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MODELLATION AND SIMULATION OF SHUNT ACTIVE POWER FILTERS TYPE FOR VARIABLE NONLINEAR LOAD

[1] **Nicolae Badea,** [2]**Ion Voncila,**
[3]**Laurențiu Codreanu**

[1,2]*Dunarea de Jos University, Domneasca Street no. 47, 800008 Galati,*
Romania (e-mail: nicolae.badea@ ugal.ro;ion.voncila@ugal.ro).
[3]*SC ICPE-ACTEL SA, București, Romania*
(e-mail: laurentiu.codreanu@icpe-actel.ro)

Abstract: The paper is dealing with modelling and simulation of running principle of shunt type active power filter. It is possible to highlight the running of the active filter as a result of correlation of power supply voltage, the power outage on filter coil and converter input voltage. The mathematical equations for filter running were implemented into the PSIM software, both with instantaneous variables without DC voltage control and Vdc voltage control in the (dq) coordinate system. The numerical simulations performed without DC voltage control have shown a Vdc voltage overgrown. Vdc voltage control is taking off this inconvenience and allows harmonics balance putting in a filter current in phase opposition with the harmonic current of nonlinear load. By numerical simulation of varable voltage power supply of the nonlinear customer it was highlighted existence of an optimal area of THD_i thanks to correlation between grid voltage, coil and converter input voltage. Choosing and dimensioning of three phase coil of power circuit of SAPF has a decisive influence on the voltage range of adjustment of nonlinear customer and implicit on THD_i grid current.

Keywords: active power filters, modelling, simulation, $THD_{i,}$ power factor.

1. INTRODUCTION

In the last few years, the quality of industrial and household electric energy became a serious problem as it concerns work-intensive use of electronic power equipments. Nonlinear loads cause disturbances such as harmonic pollution and reactive power problems in the distribution energy networks [1]. Nonlinear load limits of emission are settled in Romania based on electromagnetic compatibility criteria [2] so as to provide a ratio under 0.2 % between nonlinear load power and maximum short-circuit power in the point of common connection (PCC). Usually, these problems are solved by using LC passive filters. Although simple and inexpensive, these filters lead to harmony, resonance and big size problems and are limited to few harmonics, usually of low level [3, 4]. Moreover, compensation features of these filters are influenced by source impedance and consequently filter design depends on the power supply. The solution to the problem of energy quality, decreased by nonlinear load containing power electronic components was given by the remarcabile progresses of power electronics by the development of active power filters (APF) to reduce harmonic distortion. APF basic principle is to use power electronics technologies to give current specific components which deletes the components of harmonic currents caused by the nonlinear load. Figure 1 shows the typical APF system components and its connections. The data refering to harmonic currents and other system variables are sent to referential signal estimating device for current and voltage compensation.

The compensation reference signal of the estimation device controls the general controler of the system. The estimation device provides the control of converter signal generator. The output of the control signal generator is controlling the power supply through a suitable interface.

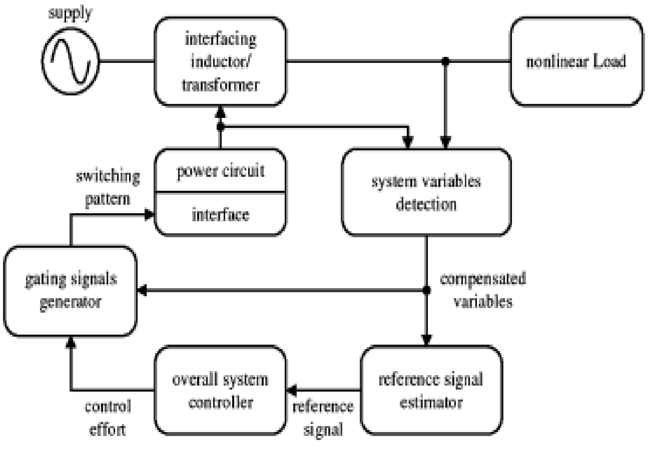


Fig. 1 General block diagram of. APF [5].

Ultimately, the power circuit in the general block diagram can be connected in parallel, serial or parallel/serial configurations considering the inductor/ interface transformer used. APFs have a number of advantages over the passive filters as they can suppress not only the supply current harmonics, but also the reactive currents and unlike passive filters, they do not cause harmful resonances with the power distribution systems. Consequently, the APFs performances are independent on the power distribution system properties.

2. SHUNT ACTIVE POWER FILTER (SAPF)

The simplified scheme of a parallel (shunt) active power filter which compensates harmonic currents given by the nonlinear load is shown in figure 2. The structure of the shunt active filter is formed by the *power circuit* and the *control circuit*. Considering figure 2, and SAPF not yet connected, the current flow in the system of harmonic pollutive energy may be expressed as follows:

$$i_s = i_L = i_{fund} + i_h \qquad (1)$$

Where: i_{fund} is the current of fundamental and i_h is the harmonic current generated by the nonlinear load.

