Harmonic Pollution in Italian Distribution Networks in Coincidence with Important Sport Events

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Abstract:. **The impact of television viewing (and other electronic loads) on the utility grid harmonic distortion is considered. Reference is made to the Italian distribution networks during the final days of the 2006 FIFA World Cup in Germany. Such sport events have a great popularity in Italy and the ability of polarizing the attention of a large percentage of population that participate to the events viewing television. Laboratory tests and modeling considerations on power supply units for TV sets are developed. Numerous field measurements performed in a LV network supplying a residential area according to the IEC guidelines are reported and analyzed.**

Index terms: **Harmonic Measurement, Televisions, IEC Standard.**

I. INTRODUCTION

As a result of the opening up of the electricity markets, system operators are being increasingly encouraged to report more and more to external parties, namely users and regulators, information relating to power system performance. Whereas in the past, power quality was often seen as an implicit duty on system operators, today quality objectives have become more and more explicit. Meeting power quality targets is very important and the way of gathering and presenting power quality data is an important aspect. The duration of observation, the period of the year, the day of the week for daily measurement, and, finally, the presence of important events that polarize the human activities have a great influence on the results.

Among the human activities of relevance, the impact of television viewing (and other electronic loads) on the utility grid harmonic distortion may be of great relevance. It is commonly recognized in industrial countries that the peak of fifth harmonic distortion, even at highest voltage levels, generally appears in coincidence with the night hours characterized by the peak in television viewing.

In this paper, the impact of television viewing is considered with reference to Italian distribution networks, in coincidence with sport events, during the final days of the 2006 FIFA World Cup in Germany. Such sport events have a great popularity in Italy and the ability of polarizing the attention of a large percentage of population that participate to the events viewing television. This is particularly evident when the Italian team is successful.

In what follows, after some brief recalls on measurement aspects and existing indices for harmonic distortion, laboratory tests and modeling considerations on power supply units for TV sets are developed. Finally, numerous field measurements performed in a LV network supplying a residential area according to the IEC guidelines are reported and analyzed.

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II. MEASUREMENT ASPECTS

Various methods for obtaining the spectrum are being discussed in the technical literature, but the method almost exclusively used in power quality monitoring is the Fourier transform.

A method, aimed to standardize the harmonic and interharmonic measurement, has been proposed by the IEC [1, 2]. This method utilizes Discrete Fourier Transform (DFT) performed over a Rectangular time window (RW) of exactly ten cycles for 50 Hz systems or exactly twelve cycles for 60 Hz systems, corresponding in both cases to 200 ms approximately. Phase Locked Loop (PLL) or other line frequency synchronization techniques should be used to reduce the errors in frequency components due to spectral leakage effects. The window width fixes the frequency resolution at 5 Hz, so the interharmonic components that are between the bins spaced of 5 Hz would spill over primarily into adjacent interharmonic bins with a minimum of spill into harmonic bins. Furthermore, the harmonic and interharmonic groups and sub-groups are introduced [2].

Some papers [3-5], have shown that also a small error in synchronization causes severe spectral leakage problems and some signal processing techniques that improve measurement accuracy by reducing sensitivity to desynchronization have been proposed. A first technique makes the IEC grouping compatible with the utilization of Hanning window (HW) instead of the RW [3]. A second, in the framework of synchronized processing, utilizes a self-tuning algorithm synchronizing the analyzed window width to an integer multiple of the actual fundamental period [4]. A third, in the framework of desynchronized processing, is based on a double stage algorithm: harmonic components are filtered away before interharmonic evaluation [5].

III. EXISTING INDICES [6]

Obtaining harmonic indices consists of a number of steps. The process recommended by IEC 61000-4-30 [1], and 61000-4-7 [2] proceeds as follows:

- obtain the spectrum over a 10-cycle (50 Hz systems) or 12-cycle (60 Hz systems) window;
- the spectra are combined (rms) to a spectrum over a 3-s interval (150-cycles for 50 Hz systems and 180-cycles for 60 Hz systems) and the so obtained values are referred to as ''very short time'' indices ($U_{h,vs}$);
- the 3-s values are combined to a 10-min value and are referred to as ''short time'' indices ($U_{h,sh}$);
- 3-s and 10-mi values are evaluated over a one-day or a one-week period depending on the index.

