# Solar Photovoltaic System Connected to the Electricity Grid and Associated with Shunt Active Power Filter

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***Abstract:*** *In this paper, a photovoltaic generator is connected to the electrical network by associating the functionalities of shunt active power filter in order to improve the quality of the energy. The proposed system consists of a field of solar panels, a three-phase voltage inverter connected to the grid and a non-linear load constituted by a diode rectifier bridge supplying a resistive load in series with an inductor. Direct current and power controls are proposed to compensate for harmonic currents and reactive power, as well as the injection of active solar power into the grid. The global method for finding the maximum power point tracking (MPPT) is applied.*
*The simulation of the system under the Matlab / Simulink environment prove the robustness of the direct commands, which simultaneously guarantee the compensation of the harmonic currents, the correction of the power factor and the injection of the solar power towards the electrical network. Several regimes are approached according to the levels of the solar PV power injected and consumed by the nonlinear load.*

***Keywords:*** *Solar Photovoltaic System, Direct Power Control, Shunt Active Filter, MPPT.*

## 1. Introduction

Solar energy captured with photovoltaic panels is a viable alternative to electricity generation as it is a renewable source, both clean, unlimited and with a very low level of risk. Its potential is very important on the scale of the need for human activity; it is also very widely distributed throughout the globe which gives it an interest shared by all. With the price of photovoltaic (PV) modules rising and the price of fossil fuels increasing, the exploitation of this resource with PV generation systems becomes viable and profitable [1-2]. The rapid growth in the use of non-linear loads in power systems tends to degrade the quality of electrical energy supplied to consumers.

Renewable energy has already attracted much interest of several researchers. Among them, Mohamed Amin M. et al. [3], to improve the quality of energy (PQ), introduced an application of the Active Power Filter (APF) in the photovoltaic (PV) renewable energy system, In order to prove its powerful in detecting the reduction of total harmonic distortion (THD) and the rapid regulation of voltage. They simulated their system with MATLAB / SIMULINK software package. As well, M Senthil Kumar and PS Manoharan [4] combined the cascaded multi-level inverter (CMI) with the quasi-Z-Cascade multilevel inverter (QZS-CMI) to minimize its complexity and switching which results in additional loss of voltage gain. Their approach is developed to improve the gain of voltage and the reduction of the total harmonic distortion (THD) according to IEEE Standard 519. Rekioua T. [5], presented a control of a photovoltaic system connected to the network, to overcome the undesirable disadvantages of controlling the hysteresis current, and to obtain a constant switching frequency, they applied a modulated hysteresis control. A simulation studies under Matlab / Simulink is conducted to show the control performance of the grid connected photovoltaic system. However Rajeshbabu S. and Manikandan B.V. [6] used a Neuro Fuzzy artificial inference system (ANFIS) controller, and unified power quality conditioner (UPQC) to improve the quality of power in a grid connected to the renewable energy system. Simulation results were used to analyze the effect of energy quality events at the Common Coupling Point in a grid connected renewable energy systems. In the same scopes, Zoubir B. and Djamila Rekioua Z. [7] presented a direct decay power control of the pulse width modulated constant current pulse width (PWM) rectifier. Their control method, called DPC-SVM, to generate the converter switching signal uses the SVM technique, and it has many advantages, including providing a line current very close to sine waveforms (TDH <2%), and good DC bus voltage regulation is achieved using a PI controller.

However, in order to overcome problems of harmonic pollution, active power filtering proves to be an adequate and efficient solution [8]. The purpose of this article is to examine the characteristics of an association between a photovoltaic generator, which aims to inject active power into an electrical network and a parallel active filter whose task is to eliminate disturbances present at this network [9].

