Paper No. T6-2.9, pp. 1-4

16th INTERNATIONAL SYMPOSIUM on
POWER ELECTRONICS - Ee 2011

NOVI SAD, REPUBLIC OF SERBIA, October 26th - 28th, 2011

# A NEW METHOD FOR DETECTING SOURCE OF HARMONIC POLLUTION AT GRID

**Dejan Stevanović, Predrag Petković***
Innovation Center, School of Electrical Engineering in Belgrade d.o.o. (ICEF),Belgrade, Serbia
*University of Niš, Faculty of Electronic Engineering, Niš, Serbia,
dejan.stevanovic@venus.elfak.ni.ac.rs, *predrag.petkovic@elfak.ni.ac.rs

**Abstract:** *This paper suggests a new and efficient method for location of non-linear loads on a grid. It is based on measuring of distortion power. Paper starts with a brief analysis of methods for identification sources of harmonic pollution at power grid. The central part suggests a new method for detection and location of non-linear loads at the grid. The proposed solution can easily be added as option to existing solid-state power-meters. Simulation results confirm effectiveness when implemented within home power-meters*

**Key Words:** ***Distortion power/ harmonic source detection/ power quality***

## 1. INTRODUCTION

According to Fourier's theorem, any periodic signal can be decomposed into a series of sine-waves signals with frequencies that are integer multiple of the basic frequency – called harmonics. Each harmonic component is characterized by its amplitude and frequency. The word "harmonic" was introduced in a magazine written in 1894 by Houston and Kennelly [1]. Nevertheless, the issue of harmonic and harmonic distortion has not been important to electrical power providers until recently. It has been assumed that power-line voltage distributed to consumers is pure sine-wave signal characterized with frequency of 50Hz (60Hz) and RMS value of 240V (110V). Most loads at power grid used to be linear with possible reactive character. Consequently, they caused reactive component of power but did not distort voltage waveform. The last quarter of the previous century enriched our lives with plentiful smart electronic appliances that make life comfortable. Simultaneously, the electronics control systems becomes inevitable parts of equipments for industrial production. Most of electronics gadgets and apparatus require DC supply. Therefore, AC to DC converters have become the most numerous loads at power grid. Unfortunately their non-linear nature generates harmonics in the power network causing numerous unwanted problems [1], [2], [3]. Permanent growth of non-linear loads enhances problems caused by harmonics. This enforced the electrical community to introduce standards that restrict the allowed amount of each harmonic. Two the best known standards in this area are the IEEE 519-1992 and IEC 61000 series [1], [3], [4]. The standard IEC/EN61000-3-2 that entered into force in the European Union is essential for our region. It specifies the limits of the value of non-linear distortion of input current up to the fortieth harmonic. The standard treats distortion produced by electronic and electrical appliances in households. This includes consumers up to 16A per phase, with the voltage up to 415 V. Practically, it comprises wide group of electrical device from welding apparatus to consumer electronics. This standard does not cover the equipment which has a nominal operating voltage less than 240 V and does not notifies equipment with nominal power exceeding 1 kW.

Despite the standardised limits for each harmonic, there are consumers who do not respect these limits. The power distributors would like to be able to detect all consumers who pollute the grid. Therefore, a number of experts deal with the problem of power quality measuring and location of non-linear loads. This paper suggests a low-cost solution that is practical and applicable within standard power-meters.

The paper is organised in six parts. The next section gives a review of basic definitions that correlate power parameters with measured current and voltage data. Review of existing solutions for non-linear loads detection on the grid and their shortcomings will be given in the third section. The fourth section will propose a new method that can be used to find the source of harmonic pollution. The method is confirmed by simulation results that are presented in the fifth section before conclusion.

