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A single-point strategy based on IEEE 1459-2000 for the Detection of Dominant Harmonic Sources in Power Systems

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Abstract- This paper deals with a novel single-point strategy for the detection of harmonic sources in power systems. It is an enhancement of a previous strategy, developed by authors, which is based on the IEEE Std. 1459-2000 approach. In the paper, the effectiveness of the strategy is investigated, by means of simulation tests, which were carried out on a IEEE standard three-phase test power system. The analysis is carried out by considering also the presence of the measurement transducers.

I. Introduction

The traditional quantities used for the electrical energy pricing do not take into account the presence of harmonic distortion at the metering section. In fact, they are based upon the traditional concepts of active, reactive and apparent power (and energy), and related power factor, that are well defined only for sinusoidal voltages and currents [1]. However, with the deregulation of the electricity markets, new billing strategies are needed, taking into account not only the energy consumption but also the power quality levels and the responsibilities for disturbances affecting the power networks. In this contest, the harmonic distortion is one of the most important features because of the large number of non-linear and/or time-variant loads which inject harmonics in the line currents.

In the scientific literature, several methods, both single-point and multi-point, have been proposed for the detection of the harmonic sources; many of them have been based on the measurement of the harmonic active power flow at the metering section. However, it has been demonstrated that in some practical situations this approach gives an incorrect information about the location of the harmonic sources [2-5]. In these cases, it could be interesting to pay attention to the “nonactive” components of the apparent power. As regard this, in [1] the authors proposed a novel strategy, which was based on the simultaneous evaluation of different nonactive power quantities at the same metering section. This strategy was able to give useful information on the location of the dominant harmonic source, but it required to perform a spectral analysis of voltage and current.

In this paper the authors present an enhancement of the approach of [1], by substituting one of the nonactive powers previously used with a new parameter which is obtained from the IEEE Std. 1459-2000 approach [6] [7]. The new strategy is easier to be implemented than the previous one, because it is based only on the separation of the fundamental components from the harmonic content of voltage and current, thus simplifying the measurement system. It can be entirely implemented in the time domain [7], by using a technique already developed by authors for the detection of fundamental and harmonic components of voltages and currents [8]. In the paper, firstly, the theoretical formulation of the proposed strategy is recalled. Secondly, some simulation tests are presented, which were carried out on a IEEE standard test power system [9] proposed by other authors as a benchmark system for the analysis of multi-point measurement techniques for harmonic pollution monitoring. Finally the effectiveness of the proposed technique is investigated also in the presence of the measurement transducers.

II. The proposed strategy

The proposed single-point strategy for the detection of the dominant harmonic source, upstream or downstream the metering section, is based on the comparison of the following nonactive power quantities derived from the IEEE 1459-2000 approach:

$$Q_1 = V_1 I_1 \sin\theta_1 \tag{1}$$

$$N = \sqrt{S^2 - P^2} \tag{2}$$

$$Q_X^2 = V^2\left(I_1^2 \sin^2\theta_1 + I_H^2 \sin^2\theta_H\right) = V^2\left[I_1^2 \sin^2\theta_1 + \frac{D_H^2}{V_H^2}\right] \qquad (3)$$