## 2. The Configuration Studied

The configuration studied consists of a solar PV generator connected to the DC bus of a three-phase voltage inverter, coupled in parallel to the network through an inductor. This electrical network supplies a non-linear receiver constituted by a rectifier PD3 having a load in series with an inductance [10, 12-15]. The diagram of Figure 1 illustrates this configuration. The analysis of the power fluxes is thus examined in various regimes imposed by the fluctuation of the level of irradiation during the diurnal period and the alternation with the nocturnal part where only the functions of the active filter are activated. It should be noted that with this principle the hardware investment is identical to a photovoltaic installation connected to the network but with the addition of the functionalities of an active filter in order to improve the quality of the energy on the network at the point of connection. It is therefore the control algorithm of the voltage inverter which is adapted in order to simultaneously ensure, at the level of the electrical network, the compensation of the harmonic pollution, reactive power, imbalances and the injection of power provided by PV panels.

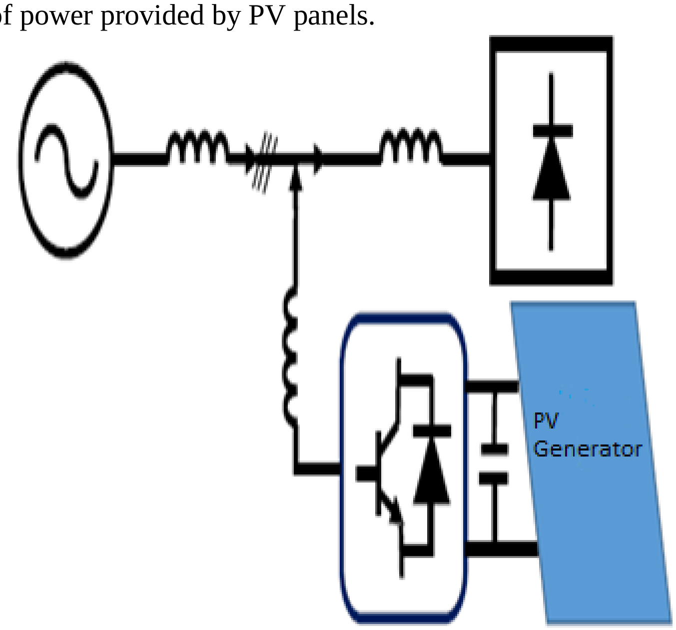



Figure 1: Synoptic diagram of the configuration studied

The photovoltaic module (BP MSX-150) is chosen for modeling and simulation. It contains (72) multi crystalline silicon solar cells, and provides a maximum rated power of 150W. The physical and electrical characteristics of this photovoltaic panel are given in the following table 1:

| **Physical characteristics** | **BP MSX-150** |
|---|---|
| Number of cells in series (NS) | NS=72 |
| Number of cells in parallel (NP) | NP=1 |
| Electrical characteristics (STC) | Ga=1000w/m$^2$.25°C.AM1.5 |
| Maximum power (Pmax) | 150w |
| Maximum point voltage (Vmpp) | 34.28 V |
| Current at maximum point (Impp) | 4.375 A |
| Open Circuit Voltage (Voc) | 43.5 V |
| Short circuit current (Isc) | 4.74 A |

Table 1: Physical and electrical characteristics of the selected PV generator for modeling and simulation.

The mathematical model of a photovoltaic generator is given by the equation 1:

$$I = Isc.\left[1-\left(\exp\left[\frac{V-Voc.Ns+1Rs.Ns}{Vth}\right]\right)\right] \quad (1)$$

Other expressions (equations (2), (3)) have been given to express *Isc* and *Voc* respectively by:

$$Isc = C1.Ga\left[1+\left(Tc-Tc(STC)\right).5.10^{-4}\right] \quad (2)$$

$$Voc = Voc(STC) + C3.\left(Tc-Tc(STC)+Vth\ln\left[\frac{Ga}{Ga(STC)}\right]\right) \quad (3)$$

To construct an equivalent model (by Simulink) of the PVG, the above expressions were used to subdivide the PV generator into blocks representing the various elements of its equivalent circuit model. The representative diagram of the mathematical current model of a photovoltaic module under matlab-simulink is given in Figure 2 and Table 2 summarizes the simulation parameters of the shunt active power filter.