## 2. THE DEFINITIONS OF THE FUNDAMENTAL QUANTITIES

Traditional power system quantities such as RMS values of current and voltage, power (active, reactive, apparent) are defined for pure sinusoidal condition. However, in the presence of non-linear loads the system no longer operates in sinusoidal condition. The effect of harmonics must be taken into account. In case when harmonics exist in the power supply system, the instantaneous values of voltage and current can be express as:

$$v(t) = \sum_{h=1}^{M} V_h \sin(\omega_h t + \alpha_h) \quad (1)$$

$$i(t) = \sum_{h=1}^{M} I_h \sin(\omega_h t + \beta_h), \quad (2)$$

where $h$ is the number of harmonic, $M$ denotes the highest harmonic, while $V_h$, $I_h$ $\alpha_h$, $\beta_h$ and $\omega_h$ are the amplitudes of the voltage, current, phase angles of voltage and current, and frequency of the $h^{\text{th}}$ harmonic, respectively. RMS values of voltage and current expressed by (1), (2) are defined as:

$$V_{\text{RMS}} = \sqrt{\sum_{h=1}^{M} V_{\text{RMS}_h}^2} \ , \quad (3)$$

$$I_{\text{RMS}} = \sqrt{\sum_{h=1}^{M} I_{\text{RMS}_h}^2} \ , \quad (4)$$

where $V_{\text{RMS}_h}$ , and $I_{\text{RMS}_h}$ are the RMS values of the $h^{th}$ harmonic of the voltage and current, respectively. Product of the voltage and current on the same harmonic frequency gives the harmonic power. Total active power is defined as:

$$P = \sum_{h=1}^{M} V_{\text{RMS}_h} I_{\text{RMS}_h} \cos(\theta_h) . \quad (5)$$

It could be presented as a sum of components related to fundamental and other harmonics:

$$P = P_1 + P_{\text{H}} , \quad (6)$$

where $P_1$ denotes contribution of the fundamental harmonic *(h=1)* and therefore known as *fundamental active power* component; $P_{\text{H}}$ comprises sum of all higher components *(h=2,…M)* and is referred to as *harmonic active power*.

According to Budeanu [3], [5], [6] reactive power is defined as:

$$Q_{\text{B}} = \sum_{h=1}^{M} V_{\text{RMS}_h} I_{\text{RMS}_h} \sin(\theta_h) = Q_1 + Q_{\text{H}} \quad (7)$$

where, similarly to (6), $Q_1$ and $Q_{\text{H}}$ denote *fundamental reactive power* and *harmonic reactive power*, respectively.

The effectiveness of $Q_{\text{B}}$ for quantifying the flow of harmonic non-active power has been questioned by many authors [7] (Czarnecki, Lyon [8]). However, according to [9], the "postulates of Czarnecki have not won universal recognition". Field measurements and simulations (Pretorius, van Wyk, and Swart [10]) proved that in many situations $Q_{\text{H}} < 0$, leading to cases where $Q_{\text{B}} < Q_1$. The reactive power, despite its negative value, contributes to the line losses in the same way as the positive reactive powers. As harmonic reactive powers of different orders oscillate with different frequencies one can conclude that the reactive powers should not be added arithmetically (as recommended by Budeanu) [8]. Accordingly, IEEE Std 1459-2010 proposes reactive power to be calculated as:

$$Q_{\text{IEEE}} = \sqrt{\sum_{h=1}^{M} \left[V_{\text{RMS}_h} I_{\text{RMS}_h} \sin(\theta_h)\right]^2} = \sqrt{Q_1^2 + \sum_{h=2}^{M} Q_h^2} \ . \quad (8)$$

Equation (8) eliminates the situation where the value of the total reactive power $Q$ is less than the value of the fundamental component $Q_1$. The other definitions of reactive power one can find in [10] as:

Fryze's reactive power.

$$Q_{\text{F}} = \sqrt{U^2 - P^2} \ , \quad (9)$$

and Sharon's reactive power:

$$Q_{\text{Sh}} = V_{\text{RMS}} \cdot \sqrt{\sum_{h=1}^{M} I_{\text{RMS}_h}^2 \sin^2(\theta_h)} . \quad (10)$$

Among all variations in reactive power definition, the equation (7) is widely known and included as a part of IEEE Standard Dictionary 100-1996. Therefore the authors of this paper decided to use it.

