Methods of reducing the distorting regime using parallel active filters

M. Marcu, F. G. Popescu, T. Niculescu, and I. R. Slusariuc

Abstract—Given the nature of voltages and currents in nonlinear electrical networks with fast and random variation, it is understood that the power measurement methods cannot be based on averages or quadratic mean values, and it is necessary to offset the negative effects due to the presence of certain loads. In order to compensate the distorting regime, it is necessary to use active filters. The paper presents the structure of an active power filter to compensate higher order harmonics. Active Power Filter Control is performed using three theories (instantaneous reactive power, generalized power, and synchronous reference theories). In each of the three theories there is an analysis of the functioning of the system for loads balanced and unbalanced. The authors present the parallel active power filter based on these theories, and the results were simulated in MATLAB-Simulink. With the aims of these simulations, the authors made a comparative analysis in order to reduce the harmonic pollution to obtain conclusions about their efficiency.

Keywords—Active filter, harmonic pollution, distorting regime, simulation.

I. Introduction

In recent years it has been observed that in developed countries, electric energy is transmitted through static power converters. These static converters, in addition to the known advantages, also have disadvantages, one of these consist in introducing higher order harmonics into electrical networks. Due to this disadvantage, it is necessary to develop solutions for compensating current and voltage harmonics.

Power Active Filter (PAF) represents a modern and efficient solution. The PAF is designed with a variable impedance that has a value to facilitate the elimination or decreasing of the harmonics.

There are a lot of topologies of PAF [2], [4], [9] due to the progress of static converters and the addition of new power semiconductors with better performance.

M. Marcu is Associate Professor PhD in the Department of Control Engineering, Computers, Electrical Engineering and Power Engineering, University of Petrosani, Petrosani, Romania (e-mail: mariusmarcu66@yahoo.com).

F. G. Popescu is Lecturer PhD in the Department of Control Engineering, Computers, Electrical Engineering and Power Engineering, University of Petrosani, Petrosani, Romania (e-mail: floringabriel82@yahoo.com).

T. Niculescu is Associate Professor PhD in the Department of Control Engineering, Computers, Electrical Engineering and Power Engineering, University of Petrosani, Petrosani, Romania (e-mail: niculescu_titu@yahoo.com).

I. R. Slusariuc is Lecturer PhD in the Department of Control Engineering, Computers, Electrical Engineering and Power Engineering, University of Petrosani, Petrosani, Romania (e-mail: razvansir@yahoo.com).

Depending on the type of construction and networking mode, the active power filters can be classified into [3], [6]:

- Parallel active filter.
- Series active filter.
- Series-parallel active filter.
- Hybrid filter.

Of all types of filters, active filter in the parallel connection is the most well-known structure and allows the elimination of harmonics, and corrects the power factor, balances line currents for unbalanced loads, and cancels null current of neutral networks.

The most used structure is based on a current-controlled voltage converter, where the energy is stored in a capacitor located on the DC part of the converter (Fig.1).

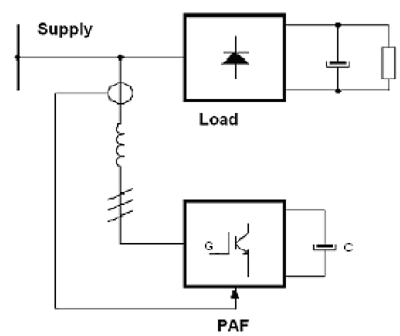

Fig.1. Parallel active filter topology

The control method is also based on the injection of a current in parallel and phase opposition with the harmonic current.

The active power filter in parallel connection is the one that will be analyzed in this paper as a reference typology for the analysis we will achieve.

For this filter, we analyzed the behavior of the control system in case of all the three methods by performing mathematical models and simulation of operation, making a comparative analysis, which has not been analyzed until now.

II. Modeling of Power Active Filters

A. Instantaneous Reactive Power Theory (TPRI)

This is one of the most popular theories that have been used, not only in theory but also in practice, and can be considered the first successful implementation through methods based on the use of static converters.

The three-phase system is transformed into a two-phase one accordingly with the following equations:

$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \cdot \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \cdot \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \cdot \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \cdot \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (2)$$

The instantaneous power is defined as a sum of the product between the instantaneous voltages and currents for each phase:

$$p = \sum_{1}^{n} v_n(t) \cdot i_n(t) \quad (3)$$

The new α-β coordination system that defines the three-phase must guarantee the equality of the instantaneous power value, independent of the reference axis system chosen and hence ensure that:

$$p = v_a \cdot i_a + v_b \cdot i_b + v_c \cdot i_c = v_\alpha \cdot i_\alpha + v_\beta \cdot i_\beta \quad (4)$$

As a new concept, Akagi, Kanazawa şi Nabae [1] defined a space vector named *Instantaneous Imaginary Power*, as a vectorial product of voltage and current:

$$q = v_\alpha \times i_\beta + v_\beta \times i_\alpha \quad (5)$$

This vector is located on an axis perpendicular to plane α-β and consists of two summations, which are the vectorial product of the voltage according to one axis, respectively the current, according to the other axis. In a graphical representation these products are vectors whose direction is perpendicular to the plane formed by the opposite axes of the α-β axes as represented in the Fig.2.

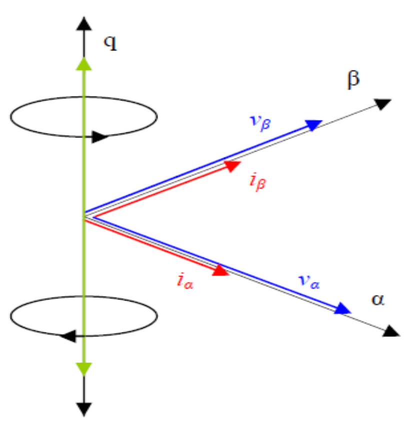

Fig.2. Spatial representation of instantaneous imaginary power

The result of the two previous equations can be expressed in the following way:

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{bmatrix} \cdot \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \quad (6)$$

The values of the currents according to the axes will be:

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \frac{1}{v^2_\alpha + v^2_\beta} \cdot \begin{bmatrix} v_\alpha & -v_\beta \\ v_\beta & -v_\alpha \end{bmatrix} \cdot \begin{bmatrix} p \\ q \end{bmatrix} \quad (7)$$

These instantaneous currents, according to α-β axes, can be expressed by dividing them into two components:

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \begin{bmatrix} i_{\alpha p} \\ i_{\beta p} \end{bmatrix} + \begin{bmatrix} i_{\alpha q} \\ i_{\beta q} \end{bmatrix} \quad (8)$$

where the meaning of each component is the following:

- Instantaneous active current according to α:

$$i_{\alpha p} = \frac{v_\alpha}{v^2_\alpha + v_\beta^2} p \quad (9)$$

- Instantaneous reactive current according to α:

$$i_{\alpha q} = \frac{-v_\alpha}{v_\alpha^2 + v_\beta^2} q \quad (10)$$

- Instantaneous active current according to β:

$$i_{\beta p} = \frac{v_\beta}{v_\alpha^2 + v_\beta^2} p \quad (11)$$

- Instantaneous reactive current according to β:

$$i_{\beta q} = \frac{v_\alpha}{v_\alpha^2 + v_\beta^2} q \quad (12)$$

The instantaneous power according to the α-β axes has the following expression:

$$p = v_\alpha \cdot (i_{\alpha p} + i_{\alpha q}) + v_\beta \cdot (i_{\beta p} + i_{\beta q}) \quad (13)$$

or

$$\begin{bmatrix} p_\alpha \\ p_\beta \end{bmatrix} = \begin{bmatrix} v_\alpha i_\alpha \\ v_\beta i_\beta \end{bmatrix} = \begin{bmatrix} v_\alpha i_{\alpha p} \\ v_\beta i_{\beta p} \end{bmatrix} + \begin{bmatrix} v_\alpha i_{\alpha q} \\ v_\beta i_{\beta q} \end{bmatrix} \quad (14)$$