The values of the cell temperature T, the Ga irradiation, and the number of series photovoltaic cells Ns are accessible as external variables and can be changed during the simulation process. This makes it possible to observe and evaluate the reaction of the system to abrupt changes in operating conditions, such as variations in sunshine.

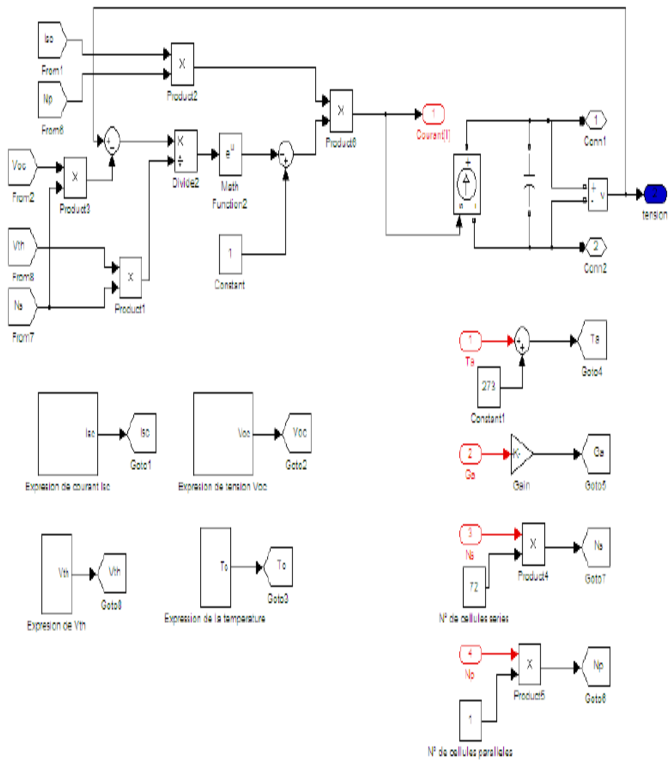


Figure 2: Modeling PV generator under matlab-Simulink.

| System | Designations | Values |
|---|---|---|
| Power source | ·The effective tension<br>·Frequency<br>·The internal resistance<br>·The internal inductance | *Vs*=100V<br>*F*=50HZ<br>*Rs*=0.1Ω<br>*Ls*=0.1mH |
| Nonlinear load | · Bridge PD3 three-phase rectifier with R-L load<br>·Inductance filtering at the input of the bridge PD3 | *RL*1=6.1 Ω<br>*RL*2=10 Ω<br>*L*=20mH<br>*Rc*=0.01 Ω<br>*Lc*=0.57mH |
| Shunt active power filter | ·Storage capacity<br>·Coupling inductance<br>· Hysteresis band | *Cdc*=2200µF<br>*Lf*=2mH<br>HB=0.2A |

Table 2: the simulation parameters of the shunt active power filter.

## 3. shunt Active power Filter Control Strategies

1. The algorithm of the MPPT method

The algorithm of the proposed MPPT method is shown in Figure 3. With $i_d\ (k)$ is the three-phase source current representation in the synchronous reference frame *d-q*,$\Delta i_G(k)$ represents the variation in power caused by the change in illumination and can be defined as follows:

$$\Delta i_G = T_e.\varepsilon.k_i = T_e.k_i\left(V_{dcref}(k-1) - V_{dc}(k)\right) \quad (4)$$

The discretized writing of the current on the axis *d* lasts a sampling period $T_e$ in a situation of variation of illumination is written as follows:

$$\Delta i_d(k) = \Delta i_G(k) + \Delta i_\vartheta(k) \quad (5)$$

$\Delta i_\vartheta(k)$ describes the variation of the current on the axis component generated by the perturbation increments of the MPPT algorithm ($Inc_v$).