The vector sum of active and reactive power represents phasor power:

$$S = \sqrt{P^2 + Q^2} \ . \quad (11)$$

However, this stands only for sinusoidal conditions. In presence of harmonics it is applicable to each harmonic component of active and reactive power separately [8]. Therefore it will not be equal to apparent power what the case was in sinusoidal condition. This difference reflects through so called *distortion power D*. Consequently, the apparent power $U$ (physically known as product of RMS values of voltage and current) represents a vector sum of phasor power and distortion power [6]:

$$\boldsymbol{U} = \boldsymbol{I}_{\text{RMS}} * \boldsymbol{V}_{\text{RMS}} = \sqrt{\boldsymbol{S}^2 + \boldsymbol{D}^2} \quad (12)$$

According to [5] the term distortion power $D$ as the part of apparent power was introduced in 1927 by C. Budeanu. Fig. 1 shows geometrical relationship between active $P$, reactive $Q$, phasor $S$, distortion $D$ and apparent power $U$, in monophase system with harmonic pollution.

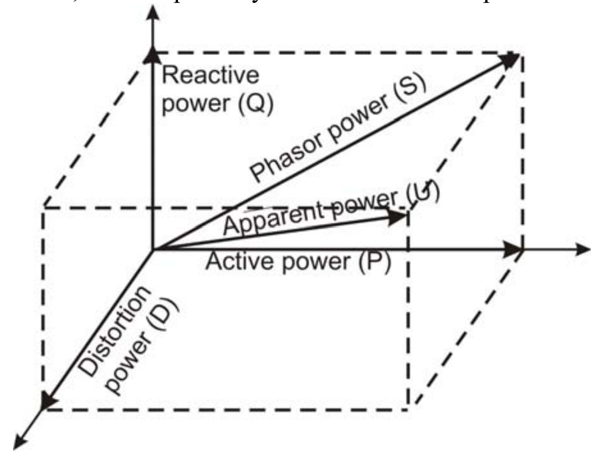


**Figure 1**. *Geometrical representation of relationship between active, reactive, phasor, distortion and apparent power, [8].*

Obviously, Fig. 1 together with (11) and (12) express the fact that in pure sinusoidal condition the distortion power will be equal to zero and apparent power *U* will be equal to phasor power *S*.

## 3. ANALYSIS OF EXISTING METHODS

There are several methods used to identify the sources of harmonic pollution on the network. They can be systematized in two categories: multi-point methods and single-point methods. The first category utilizes multiple data collected with distributed and synchronous measurement system. It is precise but requires expensive measurement instrumentation. The second category is more convenient for implementation, but less precise. Some of single-point strategies are based on monitoring the sign of the harmonic active power $P_H$ [1], [4], [5]. If $P_H < 0$ then pollution source is the consumer. Otherwise, it is utility-side which pollutes the power grid. This identification of the non-linear consumer is widespread and has been used in industry for many years [1], [4]. Manufacturers of metering equipment represent this option as a key feature of their equipment [4]. However, additional researches showed that it is not 100% accurate [1], [4]. Another method proposes to follow the sign of the harmonic reactive power. These two methods complement each other. Which method will be applied depends on the balance of resistance and reactance of loads [1], [4]. However, determining the character of impedance is, in most cases, a difficult problem.

A different approach is based on comparison of three non-active power components [11]. The method has been enhanced by the same authors in [12]. If the value of the total reactive power is closer to the value of non-active power then the consumer is the source of pollution. Otherwise, if the value of the total reactive power is closer to the value of the first harmonic reactive power, then the polluted power is distributed to the consumer. This method does not identify location of the pollution source precisely and is not very suitable for application due to the high price and the complexity of implementation.

## 4. PROPOSED METHOD

The authors offer an entirely new method suitable to identify location of the sources of harmonic pollution on the network. Unlike some other approaches this method does not require spectral analysis of voltage and current [1], [4], [5]. The method is based on the calculation of distortion power *D*. By Budeanu's definition, according to (11) and (12) the distortion power can be expressed as:

$$D = \sqrt{U^2 - P^2 - Q^2}\ , \qquad (13)$$

where *U, P* and *Q* represents apparent, active and reactive power, respectively. In presence of harmonics the expressions that define these powers must take into account the contribution of harmonics. All formulas necessary for calculating these powers can be found in section II.

