A COMPARISON BETWEEN THE COMMAND STRATEGIES OF THE PARALLEL THREE PHASED ACTIVE POWER FILTERS

D. Al. CROITORU[1], Fl. IONESCU[2]

Articolul descrie principalele probleme generate de armonicile de curent în rețea şi principiul de funcționare al filtrului activ paralel. Se face o comparație între diverse modalități de comandă ale filtrelor active prin analiza spectrală în domeniul frecvență a curentului absorbit de la rețea după filtrare. Sunt descrise topologiile şi caracteristicile fiecărei structuri de comandă şi sunt simulate în Matlab-Simulink modelele matematice ale acestora.

The article describes the main issues generated by the network power harmonics and the working principle of the parallel active filter. A comparison is drawn between several active filters command possibilities by spectral analysis in the power frequency domain absorbed by the network after filtering. We describe each command structure's typology and characteristics and their mathematical models simulated in Matlab-Simulink.

Keywords: non-linear electrical loads, power harmonics, AC/DC and DC/AC static power converters, active filters command strategies and command methods.

1. Introduction.

In the last 20 years, the development of the power electronics and the ever more extended use of the industrial equipments which include power electronics (DC rectifier, Voltage regulator, six-pulse converters) triggered the growth of harmonic distortions generated by these equipments in the power supply system. The most frequent situations are those where the AC/DC converters are used. These are non-linear reactive loads for the power supply system because they absorb reactive power and generate power harmonics, which propagate on the supply lines and generate voltage distortions.

The consequences that may appear, due to power harmonics are unpleasant: premature aging of the equipments and installations, higher power consumption,

[1] Eng., S.C. Electroproiect SA, Direcția Inginerie şi Proiectare.
[2] Prof., Dept. Of Electrical Measurements, Electrical Apparatus and Static Converters, University POLITEHNICA of Bucharest, Romania

defective working or breakdown of the command and control circuits. They can become dangerous in certain situations.

In order to eliminate power harmonics generated in the power supply system by non-linear loads and to provide a unitary power factor in the system, a parallel active filter can be used. The high filtering performances combined with the simple connection and maintenance make a parallel active power filter a very good choice to eliminate undesired harmonics from the system.

The operating principle of the parallel active power filter is to insert in the power supply network the same power harmonics as those of the non-linear load but of opposite sign (Fig. 1). Also, in order to ensure a unitary power factor, three currents in phase with the line tensions are generated in the power supply system, their amplitude being proportional with the reactive load current.

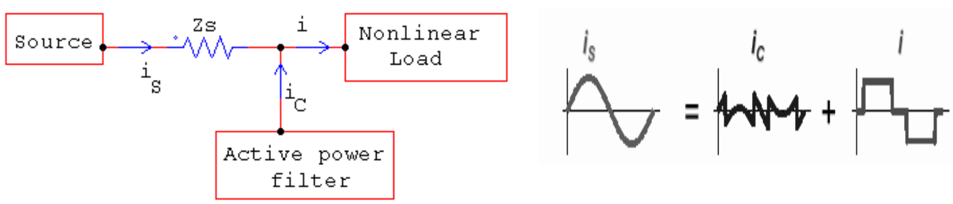


Fig. 1: The power absorbed by the power supply i_s is sum of i_c power (the compensation power generated by the active filter and the power inserted by the non-linear load).

All receivers absorbing non-sinusoidal power are considered non-linear loads. Also, the transitory events, which may appear in the electrical system may be seen as non-periodical signals from the compensation point of view.

The parallel active power filter (Fig. 2) is made up of a tension converter connected, in parallel, to the system made up of the power supply and the non-linear load, through inductances L_f for each phase. The storage of the necessary energy for the harmonic compensation is made using a capacitor C_f.

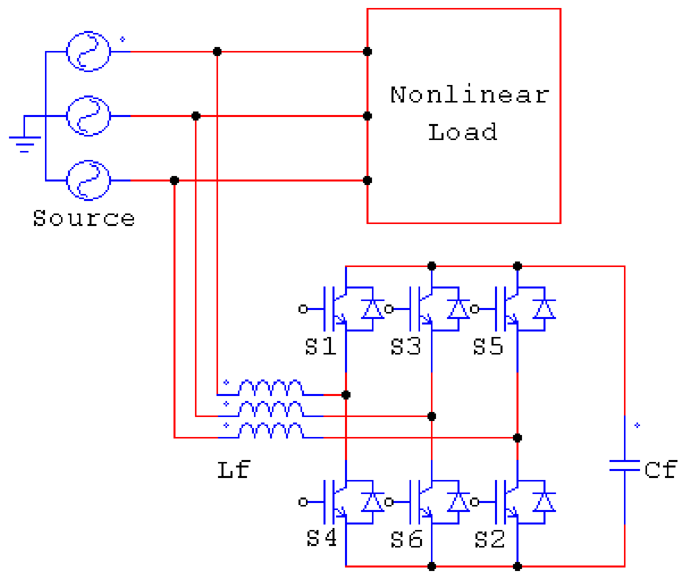


Fig. 2: The electrical scheme of a three-phased parallel active filter.

Beside the technical characteristics of the power structure, the performances of the active filter are given by the command strategy, used to generate opposite sign harmonic currents to those produced by the non-linear load and by the way this strategy is implemented in the active filter command.

Nowadays, with the extended use of digital signal processors (DSP), most of the command and control devices command strategies are made using them. This is why this paper will only tackle issues linked to the parallel active filters command strategies algorithms.

In order to evaluate the proposed command strategy performances for an active filter, we may use the total harmonic distortions factor (THD) or the spectral analysis in the frequency domain of the power absorbed from the network after filtration. Thus, we obtain direct information about the active filter's capacity to eliminate polluting harmonics from the network.

2. Command strategies for the three phased parallel active filters.

The command of the three phased active filters is a complex process which supposes observing certain prerequisites. It may be looked upon as a three separate steps process: signal conditioning, compensation and, then, command impulses generation. For a parallel active filter, four command schemes in time domain are suggested implemented through different compensation methods:

- Instant power method
- Instant active and reactive power method: p-q method;
- Instant current active and reactive components method: i_d-i_q method;
- Current minimization method: equivalent conductance G_e method.

The wave form of the power absorbed from the network in all four cases in the absence of the active filter will be the same (Fig. 3), because the same polluting non-linear load will be considered for all four command methods.

