Integration of RES in AC grids

Professor Răzvan Măgureanu

POLITEHNICA University of Bucharest

PART 2

Power Quality in AC Grids

Abstract - The power quality problems are generated by the deviation from the standard values of the amplitude and frequency of the supplied voltages and currents. The causes of these variations are different and can be generated by the utility or by the end users. In the present paper we deal with the generation current and voltage harmonics by the nonlinear loads and their cancellation techniques.

There are several methods for harmonic cancellation, the last and most efficient one being by direct injection of currents and/or voltages by the means of power electronic converters operating as current or voltage sources. A number of advanced solutions are presented in the present paper capable to minimize the overall harmonic distortion level. A special attention was given to weak systems harmonic cancellation for which the harmonic power flow direction has to be taken into account, as well as the use of multifrequency references and the prediction techniques for nonsinusoidal load currents.

I. Introduction

60-70% of all world produced electrical energy has its parameters: voltages, currents, and frequency, modified by the means of power electronic converters. Beside the benefic aspects, these equipments can produce also by-effects as current and voltage harmonics, which can cause problems like: elevated RMS currents, increased Joule and iron losses, heating the wires, transformers, generators, robbing the system of usable electrical capacity and reducing equipment life, trips and nuisance fuse operation, high frequency currents flow, resonance phenomena and interference with sensitive equipment, reduced power factor and higher electricity bill [1,2,3].

Different types of equipments were developed and are commercially available for harmonic reduction based on passive or active technique, usually the cost being the determining factor in the final decision. From the technical point of view the Active Power Filters (APF) represent the most performant solution being the only ones which can guarantee compliance with IEEE, IEC and national standards [4,5,6]. Beside this, they offer also displacement power factor improvement and can produce system resonance damping. It has also to take into account the negative aspects of the solution: high hardware and installation costs, low or medium MTBF (Mean Time Between Failure), complicated setup, increased high frequency voltage harmonics and radio frequency emission.

There are two possible control techniques for harmonic cancellation.

The first solution is suitable for “powerful systems” with large short-circuit ratio at the Point of Common Coupling (PCC) where the voltage is all the time practically sinusoidal. The reference current for Shunt Power Active Filter (SPAF) is determined directly by calculating its fundamental harmonic and subtracting it from the total current [7,8].

The second solution is suitable for “weak systems” with low short-circuit ratio (Fig. 1), where, due to the harmonic currents produced by the nonlinear loads (Fig. 2.), the PCC voltage is no longer sinusoidal, (Fig. 3.). Consequently, even for a linear load, the currents are non-sinusoidal (Fig.5.), although these are produced by somebody else, the non-linear loads being the cause of this harmonic flow.

Under the present day regulations, if the Total Harmonic Distortion (THD) of these currents is over a certain limit, the linear customers might be obliged either to cancel somebody’s else incoming harmonics or to pay penalties imposed by the utility [4,5,6]. It is clear, that in such a case, the direct use of the first method is not suitable, and the Harmonics Power Flow Direction (HPFD) has to be taken in to consideration.

II. The Basics of Harmonic Control

Both methods are based on calculation of the fundamental harmonic current, and the higher current harmonics are calculated by subtracting the fundamental from the total current. [7,8,9]

The fundamental harmonic can be obtained by different methods like:

- by digital pass-band filters;
- by real time Sliding Fast Fourier Transformer (SFFT);
- by determining it in a synchronous rotating frame generated by the fundamental harmonic of the voltage supply, obtained by the means of a Digital Phase Lock Loop (DPLL).

Although in previous papers the authors used equally the last two techniques for the current fundamental extraction [10], in the present paper the attention is concentrated only on the third one. It is clear that in the case of weak systems a different approach should be used and that the HPFD has to decide if, when and how cancellation has to take place.

In achieving these targets it is necessary to calculate the total harmonic active power.

Let's consider a simple low voltage distribution system connected to the mains by the mean of a three phase Medium Voltage / Low Voltage (MV/LV) power trans-former (Fig.1.).

The nonlinear load (*n*) is a three phase diode rectifier (DR), with three phase entry inductive filter L_1 of 600µH, an electrolytic capacitor C_1 = 1000µF and a resistor R_1 =40Ω on the DC side. The linear load (*l*), is formed by a resistor R_2 = 100Ω. The grid impedance is considered only inductive and is of 3mH (scaled for an equivalent 10kVA transformer).

In Fig. 2. are presented the three phase nonlinear load currents i_n (a), the linear load currents i_l (b) and the mains total current i_m (c). In Fig. 3. a there are presented the supply voltages (phase "a" emphasized), and the DPLL output respectively (Fig. 3. b).