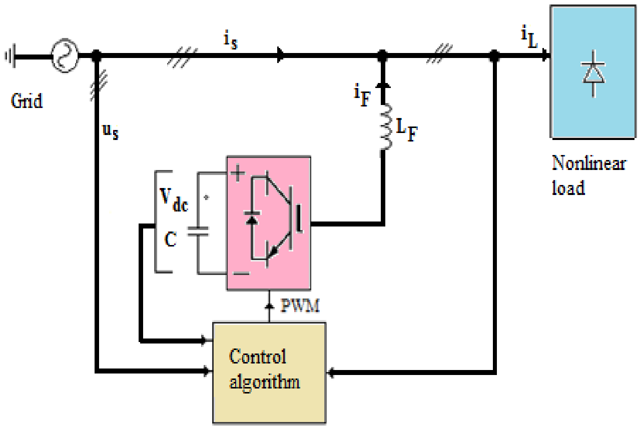


Fig. 2. Network with shunt active filter

Once the SAPF is connected to the point of common connection (PCC) (as shown in figure 2), there is a flow of additional current i_F in the system of harmonic pollutive energy. This is achieved by reducing the current pumped in by SAPF into the power supply to delete the harmonic current i_h. Consequently, by using a SAPF, the equation (1) may be re-writtten accoding to Theorem I of Kirchhoff as follows:

$$i_s = [i_{fund} + i_h] - i_F = i_{fund} + [i_h - i_F] \qquad (2)$$

The function of the parallel active filter (SAPF) is to recover efficiently the sinusoidal form of power supply current i_s, pumping in the current i_F into the system of harmonic pollutive energy with the same amplitudes as the harmonic currents generated by a given nonlinear load, but with phases opposed to delete i_h contained in the load current i_L. This purpose can be reached by making i_F equal to i_h. This way, i_S is going to recover the sinusoidal form and work in phase with the power supply voltage.

3. THE MATHEMATIC MODEL OF SAPF POWER CIRCUIT

SAPF power circuit consists of a three phased voltage converter with the equivalent scheme shown in figure 3.

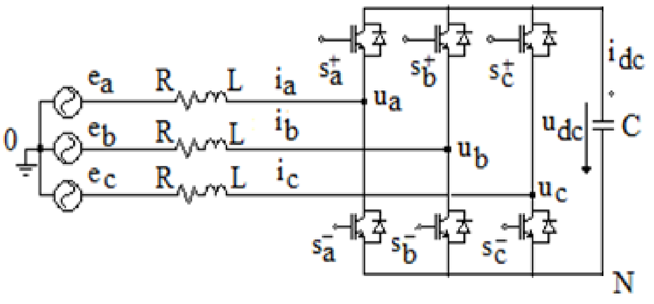


Fig. 3. Equivalent scheme of power circuit of SAPF

The operating principle of the triphased converter with PWM control is based on the effect of putting a triphased coil between the power supply and the voltage convertor (figure 4). The coil voltage is dephased relative to its current with an angle of 90 degrees before it.

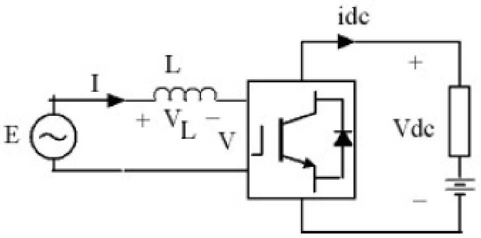


Fig. 4. Equivalent scheme of triphased converter with unit power factor [6].

Considering the voltages in figure 4, the following equation can be written:

$$\underline{E} = \underline{V}_L + \underline{V} \qquad (3)$$

The adjustment of converter input voltage causes the geometric place described by the three voltages to be a circle, according to figure 5.

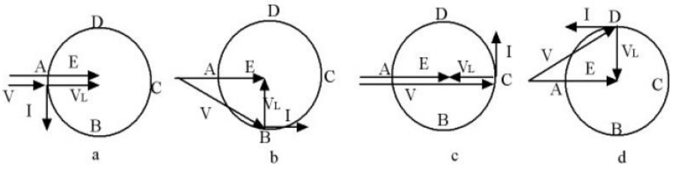


Fig. 5. The geometric place of voltages

If the V converter voltage is changing from the point A to point B, the converter operates as a rectifier. The change of phase shift between the V converter voltage and E power supply causes a change of phase position voltage on the coil. If the converter voltage is in point B (Fig. 5a: rectifier) or in point D (Fig. 5b: inverter), the current is in phase with power supply voltage and the biggest power factor can be obtained.. The unit power factor can be obtained through the control of converter voltage if the PWM rectifier has bidirectional current (reversible). To control the current, Vdc nominal voltage of DC bus has to be more or equal than the power supply peak voltage, which means that the filter can balance only when $V_{dc} > \sqrt{2}E.$ The mathematical equation for the three phases obtained by Kirchhoff law voltage are [6]:

$$\begin{aligned} e_a &= R \cdot i_a + L\frac{di_a}{dt} + u_{aN} + u_{N0} \\ e_b &= R \cdot i_b + L\frac{di_b}{dt} + u_{bN} + u_{N0} \\ e_c &= R \cdot i_c + L\frac{di_c}{dt} + u_{cN} + u_{N0} \end{aligned} \tag{4}$$