A statistical representation of the results is recommended by means of Probability density functions, Pdf, and Cumulative density functions, Cpf, of the data acquired. The 95 %, 99 %

or 100% percentile values of the distributions are used as site-indices.

Other publications [7] propose more specific indices for compliance purposes, such as:

1. the greatest 95 % probability daily value of $U_{h,vs}$ (rms value of individual harmonic components over "very short" 3 s periods);
2. the maximum weekly value of $U_{h,sh}$ (rms value of individual harmonics over "short" 10 min periods);
3. the maximum weekly value of $U_{h,vs}$.

The minimum measurement period suggested is one week and indices should be evaluated according to IEC 61000-4-7 [2].

Also IEC Standard 61000-4-30 [1] refers to IEC 61000-4-7 [2] for harmonic measurements, more specifically to class 1, 10/12-cycle gapless harmonic sub-group measurement, denoted $C_{n-200-ms}$. The standard does not specify indices, but various indices are given as guidelines for contractual applications in the informative annex A.6 of [1] as follows:

1. the number, or percentage, of values during the interval that exceed contractual values might be counted;
2. and/or the worst-case values might be compared to contractual values (the measurement interval might be different for this possibility, for example one year);
3. and/or one or more 95 % (or other percentage) probability weekly values for 10-min values, and/or 95 % (or other percentage) probability daily values for 3-s time interval values, expressed in percent, might be compared to contractual values.

Other evaluation techniques might be agreed between the parties. A minimum assessment period of one week is recommended for 10-min values, and daily assessment of 3-s values for at least one week.

Standard EN 50160:1999 [8], stipulates that during each period of one week, the percentile 95% of the 10-min mean rms value ($U_{h,sh}$) of each individual harmonic voltage is the quality index to be compared to the relevant voltage characteristic.

IV. POWER SUPPLY UNITS FOR TV SETS

TV sets, as the majority of modern electronic equipments use switched mode power supplies [9]. These differ from older units in that the traditional step-down transformer and rectifier is replaced by direct controlled rectification of the supply to charge a reservoir capacitor from which the direct current for the load is derived by a method appropriate to the output voltage and current required. The advantage is that the size, cost and weight is significantly reduced and the power unit can be made in almost any required form. The disadvantage is that the power supply unit draws pulses of current which contain large amounts of third and higher harmonics and significant high frequency components. A simple filter is fitted at the supply input to bypass the high frequency components from line and neutral to ground but it has no effect on the harmonic currents that flow back to the supply.

Concerning the actual behavior of this simple device, relevant are the effects of the strong interactions with the supply network which must be taken into account.

A. Laboratory Tests

To have a quantitative idea of the real behavior of a supply units, several experimental tests were performed by means of a hardware test system built up at Laboratories of the Second University of Naples. A simplified block diagram of the test system is reported in Fig. 1.

It is based on:

- arbitrary waveform power generator (Pacific Power source 3120AMX),
- power analyzer (Norma D6000),
- PXI system.

The main characteristics of the 3-phase arbitrary waveform power generator produced by Pacific Power (model 3120AMX [15]) are: i) Maximum Power: 12 kVA; ii) Frequency Range: 20 Hz to 50 kHz; iii) Line Regulation: 0.027 mV; iv) Load Regulation: 0.00135 mV; v) THD: 0.1 %; vi) Voltage Ripple and Noise: -70 dB.

The main characteristics of the power analyzer produced by LEM (model Norma D6000 [16]) are: i) overall accuracy of 0.05% for current and voltage measurements and <0.1% for power measurements; ii) frequency range: from DC to 1 MHz.

All the instrumentations are controlled by a PXI system produced by National Instruments (model PXI-1020) equipped with a controller NI PXI 8176 with a 1.2 GHz processor, and 128 MB ram, data acquisition board NI PXI-4472, arbitrary waveform generation board NI PXI-5411. The software implementing the test procedures and coordinating the devices has been developed in LabView environment and everything has been made automatic, thanks to the remote control of all the instruments.

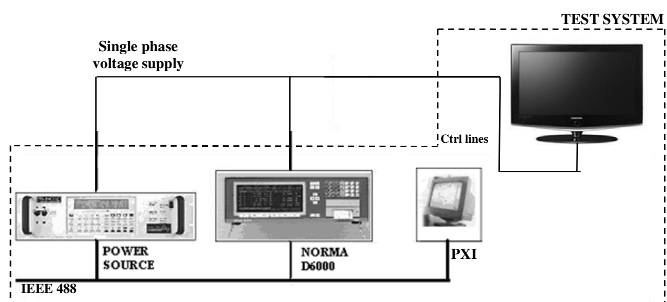

Fig. 1. The test system.