The first $Inc_v$ is used when the output voltage of the panel is removed from the voltage of the MPP, and the second $Inc_G$ in the presence of a variation of illumination.

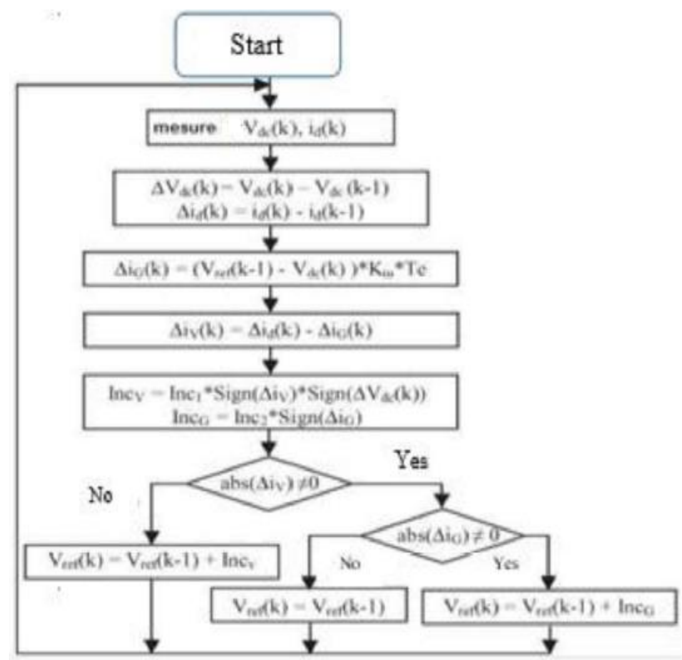



Figure 3: Proposed MPPT algorithm for estimating the reference voltage.

2. Hysteresis control

Hysteresis control, also known as all-or-nothing control, is a non-linear control that uses the error existing between the reference current $I_{fref}$ and the current produced by the inverter $I_f$. The error is compared to a template called a hysteresis band.

As soon as the error reaches the lower or higher band, a control command is sent in order to stay inside the band. The simplicity of implementation, as shown in Figure 3, is the main advantage of this technique.

Despite its simplicity of implementation, its robustness and its good dynamics, this order has some disadvantages namely:

- The switching frequency is not fixed; it depends on the hysteresis band and of the current derivative.
- The command is applied separately on all three phases. The structure electro-technical system imposes at every moment that the sum of the three currents is zero. The result obtained on

one current is not independent of the other two phases. Thus the enslaved current can not respect the limits imposed by the band of hysteresis[8].

3. Direct Power Control Study of SAPF

The principle of direct control has been proposed at [16] and has been developed later in many applications. The objective is to eliminate the modulation block and internal loops by replacing them with a switchboard whose inputs are the errors between the reference values and the measurements.

The first application developed was for the control of an electric machine and the control structure is known as Direct Torque Control (DTC). Subsequently, a similar power control technique (DPC) was proposed by [17] for a control application of the rectifiers connected to the network.

With the DPC there is no current control loop or PWM modulation element, because the switching states of the inverter, for each sampling period, are selected from a switching table , based on the instantaneous error between reference values and those measured or estimated

active and reactive powers, and the angular position of the source voltage vector. Generally with this control strategy, the DC bus voltage is regulated for active power control and operation with a factor of unit power is obtained by imposing the reactive power at a zero value [18].

## 4. Simulation results

The photovoltaic compensation system consists of a PVG, a chopper in booster mode and an active shunt filter that connects to the network. The latter feeds a non-linear load. The proposed compensation system plays the role of compensator reagents in the case of low illumination, and plays the role of a shunt active filter with a real power injection to the electricity network produced by the photovoltaic conversion chain in the case of strong illumination.

