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TIME DOMAIN METHOD TO DETECT HARMONIC SOURCES IN UNBALANCED POWER SYSTEMS

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Abstract − In recent years the problem of harmonic pollution has become more urgent, because of the development in distribution systems of non linear loads that draw non-sinusoidal currents. This paper presents a time domain method for harmonics sources detection in power systems, which can be usefully applied also in presence of unbalance or asymmetry. Harmonic power flows are calculated in real time and no spectral analysis is required for the evaluation of currents amplitudes and phase angles. The development of a new instrument is described, which is able to measure several network power quality parameters; measurement accuracy is estimated and experimental results are reported.

Keywords: harmonics, unbalance, harmonics sources.

1. INTRODUCTION

The energy markets deregulation holds a new contractual perspective between customers and utilities, in which the energy price can depend on voltage quality and load characteristics, as well as on responsibility for disturbances caused on supply voltage in power systems. Among these disturbances, harmonic distortion is one of the most important, because of proliferation in distribution networks of non-linear loads, such as power electronic devices, that draw non-sinusoidal currents. In this contest, the development of any method for harmonic distortion evaluation requires also the detection of sources of disturbance, that, in most cases, are located both upstream and downstream the metering section; so, both supply and load can be responsible for harmonic distortion. Moreover, in presence of negative sequence components in currents and voltages, harmonics sources detection can be more complex because of the overlapping of the effects due to unbalance and non linearity.

At present, the international in force and draft Standards set limits for harmonic distortion for some voltages and currents levels and for total distortion amount, for both networks and loads [1] [2]; they also define measurement methods to evaluate harmonic distortion level [3] [4]. Anywhere, there is no in force or draft document that define indices and related measurement methods for harmonic sources localization.

In literature, the proposed approaches for harmonic sources detection can be divided into two groups: distributed synchronous measurement methods and single point measurement methods [5-8]. Distributed and synchronous measurement methods are difficult to be implemented and managed because they require very complex and expensive measurement instrumentation, both hardware and software. On the other hand they can give a correct information on the harmonic state of the whole power system. On the contrary, single point measurement methods in some cases can give a not correct information about the harmonic state of the system; however they have many advantages like easy implementation, low cost and low risk of system failure. Actually single point measurements are still preferable, specially for medium and low voltage distribution systems, where it is often very difficult or impossible to know the exact network impedance values. Several approaches for single-point measurement methods can be based on the definition of numerous harmonic indexes and non-active powers [9-10]; but, the most employed are still the ones based on the harmonic power flow analysis [11-12]. Generally, it requires the evaluation of amplitudes and phase angles of each voltages and currents harmonic, which is usually carried out by means of voltages and currents decomposition into Fourier series. However, this operation needs an accurate time to frequency transformation, with a wide observation window and time consuming calculations.

In this paper a simple and fast time-domain method is proposed to locate dominant harmonic sources. It is based on the instantaneous active power measurement, by means of a harmonics detection technique, based on the instantaneous reactive power theory [13-14]. The proposed method is able to detect the harmonic active power flow, locating the dominant harmonic source upstream or downstream the metering section, for both total distortion amount and selected harmonic components. The method can also detect negative sequence components and then separate the effects due to unbalance from the ones due to non linearity. A new virtual instrument has been realized by means of a microprocessor board that performs both frequency, voltages, currents, powers, harmonic distortion factors and unbalance degree measurements, as well as harmonic source detections. In the paper theoretical fundamentals of the method are given; secondly, the development of the new instrument is described; finally, experimental results are presented and measurement accuracy is discussed.

