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A NOVEL TIME DOMAIN METHOD TO LOCATE DOMINANT HARMONIC SOURCES

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Abstract − In the last years the current and voltage distortion in distribution systems has increased, because of the large number of loads, which draw non-sinusoidal currents. The usual measurement methods cannot provide any information about the source of harmonic distortion in a given metering section. Different measurement methods are therefore searched for. The most discussed methods are generally based on the decomposition of voltages and currents into Fourier series. This paper presents a different method for singular or total harmonic sources detection in power systems, based on the instantaneous active power in three-phase circuits. Theoretical aspects are discussed, simulations and experimental results are presented, taking into account measurement accuracy.

Keywords: harmonics measurement, harmonic sources.

1. INTRODUCTION

In recent years, the problem of harmonic distortion sources localization has become more urgent, because of the development in distribution systems of power electronic devices that draw non-sinusoidal currents; the problem is also related to the liberalization of energy markets and the perspective of specific contracts between customers and utilities, in which the energy price can depend on both voltage quality and load characteristics.

In practical situations, the harmonic sources are located both upstream and downstream of the metering section, so that both supply and load are responsible for harmonic distortion; some harmonics are due to the load, some others to the network, some other to both load and network.

At present, the international Standards set limits for harmonic distortion only for some voltages and currents levels, for both networks and loads [1]; this limits are given for both singular harmonics and for total harmonic distortion, by means of indices such as the Total Harmonic Distortion Factor (THD); they also define measurement methods to evaluate harmonic distortion level [2]; moreover, they give indications about only some of power quality parameters (i.e. harmonic distortion, frequency of fundamental component, flicker) [3]. The document IEC 61000-4-30 that will give a complete view about testing and measurement techniques for power quality measurement methods is still a draft standard [4].

Anywhere, there is no in force or draft document that define indices and related measurement methods for the localization of harmonic sources.

Many of conventional methods for harmonic sources detection are based on the harmonic power flow measurement by means of the decomposition of voltages and currents into Fourier series [5], [6], [7].

A simpler and faster method, based on the instantaneous active power in three-phase circuits, has been presented in [8] that requires only a band elimination filter for the fundamental active power and a three-phase active power meter. This method works in the time domain and detects the total harmonic power flow, locating the dominant harmonic source upstream or downstream the metering section. However, this method cannot provide any information about the harmonic distortion due to load or network for a singular harmonic order.

In this paper a new time domain method is proposed to locate dominant harmonic sources. This method is based on the instantaneous active power and improve the above mentioned method by means of harmonic voltage measurement, based on the instantaneous reactive power theory [9].

This technique was proposed to separate the fundamental voltage from the total harmonic one; in this paper, it has been developed for both fundamental and singular harmonic voltages detection.

The novel proposed method is able to detect the total harmonic active power flow, locating the dominant harmonic source upstream or downstream the metering section. Moreover the harmonic distortion due to load or network for a singular harmonic order can be investigated.

In the paper theoretical fundamentals of the method are given, simulation and experimental results are presented and measurement accuracy is discussed.

2. NOVEL HARMONIC DETECTION APPROACH

2.1. Harmonic active power

The instantaneous active power in a three-phase three-wire (named *a*, *b*, *c*) system is given by:

$$p = v_{ac} i_a + v_{bc} i_b \tag{1}$$

where v_{ac} and v_{bc} are two line to line voltages and i_a and i_b are two line currents.

If voltages fundamental components are extracted, the harmonic instantaneous active power can be written as follows:

$$p_h = v_{hac} i_a + v_{hbc} i_b \quad (2)$$

where v_{hac} and v_{hbc} are the harmonic line to line voltages.

It has been demonstrated in [8] that the dc component of p_h (P_h) is given by the sum of harmonic active powers for each phase; in particular, the sign of P_h is relevant to find the dominant harmonic distortion source:

- if $P_h < 0$, the dominant harmonic source is located downstream the metering section;
- if $P_h > 0$, the dominant harmonic source is located upstream the metering section.

The Authors have observed that the same consideration can be carried out with respect to the active power related to a selected harmonic order. Therefore each singular harmonic power can be evaluated if the corresponding harmonics is insulated from the total harmonic voltages; so, dominant harmonic sources can be detected also with respect to each singular selected harmonic.

2.2. Harmonic voltage detection

The detection method for harmonic voltages is based on the instantaneous reactive power theory [9] [10].