The temperature and the illumination are fixed at standard conditions (STC) (Ga=1000w/m$^2$ Ta=25°C) and the global system is simulated with two types of control of the inverter (active filter), the hysteresis control and the direct power control (DPC) so as to operate the system as a source of energy (injection of mains power) and an active shunt filter (harmonic compensation and reactive power).

Figure 4(a) and (b) shows the waveforms of the three-phase source current and the current consumed by the non-linear load, and the active and reactive powers of the three-phase source before the introduction of the photovoltaic compensation system.

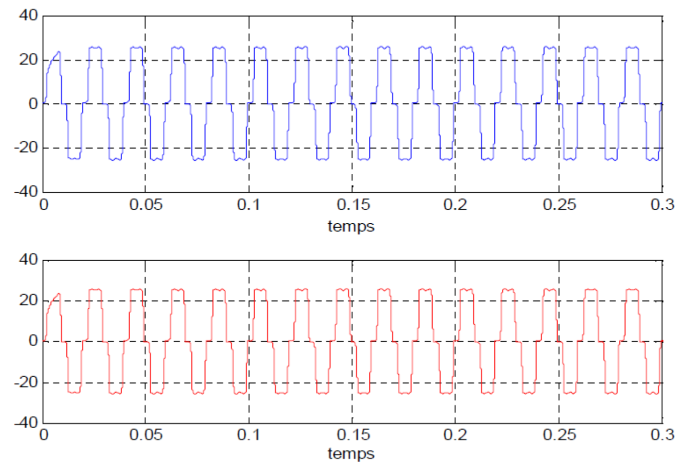


Figure 4 (a) current waveforms before photovoltaic compensation.

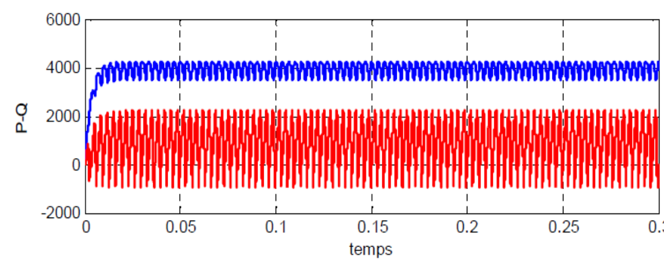


Figure 4(b): Active and reactive power characteristic.

Initially the system operates without SAPF, the load consumes an active power of 4 Kw, the source currents are identical to those of the nonlinear load ($i_s$ = $i_l$ = 27.84A) characterized by a spectrum containing only harmonics of odd order (not multiples of three) and a THDi = 23.29% Figure 5.

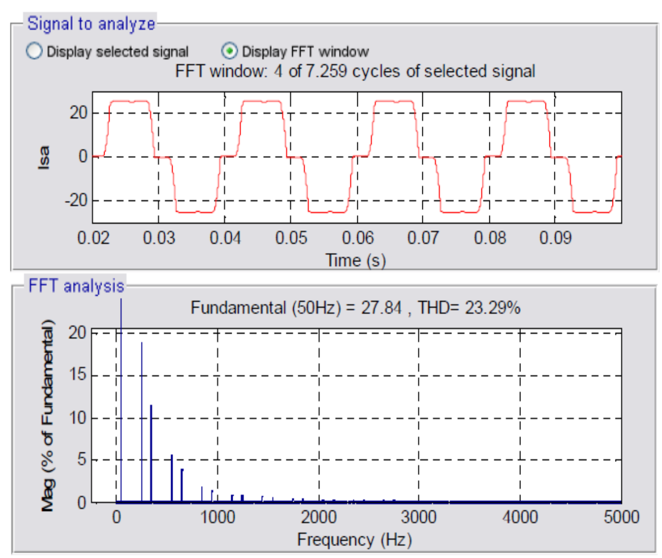


Figure 5: Spectral analysis of the source current before commissioning of the SAPF.