And by applying the Kirchhoff law current:

$$i_{dc} - i_a \cdot s_a - i_b \cdot s_b - i_c \cdot s_c = 0 \tag{5}$$

$$i_{dc} = C\frac{du_{dc}}{dt}$$

By noting:

$$u_k = u_{dc} \cdot s_k$$

$$\text{with} \quad : \quad s_k = \begin{cases} 1 & if \quad s_k^+ \, closed \quad and \quad s_k^- \quad open \\ 0 & if \quad s_k^- \, closed \quad and \quad s_k^+ \quad open \end{cases}$$

$$k = a, b, c \qquad and \qquad R \cdot i_k + L\frac{di_k}{dt} = z \cdot i_k$$

Considering figure 3, the coil currents are:

$$i_k = \frac{e_k - u_k}{z}$$

By applying the theorem of Millman in figure 3 the expression of the displacement voltage is obtained:

$$u_{N0} = \frac{\dfrac{e_a - u_{dc}s_a}{z} + \dfrac{e_b - u_{dc}s_b}{z} + \dfrac{e_c - u_{dc}s_c}{z}}{\dfrac{1}{z} + \dfrac{1}{z} + \dfrac{1}{z}} \tag{6}$$

In this relationship, it was considered that the electromotive voltages forms a three phased symetric system $(e_a + e_b + e_c = 0)$ and considering the balanced operating mode with $s_a + s_b + s_c = 0$,the final expression of the displacement voltage is:

$$u_{N0} = -\frac{u_{dc}}{3}(s_a + s_b + s_c) \tag{7}$$

And the system of equations (4) can be written as:

$$\begin{aligned} R \cdot i_a + L\frac{di_a}{dt} &= e_a - u_{dc}s_a \\ R \cdot i_b + L\frac{di_b}{dt} &= e_b - u_{dc}s_b \\ R \cdot i_c + L\frac{di_c}{dt} &= e_c - u_{dc}s_c \\ C\frac{du_{dc}}{dt} &= i_a \cdot s_a + i_b \cdot s_b + i_c \cdot s_c \end{aligned} \tag{8}$$

The pass of the system of equations (8) from the coordinates (abc) in d-q, with notations:

$$\begin{aligned} &\frac{2}{3}(i_a + \underline{a}i_b + \underline{a}^2 i_c) = \underline{i} = i_d + ji_q \\ &\frac{2}{3}(s_a + \underline{a}s_b + \underline{a}^2 s_c) = \underline{s} = s_d + js_q \end{aligned} \tag{9}$$

is leading to the following system of equations:

$$\begin{cases} R \cdot i_d + L\dfrac{di_d}{dt} = e_d - u_{dc}s_d \\ R \cdot i_q + L\dfrac{di_q}{dt} = e_q - u_{dc}s_q \end{cases} \tag{10}$$

$$C\frac{du_{dc}}{dt} = i_a \cdot s_a + i_b \cdot s_b + i_c \cdot s_c = \frac{3}{2}(i_d s_d + i_q s_q)$$

By power supplying from a system of three phased symmetrical voltages by direct succession with e_q=0, on condition that i_q=0, the DC current is given by the relation i_{dc}=i_d . This way, it is obtained the following system of equations wich will be implemented in the control scheme:

$$\begin{aligned} R \cdot i_d + L\frac{di_d}{dt} &= e_d - u_{dc}s_d \\ R \cdot i_q + L\frac{di_q}{dt} &= 0 \\ C\frac{du_{dc}}{dt} &== \frac{3}{2}i_d s_d \end{aligned} \tag{11}$$

4. ALGORITHM FOR BALANCING THE HARMONIC CURRENT

4.1 Algorithm for balancing the harmonic current without DC voltage control of SAPF

The algorithm for SAPF balancing, described by the system of equations (6), is based on the definition suggested by S. Fryze [7] which enables extraction of fundamental component of load current, known as Fryze power theory, meaning that the current is divided in two components, according to the relation:

$$i_s = i_a + i_r \tag{12}$$

The first component, i_a, is a current with the same waveform and phase angle as the voltage. The second component is just a residual term i_r. The reason of this division is the association of current i_a of a purely resistive load, which for the same voltage would develop the same power as the nonlinear load. When the active filter is connected in the point of common connection (PCC) (as shown in fig. 6), there is an additional current flow i_F suplimentar, pumped in by the filter into the power supply system so as to delete i_h.

