CHARACTERIZATION AND COMPENSATION FOR HARMONICS AND REACTIVE POWER OF RESIDENTIAL AND COMMERCIAL LOADS

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***Abstract* - This paper uses data from experimental measurements of typical residential loads to verify whether they behave as current or voltage type non-linear loads, and discusses the drawbacks of passive shunt compensation for harmonics and reactive power. Additionally, based on field measurements in a residential low-voltage distribution grid, identify the share between linear and non-linear loads, as well as the kind of non-linearity present in the grid.**

***Keywords* – Non-linear load models; Passive compensation; Harmonics; Diode rectifier; Distribution system compensation.**

I. INTRODUCTION

The traditional approach for current harmonics compensation, focused in industrial applications, considers that the non-linear load can be well modeled by current sources. A more general model should include not only the source but also its impedance. This way it would be possible to use the Norton equivalent or the corresponding Thevenin equivalent.

Representation of the non-linearity simply as a summation of harmonic sources can allow analyzing its effect on the overall system in which the distortion was evaluated. However, it is not possible to get reliable conclusions if any modification is introduced in the circuit as, for example, including a filter or an additional load.

Another important aspect is that many non-linear loads are better modeled by non-linear voltage sources than by current sources. Such typical loads are diode rectifiers with capacitive filter, and are the usual interface between electronic loads and the AC feeder [1,2].

One can consider that these circuits impose the voltage at the PCC (Point of Common Coupling) and the result is a distorted current absorption. This load is well modeled by a harmonic voltage source in series with a low impedance. Obviously it has a Norton equivalent, but the source current is much higher than the current injected into the grid because of the low shunt impedance. Typical applications are TV, lamp ballast for fluorescent lamps, computers, etc. [3].

This paper uses data from experimental measurements of typical residential loads to verify whether they behave as current or voltage type non-linear loads, and discusses the drawbacks of passive shunt compensation for harmonics and reactive power. Additionally, based on field measurements in a residential low-voltage distribution grid, identify the share between linear and non-linear loads, as well as the kind of non-linearity present in the grid.

II. NON-LINEAR LOADS TYPES: CURRENT SOURCE X VOLTAGE SOURCE

A. Current source load-type

Besides the mentioned residential non-linear loads, other sources of current distortion are the appliances with electromagnetic devices, as motors and transformers. Refrigerators, freezers, washing machines and air-conditioning can be included in this group. In this case, the current distortion depends on the design of the motor and varies with the voltage level. Fig. 1 shows the measured current, voltage and power of a low-consumption refrigerator (target for 26.6 kWh/month). The apparent power is 170VA and the power factor (PF) is 0,64 (131VAr and 108.5W). Fig. 2 shows the current spectrum for this refrigerator. The main current harmonics are: 3rd (6,2%), 5th (5%) e 7th (1,5%).

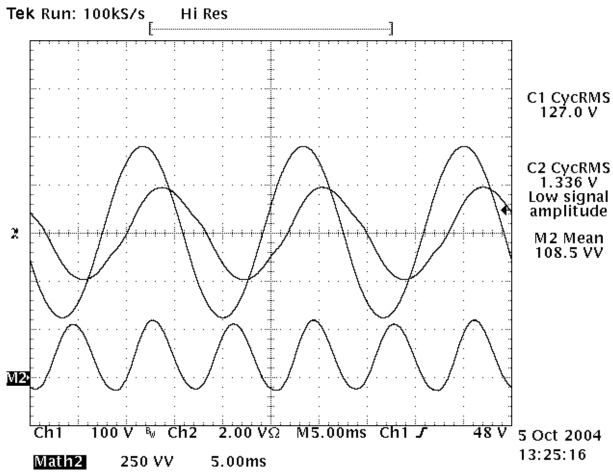

Fig. 1 Voltage, current and instantaneous power for a refrigerator.

If this load effectively presents a current source behavior, a shunt filter could be used to deviate the harmonics from the supply.

To verify this fact, a 5th harmonic shunt filter was inserted at the refrigerator input and the result is shown in Fig. 3. The supply has a series impedance of 2% (5 mH), which is about 7 times higher than the filter at the tuned frequency (285 Hz). The capacitance was calculated to compensate the displacement factor (20 μF), as shown in Fig. 4, resulting a filter inductance of 15,6 mH.