- Simulation of the system with the hysteresis control for the SAPF

Figure 6 (a) (b) shows that the SAPF is put into operation, producing currents $i_f$ which arrive, after a transient of t = 0.01s, making the sinusoidal source currents and in phase with the corresponding voltages, the active power returns to its nominal value after a transient while the reactive energy continues to oscillate around zero. Therefore, the harmonic distortion rate of the source current is improved and is worth THDi = 2.51% (FIG. 7 (a)) and the harmonic distortion rate of the source voltage becomes THDv = 3.55% (FIG. 7 (b)).

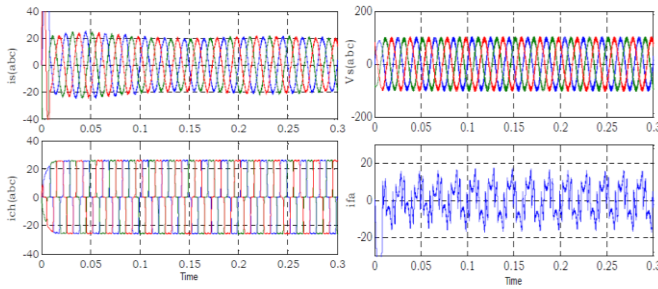



Figure 6 (a): Transient simulation results when closing the SAPF for a PD3- [RL1, L] nonlinear load.

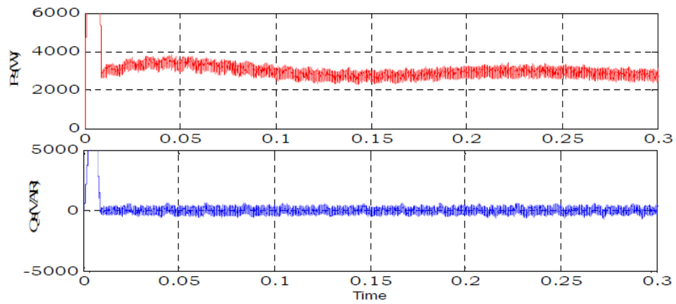
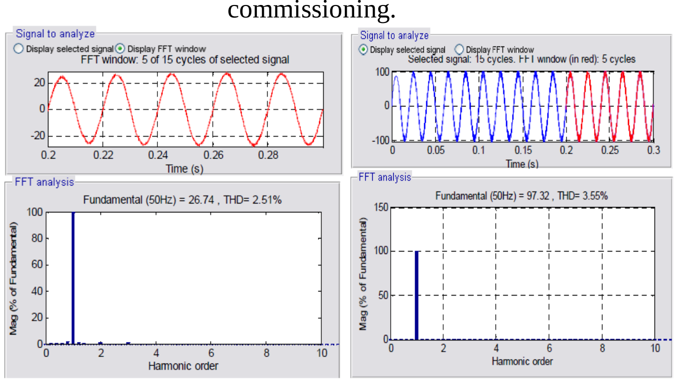



Figure 6 (b): waveform of instantaneous powers after SAPF commissioning.




(a) (b)

Figure 7: Spectral analysis of signals after SAPF commissioning: (a) source current, (b) source voltage.

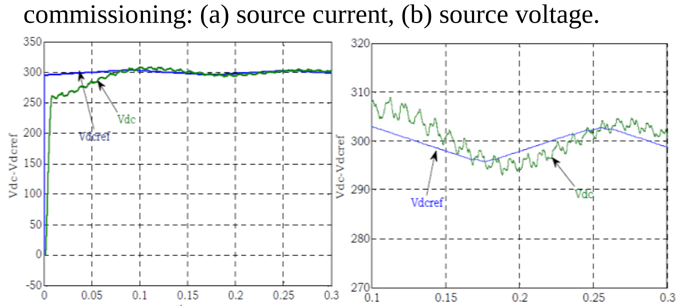



Figure 8: waveform of the DC bus voltage and its reference voltage.

