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doi:10.15199/48.2023.06.13

Compensation of harmonics using a shunt active power filter powered by a photovoltaic source

***Abstract**. Electronic devices feature non-linear switching functionality, current distortion gives rise to harmonics that shorten the life of devices and damage electrical networks, causing malfunctions and overheating. Mitigation of harmonics problems and improvement of power quality are necessary. The shunt active power filter reduces harmonics and greatly improves the sinusoidal shape of the current. This work presents a study with two different voltage sources of a two-level inverter applied to a shunt active power filter based on three phases connected to the grid, the first is a continuous direct source and the second is a photovoltaic source. Simulation results provided good efficiency of the SAPF with the photovoltaic system integration.*

***Streszczenie.** Urządzenia elektroniczne posiadają funkcję przełączania nieliniowego, zniekształcenia prądu powodują powstawanie harmonicznych, które skracają żywotność urządzeń i niszczą sieci elektryczne, powodując awarie i przegrzewanie. Niezbędne jest łagodzenie problemów z harmonicznymi i poprawa jakości energii. Bocznikowy aktywny filtr mocy redukuje harmoniczne i znacznie poprawia sinusoidalny kształt prądu. W pracy przedstawiono badanie z dwoma różnymi źródłami napięcia dwupoziomowego falownika zastosowanego do bocznikowego filtra mocy czynnego opartego na trzech fazach podłączonych do sieci, przy czym pierwsza jest ciągłym źródłem bezpośrednim, a druga jest źródłem fotowoltaicznym. Wyniki symulacji zapewniły dobrą wydajność SAPF z integracją systemu fotowoltaicznego. (**Kompensacja harmonicznych za pomocą bocznikowego filtra mocy czynnej zasilanego ze źródła fotowoltaicznego**)*

Keywords: Instantaneous Power Method, Maximum Power Point Tracking, Photovoltaic, Shunt Active Power Filter
Słowa kluczowe: Metoda chwilowej mocy, śledzenie maksymalnego punktu mocy, fotowoltaika, aktywny filtr mocy bocznikowej

Introduction

Solar energy is used to generate electricity using sunlight captured from photovoltaic panels (PV). Our article applies this source seen that it is clean and free to supply the inverter of SAPF as shown in the diagram in Figure 1.

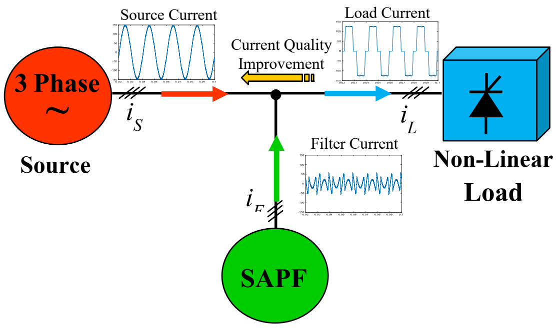

Fig.1. Shunt Active Power Filter

The SAPF ensures the attenuation of the harmonics of the source current from to non-linear loads in electrical networks [1, 2]. For this, the voltage of the PV system is obtained by means of a PI regulator. Thus, the control by the MPPT method guaranteed by the use of the P O algorithm and the DC-DC boost converter a maintain of the voltage output of the PV module constant according to the reference value. The three-phase two-level inverter is controlled by PWM technique and the control algorithm for the detection of harmonics is based on the p q method. The results of the simulation on MATLAB/Simulink environment are compared to a DC voltage source clearly showing the efficiency and reliability of the introduction of the PV system into a SAPF and the source current THD aft compensation is less than 5 percent as stated by IEEE recommendation 519-92 [3].

The SAPF is supplied by a PV system and controlled by the p-q method, as shown in Figure 2.

