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The Efficient Technique for Harmonic Sources Detection at Power Grid

***Abstract**: In this paper, we propose a new and efficient method for detection and quantifying the level of distortion caused by non-linear loads on the power grid. It is based on measurement of distortion power. Simulated and measured results confirm its effectiveness when implemented within electronic power-meters. The proposed solution can easily be added as an option to existing solid-state power-meters. It can be implemented as a software update or in the form of hardware upgrade within a dedicated DSP.*

***Streszczenie.** W artykule zaprezentowano metodę detekcji oraz oceny zakłóceń energii w sieci energetycznej wywołanych przez odbiorniki nieliniowe. Wyniki symulacyjne potwierdzają skuteczność metody. (**Skuteczna metoda detekcji źródeł wyższych harmonicznych w sieci energetycznej**)*

Keywords: Distortion power, harmonic source detection, power quality, power-metering.
Słowa kluczowe: Zakłócenia energii, detekcji źródeł wyższych harmonicznych, jakość energii, pomiar mocy

Introduction

The last few decades are characterized by a wide use of smart electronic appliances and a massive use of the electronics control systems in industrial production. Most of the electronic equipment need DC supply for operation making the AC to DC converters to become among the dominant loads at the power grid. The non-linear nature of these converters introduces a huge amount of harmonics. It is well known that any deviation of the line voltage produces serious problems [1, 2]. The continuous rise of the number of non-linear loads - gives rise to all problems related to the influence of harmonics. To face this regulations that limit of the allowed amount of each harmonic were created. Two the widely used standards in this area are the IEEE 519-1992 and IEC/EN61000-3-2 [1, 2, 3].

The standard IEC/EN61000-3-2 is in use in the European Union since 2001. It restricts the value of input current distortion up to the fortieth harmonic in electrical household appliances. It considers consumers up to 16A per phase, with the nominal voltage from 240V up to 415 V.

So far, there are no regulations that specify what happens if a customer exceeds the allowed amount of harmonic pollution. However, in order for the utility to carry out any measure one needs a proper and efficient method to detect and quantify the level of distortion of the respective customer (PCC *Point of Common Coupling*). Thereafter, it needs a procedure to discipline the irresponsible customer.

Practically, the utility could apply one of two approaches. The first is to disconnect the harmonic producer. The softer alternative is to charge for extra-losses. From the point of view of the general public, the former is better because it encourages customers to avoid using appliances that pollute the grid. Actually, the main problem in the tax driven regulation is the lack of the measurement tools to detect the dominant source of harmonics producer. One of the suggestions is to implement new electronic power meters able to provide for data on harmonic distortion. However, measuring THD is not sufficient for analysis of the effects of the harmonic polluter [4]. Therefore, the computation of another quantity named Power Quality Index (*PQI*) was suggested.

A number of experts deal with the problem of power quality measurement and location of non-linear loads [3, 4, 5, 6, 7]. We are here trying to offer a solution that could be implemented using existing solid-state electronic meters. That we consider to be the main advantage of the proposed idea.

The paper is organized in six parts. The next section presents a survey of correlations between power parameters and measured current and voltage data. The subsequent section reviews existing solutions for detection of non-linear loads on the grid together with known shortcomings. The fourth section will propose a new method that can be used to find the source of harmonic pollution. Description of the method verification by simulation and its confirmation by measurement precede the conclusion given in the sixth section.

The Definitions of the Fundamental Quantities

Traditional power system characterization quantities such as RMS values of current and voltage, power (active, reactive, apparent) are defined for ideal sinusoidal condition. However, in the presence of non-linear loads, these definitions need correction. The instantaneous values of a quantity reach with harmonics (voltage or current) can be express as:

$$x(t) = \sum_{h=1}^{M} X_h \sin(\omega_h t + \alpha_h) \tag{1}$$

where h is the number of the harmonic, M denotes the highest harmonic, while X_h , ω_h ***and*** α_h, represent amplitude, frequency and phase angle of the h-th harmonic. The RMS value of the signal expressed by (1) is defined as:

$$X_{\mathrm{RMS}} = \sqrt{\sum_{h=1}^{M} X_{\mathrm{RMSh}}^2}\ , \tag{2}$$

where X_{RMSh} is the RMS values of the h-th harmonic.