With this filter, the 5th current harmonic at the supply is reduced 18 dB (8 times). For this kind of load (refrigerator), considering the effectiveness of the shunt filter, one can consider that the current source is an adequate model.

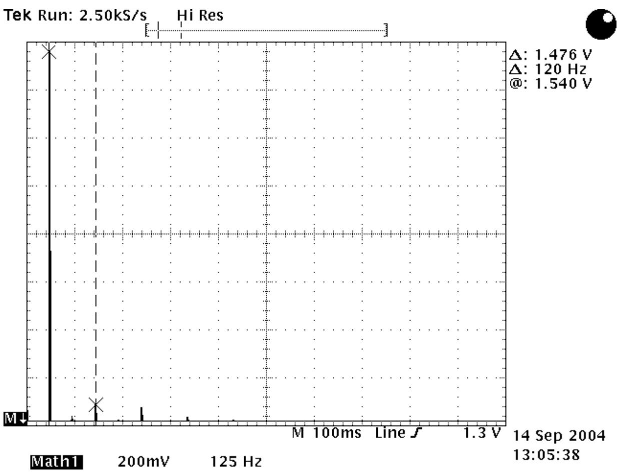

Fig. 2 Current spectrum (0.2A/div., 125Hz/div.).

The relationship between the supply current and the load current is given by:

$$\frac{I_i}{I_L} = \frac{Z_f}{Z_f + Z_i} . \tag{1}$$

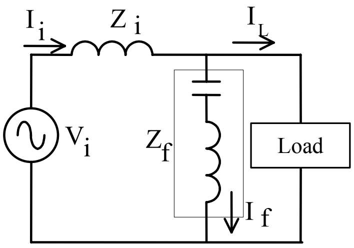

Fig. 3 Tunned shunt filter

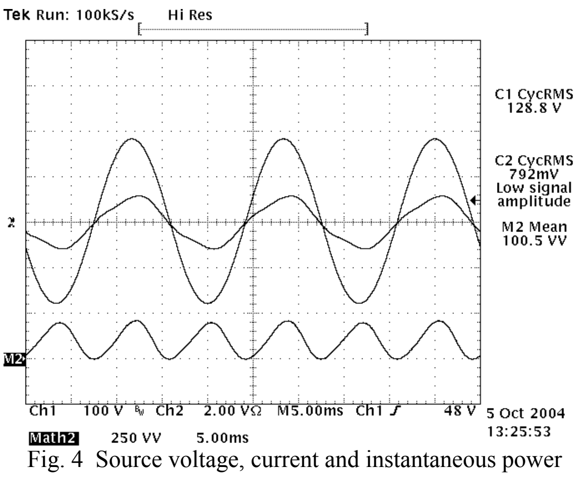

Fig. 4 Source voltage, current and instantaneous power after filter connection.

B. Voltage source type load

Fig. 5 shows the circuit of a diode rectifier with output capacitive filter. Fig. 6 displays the voltage and current of a 20' TV set, for the same supply used in the previous test. Such loads usually consume constant power, and vary the current according to the input voltage. This kind of circuit is typical of many residential and commercial loads as, computers, video monitors, fluorescent lamp ballasts, etc. The voltage distortion at the PCC THD=3.2%, while the current THD is 108% and the PF is 0,66. The displacement factor is 0,97, capacitive.

As the rectifier has a capacitive behavior at the fundamental frequency, it is not possible to design a passive tuned filter that simultaneously reduces the current distortion and improves the power factor. The individual compensation is possible only using series filters or active solutions [4].

The equivalent circuit is shown in Fig. 7. The load impedance Z_o is not known, and varies with many parameters (voltage, power, DC capacitor, frequency, etc.). A modeling method has been proposed [4] but it is not valid for the discontinuous conduction mode, as is the case of the non-linear loads considered in this paper.

Even without knowing the value of Z_o (load impedance) it is evident that (1) does not apply for this rectifier type load. For a voltage-type load, the source current due to a harmonic voltage generated by the load is [1]:

$$\frac{I_i}{V_o} = \frac{Z_f}{Z_o Z_i + Z_o Z_f + Z_i Z_f} . \tag{2}$$

If one is interested in reducing current harmonics in such feeders, the alternative is to increase both, source (Z_i) and load series impedance (Z_o).