If the supply voltages are the inputs of a three phase DPLL, its outputs represent the argument $\omega_1 t$, $\sin\omega_1 t$ and $\cos\omega_1 t$ functions of the fundamental (Fig. 3. b), allowing us to generate the rotating synchronous frame [11,12,13]:

$$T = e^{j\omega_1 t}. \qquad (1)$$

The nonsinusoidal supply voltages v_A, v_B, v_C can be replaced by a two phase quadrature system:

$$v_\alpha = v_A; \quad v_b = \left(v_B - v_C\right)/\sqrt{3}$$

or in a complex form:

$$\underline{v} = ve^{j\theta};$$

where: $v = \sqrt{v_\alpha^2 + v_\beta^2}$; $\theta = arctg\left(v_\beta / v_\alpha\right)$ (2)

Similarly, for a set of three phase nonsinusoidal currents (no neutral load connection), i_a, i_b, i_c currents can be replaced by a two-phase quadrature system:

$$i_\alpha = i_a; \quad i_\beta = \left(i_b - i_c\right)/\sqrt{3}$$

or in a complex form:

$$\underline{i} = i_\alpha + ji_\beta = ie^{j\gamma};$$

where: $i = \sqrt{i_\alpha^2 + i_\beta^2}$; $\gamma = arctg\left(i_\beta / i_\alpha\right)$ (3)

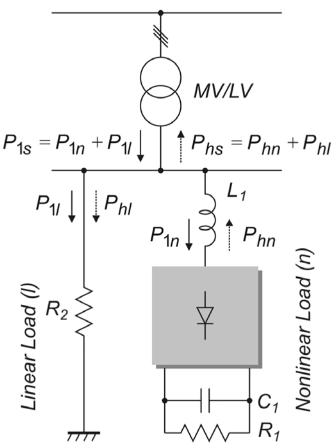
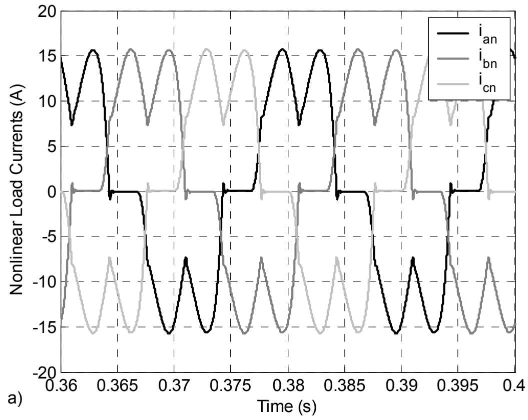
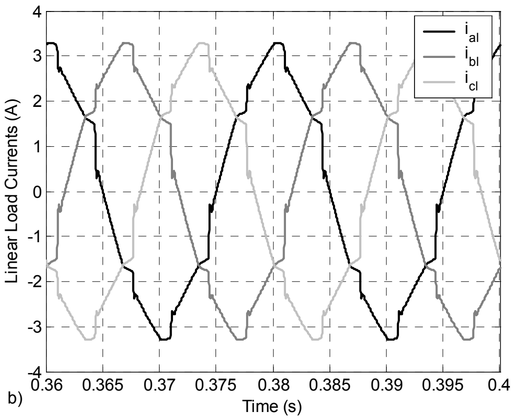


Fig. 1. Simplified low voltage power circuit model with a linear and a nonlinear load





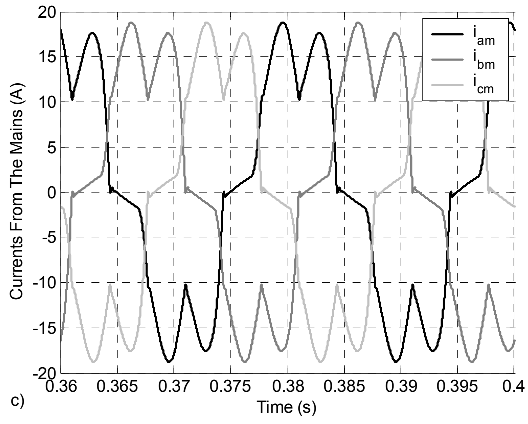
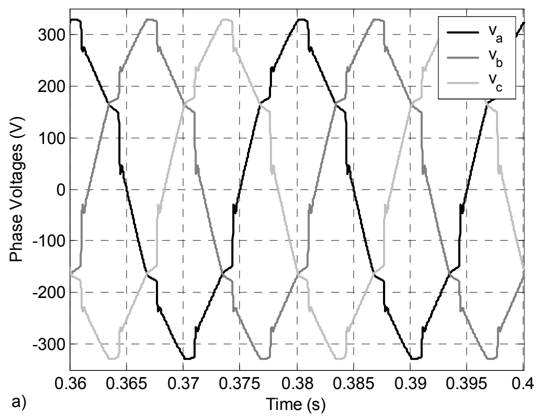


Fig. 2. Current waveforms: a) for the nonlinear load; b) for the linear load; c) for the mains