2. HARMONIC AND UNBALANCE DETECTION APPROACH

2.1 Harmonic and negative sequence components detection

The developed detection method for both harmonic and negative sequence components is based on the instantaneous reactive power theory [14]. Let us consider a three phase ac line to line voltages system (namely v_{ab}, v_{bc} and v_{ca}); according to the above mentioned theory, they can be transformed into two phase $\alpha\beta$ coordinates, as follows:

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

A second coordinate conversion (Tpq) can be applied, to obtain the instantaneous voltages v_p and v_q, referred to a two-phase orthogonal system, (s_α, s_β) rotating at the fundamental frequency:

$$\begin{bmatrix} v_p \\ v_q \end{bmatrix} = \begin{bmatrix} s_\alpha & s_\beta \\ -s_\beta & s_\alpha \end{bmatrix} \begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = \left[T_{pq}\right] \begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} \quad (2)$$

It is obtained if in (1) voltages are substituted with a three phase sinusoidal symmetrical system:

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

where h=1 is corresponding to the fundamental frequency. In this case, applying the $\alpha\beta$ transformation, s_α and s_β are given by:

$$s_\alpha = \frac{\sqrt{3}}{2}\sin\omega\, t \qquad s_\beta = -\frac{\sqrt{3}}{2}\cos\omega\, t\,. \quad (4)$$

In practical terms, (s_α, s_β) rotating system can be generated by means of a software Phase Locked Loop (PLL) whose VCO is synchronized with voltage fundamental frequency.

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 means of two low-pass filters. Applying the inverse coordinate transformations $[T_{pq}]^{-1}$ and $[T_{\alpha\beta}]^{-1}$, the fundamental voltage components are detected; then they can be subtracted from the line voltages, so that the total harmonic voltages are obtained and the total distortion amount can be evaluated at the metering section.

A similar and recursive investigation, can be used to detect harmonic components and to evaluate harmonic active powers with respect to selected harmonic orders. This operation can be made by using further and recursive coordinate conversion, with respect to different orthogonal systems rotating at the selected harmonic frequencies ($h\neq1$) [16]. More in detail, two cases can be pointed out. When $h=3n-1$, (n is a positive integer number) inverse order harmonics can be detected; in this case, the application of the $\alpha\beta$ transformation to system (3) leads to:

$$s_\alpha = \frac{\sqrt{3}}{2}\sin h\omega\, t \qquad s_\beta = \frac{\sqrt{3}}{2}\cos h\omega\, t\,. \quad (5)$$

On the other hand, when $h=3n+1$, direct order harmonics can be detected and the application of the $\alpha\beta$ transformation to system (3) leads to:

$$s_\alpha = \frac{\sqrt{3}}{2}\sin h\omega\, t \qquad s_\beta = -\frac{\sqrt{3}}{2}\cos h\omega\, t\,. \quad (6)$$

Moreover, the same investigation can be carried out with respect to negative sequence components, just by using similar coordinate conversions with respect to orthogonal systems rotating at fundamental or harmonic frequency but in negative sense. In this case, the rotating coordinates system (s_a^-, s_b^-) is obtained if the $\alpha\beta$ transformation is applied to a three phase negative sequence symmetrical system:

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

For example, for the fundamental negative sequence components (h=1), (s_a^-, s_b^-) system is given by:

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

So, also the unbalance degree can be evaluated at the metering section, as made with respect to the harmonic distortion detection.

2.2 Harmonic powers evaluation

Harmonic sources detection strategy is based upon the harmonic active power flow evaluation.

In a three-phase three-wire system, harmonic instantaneous active power is given by:

$$p_h = v_{hac} i_a + v_{hbc} i_b \quad (9)$$

where v_h are the harmonic line to line voltages and i are the line currents.

The dc component of p_h is the harmonic active power (P_h) that is given by the sum of harmonic active powers for each phase [12-13]. According to harmonic power flow theory, 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.

When fundamental components are eliminated from the line voltages, by using the harmonic detection system shown in the previous section, it is possible to perform a time domain direct measure of the instantaneous harmonic active power [15, 16]. So, the dominant harmonic source can be located upstream or downstream the metering section.

