-ranging results from surveys generally carried out by the operators of transmission and distribution power systems.

6.3.1. Benchmark the general performances of a power system. These can be used, for example, to:

• Plan and target preventive actions by mapping disturbance levels on a network. This helps to reduce operating costs and improve control of disturbance. An abnormal situation with respect to an average level can be detected and correlated with the addition of new loads.

• Compare the PQ of various distribution companies in different geographical areas. Potential customers may request details of the reliability of the electricity supply before installing a new plant.

6.3.2. Benchmark performances at individual points on the power system. These can be used to:

• Determine the electromagnetic environment in which a future installation or a new piece of equipment may have to operate. Preventive measures may then be taken

to improve the distribution power system and/or desensitise the customer power system.

- Specify and verify the performance levels undertaken by the electricity supplier as part of the contract. This information on the electricity quality is of particular strategic importance for electricity companies who are seeking to improve competitiveness, satisfaction of needs and customer loyalty in the context of liberalising energy markets.

### 7. HARMONICS MEASUREMENT MODULE OF POWER QUALITY ANALYZER

EN50160 defines the limits of harmonics levels to $25^{th}$ harmonic, and for calculation of THD is needed the value of the $40^{th}$ harmonic of the LV Public Supply Systems with 50Hz of frequency. This means, that the Power Quality Analyzer has to be able to measure and process a harmonic signals with 2kHz frequency. The needed modules for this purpose are an input A/D Converter for digitizing the input analog signal, and a Digital Signal Processor for making the Fast Fourier Transforms (FFT) needed for calculation of the amplitude of every harmonic to $40^{th}$ order.

For choosing the right A/D converter, it has to be taken into account the following:

- **The sampling rate.** This rate is defined by the *Sampling Theorem.* The sampling theorem indicates that a continuous signal can be properly sampled, only if it does not contain frequency components above one-half of the sampling rate. This means that if we need to know the harmonic with order 40 and 2kHz frequency, the A/D Converter has to be with minimum two times higher sampling rate than 2kHz, i.e. at least equal or higher than 4kHz.

- **It has to be defined the resolution of the A/D Converter.** But for such a measurment 12-bit A/D Converter is quite enough.

- **The number of S/H circuits and the number of channels.** As the Power Quality Analyzers are designed for 3-phase systems, the number of needed S/H circuits and the channels are six – three currents and three voltages. This is very important because the sampling of all six signals has to be made at one and the same moment.

Concluding all of the aspects, it can be designed a block circuit diagram of an analog front end for Power Quality Measurement Device of 4-wire three phase supply system. The three phase voltages are measured by using a resistive divider, and the phase currents are measured by using current transformers and I-V Converter circuit. The six normalized voltages are sampled with six channel A/D converter. The digitized signal is sent to the Digital Signal Processor (DSP), which also controls the sampling moment. The six signals are sampled at one and the same moment. An A/D Converter correspondent to the specification and shown on Fig. 3, is ADS7864 (Texas Instruments/Burr Brown). This A/D Converter is based on SAR (Successive Approximation Register) technology, with 12-bit resolution and 500kHz maximum sampling rate. It has six differential channels with the ability to take a sample on

every channel simultaneously. The digitized data is received over 16 lines in parallel or on two words by 8-bit on 8 lines.
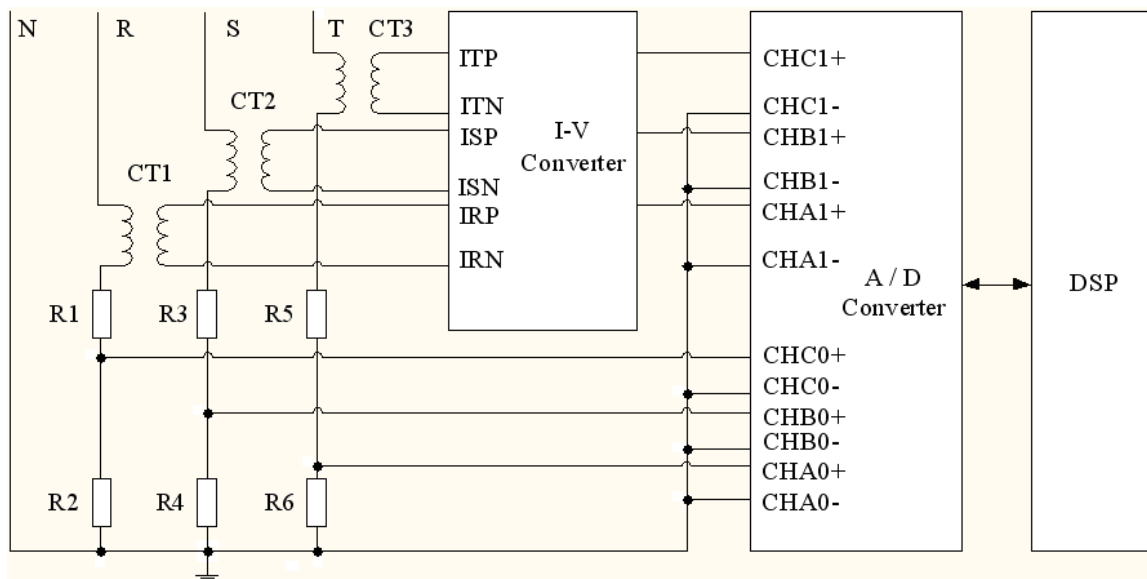


Fig. 3

## 8. RESULTS

All studies regarding the harmonics as parameter of the power quality distributed by the LV systems were needed for the development of Power Quality Metering Devices. The studies and research of the problems and effects of the harmonics, and the limits published in EN50160 standard, helped to the Research and Development Laboratory on Semiconductor Circuits of Technical University - Sofia to design a Power Quality Analyzer with features and specification correspondent to EN50160.

## 9. CONCLUSIONS

The harmonics of voltage and current supplied by the LV Public Systems is one of the most important parameters of the Power Quality. The standardized parameters of the harmonics' amplitude and order in EN50160, are very strict and the measuring devices has to be very precise. The need of the digital signal processing is obvious and because of using the DFT (Discrete Fourier Transformation) for calculations of the harmonic waveform and amplitude to order of 40 (needed for calculating the THD Factor), determines the choice of powerful Digital Signal Processing Unit when a Power Quality Analyzer is designed. The requirements of the "electricity" product as well as operating dependability of electrical and electronic equipment, whether for production, management or commerce, are increasingly great and in this way the devices for monitoring the Power Quality are more and more popular.

## 10. REFERENCES

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