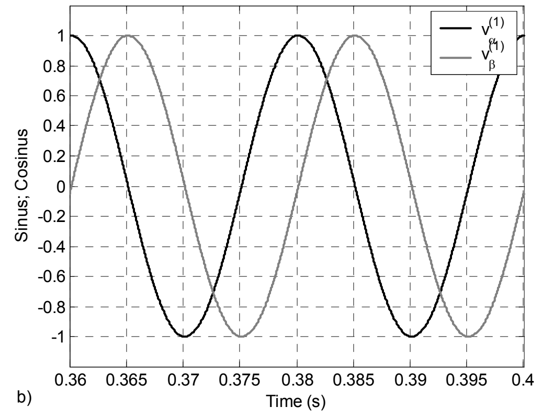


Fig. 3. Voltage waveforms: a) the mains; b) DPLL output

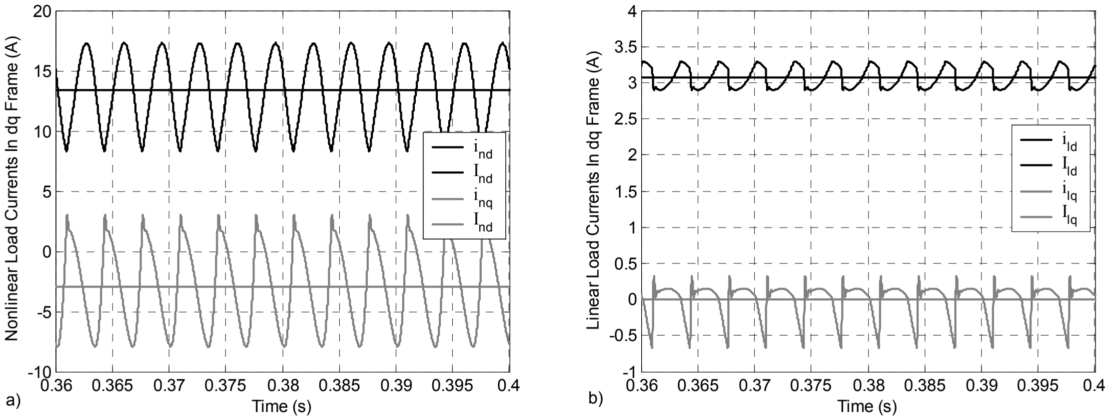


Fig. 4. The dq synchronous frame instantaneous and average value currents: a) for the nonlinear load; b) for the linear load

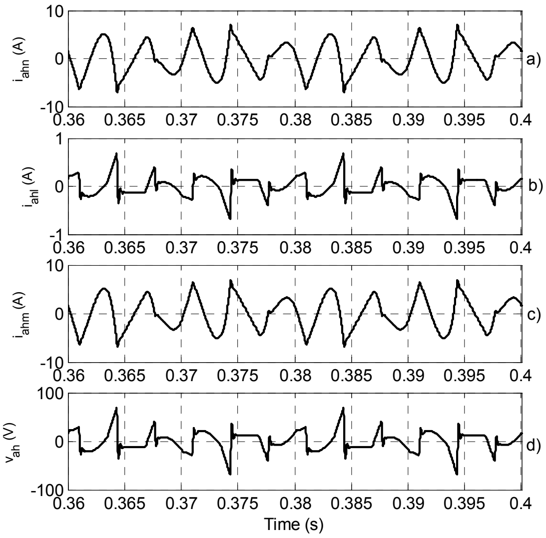


Fig. 5. Harmonic waveforms for the “a” phase: a) the current for the nonlinear load; b) the current for the linear load; c) the current for the mains; d) the voltage for the mains

If we want to operate in a synchronous frame, all the currents and voltages have to be transformed. This is done, by multiplying these variables with $e^{-j\omega_1 t}$, determined by relation (1):

$$\begin{aligned} \underline{i}^T &= e^{-j\omega_1 t}\,\underline{i} = ie^{j(\gamma-\omega_1 t)} = \\ &= i\cos(\gamma-\omega_1 t) + j\,i\sin(\gamma-\omega_1 t) = i_d + ji_q \end{aligned} \qquad (4)$$

For steady-state operation, if this output is applied to a Digital Low Pass Filter (DLPF), in order to get the mean value, the output represents only the first harmonic products:

$$I^T = I_d + jI_q \qquad (5)$$

as all the other products have a zero mean value. These results are presented in Fig. 5. a,b.

In order to determine the current harmonics in the synchronous frame, we have to subtract these values from the total current $\underline{i}^T$:

$$\underline{i}_h^T = \underline{i}^T - \underline{I}^T = i_d - I_d + j\left(i_q - I_q\right) = i_{hd} + ji_{hq} \qquad (6)$$

If we want to reconstruct the harmonic currents in the stationary frame, $\underline{i}_h^T$ has to be multiplied by $e^{j\omega_1 t}$:

$$\underline{i}_h = i_h^T e^{j\omega_1 t} \qquad (7)$$

This technique is applied for all the harmonic currents: i_n, i_l and i_m. The results are presented for the phase "a" in Fig. 5. a,b,c.