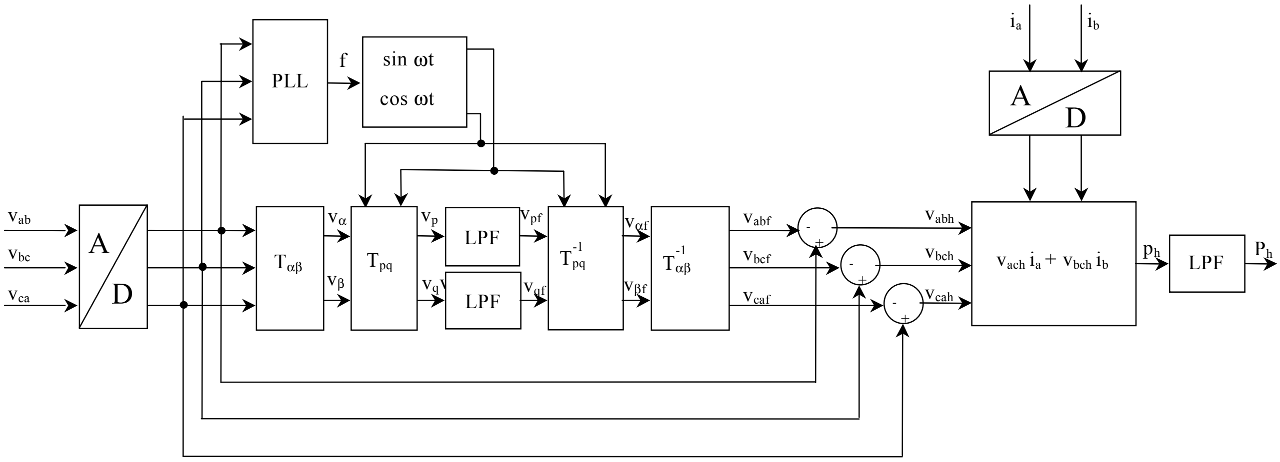

Fig. 1. Block diagram of measurement system

In Fig. 1 the block diagram of the measurement system is shown, with respect to total harmonic distortion amount detection: PLL block represents the software phase locked loop, for fundamental frequency measurement and LPF blocks represent the low pass filters, for the v_p and v_q dc component detection. The PLL is needed to synchronise the sinusoidal rotating (s_α, s_β) system with the fundamental voltage frequency; this condition can be easily obtained from the waveform analysis of v_p and v_q signals detected at low pass filters output [15].

In the same way, the Authors have observed that the same evaluation can be carried out with respect to the active power related to a single harmonic component [15-16]. It can be directly evaluated if the corresponding harmonic is insulated from voltage total harmonic content. Moreover, the same evaluation can be performed with respect to negative sequence components, so that their sources can be located, as made with respect to the harmonic distortion detection. With the proposed harmonic and negative sequence components detection method, it is possible to perform the active power flow analysis without requiring any voltages and currents spectral analysis for the evaluation of amplitudes and phase angles of voltages and currents. The investigation of disturbance sources can be easily made with respect to both total distortion amount and selected harmonic orders, as well as for unbalance degree, by using a recursive algorithm.

Moreover, a direct measure of fundamental and harmonic reactive powers can be performed too. In fact, if harmonic or fundamental voltages are extracted and shifted by -90° (-π/2 rad), the related reactive powers can be simply measured as made with respect to active power.

The harmonic or fundamental quadrature voltages can be easily obtained as follows

$$v'(n) = \frac{v(n-1) - v(n+1)}{2\sin\Omega_0}\,. \qquad (13)$$

where *v(n)* and *v'(n)* are respectively a measured voltage discrete time signal and the quadrature one, and Ω_0 is the oscillation frequency of the VCO employed in the PLL system [17]. A block diagram of the generic h-harmonic reactive power (Q_h) measurement system is shown in Fig. 2, where $\mathbf{v}_h$ is h-harmonic voltages vector (v_{abh}, v_{bch}, v_{cah}), $\mathbf{v}_{qh}$ is the related quadrature voltages signals vector, f_h is the harmonic frequency and T_s is the sample time.

3. THE NEW INSTRUMENT

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.

The virtual instrument has been developed in order to perform measurements of: supply voltage frequency, voltage and current total distortion factors, harmonic voltages amplitudes and unbalance degree. Moreover the evaluation of the following powers has been implemented: fundamental active and reactive powers; inverse sequence fundamental active and reactive powers; single harmonic active and reactive powers; total active power; total harmonic active power. The virtual instrument front panel is shown in Fig. 3.