The results obtained with reference to two different supply conditions are reported in Fig. 2. Fig.2a shows the spectrum of supplying voltages: white bars stay for the minimum THD supply conditions that can be obtained by means of the available Power Source, that means ideal laboratory conditions, and black bars for a real condition corresponding to measured distortion in the LV network supplying the laboratory. Fig. 2b shows the harmonic current spectrum absorbed by a power supply unit in conditions that correspond to supply voltage of Fig. 2a. By comparing the ideal spectrum with the real one, the effects of voltage distortion are evident and correspond to a remarkable reduction of the harmonic current absorbed when the supply voltage is distorted.

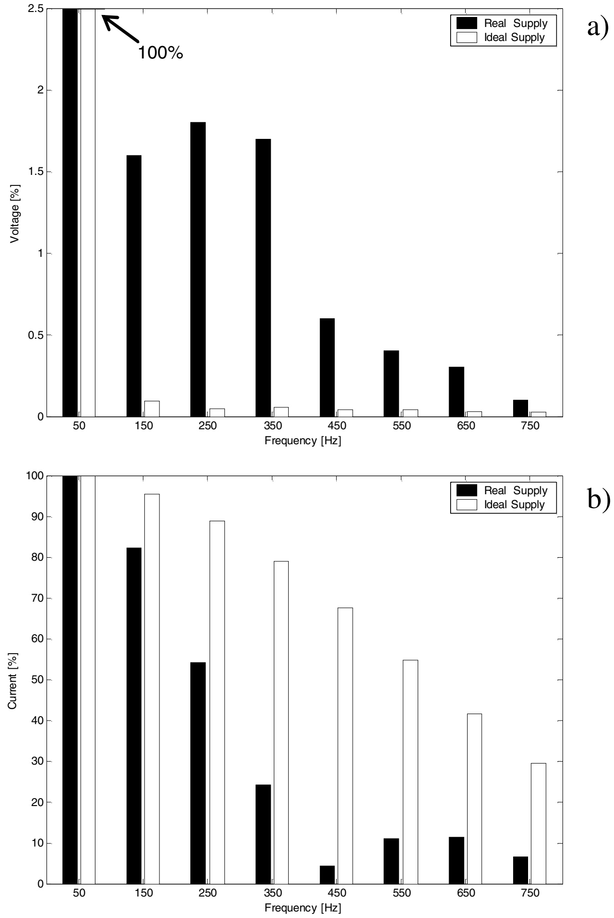

Fig. 2: Harmonic spectrum during laboratory tests on a TV power supply unit, in different conditions: white bars stay for ideal supply and black bars for real: a) applied voltages, b) absorbed currents.

B. Modeling Aspects

In general, it is necessary to take into account the interactions with the supply network and the other loads as illustrated in Fig. 3 with reference to a simple situation. The harmonic currents absorbed by a power supply unit of a TV set, I_h, depend on the combined effects of the background harmonic voltage, E_h, and of the voltage drop caused by the entire amount of harmonic current, including the other load contributions, J_h, absorbed on the same feeder in the system equivalent harmonic impedance, Z_h.

To have an idea of the modeling difficulties, it is useful to refer to a simple condition in which i) the only nonlinear loads present in a LV distribution feeder are TV sets, of the same power and identical characteristics and ii) the pre-existing voltage distortion E_h is nill. In particular, the second hypothesis in reality is near to be verified for third harmonic voltages.

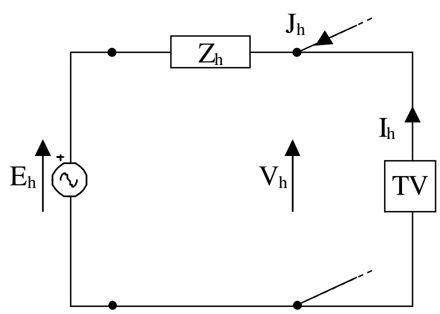

Fig.3: Equivalent circuit for modelling a power supply of a TV set taking into account of pre-existing harmonic voltages.