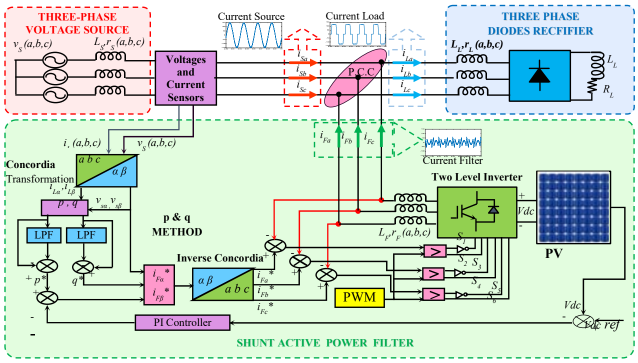

Fig.2. Functional diagram of the SAPF Powered by a photovoltaic system and controlled by the p-q method

Photovoltaic system

Figure 3 shows the photovoltaic system which delivers a voltage V_{dc} =780V which supplies the inverter, the main source for the shunt active power filter.

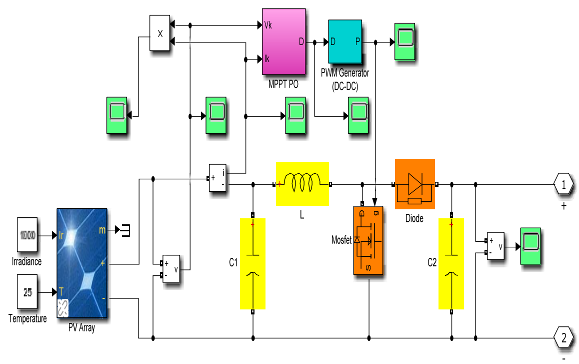

Fig.3. Simulink diagram of PV system (Panels, MPPT and Boost DC-DC converter)

The photovoltaic array generator

The photovoltaic system is made up of a set of connected cells forming a PV module. In our case the PV modules are of the SunPower SPR-305E-WHT-D type, their Electrical Data characteristics are given in the Table. 1

For the modeling of solar PV module [4], the electrical diagram of the PV cell is shown in Figure 4.

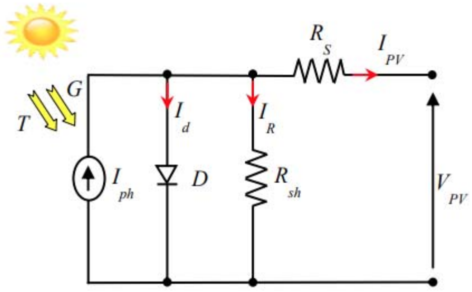

Fig.4. The equivalent model of PV cell

Table 1. Electrical Data parameters of the PV module. [5]

SunPower SPR-305E-WHT-D	
Maximum Power Point (*Pmax*)	305 W
Voltage at Pmax (*Vmp*)	54.7 V
Current at Pmax (*Imp*)	5.58 A
Open-circuit voltage (*Voc*)	64.2 V
Short-circuit current (*Isc*)	5.96 A
Series resistance (*Rs*)	0.37152 Ω
Shunt resistance (*Rsh*)	269.5934 Ω
Temperature coefficient of *Isc*	0.061745 %/°C
Temperature coefficient of *Voc*	-0.27269 %/°C
NOCT	T45°C +/- 2° C
Number of cells connected in series (*Ncell*)	96

The mathematical expression of the PV module is on equation (1) [6, 7].

(1) $$I_{PV} = I_{ph} - I_D - I_R$$

(2) $$I_{PV} = I_{ph} - I_0\left[e^{q\left(\frac{V_{PV}+z.R_s.I_{PV}}{z.n.k.T_{ck}}\right)} - 1\right] - \frac{V_{PV}+z.R_s.I_{PV}}{z.R_{sh}}$$

Or, I_{PV} : Current (A), I_{ph} : Photo-current (A), I_0: Reverse saturation current (A), q: Electron charge (1.602×10^{-19} Coulomb), V : Voltage (V), Z : Number of cells in series, R_s : Series resistance (Ω), R_{sh} : Shunt resistance (Ω), n : Ideality factor varies between 1 and 2. k: Boltzmann's constant (1.381×10^{-23}J/K).

The DC-DC converter and the MPPT controller

The voltage delirious by the PV modules does not meet the need to supply the inverter of the SAPF (V_{PV} = 325V), while 780 V is needed, for this we use a DC-DC boost converter [8, 9] schematized on the Figure 5.