In general, according to this theory, three phase ac voltages (v_a, v_b and v_c) and currents (i_a, i_b and i_c) can be transformed into two phase $\alpha\beta$ orthogonal coordinates, as follows:

$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} v_{ab} \\ v_{bc} \\ v_{ca} \end{bmatrix} = \left[T_{\alpha\beta}\right] \begin{bmatrix} v_{ab} \\ v_{bc} \\ v_{ca} \end{bmatrix}, \quad (3)$$

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \left[T_{\alpha\beta}\right] \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}. \quad (4)$$

The instantaneous active and reactive powers are given by:

$$\begin{aligned} p &= i\,v\cos\varphi = i_\alpha v_\alpha + i_\beta v_\beta \\ q &= i\,v\sin\varphi = i_\alpha v_\beta - i_\beta v_\alpha \end{aligned}, \quad (5)$$

where i and v are the norms of vectors $\boldsymbol{i}$ and $\boldsymbol{v}$ and φ is the angle between them. By matrix form, (5) can be written as follows:

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} i_\alpha & i_\beta \\ -i_\beta & i_\alpha \end{bmatrix} \begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix}. \quad (6)$$

It can be observed that in the case of sinusoidal voltages and currents p and q are constant quantities and represent the active and reactive powers. When both voltages and currents or one of them are unbalanced or distorted p and q aren't constant anymore, and their dc components are corresponding to the active and reactive powers of the fundamental components.

Starting from the above mentioned theory, if line to line voltages (v_{ab}, v_{bc} and v_{ca}) are considered, the three phase-two phase coordinate conversion can be realized to obtain the two-phase orthogonal voltages v_α and v_β; a second coordinate conversion to a orthogonal system (p,q) rotating at fundamental or harmonic frequency can be applied to obtain the instantaneous voltages v_d and v_q, see fig.1

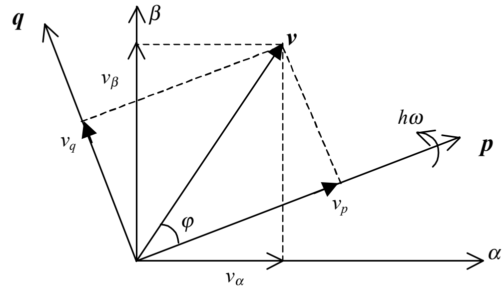

Fig. 1. Vector diagram of voltages coordinate conversion

The pq transformation is obtained if in (4) currents are substituted with the following three phase sinusoidal symmetrical system:

$$\begin{aligned} s_a &= \sin\, h\omega\, t \\ s_b &= \sin\, h(\omega\, t - \tfrac{2\pi}{3})\,. \\ s_c &= \sin\, h(\omega\, t + \tfrac{2\pi}{3}) \end{aligned} \quad (7)$$

where h is the harmonic order and h=1 is corresponding to the fundamental frequency. The sinusoidal system can be obtained from a signal synchronised with fundamental voltage.

For example, if h=1 and applying the $\alpha\beta$ transformation, s_α and s_β are given by:

$$s_\alpha = \frac{\sqrt{3}}{2}\sin\omega\, t \qquad s_\beta = -\frac{\sqrt{3}}{2}\cos\omega\, t\,. \quad (8)$$

The pq transformation can be written by matrix form:

$$\begin{aligned} \begin{bmatrix} v_p \\ v_q \end{bmatrix} &= \begin{bmatrix} s_\alpha & s_\beta \\ -s_\beta & s_\alpha \end{bmatrix} \begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = \\ &= \frac{\sqrt{3}}{2} \begin{bmatrix} \sin\omega\, t & \cos\omega\, t \\ -\cos\omega\, t & \sin\omega\, t \end{bmatrix} = \left[T_{pq}\right] \begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} \end{aligned} \quad (9)$$

After the last transformation, the components of signals v_p and v_q corresponding to the fundamental voltages are seen as dc components and can be easily extract by using two low-pass filters.

Applying the inverse coordinate transformations $[T_{pq}]^{-1}$ and $[T_{\alpha\beta}]^{-1}$, the fundamental voltage components are evaluated and subtracted from the line voltages, so that the total harmonic voltages v_{hac} and v_{hbc} are obtained.

Due to the elimination of fundamental components from the line voltages, it is possible to perform a direct measurement of the harmonic instantaneous active power, by using (1).