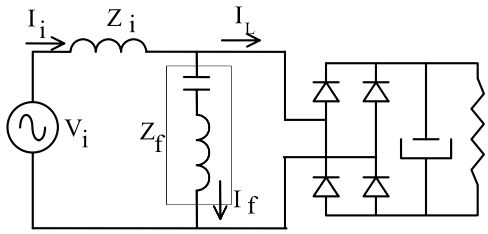

Fig. 5 Rectifier with capacitive output filter and input tuned filter.

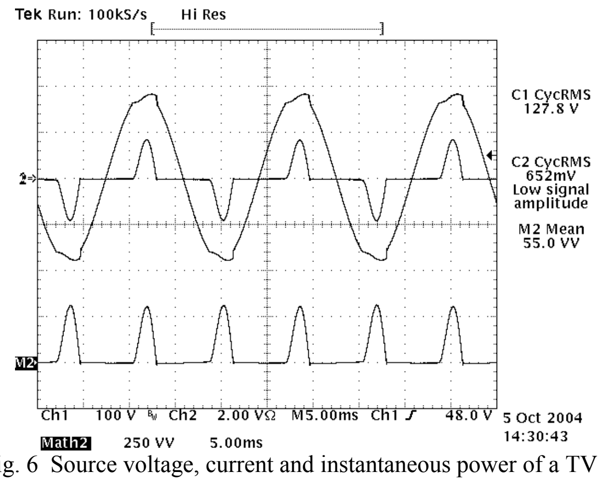

Fig. 6 Source voltage, current and instantaneous power of a TV set.

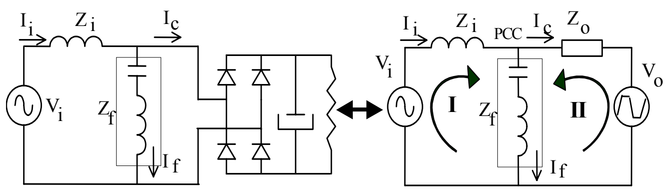

Fig. 7 Rectifier and voltage source type load model.

The voltage source behavior of this kind of load can be demonstrated by simulation and experimentally.

C. LC shunt filter compensation

Figure 8 shows simulated results of a circuit that includes a linear inductive-resistive load (equivalent to the refrigerator) and a non-linear load (equivalent to the TV set). Initially a 5th harmonic filter is connected at the PCC. The filter capacitance compensates the reactive power. As can be seen, the displacement factor is next to unity, but the source current is distorted.

Figure 9 shows an experimental result with the same compensation.

Without the filter, the load current is less distorted than with the shunt filter, as shown in Table I. The higher harmonics amplitude observed when the filter is connected proves the voltage-source behavior of the non-linear load.

Table II indicates PCC voltage harmonics. As expected, the shunt filter reduces the 5th component (and also the 7th), but increases the 3rd and 9th harmonics. Considering the limitations of IEEE 519, both cases comply with the limits. The filter installation decreases the voltage THD mainly due to the 5th harmonic reduction.

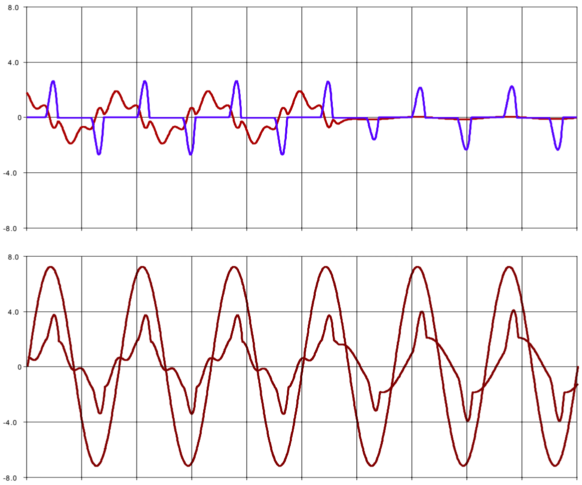

Fig. 8 Current waveforms with and without compensation. Top traces: 5th harmonic filter and rectifier currents (4A/div) Bottom traces: Source voltage(100V/div) and current (4A/div).