With switch S is open we obtain the following equations. The period T $\in$ [DT_s, T_s] :

(3) $$i_{c1}(t) = C_1\frac{dv_{pv}(t)}{dt} = i_{pv}(t) - i_L(t)$$

(4) $$ic_2(t) = C_2\frac{dv_{dc}(t)}{dt} = i_L(t) - i_o(t)$$

(5) $$v_L(t) = L\frac{di_L(t)}{dt} = v_{pv}(t) - v_{dc}(t)$$

The switch S is a MOSFET transistor its gate is controlled by the P&O algorithm (perturbation & observation) to extract the Max of power from the photovoltaic panels to be extracted by applying the MPPT method (Maximum Power Point Tracking), as shown in the diagram of Figure 6.

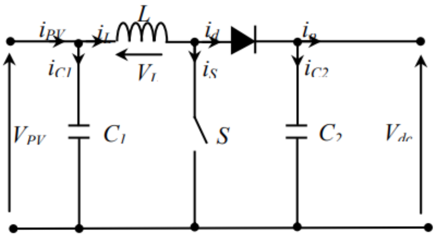

Fig.5. DC-DC converter circuit of the PV system

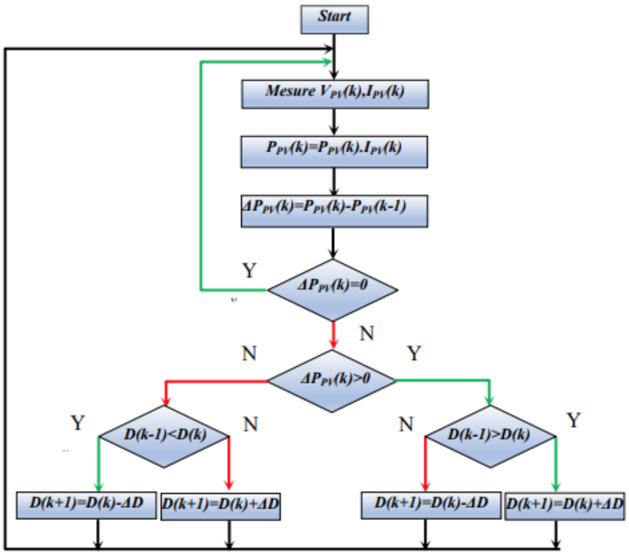

Fig.6. Perturbation and Observation algorithm

Instantaneous active and reactive powers method

The concept of which relies on a variable transformation in the plane α-β reference the instantaneous powers, currents and voltages of the *a-b-c* frame of reference [10, 11].

The transformed equations from three-phase plane to second with two-phase coordinates are given by the following equations :

(6) $$[v_S] = \begin{bmatrix} v_{Sa} \\ v_{Sb} \\ v_{Sc} \end{bmatrix} \text{ and } [i_L] = \begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix}$$

(7) $$\begin{bmatrix} v_{S\alpha} \\ v_{S\beta} \end{bmatrix} = \sqrt{\frac{2}{3}}\begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix}\begin{bmatrix} v_{Sa} \\ v_{Sb} \\ v_{Sc} \end{bmatrix}$$

(8) $$\begin{bmatrix} i_{L\alpha} \\ i_{L\beta} \end{bmatrix} = \sqrt{\frac{2}{3}}\begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix}\begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix}$$

This transformation says of Concordia and it is applicable for a well-balanced network that is perfectly sinusoidal. In this case the instantaneous active and reactive powers are given by:

(9) $$p = v_{S\alpha}.i_{L\alpha} + v_{S\beta}.i_{L\beta}$$

(10) $$q = v_{S\alpha}.i_{L\beta} - v_{S\beta}.i_{L\alpha}$$

From equations (9) and (10), the powers p and q are converted into DC and AC components as follows:

(11) $$p = \bar{p} + \tilde{p}$$

(12) $$q = \bar{q} + \tilde{q}$$

With, $\bar{p}$: DC power related to the active fundamental component of the current.; $\tilde{p}$: AC power linked to the sum of the active harmonic components of the current.; $\bar{q}$: DC power related to the reactive fundamental component of the current.; $\tilde{q}$: AC power linked to the sum of the reactive harmonic components of the current.