It follows that:

- Instantaneous active power according to α:

$$p_{\alpha p} = \frac{v_\alpha{}^2}{v_\alpha{}^2 + v_\beta{}^2} p \tag{15}$$

- Instantaneous reactive power according to α:

$$p_{\alpha q} = \frac{-v_\alpha v_\beta}{v_\alpha{}^2 + v_\beta{}^2} q \tag{16}$$

- Instantaneous active power according to β:

$$p_{\beta p} = \frac{v_\beta{}^2}{v_\alpha{}^2 + v_\beta{}^2} p \tag{17}$$

- Instantaneous reactive power according to β:

$$p_{\beta q} = \frac{v_\alpha v_\beta}{v_\alpha{}^2 + v_\beta{}^2} q \tag{18}$$

From the above equations we obtain:

$$p = p_{\alpha p} + p_{\beta p} \qquad p_{\alpha q} + p_{\beta q} = 0 \tag{19}$$

Actual instant power consists of pαp and $p_{\beta p}$ and coincides with the active power of the three-phase system and is called active instantaneous power.

The terms $p_{\alpha q}$ and $p_{\beta q}$ have the same value and the opposite sign, mutually cancel and do not contribute to the transfer of instantaneous power between the source and the load. So they form *instantaneous reactive power* and can be considered to be a power flowing between the phases and not between the source and the load, as seems logical. We also do not need to have any energy storage system to compensate for it.

Initially TPRI was developed for three-phase networks without null, but the same authors [6] immediately extended the theorem to neutral systems with the presence of homopolar voltage and current components.

This is done by transforming a system of axes a-b-c into another orthogonal axis system, called α-β-0, through the following transformation:

$$\begin{bmatrix} v_\alpha \\ v_\beta \\ v_0 \end{bmatrix} = [C] \cdot \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \sqrt{\frac{2}{3}} \cdot \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \end{bmatrix} \cdot \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \tag{20}$$

$$\begin{bmatrix} i_\alpha \\ i_\beta \\ i_0 \end{bmatrix} = [C] \cdot \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \sqrt{\frac{2}{3}} \cdot \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \end{bmatrix} \cdot \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{21}$$

In addition to the p-q power components, according to the predefined α-β axes, a new power component associated with the axis 0 and the values of the homopolar voltage and current components is introduced, so that:

$$p_0 = v_0 \cdot i_0 \tag{22}$$

This power is defined as the instantaneous power of sequence 0 or homopolar power.

Thus the initial expression of power applied in a neutral three-phase system is:

$$\begin{bmatrix} p_{\alpha\beta} \\ q_{\alpha\beta} \\ p_0 \end{bmatrix} = \begin{bmatrix} v_\alpha & v_\beta & 0 \\ -v_\beta & v_\alpha & 0 \\ 0 & 0 & v_0 \end{bmatrix} \cdot \begin{bmatrix} i_\alpha \\ i_\beta \\ i_0 \end{bmatrix} \tag{23}$$

From previous equations it can be observed that:

$$p = v_0 \cdot i_0 + v_\alpha \cdot i_{\alpha p} + v_\beta \cdot i_{\beta p} = p_0 + p_{\alpha p} + p_{\beta p} \tag{24}$$

and

$$0 = v_\alpha \cdot i_{\alpha q} + v_\beta \cdot i_{\beta q} = p_{\alpha q} + p_{\beta q} \tag{25}$$

The presence of the homopolar component is considered as an independent circuit and does not affect the components on the other axes.

B. Instantaneous Generalized Instant Power Theory (TGPI)

This theory proposes a general method for determining total power in a three-phase system, obtaining two power components called instantaneous power p and instantaneous reactive power q, [7], [8].

Applying these concepts to a three-phase voltage and current system, the respective vectors have as components, according to the coordinate axes a-b-c, the following instantaneous values:

$$v = \begin{bmatrix} v_\alpha \\ v_\beta \\ v_0 \end{bmatrix} = [C] \cdot \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \qquad i = \begin{bmatrix} i_\alpha \\ i_\beta \\ i_0 \end{bmatrix} = [C] \cdot \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{26}$$

Reverse transformations are:

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = [C] \cdot \begin{bmatrix} v_\alpha \\ v_\beta \\ v_0 \end{bmatrix} \qquad \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = [C]^{-1} \cdot \begin{bmatrix} i_0 \\ i_\alpha \\ i_\beta \end{bmatrix} \tag{27}$$

Instantaneous active power is defined as a scalar product of the voltage and current vectors that have been defined above.

$$p = v \cdot i \tag{28}$$

The instantaneous reactive power has the expression:

$$q = |q| = |v \times i| \tag{29}$$

It can be demonstrated that the condition is fulfilled:

$$i = i_p + i_q \tag{30}$$

so that the following expressions are met:

$$p = v \cdot i = v \cdot i_p \quad v \cdot i_q = 0 \quad v \times i_p = 0 \;\; i_p \cdot i_q = 0 \tag{31}$$

Thus, the current vector is composed of two orthogonal components, one of which is associated with the instantaneous active power and the other with the instantaneous reactive power.

The instantaneous active current is defined as an ip vector, which is the projection of the current vector on the voltage vector:

$$i_p = \frac{p}{|v|^2} \cdot v \tag{32}$$

whose components are:

$$i_p = \frac{1}{\Delta_{abc}} \cdot \begin{bmatrix} v_a \cdot p \\ v_b \cdot p \\ v_c \cdot p \end{bmatrix} = \begin{bmatrix} i_{ap} \\ i_{bp} \\ i_{cp} \end{bmatrix} \quad \text{where}$$

$$\Delta_{abc} = |v|^2 = v^2{}_a + v_b{}^2 + v^2{}_c \tag{33}$$

In the same way, instantaneous reactive current iq is an orthogonal vector, which is defined in the following way:

$$i_q = \frac{q \times v}{|v|^2} \tag{34}$$

with the components:

$$i_q = \frac{1}{\Delta_{abc}} \cdot \begin{bmatrix} \begin{Vmatrix} q_b & q_c \\ v_b & v_c \end{Vmatrix} \\ \begin{Vmatrix} q_c & q_a \\ v_c & v_a \end{Vmatrix} \\ \begin{Vmatrix} q_a & q_b \\ v_a & v_b \end{Vmatrix} \end{bmatrix} = \begin{bmatrix} i_{aq} \\ i_{bq} \\ i_{cq} \end{bmatrix} \tag{35}$$

It can be shown that the following conditions is fulfilled:

$$i = i_p + i_q \tag{36}$$

$$p = v \cdot i = v \cdot i_p \quad v \cdot i_q = 0 \quad v \times i_p = 0 \quad i_p \cdot i_q = 0 \tag{37}$$

Thus, the current vector is composed of two orthogonal components, one of which is associated with the instantaneous active power and the other with the instantaneous reactive power.

The component of the i_p current associated with the active power is collinear and in the same direction as the spatial voltage vector v, representing the projection of the space current vector on the spatial voltage vector, while the intensity i_q is associated with the reactive power and is perpendicular to the spatial vector of voltage.

The graphical representation (Fig.3) shows the voltage and current vectors as well as the decomposition of the current vector into the two components, one aligned with the voltage vector and the other perpendicular to it.