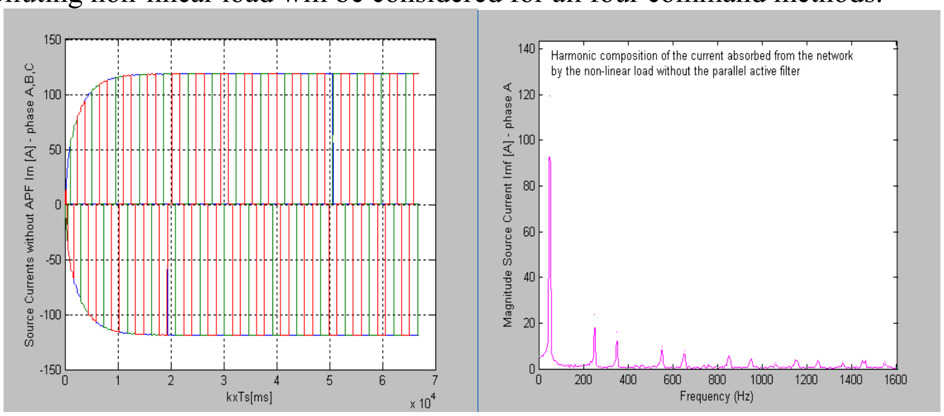


Fig. 3: (a) The currents absorbed from the network in absence of an active filter and (b) The harmonic component of the power on one of the phases in this case.

2.1. Instantaneous current method.

The compensation harmonic current is obtained directly from the power debited by the non-linear load, to calculate the compensation power a relatively high number of calculations is necessary as well as a close monitoring of the power debited/released in the system.

The block diagram of the Matlab-Simulink mathematical model is presented in Fig. 4. The command part of the active filter is presented in Fig. 5 and the active power filter command in Fig. 6. Fig. 7 presents the wave forms for the filter debited current $I_{f\text{-}A}$ [A], the current absorbed from the network I_{rf} [A] together with the network voltage U_A [V] and the harmonic content of the current absorbed by the network before and after filtering.

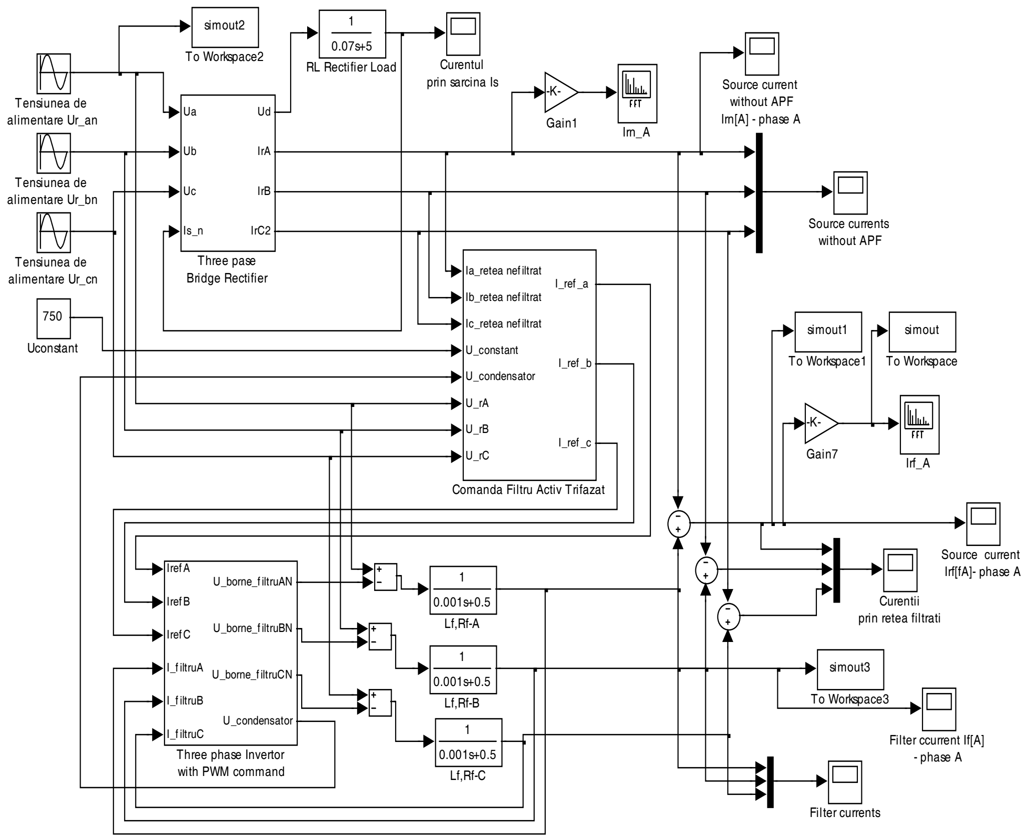


Fig. 4: The Matlab-Simulink model of the source – non-linear load -parallel active filter network with command based on the instantaneous power command method.

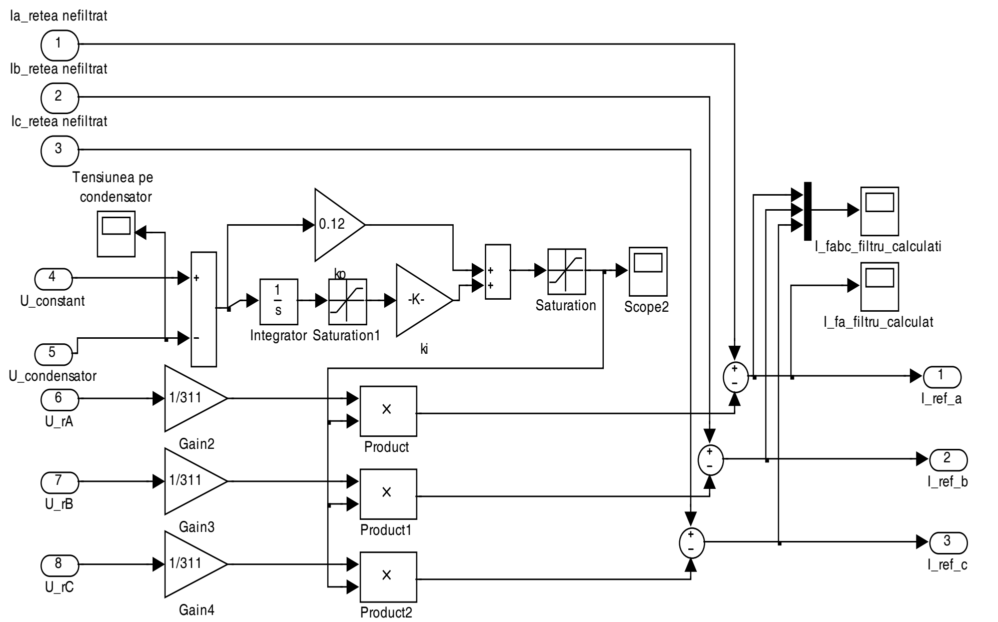


Fig. 5: Three phased active filter command through instantaneous current method.