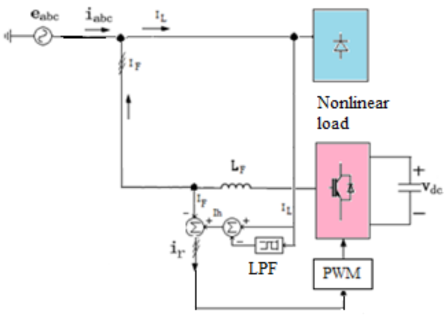


Fig. 6. SAPF without DC voltage control

Consequently, the equation of currents dependence may be described according to Kirchhoff law current as:

$$i_s = i_L - i_F = i_{fund} + [i_h - i_F] = i_a + i_r \qquad (13)$$

As a result of the equation above, the residual current i_r is a very good input for an active compensator and might be used for this purpose in the equations of operation. The function of shunt active power filter (SAPF) is to efficiently recover the sinusoidal form of power supply current i_S by pumping in i_F current into the harmonic polluted system and deleting i_h component from the load current i_L. This way, i_S would finally regain the sinusoidal component.

4.2 Algorithm for balancing the harmonic current with DC voltage control of SAPF

SAPF control is possible by the coordinate system conversion from the three phased stationary coordinate system (a, b, c), to synchronous rotative system (d, q) with synchronous rotation with the grid fundamental, and it is described by the equations (11) and (13). For this reason, the grid voltage has to be converted to synchronize the conversion (dq) of the residual current (figure 7).

Usually, the general voltage of DC connection is settled through handeling of direct voltage error in which the difference (the voltage error) between DC voltage signal V_{dc} and the reference voltage desired $V_{dc,\ ref}$ – is directly applied to a PI controller to produce the estimated value i_{dref} at the output, which is supposed to be the main control signal to adjust DC voltage.

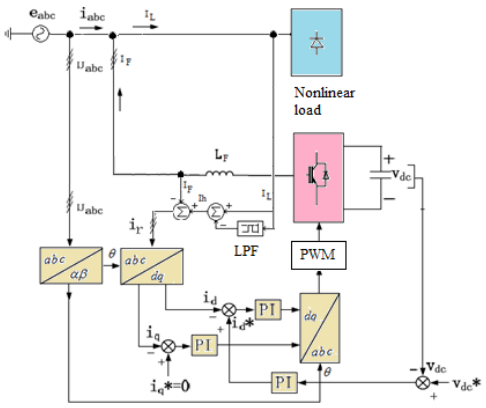


Fig. 7. Control scheme of SAPF [5].

5. NUMERICAL SIMULATION OF SAPF BALANCE PRINCIPLE

5.1 Testing of balance principle without Vdc voltage control

The simulation of active filter operation was made for a nonlinear load of 50 Ω. The power supply of bridge rectifier is the triphased grid 380 V, 50 Hz which is connected to the PCC. The scheme of numerical simulation is shown in fig. 8 in which the balance algorithm from figure 6 is done by replacing in the system of equations (4) the current given by the relation (13).

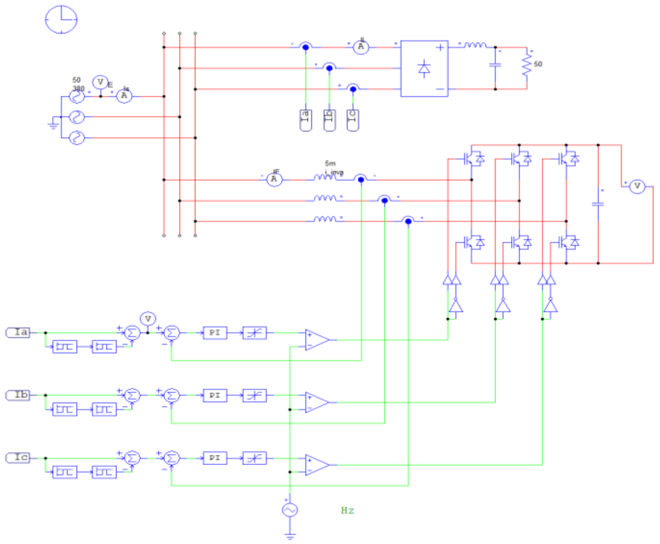
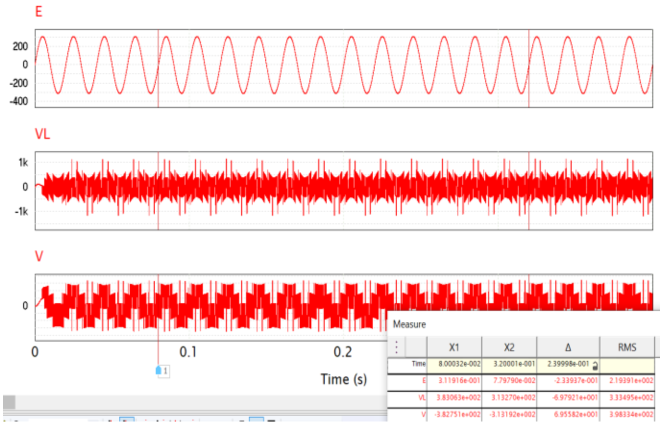