TABLE I

Rectifier (load) current (peak value)

Harmonic order	With 5th harmonic filter [mA]	Without the filter [mA]
1	830	808
3	732	687
5	563	488
7	368	275
9	192	114
11	78	60
THD(%)	123	111

TABLE II

PCC voltage characteristics

Harmonic order	With 5th harmonic filter [%]	Without the filter [%]	Capacitive compensation (%)
3	2.92	2.2	2.44
5	0.83	2.58	3.65
7	1.73	2.03	5.07
9	1.27	1.08	4.02
11	0.66	0.69	1.09
THD(%)	4.05	4.46	7.92

Table III shows the supply current harmonics. The 5th harmonic filter reduces this component but increases the 3rd harmonic, elevating the THD. The fundamental component reduces due to the reactive power compensation.

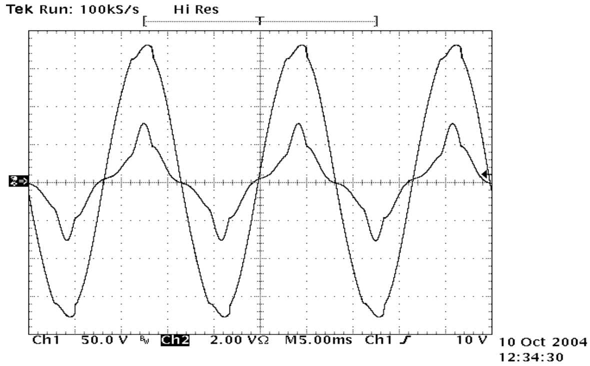

Fig. 9 Source voltage and current feeding a TV set and a refrigerator, with the shunt passive filter.

TABLE III

Supply current components (peak value)

Harmonic order	With 5th harmonic filter [A]	Without the filter [A]
1	2.2	2.68
3	0.904	0.671
5	0.157	0.477
7	0.232	0.268
9	0.132	0.11
11	0.056	0.058
THD(%)	43.7	32.8

The use of shunt filters can produce the opposite effect in terms of waveform improvements if there is a voltage harmonic component in the grid. In this case the low-impedance path produced by the filter will absorb current from the supply, increasing the current and voltage distortion.

Fig. 10 shows the effect of the same filter, applied to the refrigerator, but including 2% of 5th harmonic to the input voltage. The filter amplifies the current harmonic to 23% of the fundamental. As this situation is very common in the low-voltage distribution grid, the use of tuned shunt filters must be avoided.

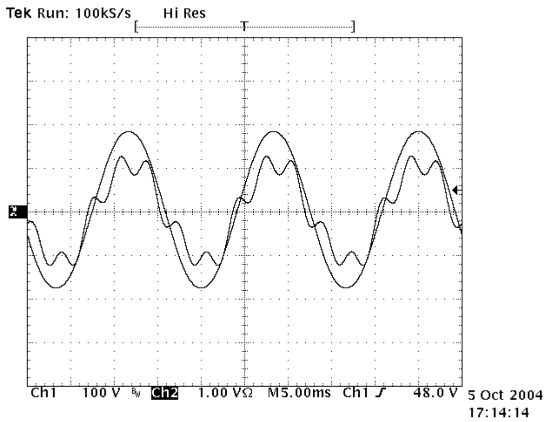

Fig. 10 – Source voltage (2% of 5th harmonic) and current resulting for the refrigerator with tuned shunt filter.

D. Capacitive compensation

Since the tuned filter installation can result in dangerous situations, another possibility is to use only the capacitor for compensating the displacement factor. Fig. 11 illustrates the simulated result of such compensation method, which results are in Table II, last column. In this case the PCC voltage distortion increases from 4.46% to 7.92%.

Assuming that the non-linear load behaves like a voltage source, it is necessary to consider the parallel resonance between the capacitor and the source impedance. The harmonic voltage component at the PCC is given by:

$$\frac{V_{hPCC}}{V_{oh}} = \frac{Z_i \,//\, Z_f}{Z_o + Z_i \,//\, Z_f} \tag{3}$$

In this case the resonance is about 500 Hz (5mH, 20µF), and explain the amplification of the 7th and 9th harmonics. A high PCC voltage harmonic will produce a high current on the capacitor and on the source. Figure 12 shows experimental results with capacitive compensation.