The nonlinear load harmonic currents in stationary frames: i_{ahn}, i_{ahl}, i_{hm} or in rotating frames: i_{hdn} and i_{hqn} can be used for "powerful systems" directly as references for the IGBT converter which operates as an Active Filter.

For weak systems, as we mentioned, in order to cancel only the harmonics produced by the nonlinear sink itself we need to know the sense of harmonics power. In order to get this, we have to determine also the voltage harmonics with the same technique as in the previous case for the currents:

$$\begin{aligned} \underline{v}^T &= e^{-j\omega_1 t}\underline{v} = ve^{j(\theta-\omega_1 t)} = \\ &= v\cos(\theta-\omega_1 t) + jv\sin(\theta-\omega_1 t) = v_d + jv_q \end{aligned} \quad (8)$$

As previously, this signal will be applied to a DLPF, the outputs will represent only the fundamental of the applied voltages in synchronous frame:

$$\underline{V}^T = V_d + jV_q \quad (9)$$

and the voltage harmonics in the synchronous frame:

$$\begin{aligned} \underline{v}_h^T &= \underline{v}^T - \underline{V}^T = \\ &= v_d - V_d + j\left(v_q - V_q\right) = v_{hd} + jv_{hq} \end{aligned} \quad (10)$$

As for the currents, the voltage harmonics in stationary frame $\underline{v}_h$ can be calculated by the mean of inverse transformation $e^{j\omega_1 t}$,

$$\underline{v}_h = v_h^T e^{j\omega_1 t} \quad (11)$$

The reconstructed voltage v_{ha} is presented in Fig. 5. d.

The total harmonic power (which is the same in the fixed and in the rotating frame) can be obtained by multiplying the transformed harmonic voltages with the transformed conjugate harmonic currents:

$$\begin{aligned} \underline{s}_h &= \underline{v}_h^T \underline{i}_{hs}^{T*} = \left(v_{hd} + jv_{hq}\right)\left(i_{hd} - ji_{hq}\right) = \\ &= \left(v_{hd}i_{hd} + v_{hq}i_{hd}\right) + j\left(-v_{hd}i_{hq} + v_{hq}i_{hd}\right) = \\ &= p_h + jq_h \end{aligned} \quad (12)$$

Applying this set of signals to a DLPF is obtained the harmonic average power $\underline{S}_h$ which is produced only by the voltage and currents of the same frequency:

$$\underline{S}_h = P_h + jQ_h \quad (13)$$

The harmonic active powers for nonlinear load and the linear load are presented in Fig. 6. a,b.

Considering the signs of the average active power P_h an indication for the sense of harmonic power flow, one can say that it is necessary to compensate the current harmonics only when active power P_{hn} is negative, i.e. the harmonic currents are produced by the nonlinear load and not when the currents are received and the power P_{hl} is positive.

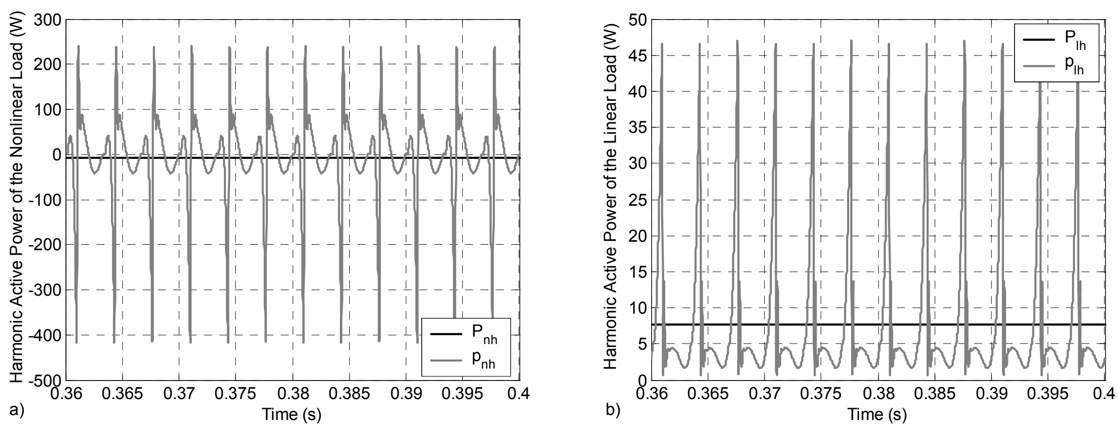
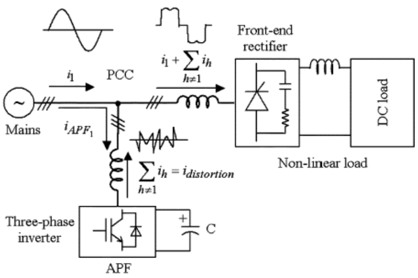
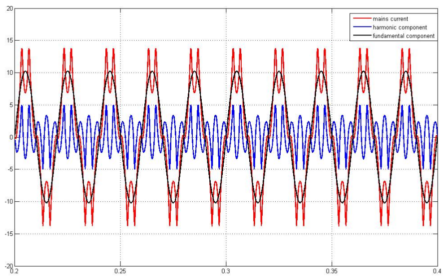