Fig. 8. Simulation scheme of SAPF without DC voltage control

As a result of the numerical simulation there were highlighted the forms of variation of the three voltages (figure 9) given by the equation (3). The actual values were E=220V, V_L=333V, V=398V, indicating the correlation V>E. The variations of the load current i_L, of its harmonic component i_h, of the current pumped in by filter i_F, in opposition with i_h, respectively, of grid current i_s are shown in figure 10a.

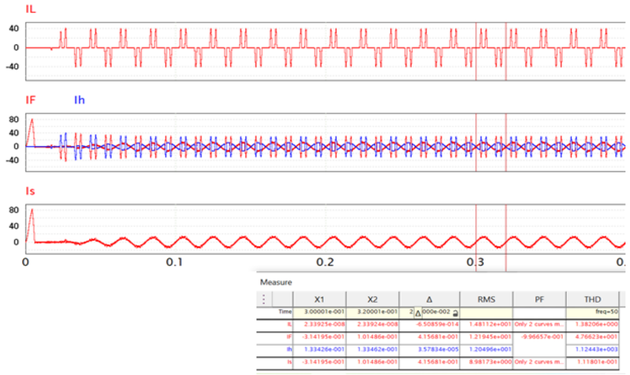


Measure

	X1	X2	Δ	RMS
Time	8.00032e-002	3.20001e-001	2.39998e-001	
E	3.11916e-001	7.79790e-002	-2.33937e-001	2.19391e+002
VL	3.83063e+002	3.13270e+002	-6.97921e+001	3.33495e+002
V	-3.82751e+002	-3.13192e+002	6.95582e+001	3.98334e+002

Fig. 9. Voltage correlation of SAPF running

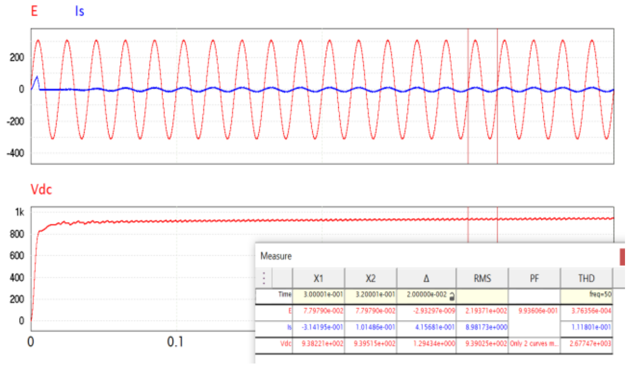
The figure 10b shows the grid voltage and current, in phase, and capacitor DC voltage.



Measure

	X1	X2	Δ	RMS	PF	THD
Time	3.00001e-001	3.20001e-001	2.000e-002			freq=50
IL	2.33925e-008	2.33924e-008	-6.50859e-014	1.48112e+001	Only 2 curves m...	1.38206e+000
IF	-3.14195e-001	1.01486e-001	4.15681e-001	1.21945e+001	-9.96657e-001	4.76623e+001
Ih	1.33426e-001	1.33462e-001	3.57834e-005	1.20496e+001		1.12443e+003
Is	-3.14195e-001	1.01486e-001	4.15681e-001	8.98173e+000	Only 2 curves m...	1.11801e-001

a. Nonlinear harmonic current of filter and grid



Measure

	X1	X2	Δ	RMS	PF	THD
Time	3.00001e-001	3.20001e-001	2.00000e-002			freq=50
E	7.79790e-002	7.79790e-002	-2.93297e-009	2.19371e+002	9.93606e-001	3.76356e-004
Is	-3.14195e-001	1.01486e-001	4.15681e-001	8.98173e+000		1.11801e-001
Vdc	9.38221e+002	9.39515e+002	1.29434e+000	9.39025e+002	Only 2 curves m...	2.67747e+003

b. Voltage vs. grid current and voltage in DC bus

Fig. 10. SAPF circuit signals

5.2Testing of SAPF running with control algorithm of V_{dc} voltage

The simulation of active filer operation was made for a nonlinear load of 50 Ω. The power supply of the bridge controlled by the three phased grid of 380 V, 50 Hz which is connected to the PCC, and the DC voltage was given, V_{dc} =690 V.