The currents relative to the instantaneous powers in the transformation α-β is raised by:

(13) $$\begin{bmatrix} i_{c\alpha} \\ i_{c\beta} \end{bmatrix} = \frac{1}{v_{S\alpha}^{2} + v_{S\beta}^{2}} \left\{ \begin{bmatrix} v_{S\alpha} & v_{s\beta} \\ v_{S\beta} & -v_{s\alpha} \end{bmatrix} \begin{bmatrix} p \\ 0 \end{bmatrix} + \begin{bmatrix} v_{S\alpha} & v_{S\beta} \\ v_{S\beta} & -v_{S\alpha} \end{bmatrix} \begin{bmatrix} 0 \\ q \end{bmatrix} \right\} = \begin{bmatrix} i_{L\alpha p} \\ i_{L\beta p} \end{bmatrix} + \begin{bmatrix} i_{L\alpha q} \\ i_{L\beta q} \end{bmatrix}$$

To calculate the reactive power as well as the harmonic currents, the reference currents are calculated by:

(14) $$\begin{bmatrix} i_{F\alpha}{}^{*} \\ i_{F\beta}{}^{*} \end{bmatrix} = \frac{1}{v_{S\alpha}^{2} + v_{S\beta}^{2}} \begin{bmatrix} v_{S\alpha} & v_{S\beta} \\ v_{S\beta} & -v_{S\alpha} \end{bmatrix} \begin{bmatrix} \tilde{p} \\ \bar{q} + \tilde{q} \end{bmatrix}$$

Finally, obtain the compensation currents on the plan *a-b-c* without taking the zero-sequence component with the following equation:

(15) $$\begin{bmatrix} i_{Fa}{}^{*} \\ i_{Fb}{}^{*} \\ i_{Fc}{}^{*} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ \frac{-1}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{F\alpha}{}^{*} \\ i_{F\beta}{}^{*} \end{bmatrix}$$

To ensure the speed of the execution of the switching of the switches of the static voltage inverter, the control technique of Pulse Width Modulation (PWM) allows making the implementation of the algorithm with a good situation [12].

Table 2. Simulation settings

Settings		**Numerical values**
Power network	RMS voltage E_S	230 V
	Frequency f	50 Hz
	Resistor Line R_S	0.1 Ω
	Inductor Line L_S	0.03 mH
Nonlinear load (Rectifier) Linear load	Load inductor N_L	0.3 mH
	Load resistor R_L	4 Ω
	Load inductor L_L	25 mH
	Load capacitor C_L	470 µF
Active Parallel Filter	Filter inductor L_F	1.3 mH
	Direct voltage V_{dc}	780 V

Simulation results and discussions

The SAPF the model is developed under MATLAB/Simulink by introducing the parameters displayed on the table 2, the shape of the source curve before the application of the filter are shown in Figures 7 and 8. Harmonic distortion is not the only problem (THD=24.03%) encountered here because the Figure 9 indicate an important value of the power factor (0.0017s, therefore φ=30.6°, that is to say a cosφ=0.86) therefore, a variation in the reactive energy of the system can be expected.