Fig. 6. The instantaneous and average value active power





III. Experimental Results

The experimental results were done on a 10 kVA IGBT converter which was initially developed for a Unity Power Factor equipment. The control was done at the first stage using a DSP EVM-805 40MHz Motorola Board and in a second stage with a dSPACE controller (Fig.9).

The results are presented in Fig. 10, a THD under 4.5% being obtained. At present time a new 4 legs 1700V and 200A, 70 kVA inverter was built and is under test.

In the upper group of pictures are presented the nonlinear load (i_{LOAD}) and the harmonics compensation currents produced by the Active Filter (i_{FILTER}). After compensation the three phase currents from the mains are presented in the third picture (i_{TOTAL}) and in the fourth the reference current and the compensated current (i_{TOTAL}, $i_{REF\ PH\ A}$).

In the lower group of pictures, in the first (Voltage Reg) is presented the voltage on filter condenser V_{cc} (the spikes are just noise which is rejected later in the control proces), $i_{0d}^{(1)*}$ represents the voltage controller output which is applied as one of inputs on PI i_d controller. This current, in phase with the main voltage is recharging the filter capacitor maintaining the level of voltage constant and covering the switching losses of the Active Filter. The third and the fourth pictures represent in d and q axis the reference and the measured filter currents (i_f^* and i_f). v_f^* represent the reference voltages for the inverter which are transformed in stationary frame and applied to the PWM interface. Although the inductances on the load and Active Filter were not the optimal but out of shelf, designed for other applications and there were not used trapping capacitors on the Active Filter output, the results obtained demonstrated the capacity of this compensation equipment for most demanding nonlinear loads.