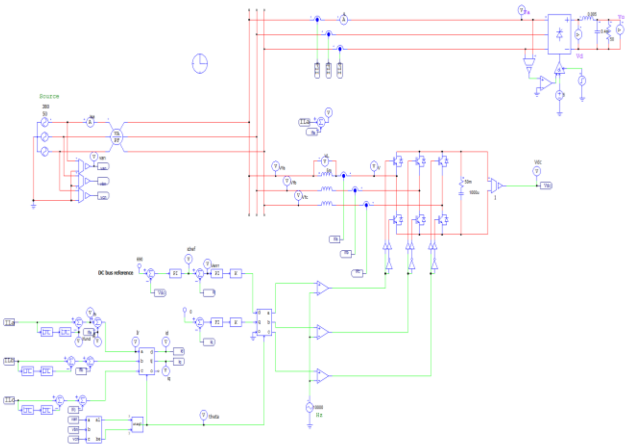
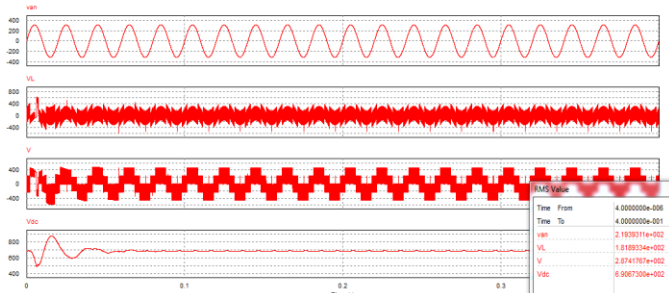


Fig.11. Simulation scheme of SAPF for adjustable angle control of Thyristor Bridge

5.2.1 The results of the numerical simulation of testing SAPF operation

The numerical simulation was performed for various control angles of the bridge looking at the balance mode of the active filter. The first numerical result, shown in figure 12, for a control angle of five degrees of the nonlinear consumer showed the correlation between the three phase voltages, of the power supply, coil and converter input with the actual values: E=220V, V_L=181V, V=287V și V_{dc}=690V.

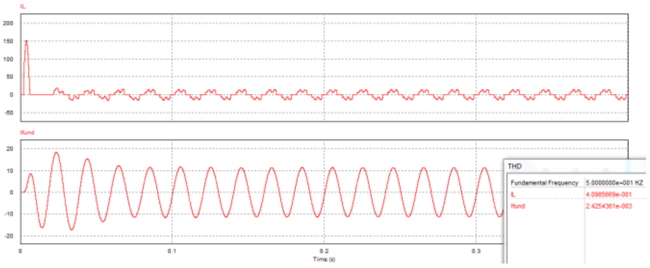


RMS Value

Time From	4.0000000e-006
Time To	4.0000000e-001
van	2.1939311e+002
VL	1.8189334e+002
V	2.8741767e+002
Vdc	6.9067300e+002

Fig. 12Voltage correlation of SAPF.

The nonlinear load current (figure 13) is 14,1A, THDi=40% and a fundamental of I_{fund}=8,54A.



THD

Fundamental Frequency	5.0000000e+001 HZ
IL	4.0985689e-001
Ifund	2.4254361e-003

Fig. 13. Nonlinear load current

The Fourier transform of load current indicates the presence of harmonics of degrees 5,7,11,13,17 with values over 1A (I_5=2,8A, I_7=1,7A și I_{11}=0,96A), shown in figure 14.

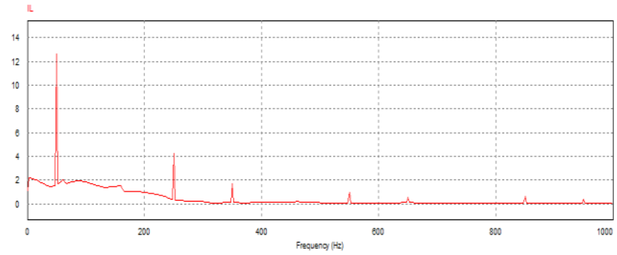
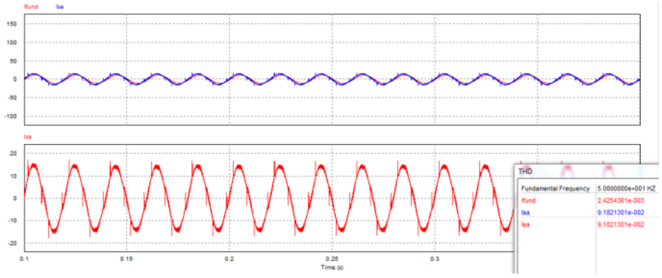


Fig. 14. Load current harmonics

The variation of grid current is close to the nonlinear load current fundamental, according to figure 15, with THDi=9%.