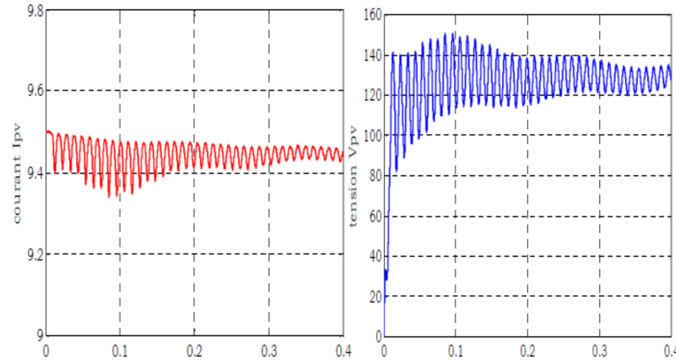



Figure 9: Characteristic of the PV Generator.

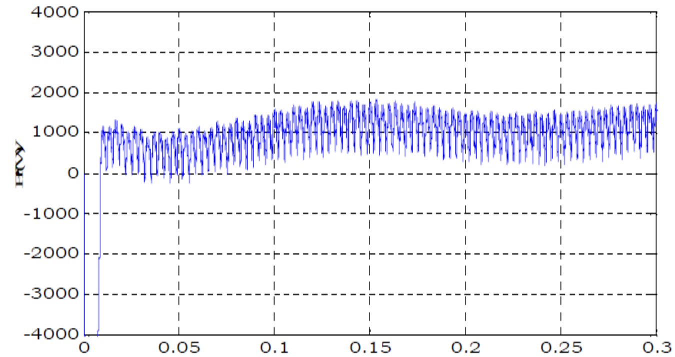



Figure 10: waveform of the active power injected into the grid by the PV Generator.

The value of the DC bus voltage tends to its reference value *Vdcref* Figure 8, obtained by the adaptation algorithm presented in section 3.1 after a transient of $\Delta t = 0.08s$. These results show the effectiveness of the proposed algorithm.

Figure 9 represent the voltage and the current of the PVG.

From this simulation, we notice an injection of active power to the grid due to the PVG.

This is characterized by a decrease of active power supplied by the three-phase network $P_s$ = 3Kw (current decrease of source $i_s$ = 20A), so one has a power of $P_f$ = 1000W produced by the PVG to meet the energy requirement of the nonlinear load (Figure 10).

- Simulation of the system with the command DPC for the SAPF

After the commissioning of the SAPF we can notice that the source currents (Figure 11 (a)), after a transient of t = 0.01s become sinusoidal with a THDi = 1.61% (Figure 12 (a)), and are in phase with source voltages with THDv = 2.77% (Figure 12 (b)). As regards the DC bus voltage, it tends towards its reference after a transient of $\Delta t = 0.08s$ (Figure 13 (a)). This control technique provides better energy quality compared to the previous technique (Figure 11 (b)).

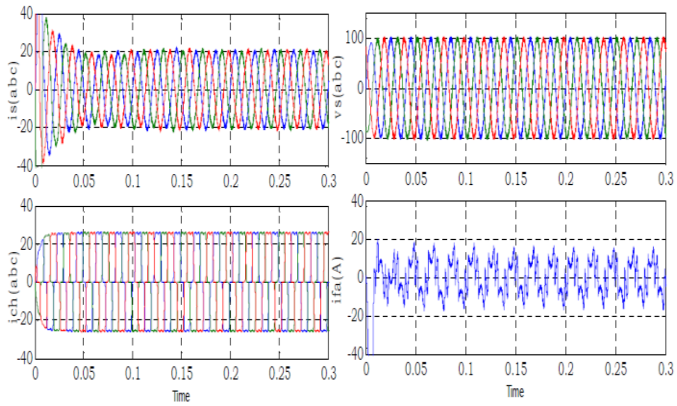



Figure 11 (a): Transient simulation results at closure of SAPF for a PD3- [RL1-L] nonlinear load.