The same operation can be carried out for selected h harmonic orders (h>1); in this case, after the transformations $[T_{\alpha\beta}]$ and $[T_{pq}]$, the dc component of signals v_p and v_q are corresponding to the h harmonic voltages and can be easily exctract by using the above mentioned low-pass filters;

applying the inverse coordinate transformations $[T_{pq}]^{-1}$ and $[T_{\alpha\beta}]^{-1}$, the *h* harmonic voltage components are evaluated.

Starting from the measured *h* harmonic, the *h* harmonic instantaneous active power can be obtained, by performing the same above mentioned power measurement.

Fig. 2 shows the block diagram of fundamental or harmonic voltage detection system.

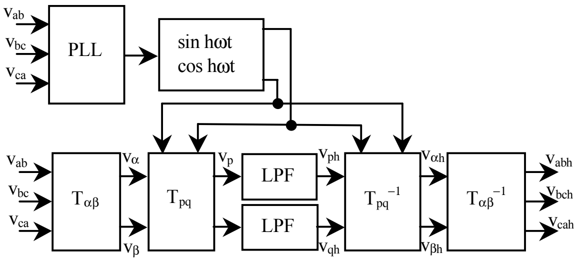

Fig. 2. Block diagram of fundamental/harmonic voltage system

In Fig. 2 PLL block represents a phase lock-in loop, for fundamental frequency measurement, and LPF blocks represent the low pass filters, for the v_p and v_q dc component detection.

With the proposed harmonic detection approach, it is possible to evaluate the total amount of distortion at the metering section and locating the dominant harmonic source, upstream or downstream the metering section. Moreover a similar and recursive investigation, can be used to detect dominant distortion sources at selected different harmonic orders (for example typical harmonic measuring load content). This operation is made by using further coordinate conversion with respect to different orthogonal systems rotating at the selected harmonic frequencies. In this way, the *h* harmonic can be measured and the *h* harmonic active power can be evaluated.

3. EXPERIMENTAL RESULTS

The measurement technique has been implemented on a microprocessor IBM Power PC 604e of the controller board dSPACE® DS1103 programmed through the software package SIMULINK®, a toolbox of MATLAB® (software from the Math Works Inc.). The sampling time has been set to 200 µs.

In order to proof the developed instrument in different working conditions an artificial test power system has been realized. The test power system consists on: a three phase voltage supply, either sinusoidal or distorted with known harmonic contents; an equivalent network impedance; a resistive load (P = 5 kW) and a non linear load (a diode bridge rectifier with a dc load, P = 5 kW). Measurements have been carried out for different supply voltage and load conditions.

A virtual instrument panel has been realized in order to control network and load working conditions and to measure and detect harmonic distortion. In fig.3 is shown the virtual instrument panel.