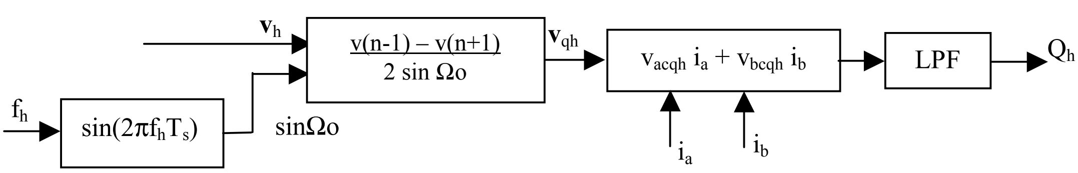

Fig. 2. Block diagram of reactive power measurement system

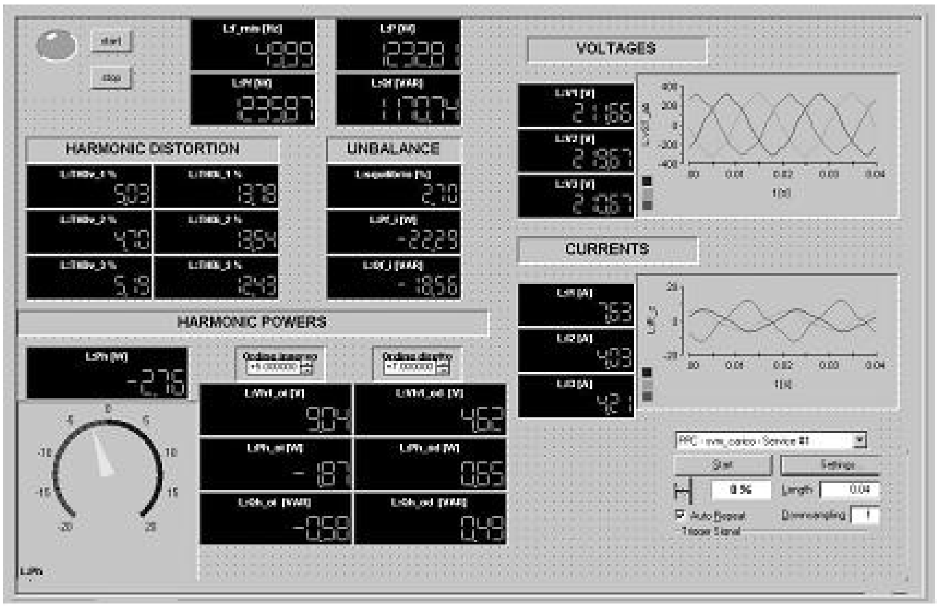

Fig. 3. Virtual instrument front panel

3.1 Experimental results

In order to test the developed instrument in different working conditions, measurements have been performed on a test system, which has been realised with: a linear load, consisting on a three phase resistive bench, rated values V = 220 V, P = 120÷4.500 W; a non linear unbalanced load, consisting on the above mentioned resistive load, supplied with a transformer, k = 220/380 V/V; the unbalance and non linearity has been created with a single phase DC supplier, connected in parallel with one of the transformer secondary phases, feeding a DC load with rated values 300 V, 2 A. A block diagram of the test system is shown in Fig. 4.

Voltage and currents have been filtered by an active low pass filter (cut-off frequency 2000 Hz); currents have been sensed by two Hall sensors, with a DC to 100 kHz bandwidth and ±1% accuracy; voltages have been sensed by two high voltage differential probes, with a DC to 25 MHz bandwidth and ±3% accuracy. The A/D conversion has been performed by means of 14 bit ADC.

The test system has been supplied with network three phase line to line low voltages (380V, 50Hz); an autotransformer has been employed, to supply the linear load with the nominal voltages, in all working conditions, during the experimental tests. Measured supply voltages characteristics, in no load conditions, are reported in Table I.