where Q_1 is the fundamental reactive power, N is the nonactive power, defined in the IEEE Std. 1459-2000 [6] and Q_X is a "fictitious" reactive power, which was introduced in [7], starting from the approach of the aforesaid standard [2]. In the previous equations: V_1 and I_1 are the rms values of the fundamental components of voltage and current and θ_1 is their displacement; S is the apparent power and P is the active power; V is the RMS value of the whole voltage, I_H and V_H are the RMS values of the whole harmonic current and voltage respectively and D_H is the harmonic nonactive power [6].
A comparison among Q_1, Q_X and N, calculated in the same metering section and in the same working condition, can give a piece of information on the presence of disturbing loads [7]. In fact, in a given distorted working condition, Q_1 can be considered as a minimum reference value, since it is the only nonactive power component in the sinusoidal condition. N is a maximum reference value since it groups all the nonactive components of the apparent power. It can be demonstrated that $Q_1 \le Q_X \le N$, since Q_X includes Q_1 but it is not the only component of the nonactive power (the three quantities are equal in sinusoidal conditions). The differences among the values of the three considered quantities depend on the supply and load conditions. For example, in the case of a nonsinusoidal supply and a linear load, the amount of current distortion is low and it is due to the distortion of the supply voltage; thus the difference between Q_1 and N is not much significant (i.e. the contribution of the harmonics is small, as generally happens in the practical cases) and Q_X is closer to Q_1 than to N (i.e. the contribution of the current harmonics is reduced mainly to the fundamental). On the contrary, when a non linear load is present, the amount of current distortion is higher, if compared with the previous case, and Q_1 and N assume values that are significantly different, because the total amount of distortion becomes more relevant; also the contribution of the harmonics to the value of Q_X increases, with Q_X closer to N than to Q_1. Finally, when both the load and the supply are responsible for the harmonic distortion, an intermediate situation occurs, where the differences among the three quantities are relevant and Q_X assumes an intermediate value between Q_1 and N.
The proposed approach based on the comparison of nonactive powers was extended to the three-phase balanced systems, just considering each of the nonactive powers Q_1 , Q_X and N as the sum of the respective phase quantities. On the other hand, the validity of the proposed approach was investigated also in the unbalanced case, showing that some meaningful results could be obtained also in this case, even if the separation of the effects of the unbalance and nonlinearity is not directly achievable (the strategy is sensitive to the harmonic distortion and not to the unbalance).
In [7], a preliminary validation of the proposed strategy was carried out in both the single-phase and the three-phase case, showing its effectiveness in different working conditions and also in some critical cases, where other methods could give incorrect results (such as the method based on the harmonic active power).

III. Simulation results in the absence of transducers

The simulations were carried out on the IEEE Test System n. 2 proposed in [9]. This system was already used by the authors for the validation of the previous strategy proposed in [1]; thus a direct comparison of the enhanced strategy with the previous one could be made.
With some simplifying assumptions [1], the IEEE network (see figure 1) essentially consisted of a power source (at node 50), a transformer (between nodes 50 and 31) and the following five loads:

- L1 (at node 33, including the single-phase load 34);
- L2 (at node 32, consisting of the single-phase load 45, the phase-phase load 46, and half the distributed load between nodes 32 and 71);
- L3 (at node 71, consisting of half the distributed load between nodes 32 and 71, the phase-phase load 92 and the single-phase loads 52 and 911, with shunt capacitors);
- L4 (at node 71, consisting of a three-phase load);
- L5 (at node 75, consisting of a three-phase load, with shunt capacitors).

Table I shows the THD factors and the unbalance degrees for the five loads, in the original configuration of the network.

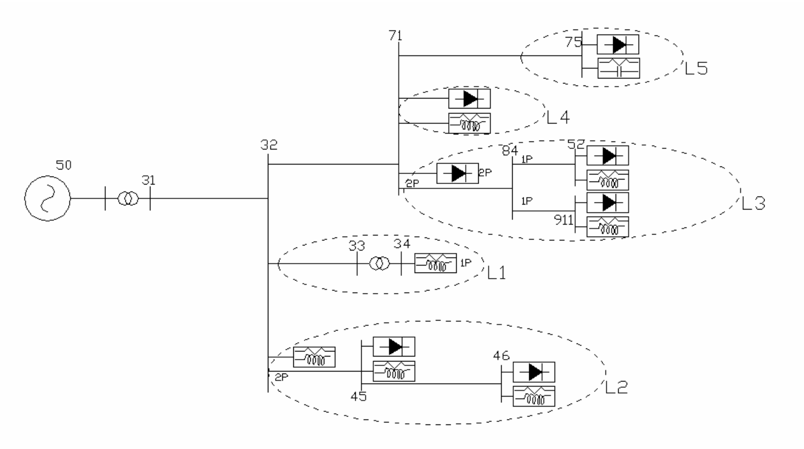


Figure 1. IEEE Test System

Table I: THD factors and unbalance degrees - All nonlinear loads (original network configuration).