It should be noted that in the real world, the actual contribution of harmonic frequencies to active and reactive power is small (usually less than 3% of the total active or reactive power [6]). These harmonic components mainly contribute to the distortion power. The current through a non-linear load introduces harmonics that do not exist in the network. These harmonics affects the $I_{RMS}$ and consequently the apparent power *U* and distortion power *D*.

One easily concludes that $D > 0$ decidedly means that a non-linear load exists on the grid. This is the ground of the method that we propose. Its benefits relay on the fact that it is suitable to be implemented in electronic power-meters. Namely, all solid-state power-meters available on the market are able to register *P*, *Q* and *U*. Therefore only a minor intervention in the software (or DSP hardware) enhances the capabilities of the meter. However, one should not forget that the amount of measured *Q* in presence of harmonics depends on the applied definition.

It is important to remind that the purpose of the method is to provide the utility opportunity to penalize or to disconnect the harmonic producers from the grid.

Therefore our intention is to suggest a method capable to detect and quantify the amount of the distortion. The effectiveness of the suggested method is verified by a set of simulations. Results of simulation will be presented in the following section.

## 5 . RESULT OF SIMULATIONS

The proposed method is verified using an original MATLAB script based on equations given in the second section. Practically, it emulates a virtual power meter. In order to simulate possible realistic case the virtual grid is supplied with voltage polluted with the highest total harmonic distortion (THD) allowed by standard ($THD_V$= 5%). Four different types of loads were considered:

a) Heater (resistive load)
b) Induction motor (reactive load)
c) 6-pulse 3-phase diode rectifier dc power supply
d) 6-pulse switched-mode power supply

Cases a) and b) represent purely linear loads. Therefore currents through the loads had the same waveform as the supply voltage. In the first case the phase angle between voltage and current is 0 and the virtual meter registered only the active power *P*. In case of the induction motor the current lags the voltage for a phase angle $\theta=30^o$. Consequently, the meter registered both, active and reactive power (*P*, *Q*).

Cases c) and d) represent very non-linear loads. Amplitude and phase angle for each harmonic of current are taken from [3]. Fig.2 shows waveform of current through 6-pulse three phase diode rectifier dc power supply. It obviously differs a lot from a sine-wave. Therefore, we expect to measure distortion component of power. Fig.3 represents waveform of the current through 6-pulse switched-mode power supply. It is even more distorted than current in case c) that implies greater expected value of *D* than in the previous case.

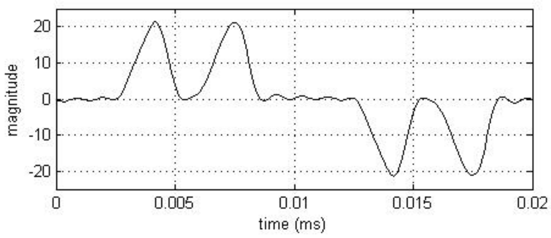


**Figure 2**. Current waveforms of 6-pulse 3-phase diode rectifier dc power supply, [3]

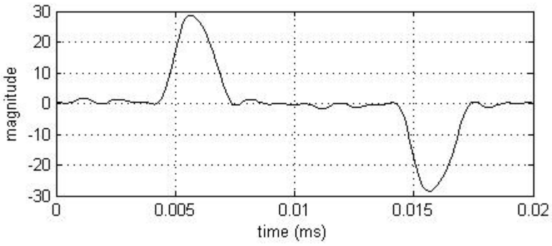


**Figure 3**. Current waveforms of 6-pulse switched-mode power supply, [3]

Table 1 Simulation results of four different types of loads

| | a) | b) | c) | d) |
|---|---|---|---|---|
| $I_{RMS}(A)$ | 10.01 | 10.01 | 13.53 | 14.84 |
| $V_{RMS}(V)$ | 230.29 | 230.29 | 230.29 | 230.29 |
| *P(W)* | 2305.8 | 1996.8 | 2251.4 | 2183.9 |
| *Q(VAR)* | 0 | 1152.9 | 470.34 | 412.33 |
| *U(VA)* | 2305.8 | 2305.8 | 3115.4 | 3416.9 |
| $THD_V$ | 5% | 5% | 5% | 5% |
| $THD_I$ | 5% | 5% | 67.35% | 73.88% |
| *D(VAR)* | 0 | 0 | 2101.4 | 2595.3 |