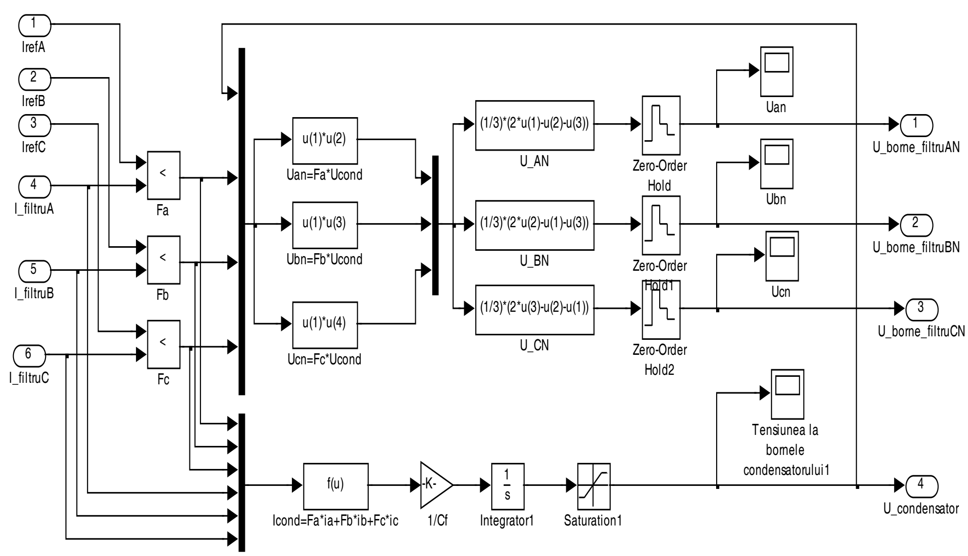


Fig. 6: Matlab-Simulink model of the three-phased active filter.

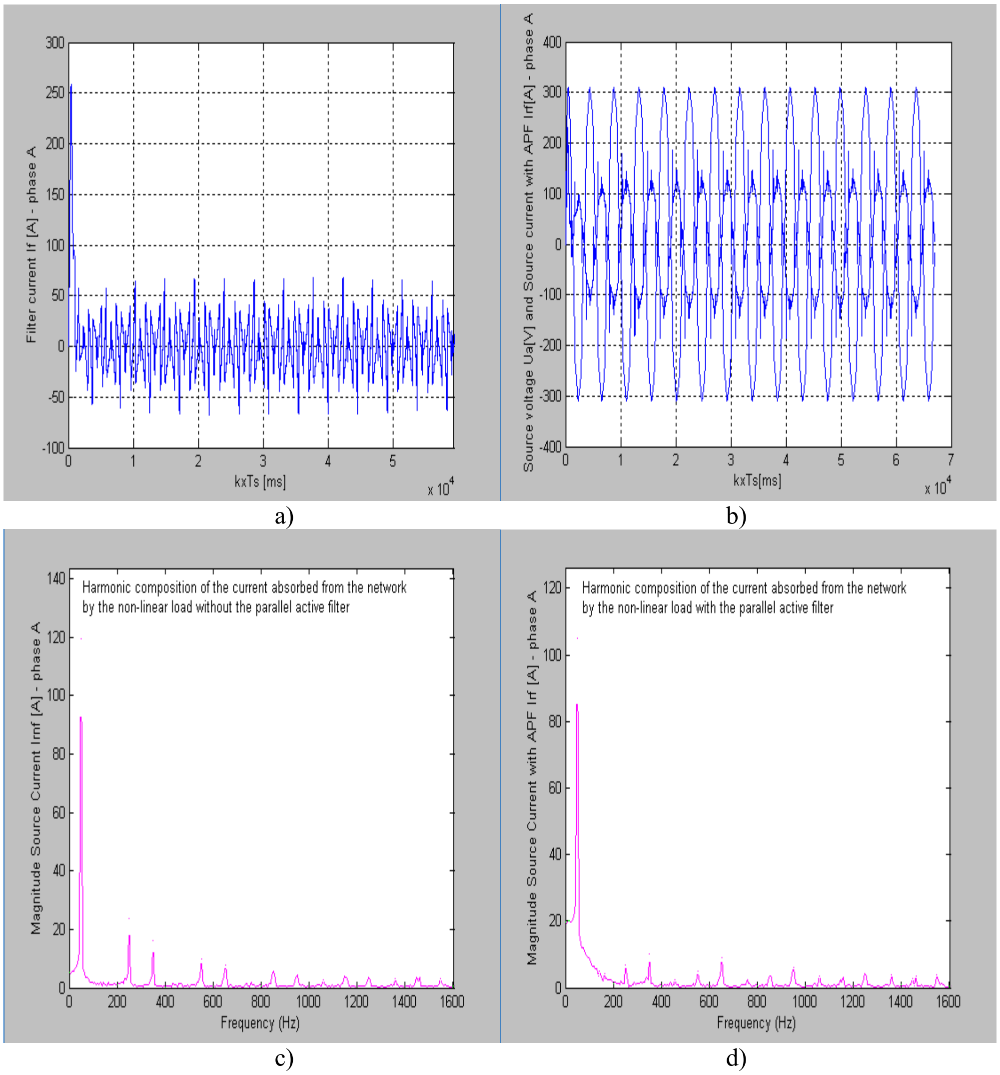


Fig. 7: Electrical measure on phase: (a) the current debited by the active filter $I_{f\text{-}A}$ [A]; (b) the absorbed current from the network by the non-linear load I_{rf} [A] together with network voltage U_A[V], (c) harmonic content of the current absorbed from the network by the non-linear load without a parallel active filter, (d) harmonic composition of the current absorbed from the network by the non-linear load with the parallel active filter

2.2. Instant active and reactive powers method: p-q method

This is one of the first compensation methods ever used, based on the theory of the H. Akagi [6] presented in several articles and studies. Briefly, this theory introduces a new electrical characteristic for the three phases systems called instant imaginary power.

We know the fact that the voltages on the three phases and the corresponding currents can be represented by spatial vectors in abc coordinates. These vectors can be transformed in αβ stationary coordinates using the Park transformation:

$$\begin{bmatrix} e_\alpha \\ e_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & \frac{-1}{2} & \frac{-1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \quad (1)$$

The αβ coordinated are orthogonal and the instant active power may be written as such:

$$p = e_\alpha \cdot i_\alpha + e_\beta \cdot i_\beta \quad (2)$$

Akagi proposed a new perpendicular measure on plan αβ, mathematically described by the following equation:

$$q = e_\alpha \cdot i_\beta - e_\beta \cdot i_\alpha \quad (3)$$

called instant reactive power.

Thus we may write the equation:

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} e_\alpha & e_\beta \\ -e_\beta & e_\alpha \end{bmatrix} \cdot \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \quad (4)$$

These quantities are illustrated in Fig. 8 for an electrical system represented in a-b-c coordinates.

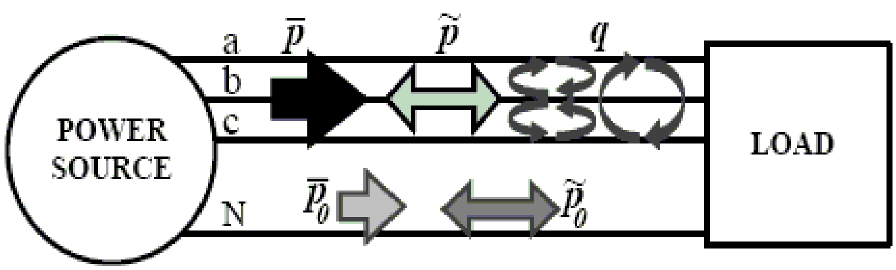


Fig. 8: Power components of the p-q theory in a-b-c coordinates.