		Load L1	Load L2	Load L3	Load L4	Load L5
THD_V [%]	Phase A	4,71		7,85		
	Phase B	4,10		6,77		
	Phase C	4,40		7,45		
THD_I [%]	Phase A	2,11	4,40	5,97	7,48	22,8
	Phase B	2,12	6,90	5,78	6,99	38,9
	Phase C	2,24	7,98	11,85	7,56	29,4
Vi/Vd [%]		0,33	0,33	0,91	0,91	0,91
Ii/Id [%]		84,6	95,6	74,3	3,24	29,7

The IEEE network was implemented by means of the PSCAD/EMTDC software. Five metering sections, one for each considered load, were defined.

Different working conditions were simulated, by considering the original configuration of the network, or by substituting some of the original nonlinear and/or unbalanced loads with equivalent linear and balanced loads having the same power characteristics of the original ones [1]. In each test, the simulation on the PSCAD/EMTDC environment was run and the instantaneous values of voltages and currents were measured at the five metering sections. The obtained data were saved in a MATLAB file and they were used as input data for the evaluation of Q_1, Q_X and N; also the THD factors and the unbalance degree were evaluated.

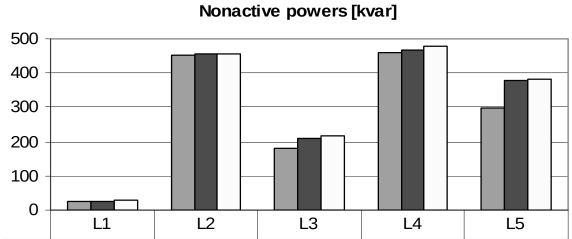
The measurement of the aforesaid quantities was implemented in MATLAB environment, by using a time-domain technique already proposed by the authors for the detection of the fundamental components of voltages and currents [6, 8] This technique makes use of a double time-domain coordinate transformations; the first one is the Park transformation, which transforms the voltages (or currents) into their alpha, beta and zero components; the second one transforms the Park components on a rotating coordinate system, which is synchronized with the fundamental power supply frequency, by means of an internal software PLL [10-11].

In the figure 2a), 2b) and 2c) there are reported some of the results obtained for the nonactive powers Q_1, Q_X and N.

Figure 2a) refer to the original configuration of the IEEE network, with all nonlinear loads. In all cases the proposed strategy based on nonactive powers led to the identification of the disturbing loads. In fact, at each metering section, the three power quantities Q_1, Q_X and N are different and Q_X is closer to N than to Q_1, thus indicating the presence of a disturbing load. Obviously, the values assumed by the considered power quantities and the amount of their differences depend on the harmonic state of the power system and the nature of each load. For example, for the loads L3, L4 and L5 the distortion levels in both voltages and currents are higher than those of the loads L1 and L2 while, for these last two loads, the contribution of unbalance is more significant. As a consequence, the differences among the considered power quantities are more relevant for L3, L4 and L5, while these differences are less significant for L1 and L2. This means that the proposed method is more sensitive to harmonic distortion than to unbalance.

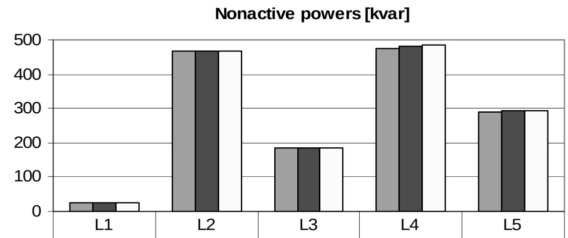
Figure 2b) refer to the network configuration with loads L1, L2, L3, L5 linear and load L4 non linear. It can be observed that for the loads L1, L2, L3 and L5, the values of Q_1, Q_X and N are very close, while for L4 the differences between them are more significant and Q_X is close to N. From this results it can be deduced that L1, L2, L3 and L5 have a linear behavior and the dominant harmonic source is upstream each metering section, i.e. the distortion is due to the supply; on the contrary, L4 has a nonlinear behavior and the dominant harmonic source is downstream the metering section, i.e. the distortion is due to the load L4 itself. Thus, the analysis of the nonactive powers led to the correct identification of the dominant harmonic source at each metering section.