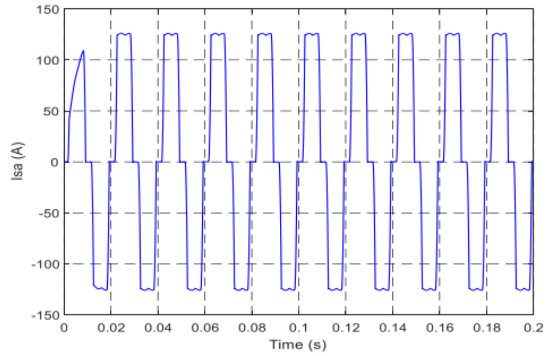

Fig.7. Waveform of current i_{Sa} before filtering

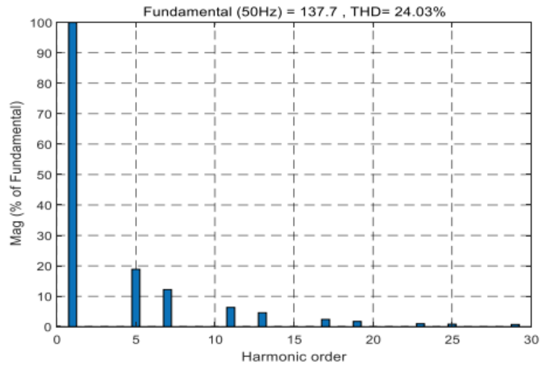

Fig.8. Spectrum of i_{Sa} before filtering

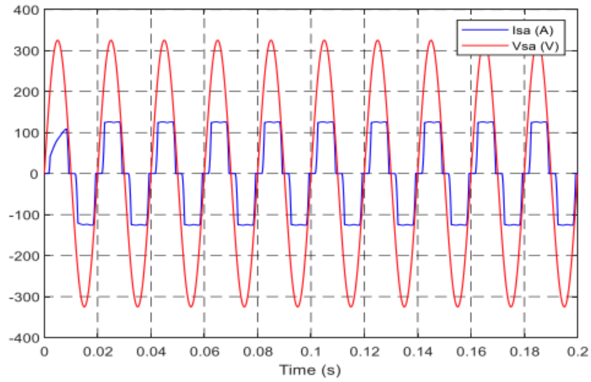

Fig.9. Phase shift of the i_{Sa} with respect to voltage v_{Sa} before filtering

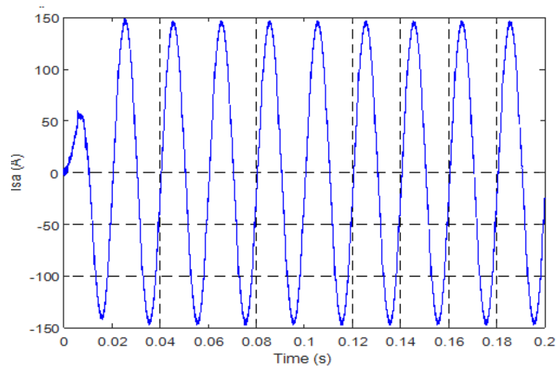

Fig.10. Waveform of current i_{Sa} after filtering with DC source

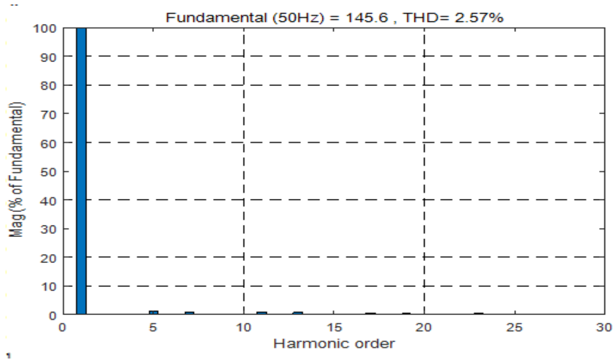

Fig.11. Spectrum of i_{Sa} after filtering with DC source

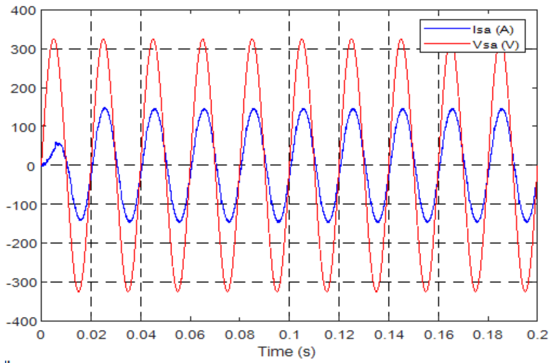

Fig.12. Phase shift of the i_{Sa} with respect to voltage v_{Sa}

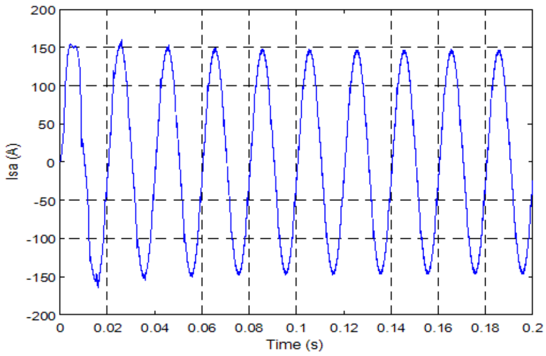

Fig.13. Waveform of current i_{Sa} after filtering with PV source

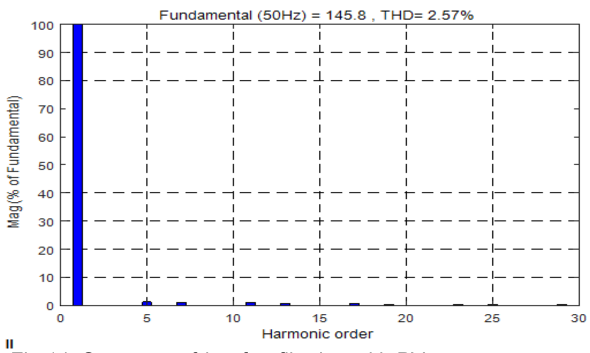

Fig.14. Spectrum of i_{Sa} after filtering with PV source

The introduction of the SAPF using a DC voltage source, allows us illustrated the signals of Figures 10, 11 and 12. We can clearly see that the source current i_{Sa} becomes sinusoidal again and the distortion is reduced: THD=2.57% as well as the improvement of the power factor (0.0006 s, therefore φ = 10.8 °), that is to say a cos φ = 0.98.

When replacing the DC voltage source by a photovoltaic voltage source as indicated in the Figures 13, 14 and 15, the same THD results were obtained.

Figures 16, 17 and 18 present our photovoltaic system whose voltage supplied by the panels is 320 V, the duty cycle generated by the MPPT command is fixed to 0.5 (in our case we do not vary the temperature and the irradiance they are set at 25°C and 1000 W/m^2 respectively) and the voltage delivered by the step-up converter it reaches the value of 780 V at 0.115 s of simulation.