Product of the voltage and current having the same harmonic frequency gives the harmonic power. Total active power is defined as:

$$P = \sum_{h=1}^{M} V_{\mathrm{RMS}_h} I_{\mathrm{RMS}_h} \cos(\theta_h), \tag{3}$$

where θ_{h} denotes phase angle between voltage and current.

One could present the total active power as a sum of the fundamental and other harmonic powers:

$$P = P_1 + P_{\mathrm{H}}\ , \tag{4}$$

where P_1 denotes power of the fundamental component *(h=1)*. Therefore, it is known as *fundamental active power* component. P_H comprises sum of all higher components *(h=2,..., M)* and is referred to as *harmonic active power*.

According to Budeanu [2, 8, 9] reactive power is defined as:

(5) $$Q_B = \sum_{h=1}^{M} V_{RMS_h} I_{RMS_h} \sin(\theta_h) = Q_1 + Q_H$$

where, similarly to (4), Q_1 and Q_H denote *fundamental reactive power* and *harmonic reactive power*, respectively.

Many scientists claim that the Budeanu's definition is not correct and cannot be used for calculating reactive power. According to one of the authors of IEEE1459-2010 standard, professor Emanuel [10, 11], "even today this definition occupies a significant number of pages on *The IEEE Standard Dictionary.* Its past acceptance and popularity among engineers and top scientists is hard to dispute. Modern textbooks written by highly respected researchers are presenting Budeanu's resolution of apparent power as the right canonical expression". More about calculating reactive power can be found in [10].

It is well known that the apparent power is a product of RMS values of voltage and current. In presence of harmonics, the apparent power is calculated as:

(6) $$S = I_{RMS} * V_{RMS} = \sqrt{\sum_{h=1}^{M} V^2{}_{RMS\,h}} * \sqrt{\sum_{h=1}^{M} I^2{}_{RMS\,h}}$$

Using (3), (5) and (6) one gets the inequality:

(7) $$S^2 > P^2 + Q_B{}^2 .$$

However, for the sinusoidal case $S^2=P^2+Q_B^2$. Consequently, it is quite clear that a difference exists due to harmonic distortion. Following the logic about defining active and reactive power, Budeanu introduced the term *distortion power* D_B that quantifies the discrepancy within the inequality (7):

(8) $$S^2 = P^2 + Q_B{}^2 + D_B{}^2 .$$

The essence of this revision is contained in the fact that in absence of harmonics, D_B=0 and $S^2=P^2+Q_B^2$.

Review of Existing Methods for Harmonic Source Detection

There are several known methods for detection nonlinear loads on the network. In general, they can be classified as:

-multi-point methods and

-single-point methods.

The first category utilizes multiple data collected simultaneously from a distributed measurement system. It is precise but requires expensive measurement instrumentation.

The second category is more suitable for implementation, but less accurate. It is applied on Point of Common Coupling (PCC). Some of the single-point strategies rely on the sign of the harmonic active power P_H [1, 3, 8]. If P_H < 0, the pollution source is on the consumer side. Otherwise, it is at the utility side. This identification of the nonlinear loads is widespread and has been used in industry for many years [1, 3]. Manufacturers of metering equipment represent this option as a key feature of their equipment [3]. However, additional researches showed that it is not absolutely precise [1, 3]. Therefore they propose monitoring the sign of the harmonic reactive power instead of P_H. These two methods complement each other. The balance of resistance and reactance of loads defines what method will be applied [1, 3]. However, determining the character of impedance is, in most cases, a difficult problem.

An alternative approach is based on impedance measurement of the grid and the end-user side. The method is very well theoretically funded so that appears in numerous variations [5]. However, its practical implementation requires thorough and costly analysis of all connected loads. Therefore, it is not suitable for wider implementation.

An additional method is based on comparison of three non-active power components [6]. It has been improved in [7].

A recently published paper introduces a new Power Quality Index (PQI) to monitor the effect of each nonlinear load on a PCC [4]. It is used to define harmonic pollution ranking of particular loads. PQI represents a product of *Load Composition Rate* (LCR) and THD derived from the load current waveform. The authors state that THD is not sufficient for reliable detection of dominant nonlinear loads. Hence, they utilise an own *Reduced Multivariate Polynomial Model* to estimate LCR and THD and calculate PQI.