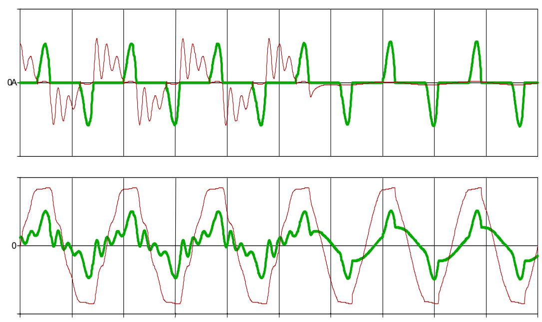

Fig. 11 - Current waveforms with and without capacitive compensation.
Top traces: Capacitor and rectifier currents (4A/div)
Bottom traces: PCC voltage(200V/div) and current (8A/div).

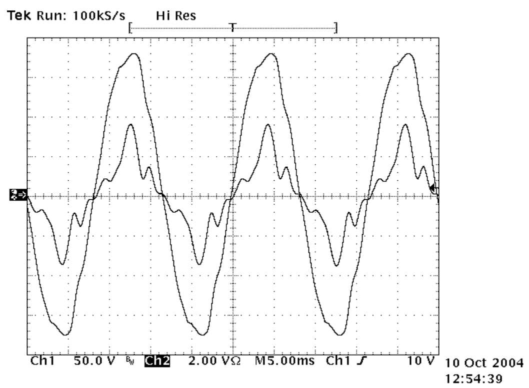

Fig. 12 – Load (refrigerator + TV) with capacitive compensation.

Table IV, shown at the last page, indicates the measured values on the experimental set-up. The results confirm the results obtained analytically and by simulations.

III. REACTIVE AND HARMONIC CHARACTERISTICS OF A RESIDENTIAL LOW-VOLTAGE DISTRIBUTION GRID

The following data were measured in a distribution grid with 70% of residential load (141 consumers), 25% of commercial load (8 consumers) and 5% of industrial load (1 consumer). This is a medium class zone, which determines the kind of power demand related to the home appliances. Fig. 13 shows the behavior of the reactive power (fundamental component) along a one-week measurement. The minimum value occurs about 6 a.m. and can be attributed to the refrigerators, as follows.

A typical two-doors refrigerator consumes 300VA. Considering the typical reactive power, the refrigerator duty-cycle (1/3 on, 2/3 off) and the number of consumers, we obtain 5kVAr/phase, which is consistent with the measurements. Other reactive power sources are the public illuminations (40 lamps, 200W, PF>0.92) contributing with about 1 kVAr/phase.

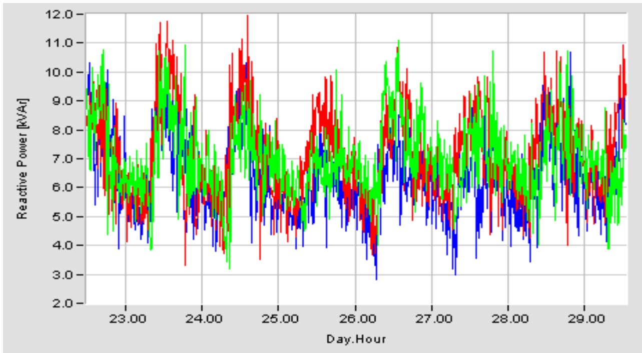

Fig. 13: Measured reactive power at the transformer.

The reactive power quickly increases during the morning, probably due to the use of other electric machine driven appliances, like washing machines. In the afternoon, evening and night, the reactive power progressively reduces, due to the capacitive behavior of the electronic loads that progressively are turned-on.

Similar analysis can be done for the current harmonics, as shown in Fig. 14 for the 3rd component. The minimum value occurs at the early morning and the value is compatible with the measured component of the refrigerator, considering all the consumers and the power values shown above.

Along the day, until 9 or 10 p.m., this harmonic component increases, indicating that more and more non-linear loads are turned-on. Such loads probably are of the voltage-source type (rectifiers with output capacitive filter).