Table I: Supply voltage characteristics

Frequency [Hz]		50,000
Line to line	Vab	380
	Vbc	380
	Vca	378
THD [%]	THDv_ab	4,64
	THDv_bc	4,66
	THDv_ca	4,77
Unbalance degree [%]		0,37

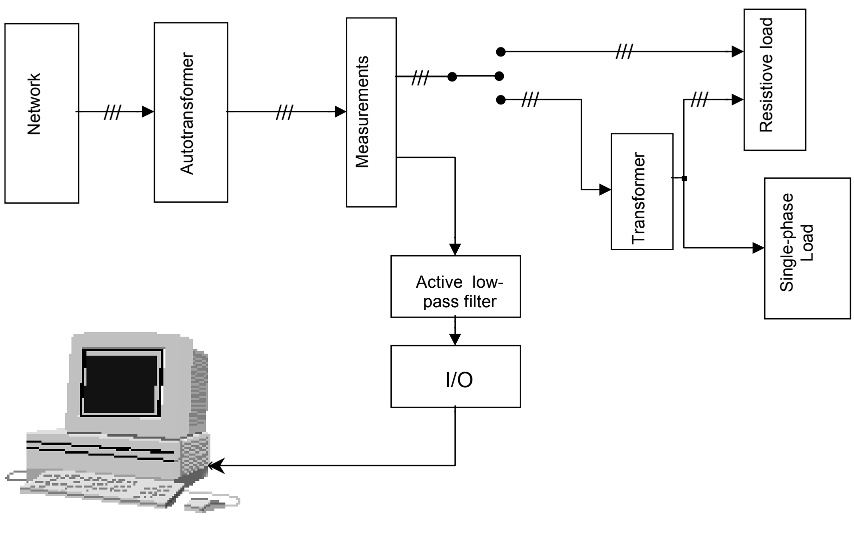

Fig. 4: Block diagram of the test bench

Some measurement results are reported in Table II. In the reported tests, load conditions were the following:

- L_1, L_2, L_3: linear load conditions; resistive load rated powers values were the following: P_1=600 W, P_2 = 1.200 W, P_3 = 4.500 W
- NLU_0, NLU_1, NLU_2, NLU_3, NLU_4: non linear and unbalanced loads; resistive load rated powers values were the following: P_1=300 W, P_2 = 600 W, P_3 = 1.200 W, P_4 = 2.400 W; in NLU_0 case, no resistive load was connected to the transformer.

Measurement results confirm that the proposed method can be usefully applied in order to locate the dominant harmonic source, even in respect to selected harmonic components (for the reported tests 5^{th} harmonic component). Moreover, they show that the proposed method is also able to detect the presence of negative sequence components due to unbalance and to locate their source upstream or downstream the metering section.

For example, in all linear load cases, network is the dominant source of distortion and unbalance; measurement results lead to the same conclusions, because all harmonic and inverse active powers are positive. On the other end, in non linear and unbalanced load cases, load is the main responsible for distortion and unbalance at the metering section; in these cases the above mentioned powers are negative, so, measurements results confirm that load is the dominant source of disturbance. Moreover it can be observed that the increase of the resistive load connected to the transformer lead to a globally more linear behaviour; according to this fact, measured harmonic and inverse powers increase and become positive at last.

3.2 Accuracy estimation

Response and the accuracy of the measurement method depend mainly on the following factors: accuracy of the measurement system of the fundamental frequency, and the synchronization of the rotating orthogonal coordinate system; filters chosen for extracting the fundamental or the selected harmonic voltages; accuracy of measurement transducers. Moreover, instrument accuracy is influenced by typical uncertainty sources, such as the ones due to analogue-to digital conversion. Some simulation tests have been performed, which showed that the harmonic active power measurement accuracy depends on different factors, such as non linearity degree and phase angles between voltages and currents [15].