A New Method for Harmonic Source Detection based on Measuring Distortion Power

This paper suggests an original method suitable for the detection of nonlinear loads on the grid. Unlike some other approaches, this method does not require spectral analysis of voltage and current [1, 3, 8]. The method is based on the calculation of distortion power D_B. According to (8) the distortion power can be expressed as:

(9) $$D_B = \sqrt{S^2 - P^2 - Q_B{}^2} ,$$

where S, P and Q_B represent apparent, active and reactive power, respectively, that are given in section II. Using the equivalent expressions of P, Q_B, S from (3), (5) and (6) in (9) we will get the following equation,

(10) $$\begin{aligned} D_B{}^2 = &\sum_{n}^{M-1} \sum_{k=n+1}^{M} \left(V_n \cdot I_k \cdot \cos\theta_n - V_k \cdot I_n \cdot \cos\theta_k\right)^2 \\ &+ \sum_{n}^{M-1} \sum_{k=n+1}^{M} \left(V_n \cdot I_k \cdot \cos\theta_n - V_k \cdot I_n \cdot \cos\theta_k\right)^2 . \end{aligned}$$

In case of linear resistive loads (eg. heater, incandescent light bulb) current and voltage has the same harmonics. Therefore, the ratio between voltage and current is the same for all harmonics:

(11) $$\frac{V_1}{I_1} = \frac{V_3}{I_3} = ... = \frac{V_h}{I_h} ,$$

where h is the order of harmonics. The condition (11) can be rewritten in the form $V_n * I_k = V_k * I_n$. Resistive character of the load results with zero phase angle $cos\theta_n = cos\theta_k$=1. Therefore, all summands in (10) will be equal to zero, consequently, and D_B=0.

In case of linear reactive loads at the grid (eg. induction motor), the load impedances at different harmonics are not equal ($Z_1 \neq Z_3 \neq ... \neq Z_h$). Therefore, the condition (11) is not satisfied and $D_B \neq 0$.

In presence of a non-linear load, the condition (11) is not true. Namely, the current of the non-linear load consists of harmonics, which does not exist in the voltage. These harmonics does not affect the active (3) and reactive (5) power. They contribute to the RMS value of the current and consequently, to the apparent power S and distortion power D_B.

As a result, it is easy to conclude that $D_B > 0$ decidedly confirms that a non-linear load exists on the grid. Although well known, this simple fact has not been used so far. Its main comparative advantage to other methods relies on its feasibility for easy implementation in electronic power-meters. Actually, contemporary solid-state power-meters are able to register P, Q_B and S. Therefore, only a minor intervention in the software (or DSP hardware) increases the meter capability.

The purpose of the suggested method is to provide the utility with a capacity to charge or to disconnect the harmonic producers from the grid. It is capable of detect and quantify the amount of the distortion on a convenient and suitable way. The effectiveness of the suggested method is verified by a set of simulations and confirmed by measurements. The results will be presented in the following section.

Measurement and Simulations Results

The proposed method was verified using an original MATLAB script based on equations (3), (5), (6), and (9). Practically, it emulates a virtual power meter. In order to simulate a possible realistic case, it is supposed that the voltage is "polluted" with a component of the 3rd harmonic whose magnitude is 3% of the fundamental. We considered seven different types of loads connected to the grid. Namely, those are:

a) Incandescent light bulb (ILB)
b) Fluorescent lamp (FL)
c) EcoBulb Compact Fluorescent Lamp (ECFL)
d) Phillips Compact Fluorescent Lamp (PCFL)
e) 6-pulse 3-ϕ diode rectifier dc power supply (3-DR)
f) 6-pulse switched-mode power supply (SMPS)
g) 6-pulse PWM controlled variable speed drive (PWM VSD)

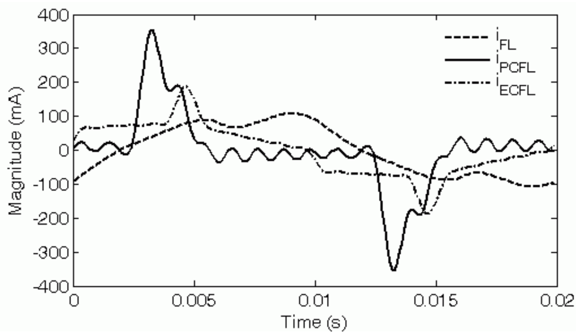

Fig. 1.a. Current waveforms for Fluorescent lamps: FL, ECFL and PCFL [12]