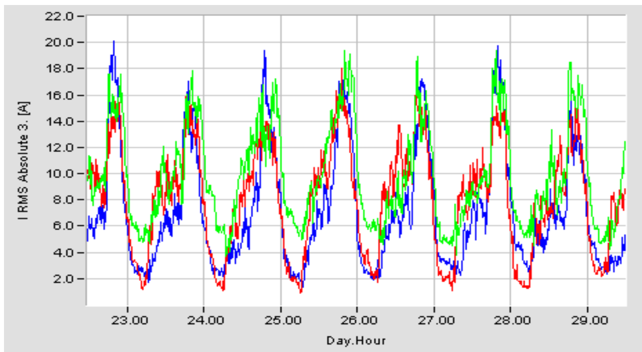

Fig. 14 – Measured transformer current 3rd harmonic.

Considering a TV set (56 W) and 3 fluorescent compact lamps (3 x 15 W) per home, the total load would produce 700 mA of 3rd harmonic. This value is 7 times the corresponding harmonic due to the refrigerator. Audience statistics indicate that at least 35% of the TV sets are disconnected, even during the evening. After this considerations, it is expected a 3rd harmonic component of 15A per phase, as obtained by the measurements.

IV. PASSIVE COMPENSATION IN LOW-VOLTAGE DISTRIBUTION GRIDS

Electric Power companies are interested in applying passive filters in low-voltage distribution grids to postpone higher cost modifications in order to achieve an adequate voltage profile along the feeder. The choice of a passive filter could, in principle, impose the displacement factor, increase the voltage profile and minimize the harmonic circulation through the transformer, reducing its losses [5-8].

The filter, or capacitor, could be installed next to the transformer. The reactive power should be calculated considering the lower "base" value (Fig. 13).

However, as shown before, one can expect the increase of voltage and current distortions caused by the non-linear voltage-source type loads. Therefore, the impact of passive compensation must be analyzed not only according to reactive power and voltage boost goals, but also considering the resulting voltage and current additional distortion.

Figure 15 shows the effective reduction of the reactive power after the installation of a 17.5 kVAr three-phase capacitive bank at the transformer secondary side. As expected, there is a voltage boost, shown in Fig. 16.

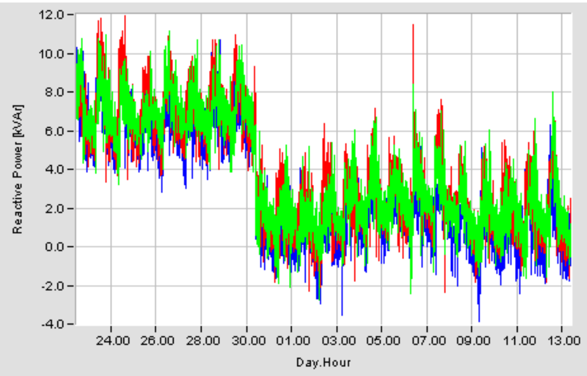

Fig. 15 – Reactive power before and after capacitive compensation.

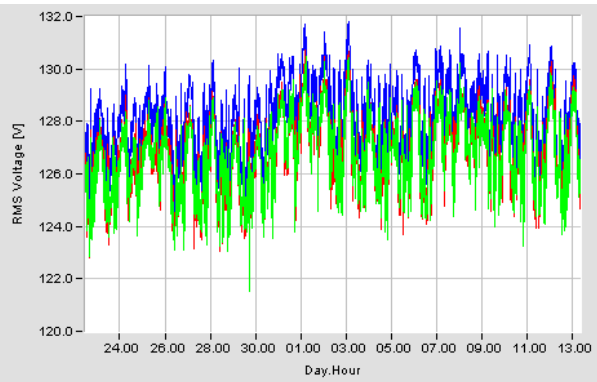

Fig. 16 – Voltage at the transformer before and after capacitive compensation.

These are the benefits of the compensations. On the other hand, both voltage and current distortion become more intense, as shown in Figs. 17 and 18.

The average voltage THD rises from 2% to 2.5%, while the current THD increases from 8.5% to 10%. This elevation is more relevant on the 7th, 11th and 13th harmonics.