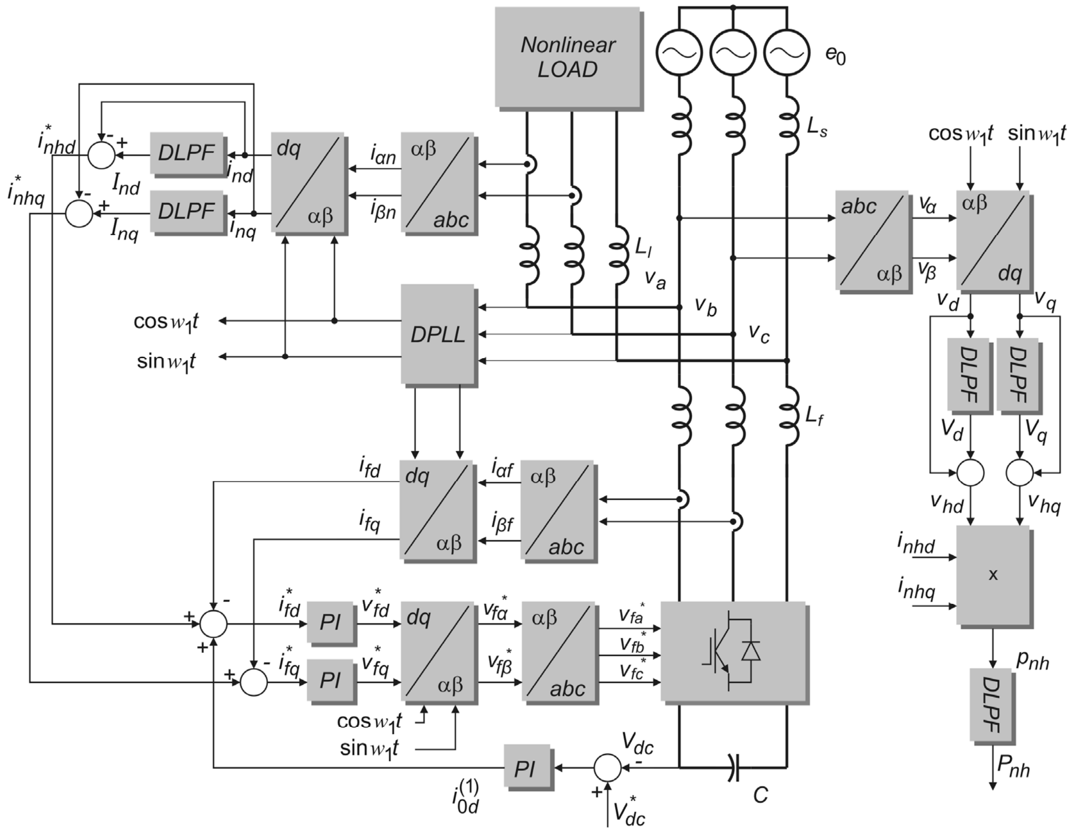


Fig. 9. The block diagram for active filter control

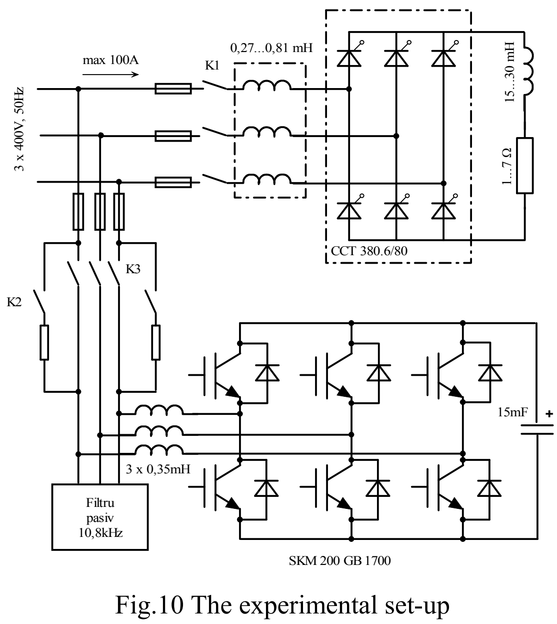


Fig.10 The experimental set-up

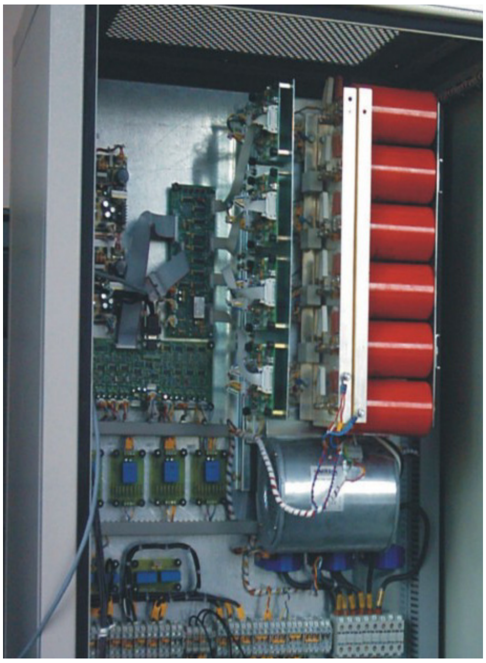


Fig. 11 The inverter component of the active filter

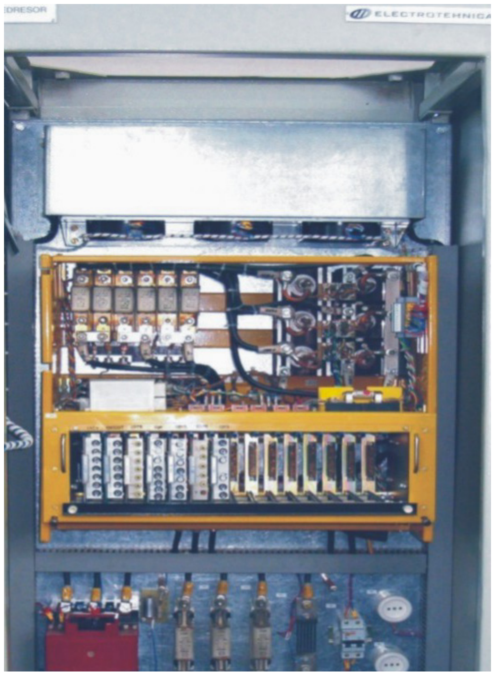


Fig. 12 The controlled rectifier as nonlinear load

IV. EFFICIENT USE OF ACTIVE FILTERS

An ideal Active Filter, which can compensate perfectly all the desired harmonics, cannot be built due to present day technical limitations. The IGBT converter cannot respond to very fast load changing even when prediction techniques are used, as the compensation is done in discrete steps and the inverter present a dead time. A better response would require a higher switching frequency and a higher voltage reserve on the filter capacitance. This means higher switching losses and higher voltage IGBTs and electrolytic capacitors, which evidently represent lower efficiency and higher investments.

A second cause for lower performances compared with the ideal ones is the fact that the Active Filters are not only current sources, but also high switching frequency and high voltage sources. These high frequency voltages produce high frequency currents, which can be reduced only by inserting on the outputs larger inductance in series, or RC filter traps in parallel, all of these for higher costs.