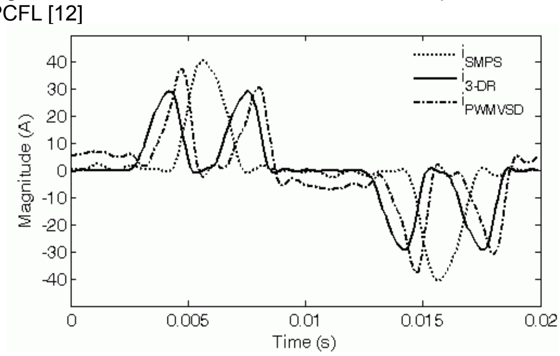

Fig. 1.b. Current waveforms for Rectifiers: 3-DR, SMPS and PWM VSD [3]

The first case represents a linear load. Therefore, it is expected and is obtained that the current tracks the voltage waveform. All other loads are nonlinear. Consequently, they draw distorted current. In order to approve the method for distortion power calculation we used measured data for currents that are already known to power electronic community [3, 12]. Fig. 1.a illustrates currents of FL, ECFL and PCFL. Fig. 1.b presents waveforms of currents through 3-DR, SMPS, and PWM VSD.

Table I summarizes the results obtained by simulation of the proposed method for all seven loads.

Table 1. Simulation results for different types of loads

	ILB	FL	ECFL	PCFL	3-DR	SMPS	PWM VSD
I_{RMS}[A]	0.44	0.1	0.09	0.13	13.53	14.84	14.23
V_{RMS}[V]	230.1	230.1	230.1	230.1	230.1	230.1	230.1
P_1[W]	100.05	17.31	18.59	16.09	2251.39	2249.74	2300
P_H[W]	0.09	0.01	-0.06	-0.14	0	-39.52	3.11
P[W]	100.14	17.31	18.53	15.95	2251.39	2210.22	2303.11
Q_1[VAR]	0	15.15	-6.04	-10.06	470.34	478.2	0
Q_H[VAR]	0	0.14	0.03	0.47	0	-39.52	-5.38
Q_B[VAR]	0	15.29	-6.01	-9.58	470.34	438.68	-5.38
S[VA]	100.14	23.6	20.9	29.69	3112.95	3414.14	3274.51
THD_V[%]	3	3	3	3	3	3	3
THD_I[%]	3	22.85	37.68	120.23	91.12	109.61	101.25
D_B[VAR]	0	4.86	7.57	23.13	2097.72	2564.92	2327.68

As expected, for linear resistive load, the active power, P, equals to the apparent power, S. Therefore, the distortion power calculated using (9) equals zero. In other cases that represent non-linear loads, non-zero distortion power is registered. The currents of each load are very rich with harmonics. Therefore, I_{RMS} increases proportionally to the harmonics, and consequently, S and D_B, as well. By analysis of waveforms in Fig.1.a it is obvious that the waveform representing the current of PCFL is the most distorted. As a result PCFL characterizes the greater value for THD_I and D_B then in cases of FL and ECFL. Similar analysis applied to the cases presented in Fig.1.b reveals that SMPS is the biggest source of harmonic pollution. Evidently, all presented examples confirm that the distortion power is in direct relation with the nonlinearity of a particular load.

The simulation results validated the presented theory. Hence the following step was to verify the suggested algorithm on true loads using off-the-shelf power meters. In that course we used a meter produced by EWG electronics [13] that is based on the standard IC 71M6533 manufactured by MAXIM and fulfils the standard IEC 62052-11 [14]. Consequently it already provides P, Q_B, and S according to (3), (5) and (6), respectively. Then after, calculating D_B as stated by (9) is straightforward. The only additional effort was to collect data provided by the meter and to acquire them to a PC.

Figure 2 illustrates the implemented set-up. The data from power meter are read using its optical port and transmitted to the PC trough the RS232 port. Dedicated software processes collected data and transfer them to Matlab script that calculates the distortion power.