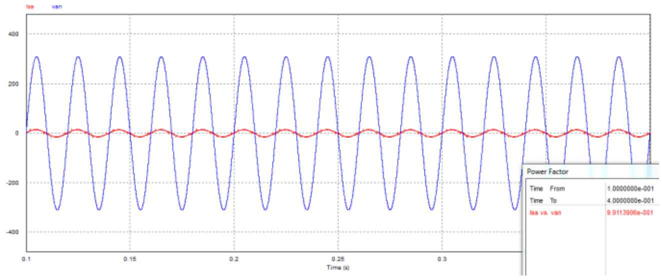


THD

Fundamental Frequency	5.0000000e+001 HZ
Ifund	2.4254361e-003
Isa	9.1821301e-002
Isa	9.1821301e-002

Fig. 15. Grid current vs. fundamental current

The power factor in steady state is shown in figure 16 and it is 99%.



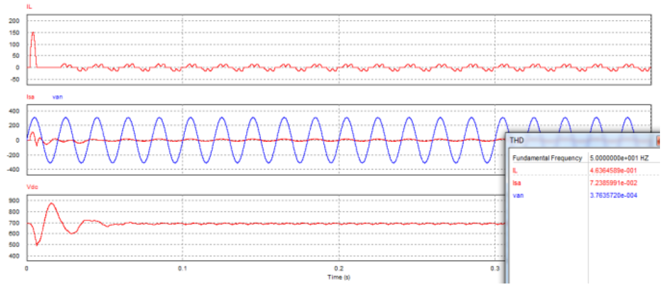
Power Factor

Time From	1.0000000e-001
Time To	4.0000000e-001
Isa vs. van	9.9113906e-001

Fig.16. Power factor (PF) of grid

5.2.2 The results of numerical simulation with the variation of control angle

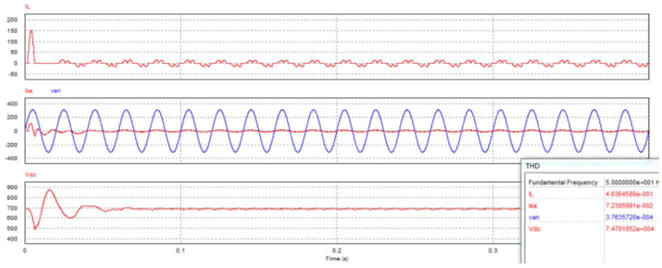
The numerical simulations with the variation of control angle shown in figure 17, reveal the variation of nonlinear load current, condenser load voltage V_{dc} and grid current and voltage variation, considering the THDi for each case.



THD

Fundamental Frequency	5.0000000e+001 HZ
IL	4.6364589e-001
Isa	7.2385991e-002
van	3.7635720e-004

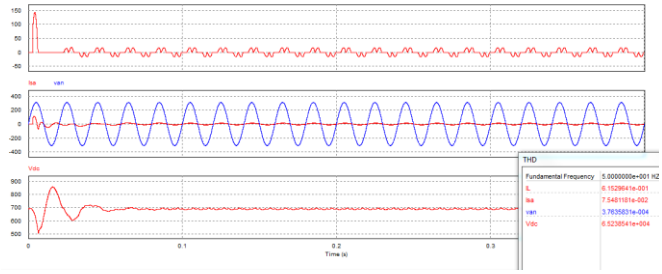
10 degrees



THD

Fundamental Frequency	5.0000000e+001 H
IL	4.6364589e-001
Isa	7.2385991e-002
van	3.7635720e-004
Vdc	7.4781852e+004

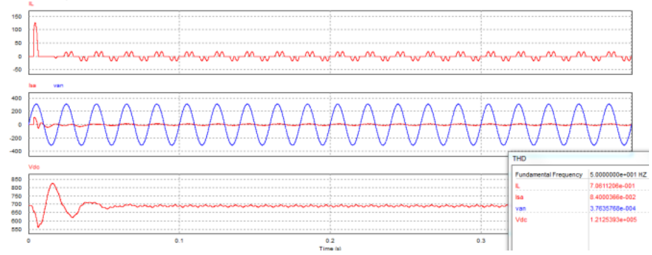
15 degrees



THD

Fundamental Frequency	5.0000000e+001 HZ
IL	6.1529641e-001
Isa	7.5481181e-002
van	3.7635831e-004
Vdc	6.5238541e+004

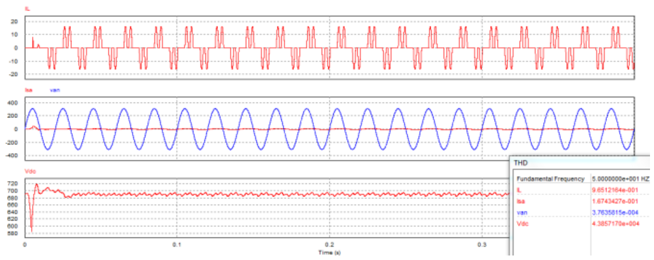
20 degrees



THD

Fundamental Frequency	5.0000000e+001 HZ
IL	7.0611206e-001
Isa	8.4000366e-002
van	3.7635766e-004
Vdc	1.2125393e+005