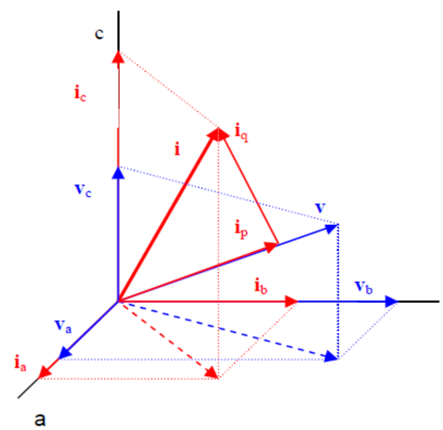

Fig.3. Graphic representation of current vector decomposition

C. Synchronous Reference Theory (SRT)

The conversion between the fixed system a-b-c and the new moving d-q-0 system will be done through Park's transformation, which is very used in the study of electric machines [9].

This method, called Synchronous Reference System (SRS), applied to reactive energy compensation and PAF harmonics, does not require knowledge of instantaneous powers as in the previously analyzed methods [7].

The transition from the a-b-c to the d-q-0 axes is done by Park equations, so that we have x_a, x_b, x_c three electrical signals, characterized by three scalar values according to time, which can be expressed in the *dq* system, according to the transformation matrix:

$$x_{dq0} = [P] \cdot x_{abc} \quad \text{where} \quad [P] = [\rho(\theta)] \cdot [C] \tag{38}$$

it follows that:

$$x_{dq0} = [\rho(\theta)] \cdot x_{\alpha\beta z} \text{ with } [\rho(\theta)] = \begin{bmatrix} \cos(\theta) & \sin(\theta) & 0 \\ -\sin(\theta) & \cos(\theta) & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{39}$$

Park's matrix will have the following expression:

$$[P] = \sqrt{\frac{2}{3}} \cdot \begin{bmatrix} cos(\theta) & cos(\theta - 2\pi/3) & cos(\theta - 4\pi/3) \\ -sin(\theta) & -sin(\theta - 2\pi/3) & -sin(\theta - 4\pi/3) \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \end{bmatrix} \quad (40)$$

For the development of this method, the rotational matrix ρ (θ) is used, so to obtain the Park's components, it will start from the knowledge of the α-β-0 components.

$$x_{dq0} = [\rho(\theta)] \cdot x_{\alpha\beta 0} \quad (41)$$

Expressed as:

$$x_{dq0} = \begin{bmatrix} x_d \\ x_q \\ x_0 \end{bmatrix} = [\rho(\theta)] \cdot \begin{bmatrix} x_\alpha \\ x_\beta \\ x_0 \end{bmatrix} = \begin{bmatrix} cos(\theta) & sin(\theta) & 0 \\ -sin(\theta) & cos(\theta) & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} x_\alpha \\ x_\beta \\ x_0 \end{bmatrix} \quad (42)$$

It can be seen that the component according to the axis 0, due to the homopolar component, remains invariant in front of the rotation transformation, as expected and already pointed out previously.

Taking off the component of the axis 0, which remains invariant, considered in a coordinate system or other and situated in the plane formed by the axes a-b or α-β, the vector x has a projection over this plane, whose components according to the axes are designated with sub-indices α-β, respectively d-q.

That projection of the three-dimensional vector over the considered plane is another vector whose representations in polar form are:

$$u_{\alpha\beta} = u \cdot e^{j\delta} = u \cdot cos(\delta) + ju \cdot sin(\delta) = x_\alpha + jx_\beta \quad (43)$$

Where *u* represents the designed vector module:

$$|u_{\alpha\beta}| = u = \sqrt{x^2{}_\alpha + x^2{}_\beta} \quad (44)$$

$$x_\alpha = u \cdot cos(\delta) \quad (45)$$

$$x_\beta = u \cdot sin(\delta) \quad (46)$$

This phasor relative to the d-q axis system represented in polar form is:

$$u_{dq} = u \cdot cos(\delta - \theta) + ju \cdot sin(\delta - \theta) = x_d + jx_q \quad (47)$$

$$x_d = u \cdot cos(\delta - \theta) \quad (48)$$

$$x_q = u \cdot sin(\delta - \theta) \quad (49)$$

where:

$$x_d = u \cdot cos(\delta) \cdot cos(\theta) - u \cdot sin(\delta) \cdot sin[\theta] \quad (50)$$

$$x_q = u \cdot sin(\delta) \cdot cos(\theta) - u \cdot cos(\delta) \cdot sin(\theta) \quad (51)$$

and tacking into account x_α şi x_β:

$$x_d = u_\alpha \cdot cos(\theta) + u_\beta \cdot sin(\theta) \quad (52)$$

$$x_q = u_\alpha \cdot cos(\theta) - u_\beta \cdot sin(\theta) \quad (53)$$

If in this expression is considered the component after axis 0, which did not change the coordinate systems, the above mentioned expression follows:

$$x_{dq0} = \begin{bmatrix} x_d \\ x_q \\ x_0 \end{bmatrix} = \begin{bmatrix} cos(\theta) & sin(\theta) & 0 \\ -sin(\theta) & cos(\theta) & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} x_\alpha \\ x_\beta \\ x_0 \end{bmatrix} \quad (54)$$

and

$$x_{\alpha\beta 0} = \begin{bmatrix} x_\alpha \\ x_\beta \\ x_0 \end{bmatrix} = \begin{bmatrix} cos(\theta) & -sin(\theta) & 0 \\ sin(\theta) & cos(\theta) & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} x_d \\ x_q \\ x_0 \end{bmatrix} \quad (55)$$

III. Simulation of Active Filters

Next, we will use the above described three theories to establish a control system that together with the power system will achieve the reduction of the harmonics.

In simulations of all PAF, the network remains constant as well as the structure of the converter and the load used, only changing the control system that determines the current values, in accordance with the theories described above.

The network will always be considered neutral, sinusoidal and balanced, unless an unbalanced network is analyzed if necessary.

Simulations will also be made for unbalanced loads, the unbalance value of which will consist of a 20% decrease in phase voltage "a".

In the simulation, a 20% voltage drop was assumed for phase "a" (ρ = 0.2), the actual values of the symmetrical components for a 380V network being $V_{0(RMS)} = 14{,}62V$, $V_{+(RMS)} = 204{,}77V$, $V_{-(RMS)} = 14{,}62V$.

The load used consists in combining the balanced three-phase non-linear load connected permanently and a single-phase non-linear load that is initially disconnected and connects between phase "a" and neutral after 0.3s.

- Balanced three-phase nonlinear load:

It is a three-phase bridge rectifier, with a DC load consisting of a current source of 65A and an inductance of the AC of 2mH with Q = 30, as shown in Fig.4.

The rectifier control angle is 300 and the average output voltage is 410 V dc with a delay factor value of about 0.8 and a THD of 28.78%.

- Single-phase nonlinear load:

It is a load consisting of an single phase rectifier with a

THD of 12.51%, which feeds a load on the DC consisting of a current source of 65 A with a series inductance on the AC of 2mH and Q = 30.

In Fig.5 and 6 are presented the harmonics for balanced and unbalanced load.

Currents on phases a, b and c, when the unbalanced load is connected, have a THD of: 17.4%, 23.4% and 23.4%.