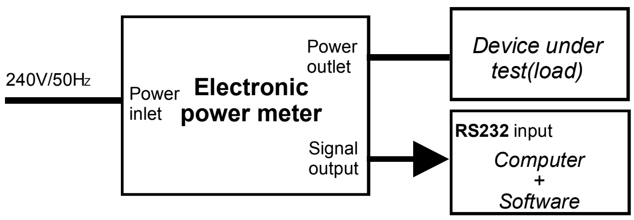

Fig. 2. Set-up circuit for distortion power measurement

Table 2 presents measured results of loads the most frequently used in offices or in households. Table 3 systematizes measurements related to energy saving lamps that are small loads when consider separately, but in total they reach up to 20% of the total power consumption [15].

Table 2. Measurement results for different types of loads common for offices and households

Load	V_{RMS}[V]	I_{RMS}[A]	S[VA]	P[W]	Q_B[VAR]	D_B[VAR]
ILB 100W	218.96	0.42	91.96	92.32	0.74	0.00
FL 18W	218.62	0.08	17.49	11.33	-5.80	11.99
PC	213.57	0.39	83.08	48.55	-1.92	67.39
Monitor LCD 21	211.58	0.19	40.41	23.99	-7.05	31.75
Monitor CRT 21	211.32	0.56	117.71	113.49	-28.72	12.24
Air conditioning	206.78	3.13	648.0	637.5	60.26	99.52

Table 3. Measurement results for different types of energy saving lamps

Load	V_{RMS}[V]	I_{RMS}[A]	S[VA]	P[W]	Q_B[VAR]	D_B[VAR]
CFL20W helix	219.01	0.14	30.66	18.61	-9.38	22.49
CFL20Wtube	219.46	0.14	31.60	18.73	-9.58	23.58
CFL15W bulb	219.74	0.09	19.56	12.10	-5.51	14.34
CFL11W helix	221.73	0.08	17.74	10.42	-5.38	13.31
CFL11Wtube	221.27	0.08	17.92	10.76	5.74	13.13
CFL11WE14	215.51	0.08	17.24	10.79	-5.26	12.38
CFL9W bulb	216.06	0.06	12.75	7.58	-3.64	9.58
CFL7Wspot	217.75	0.04	9.58	5.83	-2.87	7.04
CFL7W bulb	219.83	0.04	9.67	6.03	-2.57	7.11
LED 15W Par lamp	217.27	0.16	34.11	16.90	-3.87	29.38
LED 10W Par lamp	217.51	0.114	24.5	12.89	-2.74	21.01
LED Bulb 8 W	218.02	0.08	18.10	9.70	-2.84	15.01
LED Bulb 6W Warm White	217.93	0.04	9.15	7.76	-0.14	4.85

All results explicitly show that the value of distortion power clearly indicates if a consumer produces harmonic pollution or not. Moreover the amount of the pollution corresponds to the registered distortion power.

These give to the utility an opportunity to indicate and act against irresponsible consumers by its billing policy. The main advantage of the proposed method lies on its compatibility with the existing electronic power meters.

Actually, instead of using PC for D_B calculation an updated firmware could make the embedded microprocessor unit to provide this action. However this task can be implemented as a hardware upgrade of dedicated DSP that is a part of solid-state power meters. We intend to enhance the features of the DSP block in own ASIC power meter solution that was designed in LEDA laboratory, University of Nis [16, 17].

Conclusion

This paper suggested a new low cost method that can easily detect sources of harmonic pollution at the power grid. The method relies on measuring of the distortion power. Actually, the amount of distortion power is in direct relation with the nonlinearity of a particular load. This fact implies that information about distortion power on the consumer side is sufficient to detect whether the customer jeopardises the grid with harmonic pollution or not.

The method was verified by simulation and confirmed by measurements on a set of linear and nonlinear loads that commonly appear in offices and households. The measurement set-up was based on a standard electronic meter that fulfils the standard IEC 62052-11 and provides data for apparent, active and reactive powers. This paper describes procedure where the additional computations for distortion power were performed on adjoin PC. However, the method could be easily implemented within electronic power meter by intervention on firmware. Moreover, it is suitable for implementing in dedicated DSP realized within ASIC for power meters.

The method implemented in smart power meters that are part of Advanced Metering Infrastructure provides the utility a good insight into location and the amount of pollution entered by every particular consumer. Therefore, the power distributors will be able to control the quality of the grid by appropriate billing policy.

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