Some useful considerations can be developed. It is evident that the following functional relation applies when the (n+1)-th TV set is added to other n already present:

$$I_{h,n+1} = I_{h,n+1}(V_{h,n+1}) = I_{h,n+1}(Z_h \cdot (I_{h,n+1}+J_{h,n+1})) =$$
$$= I_{h,n+1}(Z_h \cdot (n+1) \cdot I_{h,n+1}). \quad (1)$$

Only when the n value is sufficiently high, the variations on V_h produced by the (n+1)-th TV set can be ignored; it can be assumed that:

$$I_{h,n+1} = I_{h,n+1}(V_{h,n+1}) = I_{h,n+1}(Z_h \cdot J_{h,n}). \quad (2)$$

So, if the line current $(I_{h,n^*}+J_{h,n^*})$ is measured and the number of TV sets, n*, is unknown, the relation:

$$n^* = (I_{h,n^*}+J_{h,n^*}) / I_{h,n^*} \quad (3)$$

is difficult to solve because the term I_{hn^*} is also unknowns. tarting only from the measurement of the total line current, $I^*_h+J^*_h$. This is particularly true when exceptional conditions occur and determine exceptionally high values for n*, that reflects on V_{h,n^*} and $I_{h,n^*,}$ values which might differ sensibly from eventually available mean values. Obviously in the reference conditions depicted in Fig. 3 the problem can be easily solved by means of a direct measurement of the value of I_{h,n^*}, while in the real system during large measuring campaigns for distortion monitoring this aspect is a concern.

Another relevant aspect in monitoring real systems, is that the composition of the customer loads is more complex due to the presence of a large variety of different nonlinear loads such as PC, Printers, Inverter Air Conditioning, etc. [10, 11]. It is difficult to know the percentage of each kind of load but it can be estimated, in normal conditions, from available statistical analyses on the specific situation at the hand or on similar networks. More difficult is the situation of exceptional conditions that polarize the use of all the customers on specific apparatus, as it happens in correspondence of important sport events.

As it concerns the distortion propagation, it is worthwhile noting that in four wires LV distribution systems, used in Italy, the well known typical conditions arise: when single phase loads are balanced on the three phases, the third (and triple) harmonic currents on the three phase wires are homopolar and flow back to the transformers trough the neutral wire without passing through the transformers; on the other hand, fifth (and (5+6n)-th) and seventh (and (7+6n)-th) harmonic currents have inverse sequence and direct sequence, respectively and they can pass through the transformers. Practical situations differ from this theoretical situation due to unbalances and non sinusoidal supply conditions.

V. FIELD MEASUREMENTS

The results here reported refer to a power quality monitoring campaign performed on different MV/LV utility transformers, in the town of Naples. The aim was compliance monitoring according to IEC Standards. The methods described in section II and III were used.

The Power Quality monitor was the Topas 2000 which is a Power Quality Analyzer for disturbance investigation and assessing the power quality in compliance with IEC 61000-4-30 class A. Its main characteristics are: i) overall accuracy of 0.1% for 50 Hz current and voltage measurements and <1% for frequencies up to 100 kHz; ii) frequency range: from DC to 100 kHz with a common mode rejection of -130 dB of measuring range.

Measurements were performed over some weeks. In what follows, reference is made only to the LV busbar of a MV/LV transformer feeding a residential area.

Figs. 4 report the results obtained during the week starting from Monday, July 3-rd, to Sunday, July 9-th, which includes the semi-final match Germany-Italy, from 21:00 to 24:00 of Tuesday, July 4-th, and the final match Italy-France, from 20:00 to 23:00 of Sunday, July 9-th. Fig. 4a reports the magnitude versus the time of the absorbed current at fundamental power frequency, I_1; Fig. 4b the third harmonic current, I_3, as percentage of I_1, Fig. 4c the fifth harmonic current, I_5, as percentage of I_1, Fig. 4d the fifth harmonic voltage, V_5, as percentage of V_1. All the values reported are obtained as mean values of the three single phase values obtained for each minute, and each single phase value as mean of 20 consecutive very short time (3 s) values. It is possible to note that:

- the “day-night” and the “week-end” effects are very evident in all figures;
- during the semi-final, the I_1 values are lower (about 100 A) than those present in the same hours of the other working days (about 120 A), while the I_3 and I_5 percentage values are sensibly greater (12 % and 4.5 %, respectively), in particular with reference to preceding Monday and the subsequent Wednesday (9 % and 2.5 %, respectively); the V_5 behavior which is characterized by values reaching 1.7 % against 1.25 % is impressive if one considers that the values depend on phenomenon affecting the whole system and not only the local MV/LV transformer;
- during the final mach, the I_1 values are very low (about 60 A) than those present in the same hours of Sunday, 2-nd July (about 90 A), while the I_3 and I_5 percentage values are sensibly greater (14% and 6%, respectively) with reference to the preceding Sunday, (8% and 3%, respectively); the fifth harmonic voltage reaching 1.8% against 1.3%.