Figure 2c) refer to the network configuration with loads L1, L3 and L5 linear and loads L2 and L4 non linear. Also in this case the analysis of the nonactive powers led to the correct identification of the dominant harmonic source at each metering section. In fact the values of Q_1, Q_X and N are very close for the loads L1, L3 and L5; on the contrary, for L2 and L4 the difference between the considered nonactive powers are more significant and Q_X is closer to N than to Q_1. From these values, it can be deduced that L1, L3 and L5 have a linear behavior and the dominant harmonic source is upstream each metering section, i.e. the distortion is due to the supply; on the other hand, L2 and L4 have a nonlinear behavior and the dominant harmonic sources are downstream each metering section, i.e. the distortion is due to the loads themselves. Also in this case, the difference among the considered power quantities depend on the nature of the load (i.e. the differences are more significant for L4 than for L2).



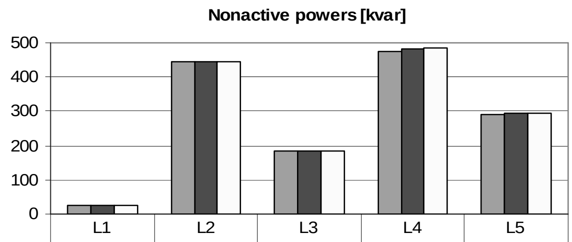
	L1	L2	L3	L4	L5
Q1	26.80	452.7	180.6	459.9	297.9
Qx	27.12	454.3	208.2	468.7	378.2
N	27.69	454.6	216.9	478.5	383.6

Figure 2a). Simulation results of the proposed strategy in the absence of measurement transducers. All non linear loads (original configuration)



	L1	L2	L3	L4	L5
Q1	27.130	466.000	183.200	475.300	290.900
Qx	27.130	466.000	183.300	481.600	292.600
N	27.130	466.000	183.300	484.600	292.600

Figure 2b). Simulation results of the proposed strategy in the absence of measurement transducers. L1, L2, L3 and L5 linear loads, L4 non linear load



	L1	L2	L3	L4	L5
Q1	27.170	444.600	183.500	476.000	291.300
Qx	27.170	446.400	183.600	482.200	293.200
N	27.170	446.400	183.600	485.800	293.200

Figure 2c). Simulation results of the proposed strategy in the absence of measurement transducers. L1, L3 and L5 linear loads, L2 and L4 non linear loads

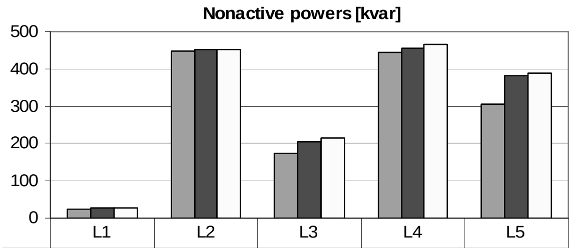
IV. Simulation results in the presence of transducers

The simulations were repeated considering also the presence of the transducers. This was made by introducing on the measured voltages and currents the amplitude and phase errors due to current and voltage transformers (CTs and VTs) of different classes of accuracy.

As regard this, the Standards EN 60044-1 [12] and EN 60044-2 [13] provide information regarding CTs and VTs accuracy and specifications only for sinusoidal conditions. None specific requirements and standardized test procedures are available for the characterization of the transducers in distorted conditions, so that in such condition their behaviour could be different from sinusoidal conditions. In literature different approaches have been proposed for the characterization of CTs and VTs in the presence of harmonics. For example, in [14] and [15] the behaviour of CTs and VTs under distorted conditions was analysed by evaluating the frequency response, as suggested from the standards IEC 61000-4-30 [16] and IEC 61000-4-7 [17].