Finally, an industrial Active Filter will never be able to cancel all the harmonics and even not to produce any. The limits of the harmonic currents a nonlinear end user is allowed to deliver in the mains are stipulated by the IEC and IEEE standards, not only by the maximum THD, but also by the amplitude of each harmonic apart. For example, in our case, the nonlinear load current has a maximum allowed THD of 5%, but only a 4% for the 5th harmonic. Instead of the total harmonic current, for power electronic loads, the prime target becomes the 5th harmonic cancellation. Over a certain power ratio, the THD allowed limit is also reached, and a mixed form of control has to be used. From that moment, beside the 5th harmonic, the rest of harmonics are in such way compensated that neither the THD, neither the 5^{th} harmonic to out-run the imposed limits.

Usually, total load of an end-user, is not only nonlinear but a mixture with other linear ones and consequently the THD amount and the 5th harmonic decreases when the ratio between the linear and the nonlinear load increases. If this ratio is about 17%, the 5th harmonic reaches the limit and the THD did the same for 20%. In consequence up to this ratios, the AF has not to operate, and over, on the new characteristic load, Fig 13 a, b [16].

The new version of IEEE-519, which is now under revision, intends to replace some definitions from harmonic standardization, as the “utility” by “electrical energy producer” which means that the PQ standards will be applied also to end users supplied by front end users. A second change concerns MV/LV transformers placed inside end-users facilities. In the future the PQ measurements and monitoring will be done on the primary Medium Voltage (MV) side, allowing customers to replace existing transformers with harmonic trap transformers of types which can decrease dramatically the 5th and 7th harmonics sent in the mains, and consequently the demands on the AF equipments.