Figs. 5 report the results obtained during six hours including the final match Italy-France, from 18:00 to 24:00 of Sunday, July 9-th, together with the results obtained in the same hours the Sunday of the week before, July 2-nd. Fig. 5a reports the magnitude of absorbed current at fundamental power frequency, I_1, Fig. 5b the third harmonic current, I_3, as percentage of I_1, Fig. 5c the fifth harmonic current, I_5, as percentage of I_1, Fig. 5d the fifth harmonic voltage, V_5, as percentage of V_1. It is possible to note that:

- the I_1 values of the 9-th of July are lower than those of the 2-nd of July and the difference increases during the final match, while the I_3, I_5 and V_5 percentage values are sensibly greater and also for them the differences increase during the match;

at the end of the match I_1, I_3, I_5 values seem to approach normal conditions and the differences sensibly decrease while the difference of V_5 continues to increase, probably due to phenomenon different from TV viewing and depends on other activities not strictly related to the sport event.

Figs. 6 report the results in the same conditions described for Fig.5, with reference to neutral. Fig. 6a reports the magnitude of fundamental power frequency current in the neutral, I_{1N}, , Fig. 6b the third harmonic current, I_{3N}, as percentage of I_{1N}, Fig. 6c the fifth harmonic current, I_{5N}, as percentage of I_{1N}, Fig. 6d the third harmonic voltage, V_3, as percentage of V_1.