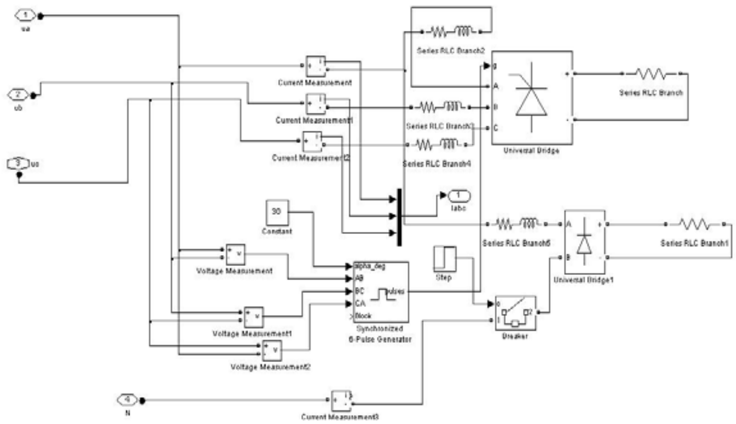

Fig.4. Simulation diagram of load

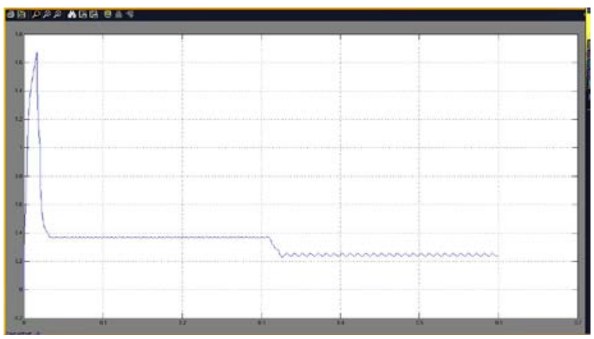

Fig.5. The variation in time of the harmonic distortion coefficient (THD)

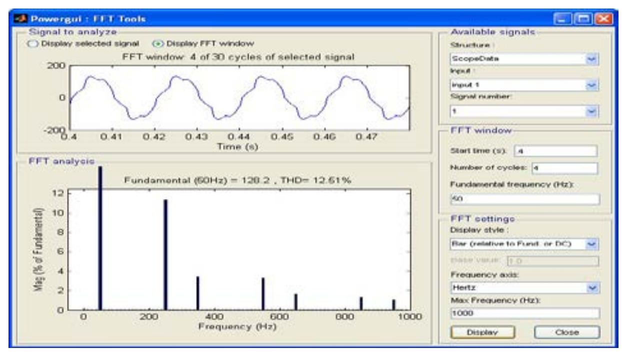

Fig.7. Harmonics for unbalanced load

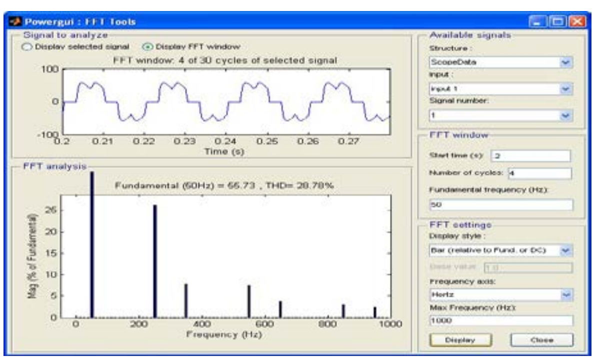

Fig.6. Harmonics for balanced load

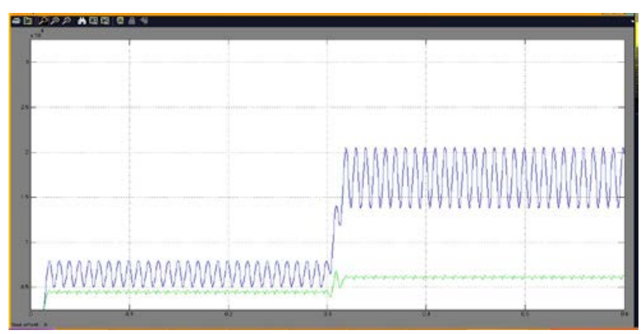

Fig.8. Active and reactive powers

In fig.9 is shown the full power circuit used to simulate all the control methods.

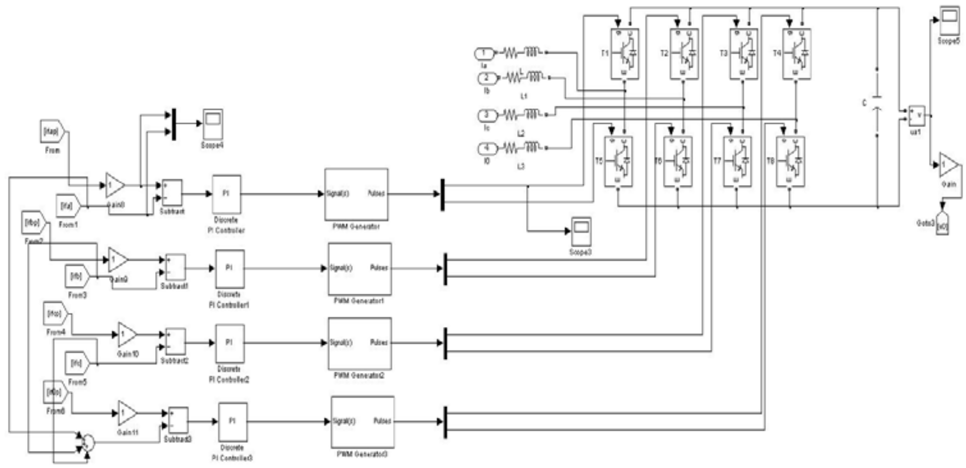

Fig.9.Simulation diagram of power circuit

This circuit includes the transducers with their transfer constants, for a 40 kVA of filter power.

Phase and neutral inductances are 1.9mH with Q = 30, and the total capacitance of the capacitor batteries in the DC is 4.700μF.

It was chosen to use a PWM control with a constant switching frequency of 8 kHz.

The constants of the PI controller correspond to a transfer function defined in the following way:

$$\frac{K\cdot(1+s\cdot T)}{s\cdot T} \tag{56}$$

with: $K = 10$ şi $T = 10ms$.

The simulation scheme is the same for all methods, with the distinction that each method has its own control circuit.

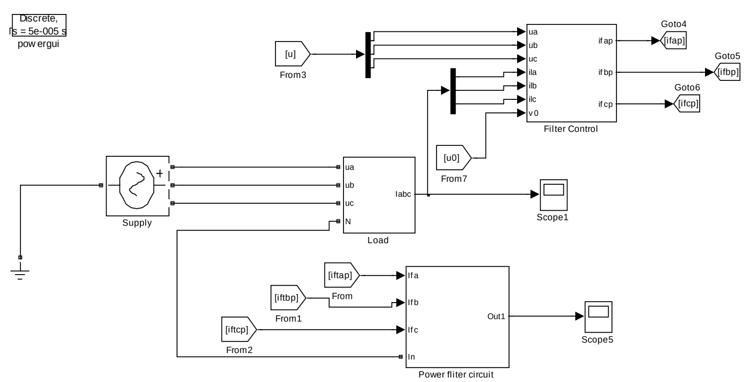

Fig.10. Simulation scheme

A. Compensation by TPRI

In the simulation, the control circuit required to determine the compensation currents, depending on the TPRI, is added.

Two compensation models are proposed to determine the compensation current that PAF has to supply. Although the final result is identical, the mathematical calculation is reduced in the second proposed method.

- **TPRI_Q method**

It is the conventional method, which determines the current that the PAF has to supply, starting from the calculation of the power components, apart from considering the homopolar component and the PAF losses.

The control circuit sets the compensation current of the PAF, with the following expressions:

$$\begin{bmatrix} i_{F\alpha} \\ i_{F\beta} \end{bmatrix} = \begin{bmatrix} v_\alpha & -v_\beta \\ v_\beta & v_\alpha \end{bmatrix} \cdot \begin{bmatrix} -\tilde{p} + \bar{p}_0 + p_{per} \\ -q \end{bmatrix} \qquad i_{F0} = -i_0 \tag{57}$$

Power loss is achieved by controlling the DC capacitor voltage so that PAF will absorb the active power losses from the α-β system and provide the instantaneous reactive power in addition to the alternative active power component.