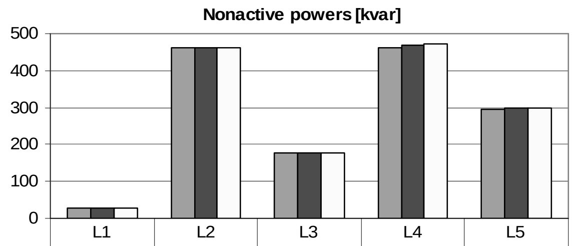
For the simulations, transducers of class 1 accuracy were considered; the amplitudes and phase errors for the fundamental components of voltages and currents were chosen in accordance with the Standards [12-13], while the amplitudes and phase errors for the harmonic components were chosen in accordance with the results of frequency response [14-15]. Moreover, the errors due to analogue-to-digital conversion were taken into account [18].

As an example, in the figure 3 a), 3b) and 3c) there are reported the results obtained for IEEE Test System configurations of the figures 2a), 2b) and 2c) respectively. It can be observed that even if the numeric results were different from the previous cases, the proposed approach maintained its validity, detecting the disturbing loads, as made in the absence of the transducers.



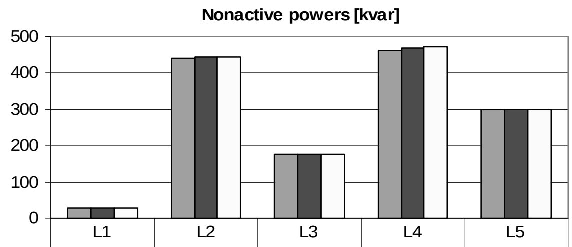
	L1	L2	L3	L4	L5
Q1	25.48	448.8	174.3	446.1	304.4
Qx	26.67	450.5	204.8	455.1	382.8
N	27.17	450.7	213.8	465.3	388.3

Figure 3a). Simulation results of the proposed strategy in the presence of measurement transducers. All non linear loads (original configuration)



	L1	L2	L3	L4	L5
Q1	26.44	461.6	176.9	463.2	295.5
Qx	26.44	461.7	176.9	469.6	300.2
N	26.44	461.7	176.9	472.7	300.2

Figure 3b). Simulation results of the proposed strategy in the presence of measurement transducers. L1, L2, L3 and L5 linear loads, L4 non linear load



	L1	L2	L3	L4	L5
Q1	26.47	441.2	177.1	462.2	299.1
Qx	26.48	443.4	177.2	468.4	300.8
N	26.48	443.4	177.2	472.1	300.8

Figure 3c). Simulation results of the proposed strategy in the presence of measurement transducers. L1, L3 and L5 linear loads, L2 and L4 non linear loads

V. Conclusions

This paper deals with a new strategy for the detection of harmonic sources in power systems, which is based on the simultaneous measurement of three nonactive power quantities, derived from the approach of the IEEE Std. 1459-2000. The proposed method is an enhancement of a previous approach, already developed by the authors. The main advantage of the novel method is that is based on the only on the separation of the fundamental components from the harmonic content of voltage and current. Thus, it can be entirely implemented in the time domain, simplifying the measurement system. The simulation tests, which were carried out on a IEEE standard test power system, show that the proposed method can give useful indications for the detection of the dominant harmonic source, upstream of downstream the metering section both in the absence and in the presence of the measurement transducers.