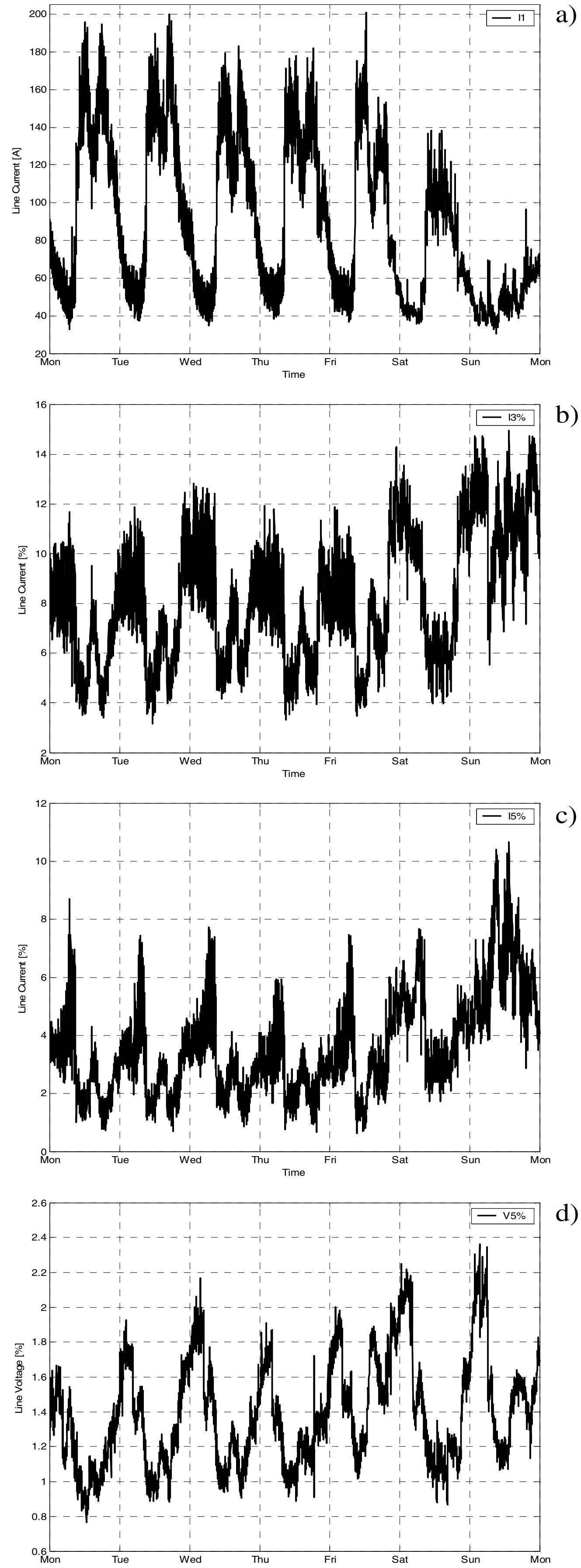

Fig. 4: Field measurements over 1 week from the 3-rd of July to the 9-th of July 2006: a) Fundamental line current, I_1; b) Third harmonic current in % of I_1; c) Fifth harmonic current in % of I_1 and d) Fifth harmonic voltage in %of the fundamental voltage.

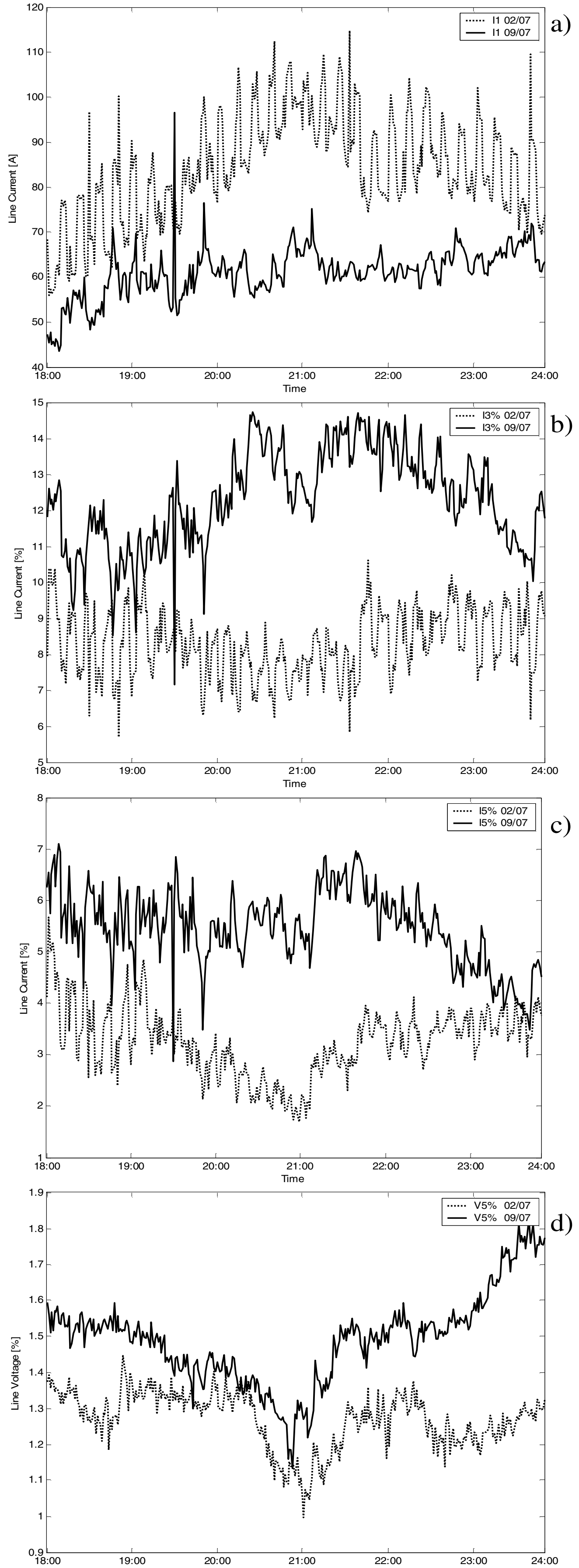

Fig. 5: Field measurements over 6 hours (from 18 to 24) of the2-nd (dotted lines) and the 9-th (continuous lines) of July 2006: a) Fundamental line current, I_1; b) Third harmonic current in %of I_1; c) Fifth harmonic current in %of I_1 and d) Fifth harmonic voltage in %of the fundamental voltage.