The power components have the following physical meaning:

- $\bar{p}_0$ = mean value of the instantaneous zero-sequence power – corresponds to the energy per time unity, which is transferred from the power supply to the load through the zero-sequence components of voltage and current.
- $\tilde{p}_0$ = alternated value of the instantaneous zero-sequence power – it means the energy per time unity that is exchanged between the power supply and the load through the zero-sequence components. The zero-sequence power only exists in three-phase systems with neutral wire. Furthermore, the systems must have unbalanced voltages and currents and/or 3rd harmonics in both voltage and current of at least one phase.
- $\bar{p}$ = mean value of the instantaneous real power – corresponds to the energy per time unity which is transferred from the power supply to the load, through the a-b-c coordinates, in a balanced way (it is the desired power component).
- $\tilde{p}$ = alternated value of the instantaneous real power – It is the energy per time unity that is exchanged between the power supply and the load, through the a-b-c coordinates.
- q = instantaneous imaginary power – corresponds to the power that is exchanged between the phases of the load. This component does not imply any transference or exchange of energy between the power supply and the load, but is responsible for the existence of undesirable currents, which circulate between the system phases.

The real power ($\bar{p}$) is usually the only desirable p-q theory power component. The other quantities can be compensated using a shunt active filter (Fig. 8). The power component $\bar{p}_0$ can be compensated without the need of any power supply in the shunt active filter. This quantity is delivered from the power supply to the load, through the active filter.

The active filter capacitor is necessary only to compensate $\tilde{p}$ and $\tilde{p}_0$, since these quantities must be stored in this component at one moment to be later delivered to the load. The instantaneous imaginary power (q), which includes the conventional reactive power, is compensated without the contribution of the capacitor.

The Matlab-Simulink mathematical model of the analysed structure (source – non-linear load – active filter) which presents this command strategy is shown in Fig. 9, the command part of the active filter, in this case, is presented in Fig. 10 and the waveforms obtained after the simulations are shown in Fig. 11.

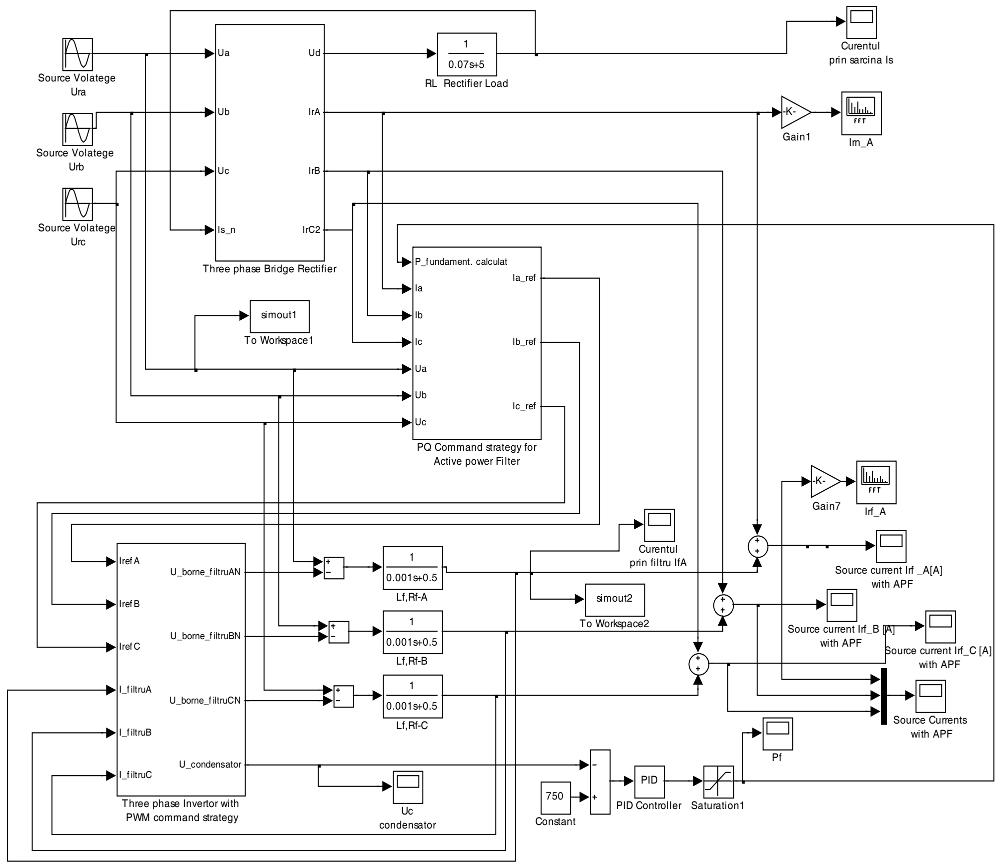


Fig. 9: The Matlab - Simulink model of the source – non-linear load - parallel active filter network with command based on p-q command method.

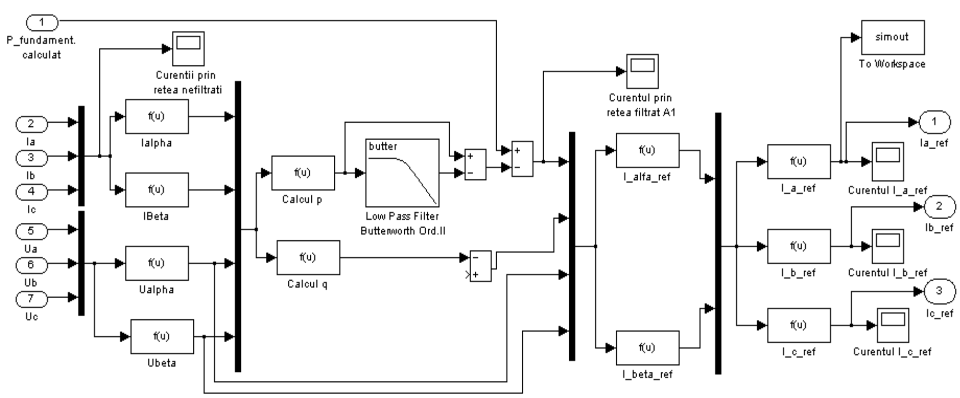


Fig. 10: Three-phased active filter command through instantaneous power p-q method