References

[1] P. V. Barbaro, A. Cataliotti, V. Cosentino, S. Nuccio, “A Novel Approach Based on Nonactive Powers for the Identification of Disturbing Loads in Power Systems”, *IEEE Transactions on Power Delivery*, Vol. 22, No. 3. July 2007, pp. 1782-1789

[2] A. E. Emanuel, “On the assessment of harmonic pollution”, *IEEE Transactions on Power Delivery*, Vol. 10 No. 3 April 2005, pp. 1693-1698

[3] W. Xu, X. Liu, Y. Liu, “An investigation on the validity of power direction method for harmonic source determination”, *IEEE Transactions on Power Delivery*, Vol. 18, No. 1, January 2003, pp. 214-219.

[4] L. S. Czarnecki, “Energy flow and power phenomena in electrical circuits: illusion and reality”, *El. Eng*., vol. 82, 2000, pp. 119-126.

[5] P. V. Barbaro, A. Cataliotti, V. Cosentino, S. Nuccio, “Detection of Disturbing Loads in Distorted and/or Unbalanced Power Systems: a Technique Based on a Comparison among Nonactive Powers”, *Instrumentation and Measurement Technology Conference – IMTC 2007*, Warsaw, Poland, May 1-3, 2007

[6] A. Cataliotti, V. Cosentino, " A Time-Domain Approach Based on the IEEE Std 1459-2000 for the detection of Loads Producing Harmonic Distortion", *I²MTC 2008 – IEEE International Instrumentation and Measurement Technology Conference*, Victoria, Vancouver Island, Canada, May 12–15, 2008.

[7] IEEE Std 1459-2000, “IEEE Trial-use standard definitions for the measurement of electric power quantities under sinusoidal, non sinusoidal, balanced or unbalanced conditions” – *IEEE Standard*, September 2002.

[8] A. Cataliotti, V. Cosentino, S. Nuccio, " A virtual instrument for the measurement of IEEE Std 1459-2000 power quantities ", *IEEE Transactions on Instrumentation and Measurement*, Vol. 57, No. 3. January 2008, pp. 85-94.

[9] IEEE Task Force on Harmonics Modeling and Simulation, “Test Systems for Harmonic Modeling and Simulation”, *IEEE Trans. on Power Delivery*, vol. 14, n. 2, 1999, pp. 579-587.

[10] M. Aiello, A. Cataliotti, V. Cosentino, S. Nuccio, "Synchronization Techniques for Power Quality Instruments", IEEE Trans. on Instrumentation and Measurement Vol. 56, N. 5, October 2007, pp 1511-1519.

[11] A. Cataliotti, V. Cosentino, S. Nuccio, " A Phase Locked Loop for the Synchronization of Power Quality Instruments in the Presence of Stationary and Transient Disturbances", IEEE Trans. on Instrumentation and Measurement, Vol. 56, N° 6, December 2007. pp. 2232-2239.

[12] EN 60044-1, “Instrument Transformers – Part 1: Current Transformers”, August 1999

[13] EN 60044-2, “Instrument Transformers – Part 1: Inductive Voltage Transformers”, March 1999

[14] A. Cataliotti, D. Di Cara, P. A. Di Franco, A. E. Emanuel, S. Nuccio “Frequency response of Measurement Current Transformers”, *I²MTC 2008 – IEEE International Instrumentation and Measurement Technology Conference*, Victoria, Vancouver Island, Canada, May 12–15, 2008.

[15] L. Cristaldi, A. Ferrero, R. Ottoboni, “A VI-Based Equipment for the Frequency-Domain Characterization of Voltage Transformers” *IEEE Instr. and Meas. Technology Conference*, Ottawa, Canada, May 19-21,1997.

[16] IEC 61000-4-30 Ed.2003: “Testing and measurement techniques – Section 30: Power Quality Measurement Methods”.

[17] IEC 61000-4-7 Ed.2002: ”Testing and measurement techniques – Section 7: General guide on harmonics and interharmonics measurement and instrumentation for power supply systems and equipment connected thereto”.

[18] S. Nuccio, C. Spataro “Approaches to Evaluate the Virtual Instrumentation Measurement Uncertainties”, *IEEE Transactions on Instrumentation and Measurement*, Vol. 51, No 6, December 2001, pp. 1347-1352.