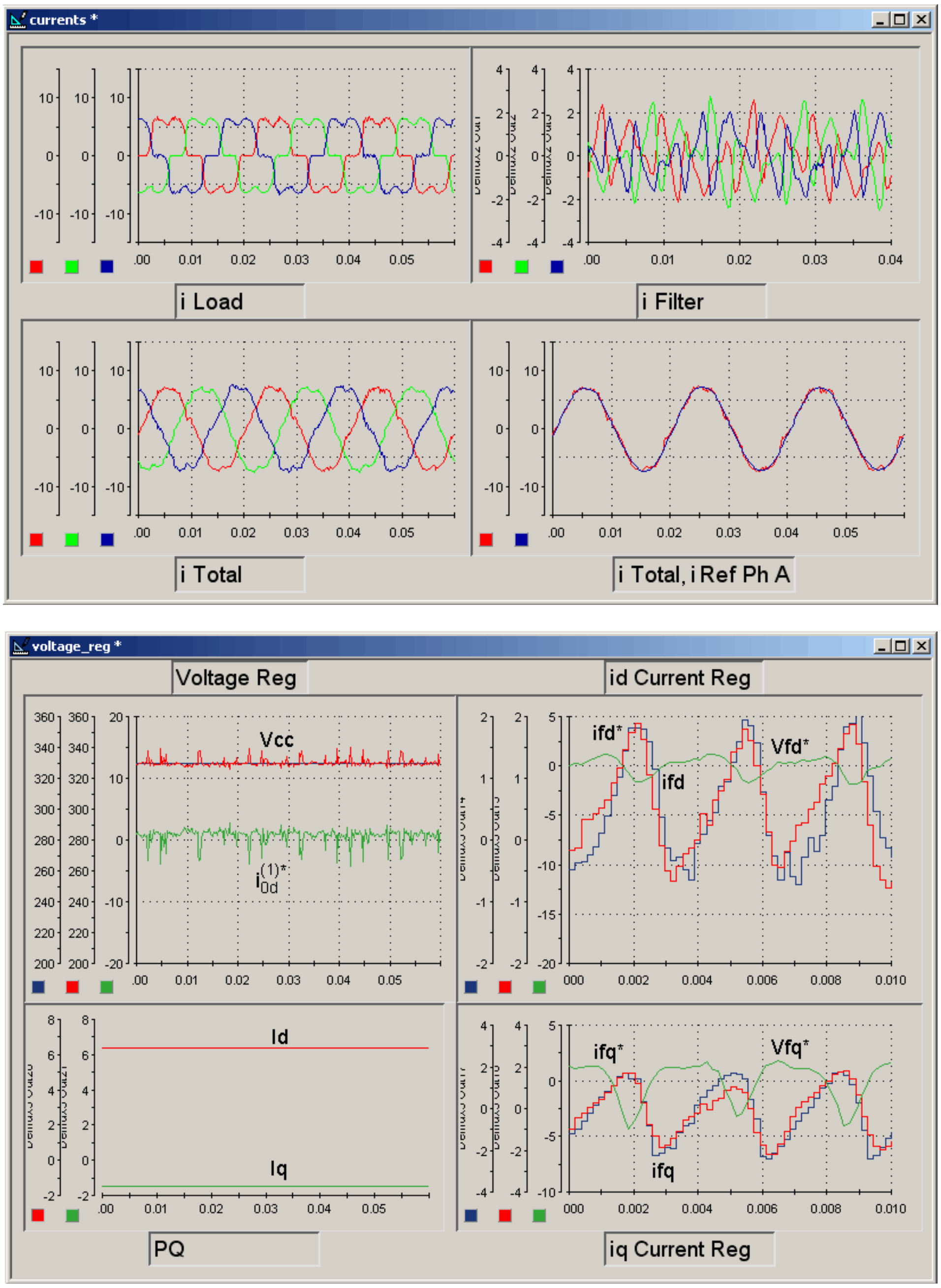


Fig. 13. Experimental results for power and control parameters

Another element of interest is the effects of de-regulation. If the producers of active and reactive energy are allowed to pump their output for commercialization in the mains why others not be able to sink the harmonic energy from the grid, in order to compensate for a fee the end-users electrical garbage. After all if an international CO_2 market was created, why not a Harmonic Energy one?

V. Conclusions

From the customer side there is a higher demand of top power quality electrical energy for the new IT technologies, automated production plants, banking and other service industries. As long that these performances can not be guaranteed by the utilities in house solutions has to be introduced by the end users themselves and such an Active Filter with electrical energy storage facilities can solve at least part of the problems.

De-regulation and commercialization of electrical energy markets made power quality a target to be reached by utilities as that can bring higher added value justifying higher price per kilowatt, allowing thus to increase the profits and the share of the market.

Taking into consideration the mentioned demand, a number of compensating equipments were developed by different companies and university laboratories from all around the world, and our work is part of this effort.

Different solutions for weak systems harmonic cancellation were presented in this paper by taking into account the harmonic flow direction. The simulated and experimental results obtained on a small (10 kVA) active filter are now verified on a new industrial 4 legs, 1700V, 200A, 70 kVA, 16 kHz inverter built recently by the authors and destined to be produced by Romanian Power Electronic Industry. The presented results demonstrated the capacity of building and controlling of such equipments which can play an important role (by simple software changes and addition of the necessary hardware) in high performance medium power UPSs, Voltage Restorers, current and voltage harmonic cancellation equipment, etc.

REFERENCES

[1] Moltgen, G., (1972) "Line commutated thyristor converters", Pitman, London.

[2] Fransua, Al., Magureanu, R., (1984), "Electrical Machines and Drive Systems", Technical Press, Oxford.

[3] Golovanov C., Albu M., Coordonatori, (2001) "Probleme moderne de masurare in electroenergetica", Editura Tehnica, Bucuresti.

[4] IEEE 519 (IEEE Standard Practices and Requirements for Harmonic Control in Electrical Power Systems)

[5] IEC 61000 (IEC Standard for Harmonic Control in Electrical Power Systems)

[6] SR EN 61000 (Romanian version of IEC 6100)

[7] Afonso, J. Couto, C. Martines, J. (2000) "Active Filter with Control Based on the p-q Theory", *IEEE Industrial Electronics Society Newsletter*, Vol. 47, No. 3.

[8] Dixon, J. W. Venegas, G. Moran, L. A. (1997) "A Series Active Power Filter Based on a Sinusoidal Current-Controlled Voltage-Source Inverter, *IEEE Transactions on Industrial Electronics*, Vol. 44, No. 5.

[9] Grady, W.M. Samotyj, M. J. Noyola, A. H. (1990). "Survey of Active Power Line Conditioning Methodologies*", IEEE Transaction on Power Delivery*, Vol. 5, No. 3.

[10] Magureanu R., Ambrosii S., Creanga D., Staicu C., Radut V. (2002) "Unity power factor rectifiers and active power filters for industrial applications", *Proceedings – National Conference on Electrical Drives*, Galati.

[11] Akagi, Y. Kanazawa, Nabae, A. (1983) "Generalized Theory of the Instantaneous Reactive Power in Three-Phase Circuits", *IPEC'83 – Int. Power Electronics Conf.*, Tokyo, Japan.

[12] H. Akagi, Y. Kanazawa, A. Nabae "The p-q Theory of in Thre-Phase Systems under Non-Sinusoidal Conditions" *ETEP*, Vol. 3, No. 1, Jan. 1993, pag. 27-31

[13] Pietro, J. Salmeron, P. Vazquez, J. R. (2001). "Control Implementation of a Three-Phase Load Compensation Active Conditioner", *EPE 2001* – Graz.

[14] M. Kazmierkowski, R.Krishnan, F. Blaabjerg, "Control in Power Electronics" Academic Press, New York, 2002

[15] R. Magureanu, S. Ambrosii, D. Creanga, L. Bratosin, A. Draghici: Active Power Filters Advanced Control, *ATEE – 2002*, Bucharest

[16] M. McGranaghan, "Sizing Active Filters for Commercial Facilities", Electrical Construction & Maintenance, May 1, 2003