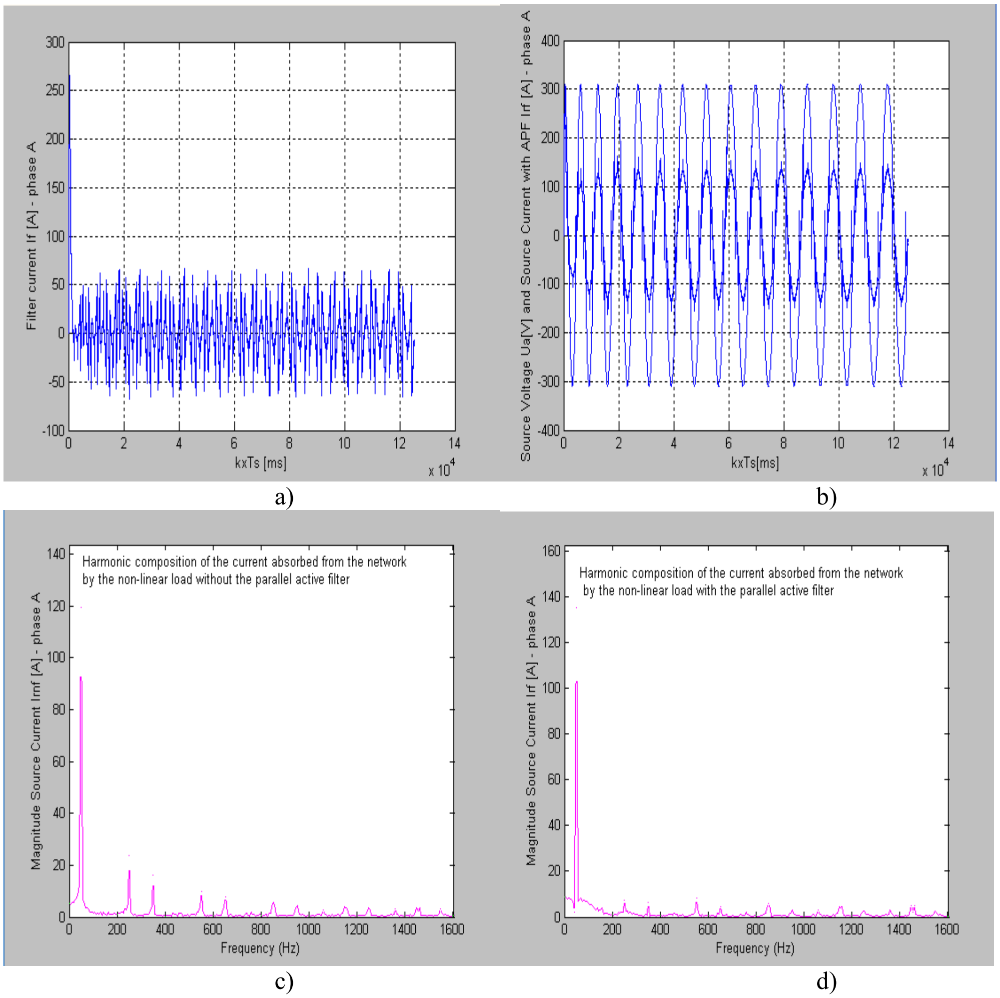


Fig. 11: Electrical measure on phase: (a) the current debited by the active filter $I_{f\text{-}A}$ [A]; (b) the absorbed current from the network by the non-linear load I_{rf} [A] together with network voltage U_A[V], (c) harmonic content of the current absorbed from the network by the non-linear load without a parallel active filter, (d) harmonic content of the current absorbed from the network by the non-linear load with the parallel active filter

2.3. Instant power active and reactive components method: i_d-i_q method.

In this method the measured currents and the network voltages are transformed in the dq synchronic reference system, rotating with the network frequency, by using the relations (5) and (6).

Thus the basic component of the measured power becomes a continuous component, while the harmonic components are shifted with ω_s in the (dq) synchronic reference system. A low-pass filter can be used in order to eliminate the continuous component.

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & \frac{-1}{2} & \frac{-1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{5}$$

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \cos(\omega_s t) & -\sin(\omega_s t) \\ \sin(\omega_s t) & \cos(\omega_s t) \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \tag{6}$$

The Matlab-Simulink mathematical model of the parallel active filter with this command strategy implemented is shown in Fig. 12, the three-phased active filter command in Fig. 13 and the waveforms obtained from the simulations are shown in Fig. 14.

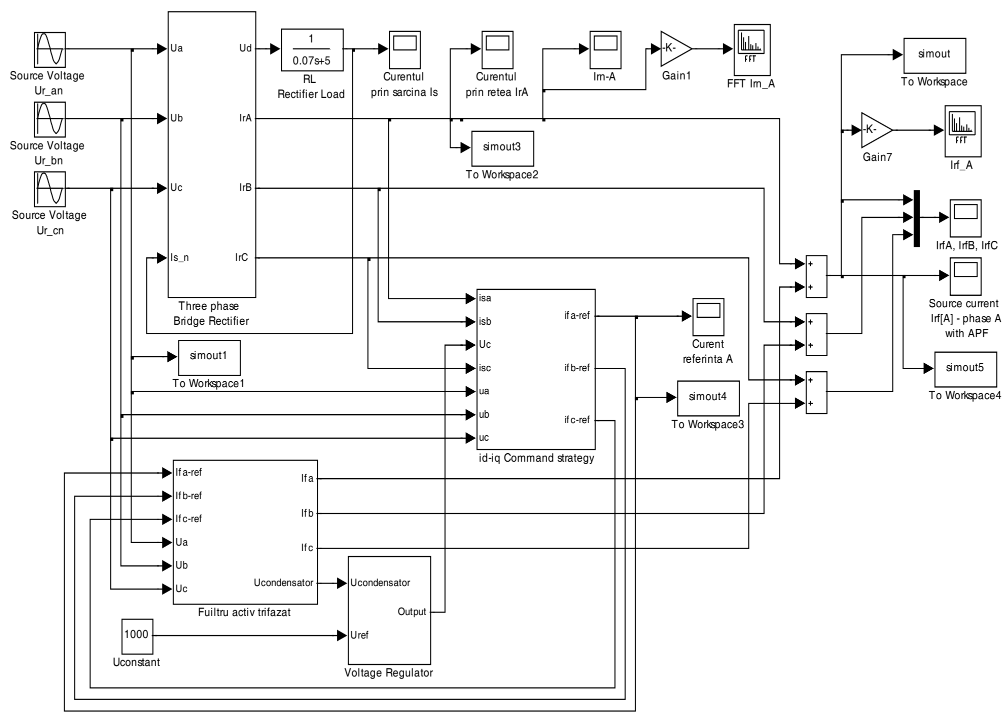


Fig. 12: The Matlab-Simulink model of the source – non-linear load- parallel active filter network with command based on i_d-i_q method.

The reference currents are obtained from instantaneous and reactive currents components of the non-linear load. The main voltage and load currents are transformed into dq equation frame using relations (5) and (6).