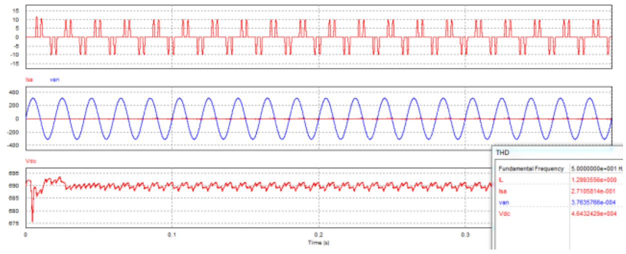
30 degrees



THD

Fundamental Frequency	5.0000000e+001 HZ
IL	9.6512164e-001
Isa	1.6743427e-001
van	3.7635815e-004
Vdc	4.3857170e+004

60 degrees



THD

Fundamental Frequency	5.0000000e+001 H
IL	1.2993556e+000
Isa	2.7105814e-001
van	3.7635766e-004
Vdc	4.6432429e+004

90 degrees

Fig. 17. Current and THD_i variation as a function of control angle

For the control angle of 90 degrees, the active filter current is not following identically the harmonic currents, as shown in figure 18.

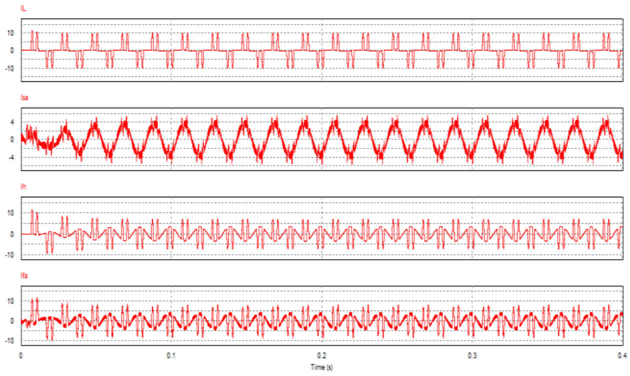


Fig. 18. Currents evolution for load control at 90 degrees angle

6. COMMENTS AND CONCLUSIONS

The figure 19 shows from 10 to 90 degrees the THD_I for the load and grid current and the power factor. The evolution of THDi corresponding to grid current and power factor shown in figure 19 reveals an optimal level of SAPF for control angles between 0 and 40 degrees, corresponding to nonlinear load voltage adjustment between 510V and 430V, that is to a power between 5.5kVA and 4.25kVA.

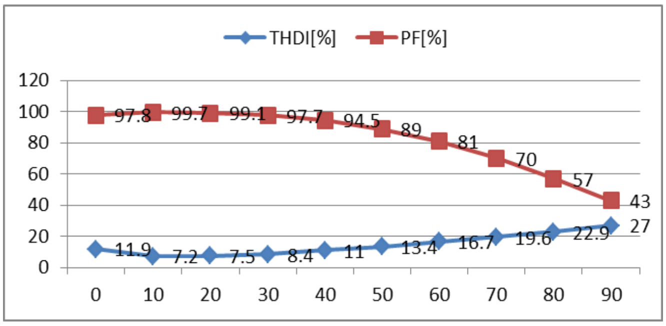


Fig. 19. Evolution of THDi and PF.

The reduction induced by the SAPF on the load current THDi is shown in figure 20.

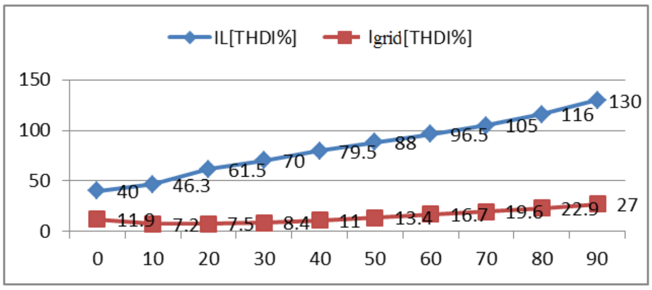


Fig. 20. THDi of currents

The following conclusions might be drawn, based on the above:

- SAPF mathematic modelling allowed to point out the operating principle of the active filter if the voltage V from equation (3) is higher than the power supply voltage;
- The balance of nonlinear load harmonic currents without condenser control load voltage (V_{dc}) results in high and variable DC voltages;
- The balance of harmonic currents of nonlinear load with condenser control load voltage (V_{dc}) allows to maintain constant this voltage for any control angle;
- Choosing and dimensioning of triphased coil of SAPF power circuit has a decisive influence on the adjustment range of nonlinear consumer voltage, and consequently on grid THDi of grid current;
- In case of adjustable drive there is an optimal area of THDi due to correlation between grid voltage, coil voltage and converter input voltage.

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