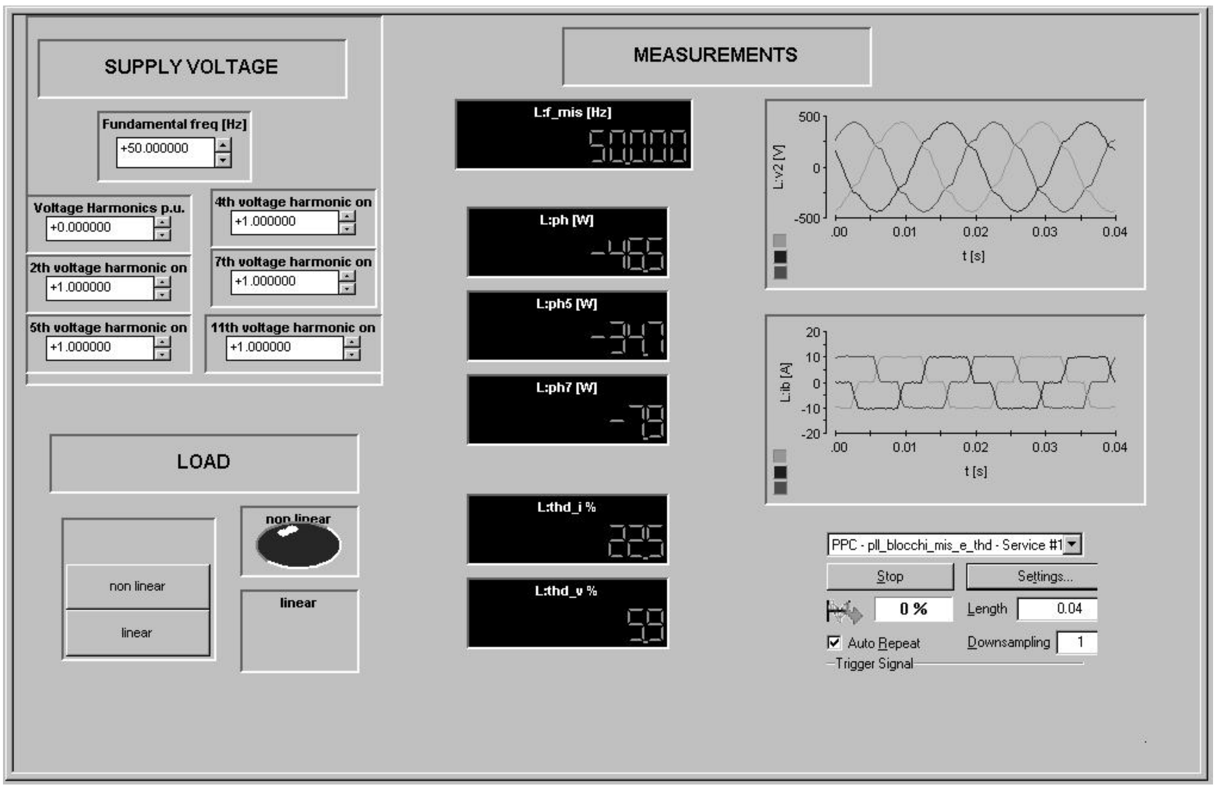

Fig. 3. Virtual instrument front panel

In Tab. I some measurement results are reported, to confirm that the proposed method can be usefully applied in order to locate the dominant harmonic source, even in respect to selected harmonic components. In particular, for the reported tests, the measurement system was set in order to evaluate the total harmonic power and harmonic distortion due to 5th and 7th harmonic components. However the investigation can be easily carried out for other harmonics.

The supply conditions were the following:

- Case 1: sinusoidal three phase symmetrical voltages;
- Case 2: distorted voltages, affected by 2th and 4th harmonics, with limit amplitudes endorsed by [3];
- Case 3, 4 and 5: distorted voltages, affected by 2th, 4th, 5th, 7th and 11th harmonics; their amplitudes were set respectively at 50% (3), 100% (4) and 150% of limit values endorsed by [3].

The load conditions were the following:

- Case L: linear load;
- Case NL: distorted load.

TABLE I. Experimental results

Supply	Load	THD_V	THD_I	P_h [W]	P_{h5} [W]	P_{h7} [W]
1	NL	5,9 %	22 %	- 46,5	- 34,7	- 7,90
2		7,4 %	23 %	- 35,2	- 32,4	- 6,70
3		10 %	23 %	- 73,5	- 56,0	- 19,5
4		15 %	24 %	- 87,2	- 72,5	- 22,5
5		19 %	26 %	- 43,2	- 50,0	- 9,55
2	L	5,2 %	5,2 %	+ 6,15	+ 0,00	+ 0,00
3		5,2 %	5,2 %	+ 6,10	+ 2,20	+ 1,45
4		10 %	10 %	+ 24,2	+ 8,70	+ 5,95

In Tab. I P_h is the value of the dc components of harmonic active power calculated after extracting the fundamental voltages; P_{h5} and P_{h7} are the same quantities calculated after extracting 5th and 7th harmonic voltages. THD_V and THD_I are respectively voltage and current total harmonic distortion factors [2]; their values have been calculated by means of rms values of fundamental and harmonic voltage and currents, obtained as described in section 2.

It can be observed from the measurement results, that the proposed method is able to locate the dominant harmonic source, upstream or downstream the metering section, with respect to both total distortion amount and singular harmonics.

For example, in the first case, the dominant harmonic source is the load, both for total distortion and for singular harmonics. Measurement results lead to the same conclusions, because all measured harmonic powers are negative; moreover, P_{h5} absolute value is comparable to P_h one and P_{h7}, is much smaller than 5th one. Therefore total distortion is mainly due to 5th harmonic even if other harmonics are present.