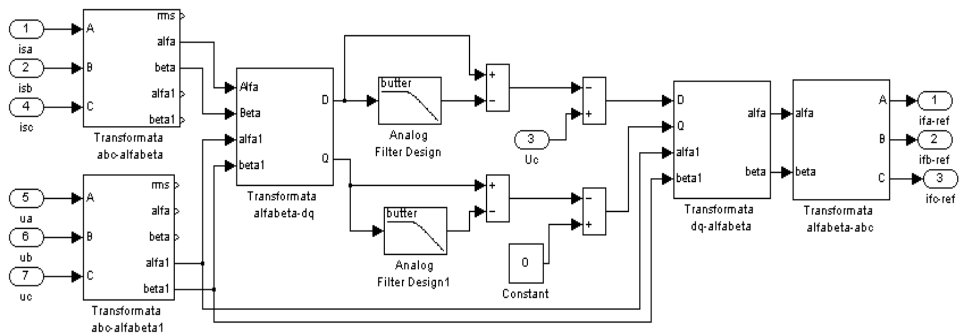
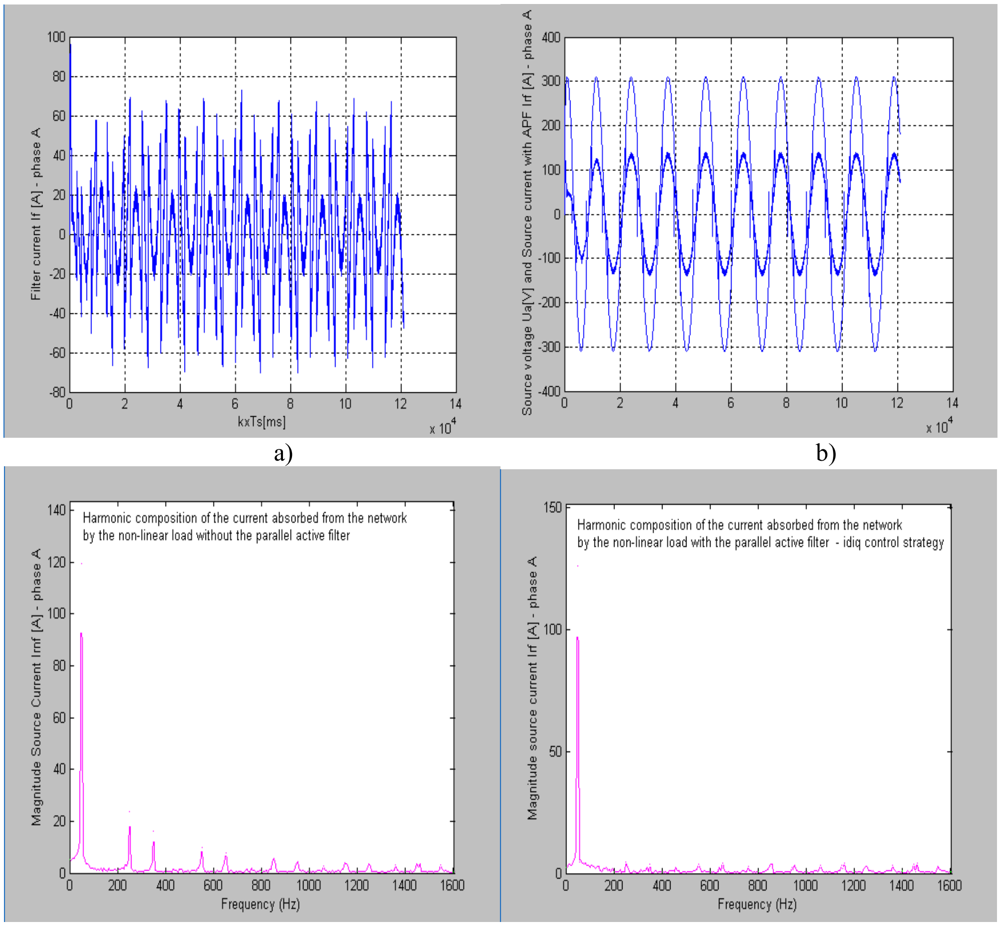


Fig. 13: Three-phased active filter command through current active and reactive components i_d-i_q method

Instantaneous active and reactive load currents can be decomposed into oscillatory and average terms. Under balanced and sinusoidal network voltage, eliminating the average current components is not a problem using a simple low pass filter. After this operation the compensating currents can be calculated with the following equation:

$$\begin{bmatrix} i_{f\alpha} \\ i_{f\beta} \end{bmatrix} = \frac{1}{\sqrt{u_\alpha^2 + u_\beta^2}} \begin{bmatrix} u_\alpha & -u_\beta \\ u_\beta & u_\alpha \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} \tag{8}$$

$$\begin{bmatrix} i_{fA\_ref} \\ i_{fB\_ref} \\ i_{fC\_ref} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}^T \begin{bmatrix} i_{f\alpha} \\ i_{f\beta} \end{bmatrix} \tag{9}$$



a) b)

c) d)

Fig. 14: Electrical measure on phase: (a) the current debited by the active filter $I_{f\text{-}A}$ [A]; (b) the absorbed current from the network by the non-linear load I_{rf} [A] together with network voltage U_A[V], (c) harmonic content of the current absorbed from the network by the non-linear load without a parallel active filter, (d) harmonic composition of the current absorbed from the network by the non-linear load with the parallel active filter

2.4. Current minimization method: G_e equivalent conductance method.

This algorithm is based on the i_{sA}, i_{sB}, i_{sC} load current measurement, a PLL synchronization circuit and a voltage regulator on the active filter's capacitor to generate the active filter command [7] (Fig. 15).

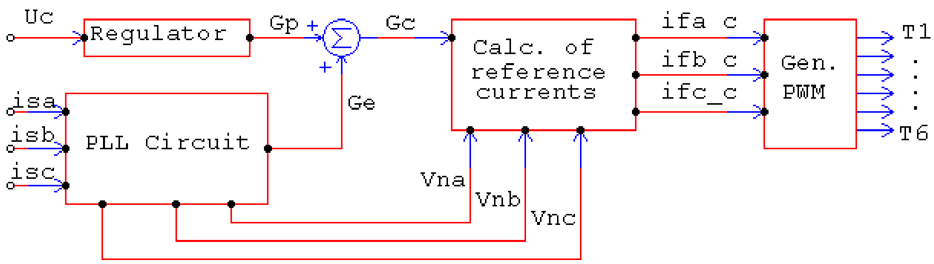


Fig. 15: System configuration of the active filter command.

The continuous voltage regulator can be represented by a PI controller used to generate the command signal. It forces the active filter to extract from the network the necessary active current to compensate the losses from the filter's power circuit.

The PLL synchronization circuit permanently monitors the basic load current frequency. The design of the PLL should allow it to function in conditions of distortion and unbalance of the phase currents. The exit signals of the PLL circuit will be the unitary system voltage phasors (v_{na}, v_{nb}, v_{nc}) corresponding to the load currents and the G_e dynamic conductance, which corresponds to the positive amplitude of the I_{+1} fundamental load current on a phase.