Table 1 summarizes the results obtained by the proposed method for all four loads. Obviously, for the case a) the calculated active power is equal to the apparent, while the reactive power and distortion power are equal to zero. In the case b) the reactive power is a significant component of the apparent power. So far no distortion power has been expected and obtained. The following two cases with non-linear loads should result with non-zero distortion power. The currents of both loads are very rich with harmonics. Namely, THD of current ($THD_I$ in table 1) are 67.35% and 73.88% for cases c) and d), respectively. Consequently $I_{RMS}$ increases proportionally to harmonics. Therefore it is greater for case d). The registered distortion powers follow the same trend with values of 2101.4 VAR for the case c) and 2595.3 VAR for non-linear load in the case d). Obviously, the measure of distortion power is in direct relation with the nonlinearity of a particular load.

## 6. CONCLUSION

This paper presented a new method that can easily locate pollution sources at power grid. The method relays on measuring of the distortion power. We propose Budeanu's definition as the background for distortion power calculation. It is suitable for upgrading dedicated DSP in ASIC power meters. Moreover in most electronic power meters it could be implemented at software level. If a power-meter unit detects non-zero distortion power the consumer has non-linear load. The amount of distortion power corresponds to the level of pollution. Implemented within a grid such meters provide to distributors good insight into location and the amount of pollution entered by every particular consumer.


## ACKNOWLEDGEMENTS

Results described in this paper are obtained within the project TR32004 founded by Serbian Ministry of Science and Technology Development.


## 7. REFERENCES


[1] Singh G.K.: "*Power system harmonics research: a survey*", European Transactions on Electrical Power, Vol.19, 2007, pp. 151–172.

[2] Integral Energy Power Quality Centre: *Harmonic distortion in the electric supply system*' Technical note, No. 3, University of Wollongong, March 2000.

[3] Wakileh. J. G., "*Power Systems Harmonics*", Springer, 2001

[4] Xu W., Liu X., Liu Y.: "*An investigation on the validity of power-direction method for harmonic source determination*", IEEE Trans.Power Delivery, vol. 18, no.1, January 2003.

[5] Emanuel A. E.: "*Summary of IEEE standard 1459: definitions for the measurement of electric power quantities under sinusoidal, nonsinusoidal, balanced, or unbalanced conditions*", IEEE Tran. On Industrial Applications, Vol. 40, No3, May 2004.

[6] Webster J. G.: 'The measurement, instrumentation, and sensors handbook', IEEE Press, 1999

[7] Czarnecki, L. S., "*What is Wrong with Budeanu's Concept of Reactive and Distortion Power and Why it Should be Abandoned*", IEEE Transactions on Instrumentation and Measurement, vol. IM-36, n.3, Sept. 1987

[8] IEEE Std 1459-2010, "*IEEE Standard Definitions for the Measurement of Electric Power Quantities Under Sinusoidal, Nonsinusoidal, Balanced, Or Unbalanced Conditions*".

[9] M. Hartman, *Orthogonality of functions describing power states in electrical circuits in Budeanu's concept*, Proc. of the International School on Nonsinusoidal Current and, June 15-18, 2010, Lagow, Poland

[10] D. M, Tagare, *Reactive power management* (McGraw-Hill Education, 2007).

[11] Barbaro P.V., Cataliotti A., Cosentino V., Nuccio S.: *A new technique to detect harmonic sources in polluted power systems*, Proc. of the XVIII IMEKO World Congress, 2006, Rio de Janeiro, Brazil.

[12] Cataliotti A., Cosentino V.: *A single-point approach based on IEEE 1459-2000 for the identification of detection of prevailing harmonic sources in distorted three phase power systems*, Proc. of the Metrology and Measurement Systems, ISSN 0860-8229, 2009.