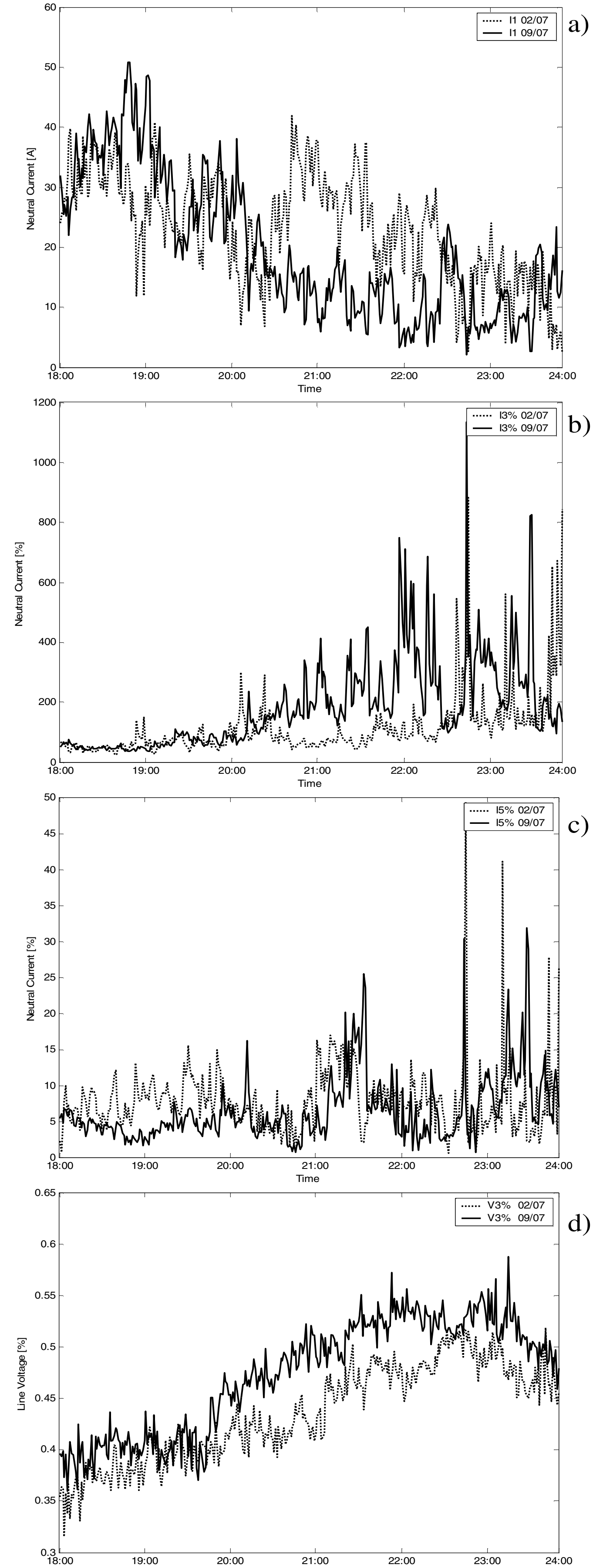

Fig. 6: Field measurements as for fig. 5: a) Fundamental neutral current, I_{1N}; b) Third harmonic neutral current in % of I_{1N}; c) Fifth harmonic neutral current in % of I_{1N} and d) Third harmonic voltage in %of the fundamental voltage.