The instantaneous values of the positive load current component for the three phases can be written depending on the equivalent conductance as it follows:

$$\begin{cases} i_{pa}=\underline{G_e}\cdot v_{na}=\underline{G_e}\cdot\sin(\omega t-\pi/2) \\ i_{pb}=\underline{G_e}\cdot v_{nb}=\underline{G_e}\cdot\sin(\omega t-\pi/2-2\pi/3) \\ i_{pc}=\underline{G_e}\cdot v_{nc}=\underline{G_e}\cdot\sin(\omega t-\pi/2+2\pi/3) \end{cases} \quad (10)$$

For each phase the load current can be compensated by determining its active components:

$$\begin{cases} i_{ma}=G_e\cdot u_{na} \\ i_{mb}=G_e\cdot u_{nb} \\ i_{mc}=G_e\cdot u_{nc} \end{cases} \quad (11)$$

where (u_{na}, u_{nb}, u_{nc}) are phase voltages and Ge is a real variable, representing a real conductance defined as it follows:

$$G_e = \frac{P_{3f}}{\left\| u_{n\Sigma} \right\|^2} = \frac{u_{na} \times i_{sa} + u_{nb} \times i_{sb} + u_{nc} \times i_{sc}}{u_{na}^2 + u_{nb}^2 + u_{nc}^2} \tag{12}$$

Considering that the energy (active power) transferred to the load currents (i_{sa}, i_{sb}, i_{sc}) is the same as the energy transferred by the active compensation currents (minimization) i_{ma}, i_{mb}, $i_{mc,}$ that is:

$$P_{3f} = u_{na} \times i_{sa} + u_{nb} \times i_{sb} + u_{nc} \times i_{sc} = u_{na} \times i_{ma} + u_{nb} \times i_{mb} + v_{nc} \times i_{mc} \tag{13}$$

and $$\left\| v_{N\Sigma} \right\|^2 = v_{Na}^2 + v_{Nb}^2 + v_{Nc}^2 = \frac{3}{2} \tag{14}$$

Replacing in expression (12) phase voltage (u_{na}, u_{nb}, u_{nc}) with generated voltage phasor (v_{na}, v_{nb}, v_{nc}) by the PLL circuit, we obtain the expression of the instantaneous equivalent conductance:

$$G_e' = \frac{2}{3} \times (v_{na} \times i_{sa} + v_{nb} \times i_{sb} + v_{nc} \times i_{sc}) \tag{15}$$

Since (v_{na}, v_{nb}, v_{nc}) are in phase with the currents (i_{sa}, i_{sb}, i_{sc}) the reactive power is null: q=0.

We conclude that G_e' corresponds to the amplitude of the fundamental load current (I_{+1}). So the average value of the conductance G_e' is actually $\underline{G_e}$.

The reference currents are calculated with formula (16):

$$\begin{cases} i_{fa\_c} = i_{pa} - i_{sa} \\ i_{fb\_c} = i_{pb} - i_{sb} \\ i_{fc\_c} = i_{pc} - i_{sc} \end{cases} \tag{16}$$

The Matlab-Simulink model is shown in Fig. 16. The active filter command part is shown in Fig. 17 and the characteristic waveforms in Fig. 18.

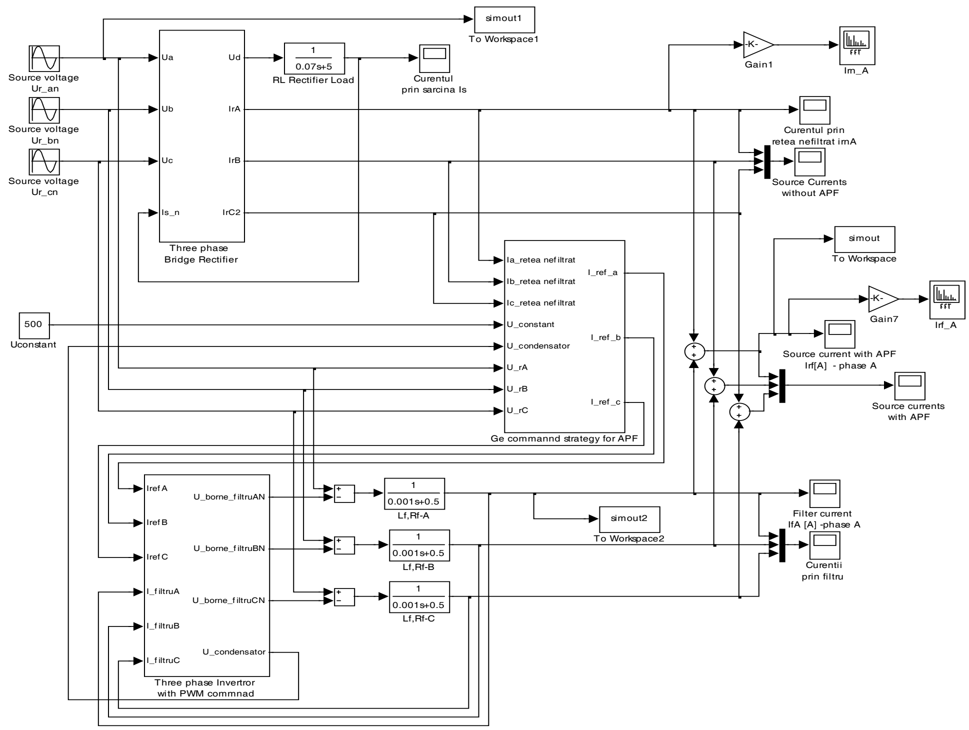


Fig. 16: The Matlab-Simulink model of the source – non-linear load- parallel active filter network with command based on current minimization method.