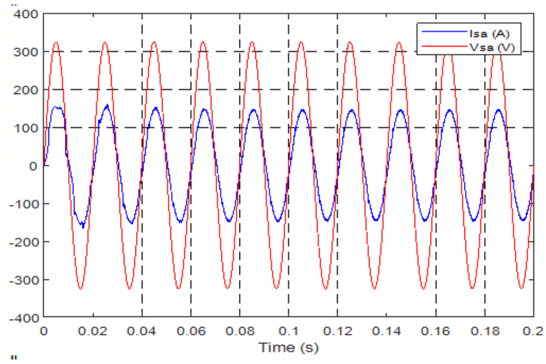

Fig.15. Phase shift of the i_{Sa} with respect to voltage v_{Sa}

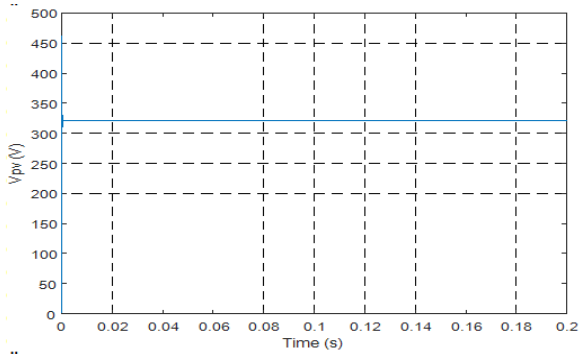

Fig.16. The voltage V_{pv} delivered by PV array

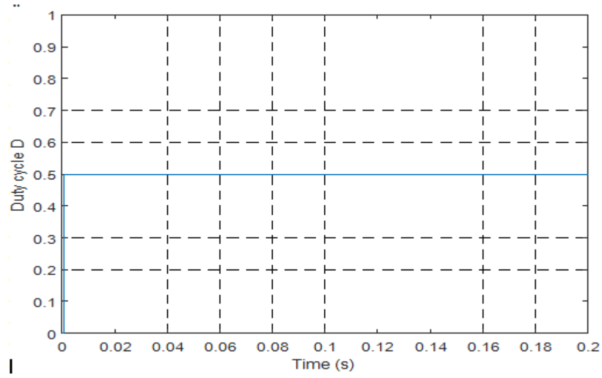

Fig.17. Duty cycle D in function of time

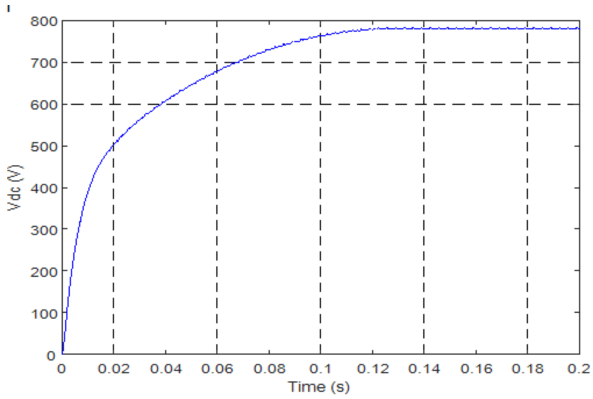

Fig.18. The voltage V_{dc} delivered by the dc-dc boost converter

Figure 19 illustrates the current generated by the SAPF to compensate the load current and Figure 20 shows it with the source and load currents in the same figure. The three-phase shape of the current is represented by Figure 21.

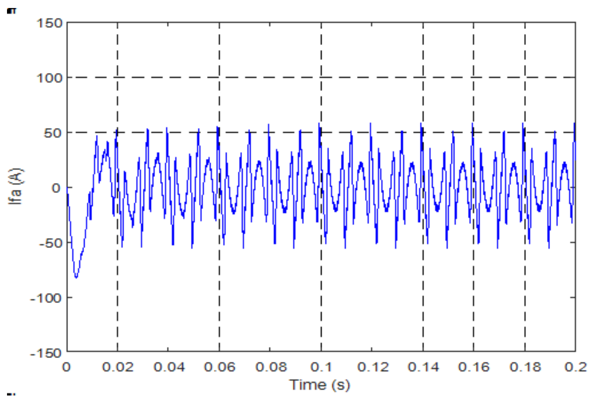

Fig.19. Filter current i_{Fa}

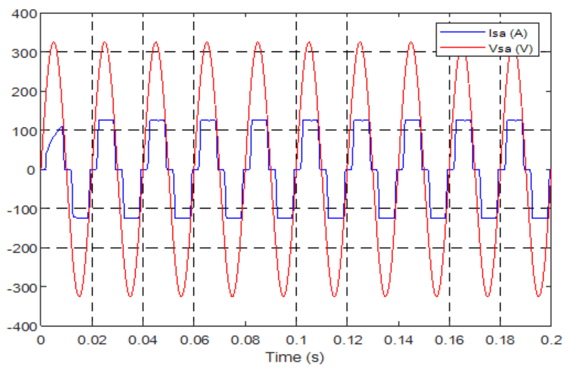

Fig.20. Three phases source current after filtering

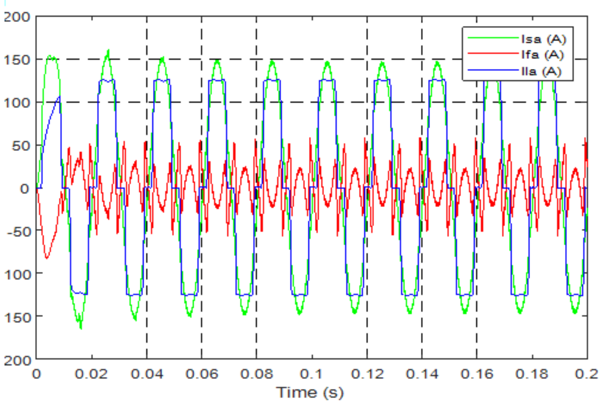

Fig.21. Load i_{La}, source i_{Sa} and filter currents i_{Fa}

Conclusion

The results obtained in this work allow us to visualize the efficiency of the SAPF using p and q identification method, the global harmonic distortion (THD) decreased from 24.08% to 2.57% and the factor of power has therefore been improved and the source voltage and current have become almost in phase in the case of a DC inverter or photovoltaic voltage sources.

Which confirms that the introduction of the PV system in shunt active power filter give us better performance of reactive power compensation. Finally, the results obtained clearly showed us that the energy quality is compatible with those indicated by the international convention IEEE519-92.

Acknowledg

At the end of this article, I would like to thank all the Co-author members for their contributions in completing the important results obtained. Without forgetting all those who have helped us from near or far, especially the research laboratory in electrical engineering and automation (LREA) of the University of Medea.

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