For example, PAF only provides non-active power, as active power must supply the network along with power loss.

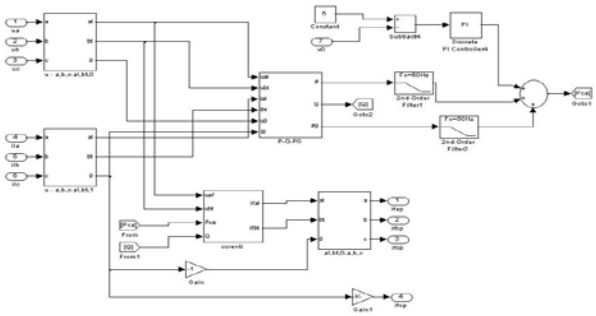

Fig.11. Control circuit according TPRI_Q

The simulation results are shown in the following graphs:

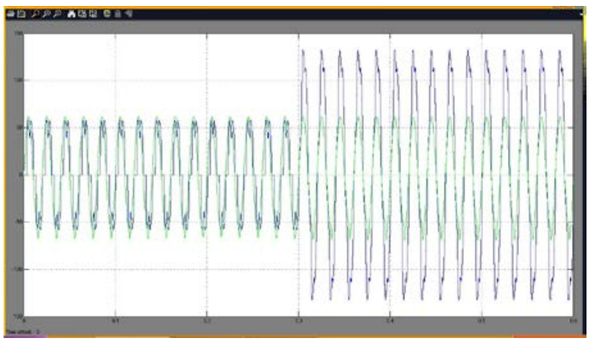

Fig.12. Unfiltered current and filtered current on phase a

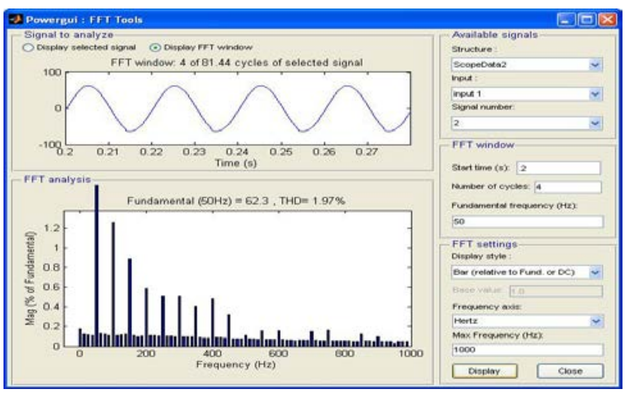

Fig.13. Harmonics for balanced load

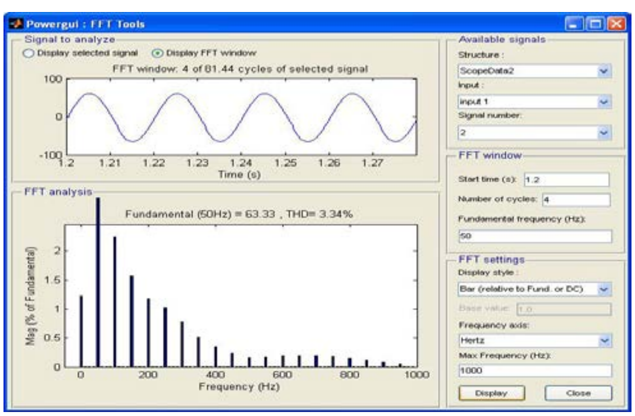

Fig.14. Harmonics for unbalanced load

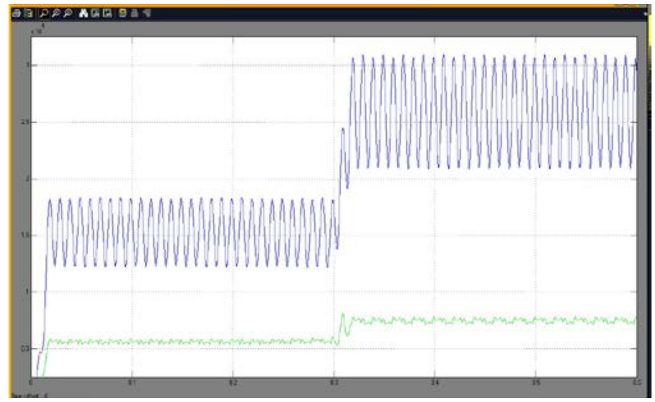

Fig.15. Active and reactive powers

- **TPRI_P method**

This method is based on the determination of the active power that the energy source has to supply, which will be the same as that imposed on the load, adding the PAF losses.

The power losses are obtained through the capacitor voltage regulator of the DC as in the previous case.

Homopolar current will be considered as if it were an independent system**.**

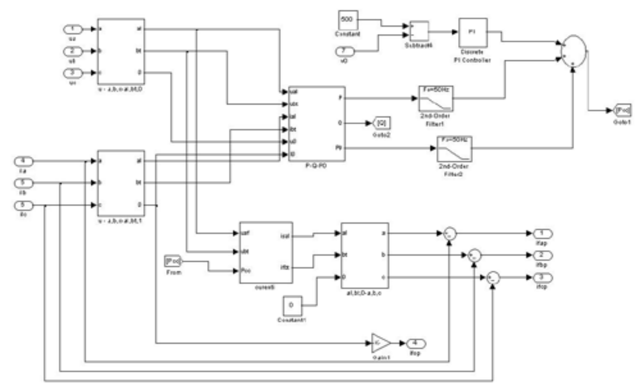

Fig.16. Control circuit according TPRI_P

As can be seen, the calculations only involve active, perfectly measurable powers.

The simulation results are as follows:

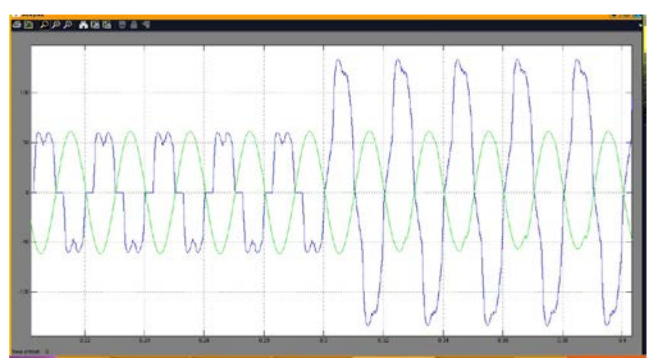

Fig.17. Unfiltered current and filtered current on phase a

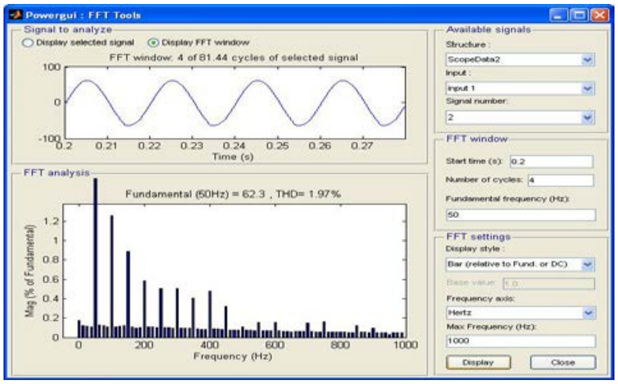

Fig.18. Harmonics for balanced load

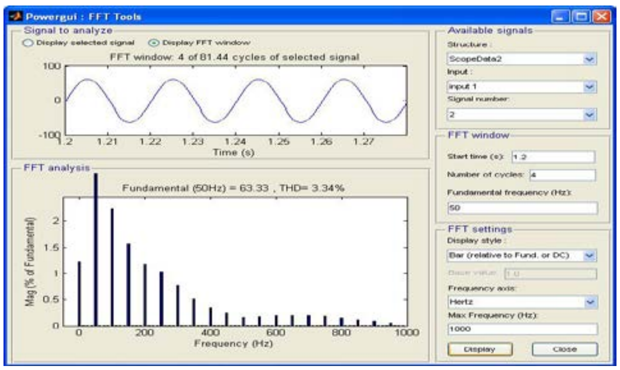

Fig.19. Harmonics for unbalanced load

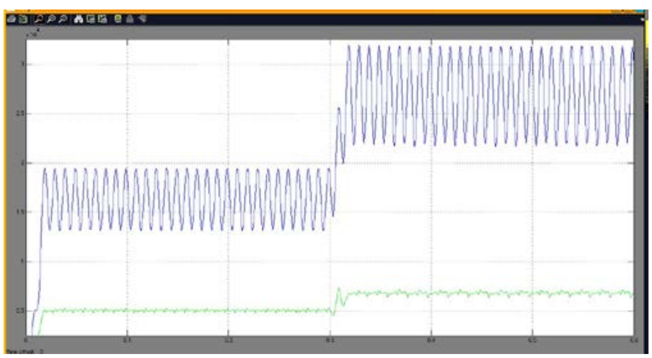

Fig.20. Active and reactive powers

It is noted that for this type of task and an unbalance of 20% per phase, there are no great differences between the two methods.

As for homopolar power, the evolution in the network is similar in both cases.

B. Compensation by TGPI

In the simulation, we consider the power circuit described in Figure 6 and add the control circuit required to determine the compensation currents according to TGPI.

In addition, and in the same way as the TPRI proposed, for each of these control strategies two methods can be used to determine the compensation current.

- **TGPI _Q method**

In this method, which is usually used, the control circuit determines the PAF compensation current based on the calculation of the reactive and homopolar components of the current.

It is necessary to equalize the null current in the load and the PAF, provided that the current in the network is also null.

$$i_{FO} = -\left(i_{La} + i_{Lb} + i_{Lc}\right) \qquad (58)$$

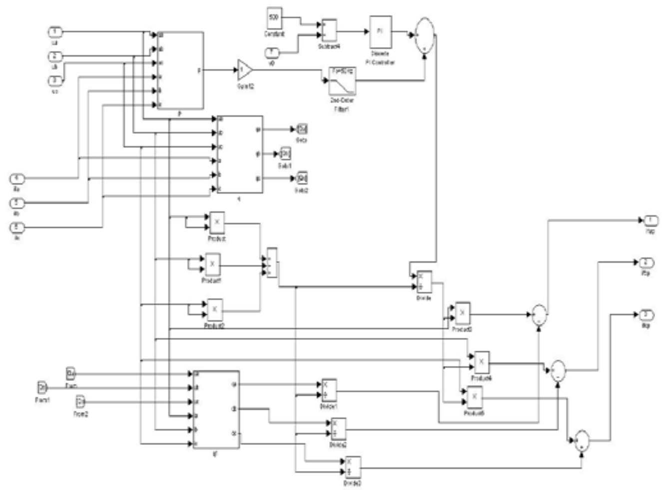

Fig.21. Control circuit according TGPI_Q

These figures show the obtaining of active and reactive powers, starting from the scalar and vector products of phase voltages and currents, as well as the respective currents according to the exposed theory.

The results obtained in the simulations are similar for both methods, as happened in the TPRI-based system, making a single representation of these results.

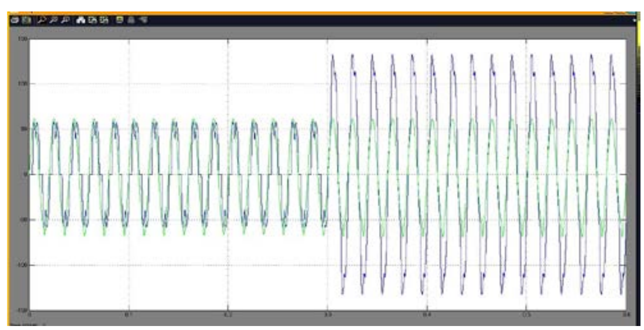

Fig.22. Unfiltered current and filtered current on phase a

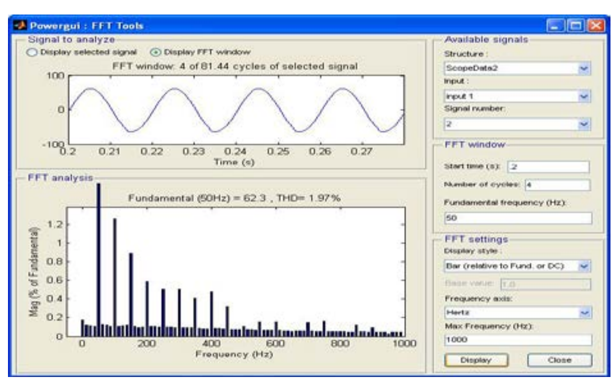

Fig.23. Harmonics for balanced load

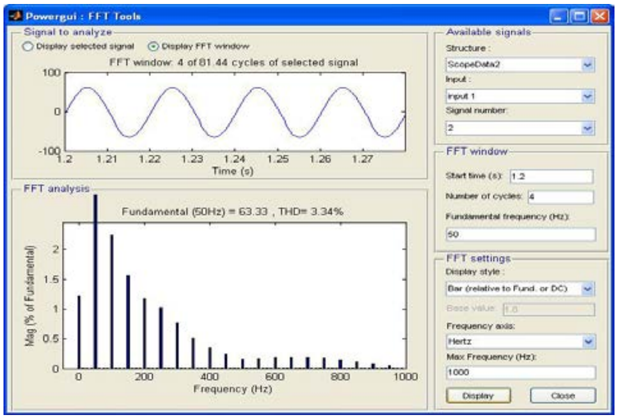

Fig.24. Harmonics for unbalanced load

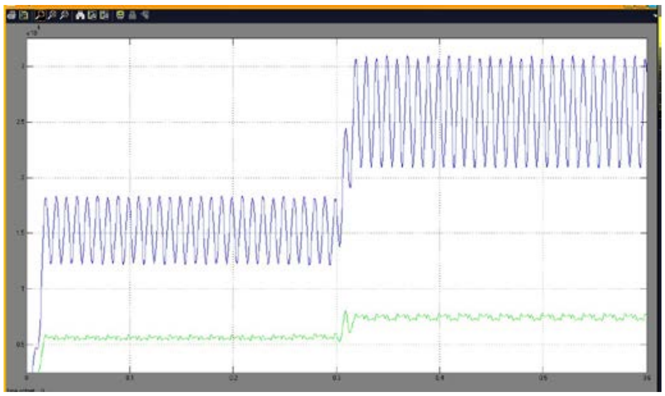

Fig.25. Active and reactive powers

- **TGPI _P method**

This is the method based on the direct determination of the active power that the power source must drive, and the corresponding active current, while the current in the PAF is indirectly obtained from the load.

$$i_F = i_S - i_L \tag{59}$$

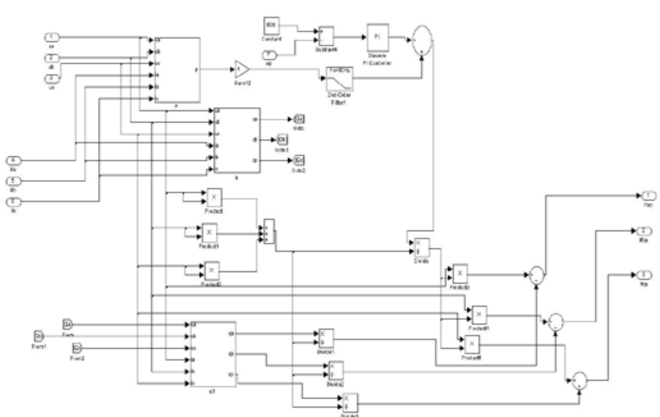

Fig.26. Control circuit according TGPI_P

The simulation results are presented in the following diagrams:

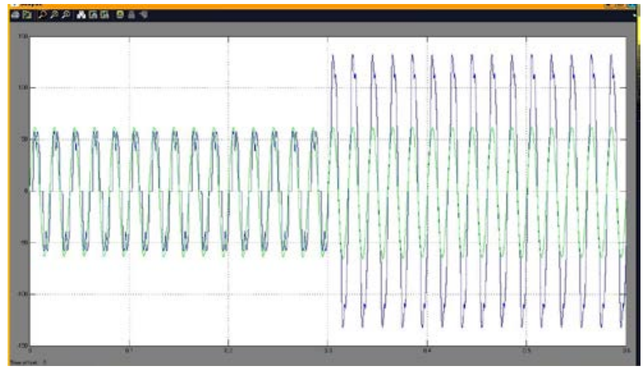

Fig.27. Unfiltered current and filtered current on phase a

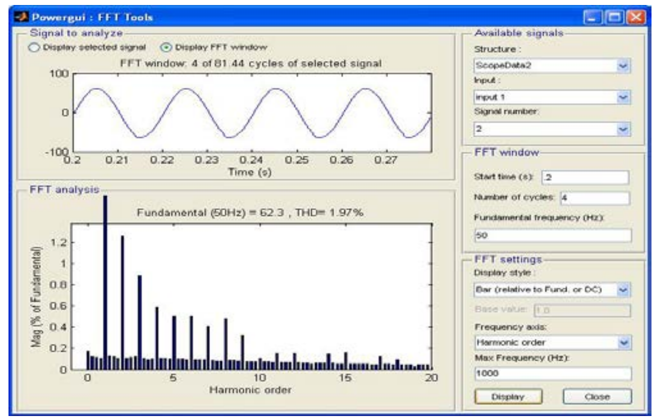

Fig.28. Harmonics for balanced load

It can be seen in this case, as in the TPRI compensation method, there are no great differences between the two studied methods, at least for this type of load and the assumed voltage.

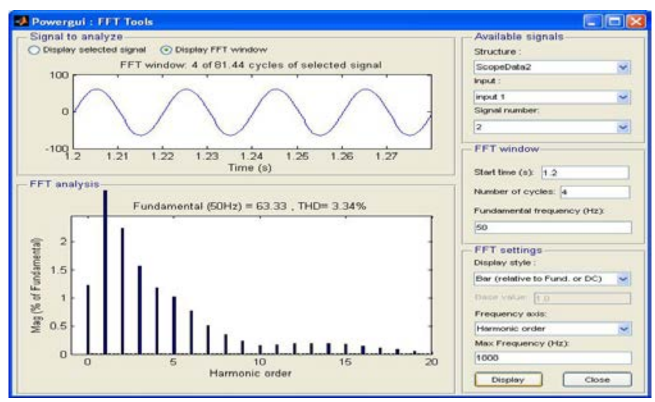

Fig.29. Harmonics for unbalanced load

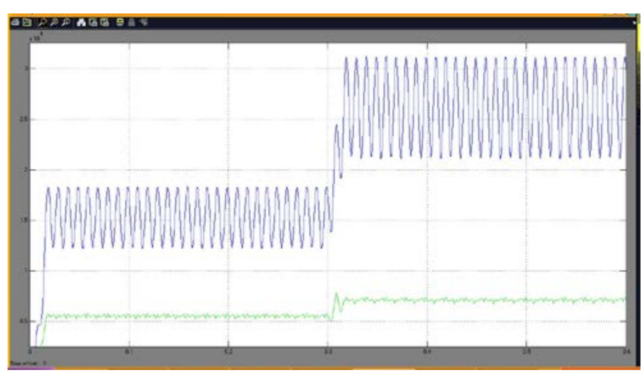

Fig.30. Active and reactive powers

C. Compensation by SRS

The SRS-based compensation method allows the direct acquisition of currents that in other systems were obtained by pre-calculation of instantaneous power. Therefore, it is not necessary to know the values of the phase voltages, except when synchronizing the d-q-0 axis system with a three-phase system voltage.

Obtaining these currents is done in the d-q-0 synchronous system with the fundamental frequency and orienting the d-axis with a-phase of the voltage system.

At this point we can say that the compensation system can be designed in two different ways, depending on the determination of the current component according to the q-axis, the method called SRS_Q or the component d according to the d-axis, the method called SRS_P.

- **SRS_Q method**

This method determines the current according to the q axis, including the continuous and alternate component.

In addition, the alternate current component according to the d-axis, summed up to the loss component and to the homopolar continuous component, must be added.

In Fig.31 is shown the control circuit according with this method.

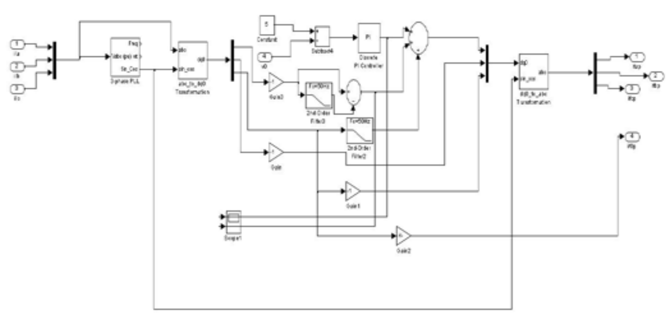

Fig.31. Control circuit according SRS_Q

The homopolar current of the load is obtained directly through the Park transformation, while the neutral current of the PAF is obtained as the sum of the phase currents.

The results are as follows:

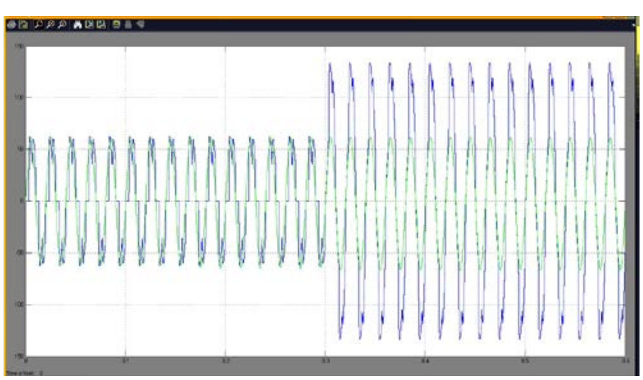

Fig.32. Unfiltered current and filtered current on phase a

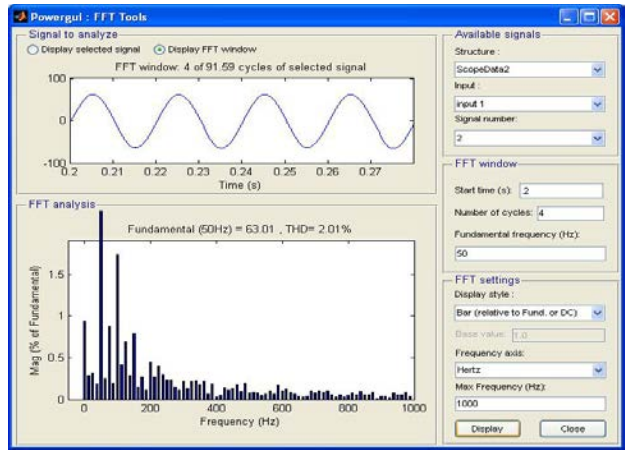

Fig.33. Harmonics for balanced load

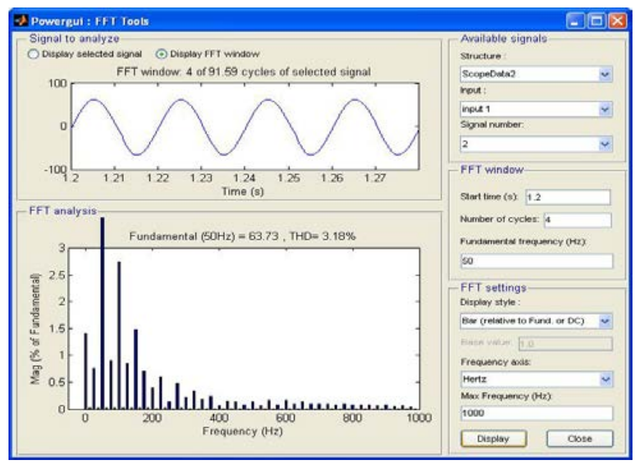

Fig.34. Harmonics for unbalanced load

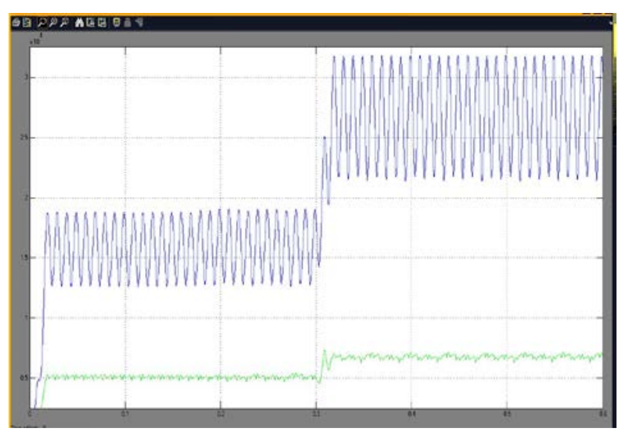

Fig.35. Active and reactive powers

- **SRS _P method**

This is the method that is considered the most appropriate because the results obtained for the total compensation of the reactive power are similar to those obtained in the previous case and require fewer calculations.

Figure 36 shows the control circuit.

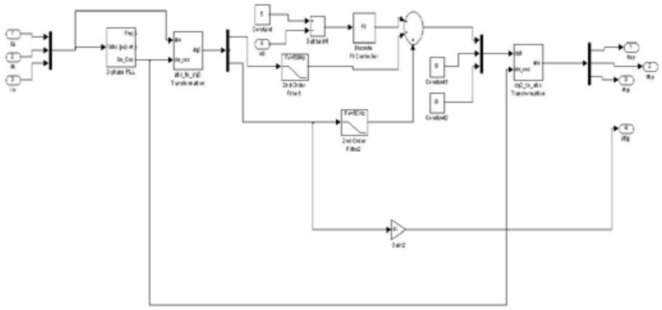

Fig.36. Control circuit according SRS_P

The simulation results are presented in the following diagrams:

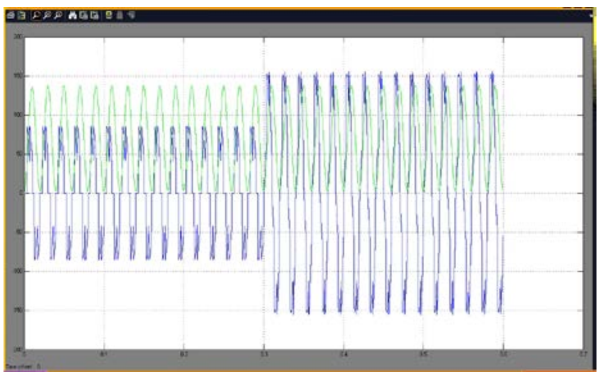

Fig.37. Unfiltered current and filtered current on phase a

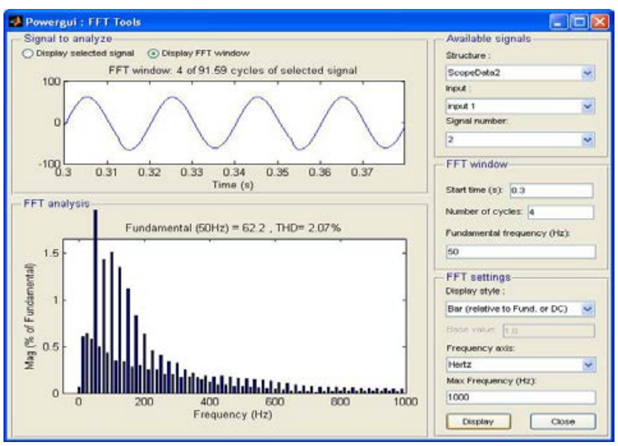

Fig.38. Harmonics for balanced load

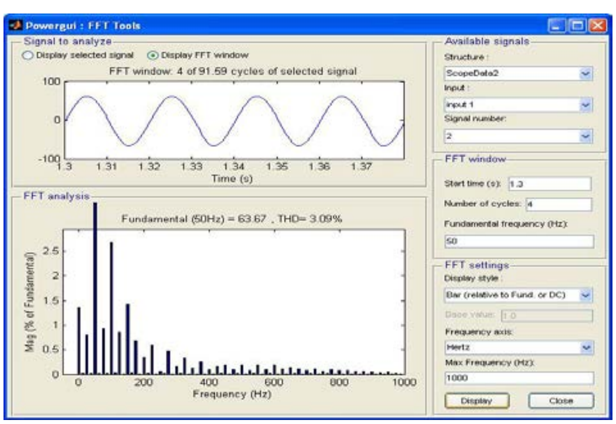

Fig.39. Harmonics for unbalanced load

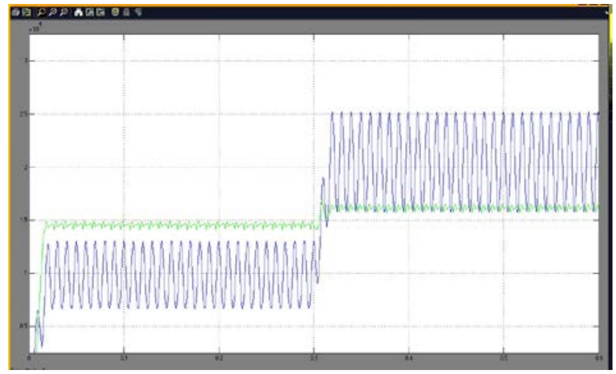

Fig.40. Active and reactive powers

IV. Conclusion

The paper describes the bases of compensation methods, their advantages and disadvantages, as well as their comparison.

All of these theories develop in the time domain and allow the immediate acquisition of various components of power, voltage or current, according to the method used.

We made an exposure to the TPRI compensation system, applying the own theory of this compensation mode, to determine the reference values of the PAF current.

As a result of the simulations, the PAF has emerged that, in the case of the TGPI method, unlike the TPRI method, it is not necessary to change the reference coordinate system, the magnitudes used to determine the offset currents are those in the three-phase system.

It can be seen that TGPI can be applied to three-phase and single-phase systems, as opposed to TPRI that can only be applied to the three-phase system.

An interesting feature of the SRS method, which distinguishes it from TPRI and TGPI, is that it does not require the determination of instantaneous powers.

From the simulations, it can be seen that the method called SRS_P is equally effective, but has the advantage of requiring fewer calculations to implement the adjustment algorithm.

As a result of these simulations, the advantages and disadvantages of each method were revealed, and the comparison of these methods shows that the synchronous reference system is the most efficient.

In the future we will develop practical realization of an active filter based on the synchronous reference method, which is the most efficient resulting from the research done in this paper.

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[12] * * * Software MATLAB.