TABLE II: Measurement results

LOAD CONDITIONS			LINEAR			NON LINEAR AND UNBALANCED				
			L_1	L_2	L_3	NLU_0	NLU_1	NLU_2	NLU_3	NLU_4
MEASUREMENTS	Frequency [Hz]		50,010	50,010	50,000	50,010	49,998	49,998	49,998	49,998
	Active power [W]		611	1,18E+03	4,13E+03	978	1,23E+03	1,49E+03	1,96E+03	2,77E+03
	Line-to-line Voltages [V]	Vab	379	378	376	212	212	210	209	206
		Vbc	379	379	376	221	220	218	216	212
		Vca	377	377	374	212	211	209	208	205
	Line Currents [A]	Ia	0,93	1,78	6,28	7,00	7,63	8,17	9,08	10,4
		Ib	0,94	1,82	6,45	3,96	4,03	4,18	4,81	6,95
		Ic	0,93	1,80	6,29	3,38	4,21	4,99	6,40	8,76
	Voltage Distortion Factor [%]	THDv_ab	4,56	4,59	4,42	4,87	5,03	5,04	4,71	4,62
		THDv_bc	4,70	4,61	4,47	4,55	4,70	4,59	4,13	4,03
		THDv_ca	4,83	4,80	4,51	5,27	5,19	4,92	4,55	4,53
	Current Distortion Factor [%]	THDi_a	4,87	4,78	4,47	15,2	13,8	12,5	10,7	8,55
		THDi_b	4,74	4,61	4,43	14,3	13,5	12,2	9,88	6,47
		THDi_c	4,94	4,79	4,49	15,5	12,4	10,4	7,93	5,34
	Unbalance Degree [%]		0,29	0,34	0,33	2,66	2,70	2,74	2,60	2,17
	Fundamental Powers	Pf [W]	609	1,18E+03	4,12E+03	981	1,24E+03	1,49E+03	1,96E+03	2,77E+03
		Qf [VAR]	50,0	50,2	66,1	1,15E+03	1,17E+03	1,21E+03	1,25E+03	1,33E+03
	Fund.Inverse Powers	Pf_i [W]	0,01	0,03	0,23	-22,0	-22,3	-22,2	-19,6	-11,4
		Qf_i [VAR]	-0,01	-0,02	-0,07	-18,4	-18,6	-19,3	-17,2	-10,5
	Harmonic Power [W]		1,38	2,58	8,22	-3,49	-2,76	-1,93	-1,00	0,26
	5th harmonic values	Vh5 [V]	14,3	14,5	14,1	9,00	9,04	8,99	8,49	8,24
		Ph5 [W]	0,84	1,55	5,02	-2,48	-1,87	-1,18	-0,15	0,70
		Qh5 [VAR]	0,03	0,02	0,01	-0,25	-0,58	-0,82	-0,97	-0,40

However it has been demonstrated that harmonic powers measurements accuracy is not more than few percents of harmonic powers values and it doesn't lead to a wrong determination of their sign. Moreover experimental tests have been carried out in order to evaluate the accuracy of the realized instrument [16]. In all cases, the instrument locked the input voltage frequency with an accuracy higher than ± 0,001%; measurements of fundamental, harmonic and negative sequence components, as well as of related powers measurements, have been performed with an accuracy higher than ± 0,05% and ± 1% respectively. These error values do not take in account the accuracy of measurement transducers in agreement with the IEC Draft [4]. Taking into account transducer accuracies the instrument do not exceed Class I limits given by [3]. About the harmonic powers measurement, it has to be observed that the uncertainty is very low, even if the harmonic powers values are small; this accuracy can be achieved because a direct measure of the harmonic powers is performed.

4. CONCLUSIONS

In this paper a new instrument have been presented for harmonic distortion and unbalance detection in three phase systems. The instrument performs measurements of: frequency, voltages, currents, active and reactive powers, harmonic distortion factors and unbalance degree; moreover a harmonic power flow analysis is carried out to locate the dominant disturbance sources upstream or downstream the metering section, with respect to both the total harmonic distortion amount and singular harmonic orders, as well as with respect to unbalance. The measurement algorithm is very simple to implement; 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. Harmonic powers can be measured directly and no spectral analysis are required for the evaluation of amplitudes and phase angles of voltages and currents. Moreover, the investigation of harmonic sources can be easily made with respect to single harmonic orders, as well as for unbalance, by using a recursive algorithm.

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