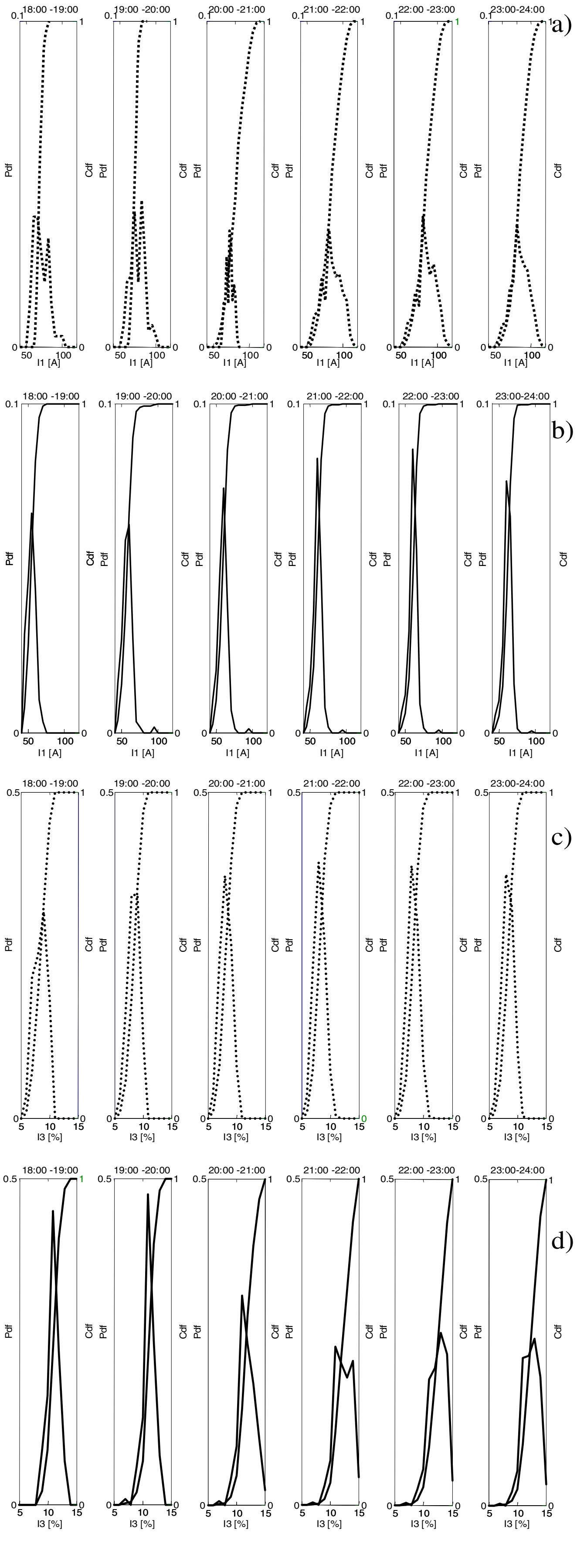

Fig. 7: Statistical analyses (Pdf and Cdf) for each of the six hours of field measurements of Figs 5a and 5b: a) and c) Fundamental line current and Third harmonic current, respectively, during the 2-nd of July; b) and d) as for a) and c) during o the 9-th of July.

It is interesting to note that:

- during the match hours the unbalance (I_{1N}) among the phases sensibly decrease (from 30 A to 10 A), and the relative values of I_{3N} increase, both coming back to normal values approaching midnight;
- the behavior of I_{5N} seems not affected by the sport events, probably due to cancellation effects deriving from phase diversity of different contributions from different loads;
- the behavior of V_3 is similar to that of I_3, described in Fig. 5b, due to absence of contributions coming from the MV network, as expected.

Figs. 7 report the results of some statistical analyses (Pdf and Cdf) of the results already described in Fig. 5a and in Fig. 5b. The analyses regard separately each of the six hours from 18:00 to 24:00 and the resulting Pdfs and Cdfs are reported in Fig. 7a for fundamental line current of the 2-nd of July; in Fig. 7b for fundamental line current of the 9-th of July; in Fig. 8c for third harmonic of the 2-nd of July; in Fig. 8d for third harmonic of the 9-th of July. The comparison among the homologous distributions of the 2-nd and of the 9-th of July, respectively, allows comments equivalent to those already presented for Figs. 5a and 5b, this time, by means of comparison of mean values and of standard deviations. In particular, the lower values of standard deviations for fundamental currents during the final match, compared to those of the 2-nd of July - evidenced by the greater sharpness of the Pdf - give a quantitative idea of the capacity of a very important sport event of polarizing the attention of people in viewing TV, so regularizing the power absorption.

VI. CONCLUSIONS

The Impact of Television Viewing (and Other Electronic Loads) on the Utility Grid Harmonic Distortion has been considered. Reference has been made to the Italian Distribution networks during the days of 2006 FIFA World Cup in Germany. Such sport events have a great popularity in Italy and the ability of polarizing the attention of a large percentage of population that participate to the events viewing television. Laboratory tests and modeling considerations on power supply units for TV sets have been developed.

Numerous field measurements performed in a LV network supplying a residential area according to the IEC guidelines have been reported and analyzed.

The main outcomes of the paper are quantitative ideas of the remarkable increases of harmonic pollution during important sport events. In particular, the data obtained give information about increases of third (and triple) harmonic currents and voltages in LV distribution feeders of residential areas and of fifth (and higher order) harmonic currents and voltages that propagate through the whole supplying system due to their known ability of passing through transformers.

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VII. ACKNOLEDGEMENTS

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VIII. BIOGRAPHIES

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