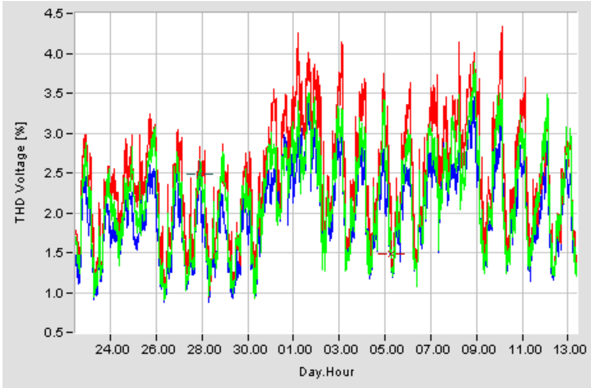

Fig. 17 – Voltage THD before and after capacitor bank installation.

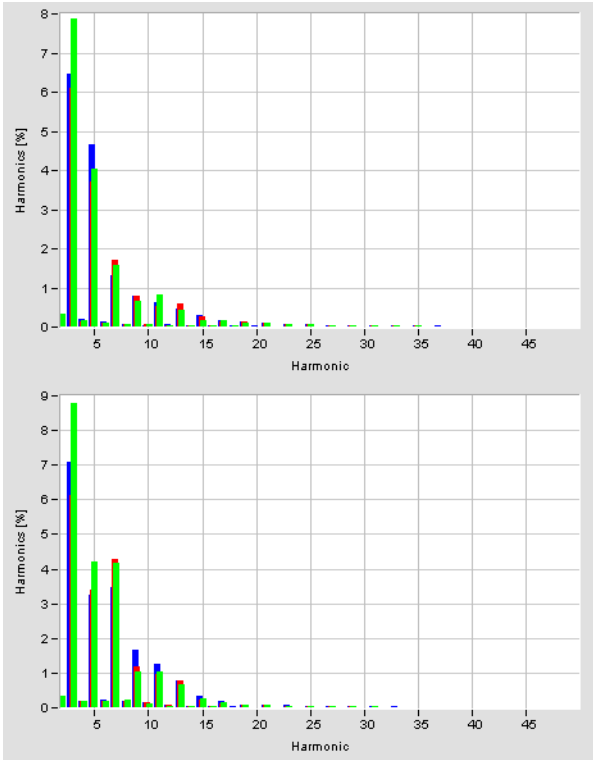

Fig. 18 – Current spectra at the transformer, before (top) and after (bottom) capacitor bank installation.

V. CONCLUSIONS

Residential and commercial supply networks typically present dominant non-linear voltage source type loads. An example of a real non-linear circuit is the single-phase rectifier with capacitive filter. Such converter does not determine the current, instead it imposes the voltage at the PCC. Refrigerators and other motor-driven loads are well modeled by current sources but its impact on the voltage and current distortions is much lower than the rectifiers.

The resulting current harmonics related to voltage-type source non-linearity will not be filtered out satisfactorily by shunt filters, since the load imposes the PCC voltage, and not the respective current.

The use of passive reactive compensation, to improve the voltage profile along the low-voltage distribution grid, will increase the voltage and current harmonics in the circuit.

If one is interested in reducing current harmonics in such feeders, the best alternative according to (2), is to increase both, the series impedances to the mains supply (Z_i) and the load series impedance (Z_o). The individual compensation is impossible for rectifier type loads because they already have a capacitive fundamental displacement factor. Thus, only series filters or active solutions are effective.

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TABLE IV:
Harmonic content obtained in laboratory tests.

	Voltage at the PCC [V]			Source current [A]			TV current [A]		
Harm. order	Without filter	Tuned filter	Capacitor	Without filter	Tuned filter	Capacitor	Without filter	Tuned filter	Capacitor
1st	122.5	125	125	1.65	1.31	1.36	0.4	0.49	0.4
3rd	1.96	2.32	1.94	0.35	0.41	0.37	0.34	0.36	0.33
5th	2.02	**0.7**	2.56	0.25	**0.1**	0.31	0.25	**0.33**	0.24
7th	1.32	**1.02**	2	0.14	**0.11**	0.2	0.16	**0.21**	0.13
9th				0.08	**0.07**	0.15	0.08	**0.11**	0.05
THD	3.2%	2.6%	4.3%						