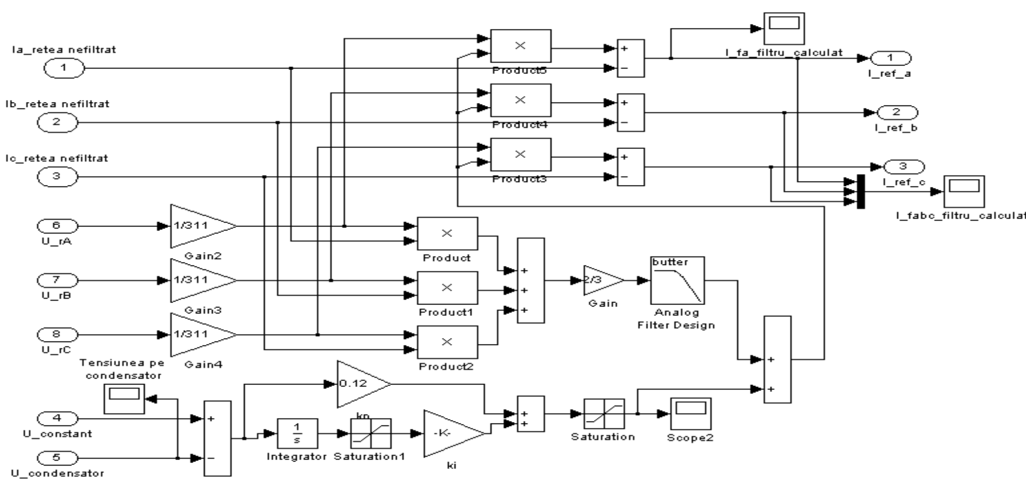


Fig. 17: Three-phased active filter command through minimisation current method

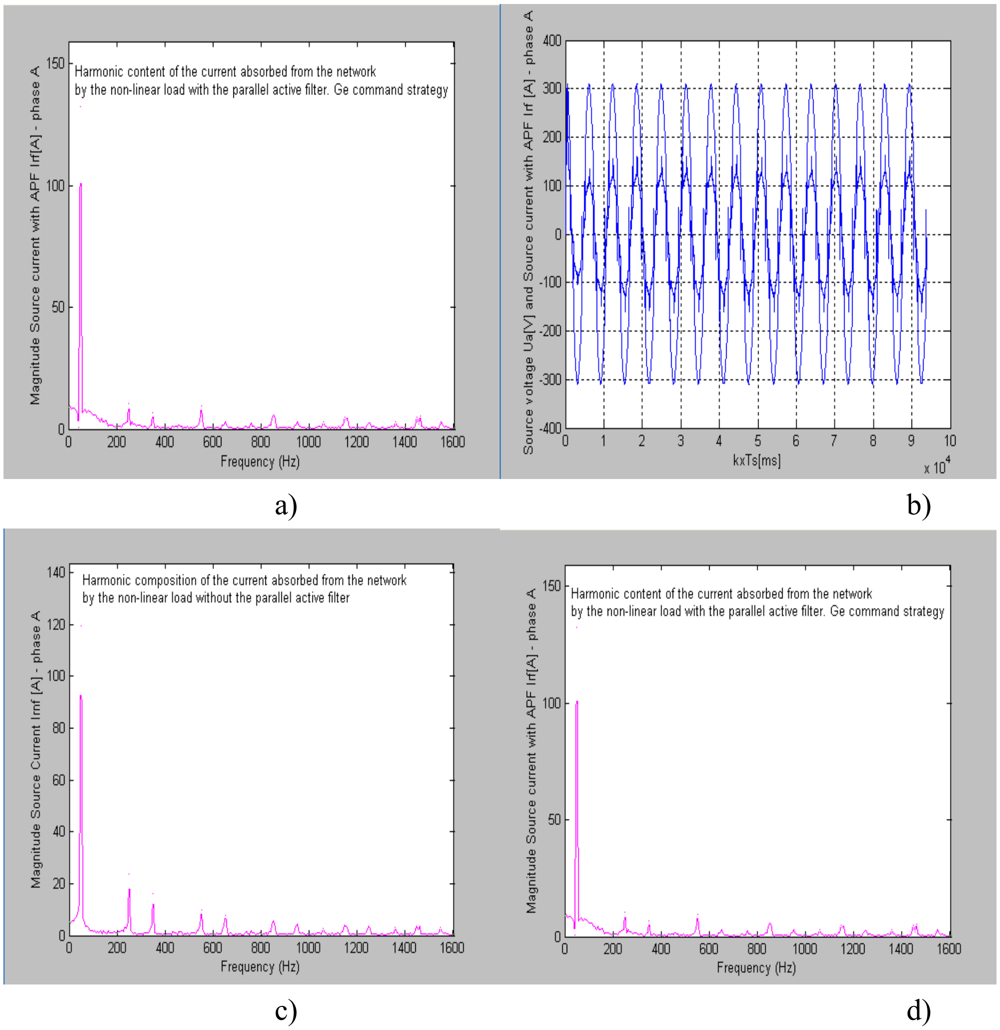


Fig. 18: Electrical measure on phase: (a) the current debited by the active filter $I_{f\text{-}A}$ [A]; (b) the absorbed current from the network by the non-linear load I_{rf} [A] together with network voltage U_A[V], (c) harmonic content of the current absorbed from the network by the non-linear load without a parallel active filter, (d) harmonic content of the current absorbed from the network by the non-linear load with the parallel active filter

3. Conclusions

In the case of three-phased active filters one of the common characteristics of the algorithm based on the d-q synchronic transformation method or of p-q instant powers is that the calculation of the compensation powers is made directly from the measures inside the network (voltage, currents) allowing the methods to be more independent of frequency. Avoiding the usage of a PLL circuit the frequency limitation is only imposed by the commutation frequency of the power control system.

The calculation methods based on p-q and dq algorithms need band-pass filters to separate the active and reactive power in the continuous and oscillatory components. These filters cause delays, which influence to some extent the performance of the active filter. Another disadvantage of these methods is they require a high number of calculations (example: the direct and reverse Park transformation*)*.

In the highly unbalanced three phased systems the used parallel active filters do not compensate the harmonic powers, introduced by the non-linear load and they also inject harmonic powers in the network. In such cases, it is preferable to use an active filter with command based on the power minimization principle, because the generation of the command power is made through a PLL circuit, which permanently monitors the parameters of the load power (phase, amplitude).

R E F E R E N C E S

[1] F. Ionescu, J.P. Six, D. Floricau, Ph. Delarue, S. Nitu, C. Bogus "Electronica de putere. Convertoare statice" Editura Tehnică, 1998, Bucuresti, ISBN 973-31-1262-3

[2] F. Ionescu & Co. (U.P.B), D. Alexa &Co (U."Gh.Asachi" Iasi), E. Milent (USTL), M.E. Rosu (U."Dunarea de Jos" Galati). "Electronica de putere. Modelare si simulare" Editura Tehnică, 1997, Bucuresti, ISBN 973-31-1086-8

[3] D.Floricău, J.C. Hapiot "Convertoare statice de putere. Structuri si comenzi." Editura Printech, 2000, Bucuresti, ISBN 973-652-248-2

[4] M.El-Habrouk, M.K.Darwish and P Mehta, IEE Proceedings Electr. Power Application "Active power filters: A review", IEE Proceedings, Electr. Power Appl. Vol. 147, Nr.5, Sept.2000, pag 403-412

[5] Luis A. Moran, Juan W. Dixon, Jose R. Espinoza, Rogel R. Wallace, "Using active power filters to improve power quality"- Inteligencia 1999.

[6] Hirofumi Akagi, Akira Nabae, Yukifumi Tsukamoto "Analysis and design of an active power filter using quad-series voltage source PWM converters" IEE Transactions on industry applications, Vol.26, Nr.1, Jan.-Feb. 1990, pag. 93-98

[7] M. Aredes, E. H. Watanabe, "New Control Algorithms for Series and Shunt Three-Phase Four-Wire Active Power Filters", IEEE Trans. Power Delivery, vol 10, no. 3, July 1995, pp. 1649-1656.

[8] Delarue, P., Six, J., Ionescu, F., Bogus, C., "New Control Method for Active Power Filter", ISIE, Athens, 1995,pp 427-432.

[9] H. Akagi, "New Trends in Active Filters for Power Conditioning," in IEEE Trans. on Industry Applications, vol. 32, no. 6, pp. 1312-1322, Nov./Dec. 1996
[10] Luis F.C. Monteiro, Mauricio Aredes, Joao A. Moor Neto "A control strategy for unified power quality conditioner" – ISIE 2003
[11] B. Singh, K. Al-Haddad, and A. Chandra, "A Review of Active Filters for Power Quality Improvement," IEEE Transactions on Industrial Electronics, vol. 46, pp. 960-971, Oct. 1999
[12] "IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems", IEEE Std. 519-1992.