Also in the second case, the dominant harmonic source is the load; all measured harmonic powers are negative, but P_h absolute value is smaller than the sum of P_{h5} and P_{h7} ones. As the previous case the dominant harmonic source is the load and its harmonic content is mainly due to the 5th harmonic. Moreover it can be deduced that the harmonics due to the network operate a compensation on the total harmonic amount.

Similar considerations can be carried out with respect to the other reported cases.

Finally it can be observed that measurements can be performed with fast response (200 μs) and accuracy (that will be discussed in section 4); moreover the harmonic sources detection can be carried out with respect to the total harmonic content, as well as to singular selected harmonic orders; the same measurement algorithm is recursively used, changing only the frequency of the rotating coordinates system.

4. MEASUREMENT ACCURACY

Response and accuracy of the proposed method depend on different factors: accuracy of PLL used for the fundamental frequency measurement and the synchronization of the rotating coordinates system; filters used for extracting the fundamental or the selected harmonic voltages; accuracy of measurement transducers.

Simulations have been made in order to test the accuracy of the proposed measurement algorithm; the simulated testing system has been implemented by using the software packages SIMULINK® and POWER SYSTEM BLOCKSET® of MATLAB®.

Simulations measurements have been performed on a simulated power test system, similar to the experimental one, realized with: a supply voltage, which simulates a low voltage three phase system, either sinusoidal or distorted; the equivalent network impedance; different loads, both linear and non linear.

To assess the algorithm accuracy, the following measurement errors have been introduced:

1. the fundamental frequency measurement error introduced by the used PLL (0,01% of the frequency value);
2. measurement transducers errors, both in amplitude and in phase (class 0,5 measurement transformers have been considered).
3. both PLL and transducers errors.

In all the above cases errors due to analogue-digital conversion have been taken into account. Simulation results are reported in Tab. II, that show the influence of the above mentioned errors on harmonic powers measurement accuracy; the following errors are reported, expressed in percentage of the harmonic powers values:

- e_{Ph}: relative error on total harmonic power P_h;
- e_{Phi}: relative error on singular harmonic powers P_{hi}.

In the reported cases the supply voltages have been distorted, by 2th to 19th harmonic components with amplitudes set at 50% of limit values endorsed by [2].

The load conditions has been the following:

- L: resistive load;

- NL1: a diode bridge rectifier with a dc load;
- NL2: NL1 with a parallel inductive load.

TABLE II. Simulation results

Load	Measurement errors	e_{Ph}	e_{Ph5}	e_{Ph7}
L	1	± 1 %	± 0,2 %	± 0,2 %
	2	± 2 %	± 1 %	± 1 %
	3	± 3 %	± 1 %	± 1 %
NL1	1	± 2 %	± 1,5 %	± 1,5 %
	2	± 3 %	± 2,5 %	± 2,5 %
	3	± 5 %	± 4 %	± 4 %
NL2	1	± 2 %	± 1 %	± 1 %
	2	± 2 %	± 1 %	± 1 %
	3	± 4 %	± 3 %	± 3 %

The harmonic power measurement accuracy depends on load and supply conditions; in the reported cases distorted supply voltages have been considered, being this the worst case. In fact measurement errors increase with the load non-linearity degree. Moreover they depend on phase angles between measured voltages and currents.

However the error in harmonic powers measurement doesn’t lead to a wrong determination of their sign.

5. CONCLUSIONS

In this paper a new method have been presented for harmonic distortion detection in three phase systems. The method is able to locate the dominant harmonic sources upstream or downstream the metering section, with respect to both the total harmonic distortion amount and singular harmonic orders.

The proposed measurement algorithm is very simple to implement; its advantages lie in the fact that harmonic detection and harmonic power measurements can be obtained in real-time, with fast response and accuracy, without using any time to frequency transformation for harmonic analysis that generally returns a mean harmonic signal content referred to the total sampling interval. Moreover, the investigation of harmonic sources can be easily made with respect to specified singular harmonic orders by using a recursive algorithm.

The experimental results confirm that the proposed method can be usefully applied for dominant harmonic source location.

The response and the accuracy of the method depend mainly on the following factors: the accuracy of the fundamental frequency measurement and the synchronization of the rotating orthogonal coordinate systems; the accuracy of the input measurement transducers, particularly with respect to the introduced phase error; the filters chosen for extracting the fundamental or the selected harmonic voltages.

Simulation results show that the accuracy of the proposed method is high, even in presence of errors introduced by the above mentioned factors.

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