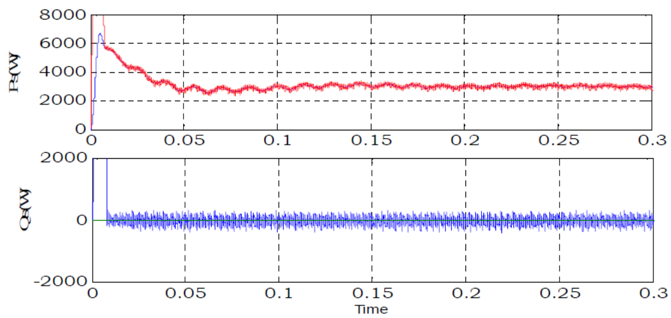
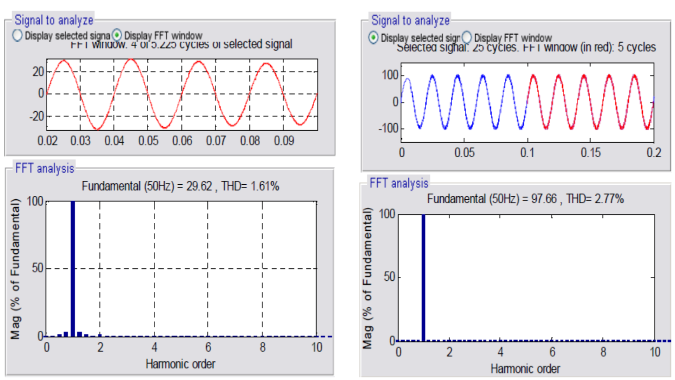



Figure 11 (b): waveform of instantaneous powers after SAPF commissioning (DPC).




(a) (b)

Figure 12: Spectral analysis of the signals after SAPF commissioning: (a) source current, (b) source voltage (DPC).

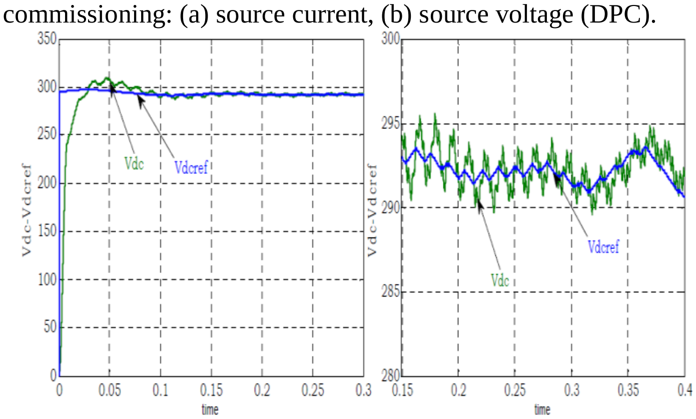



Figure 13 (a): waveform of the DC bus voltage and its reference voltage (DPC).

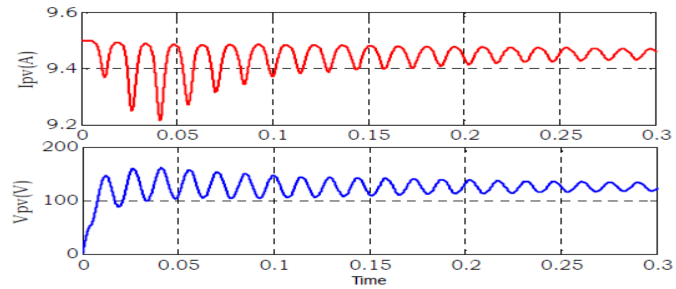



Figure 13 (b): Characteristic of the PV Generator (DPC).

Note that Figure 13 (b) shows the PVG voltage and current waveforms at the MPP operating point, with power injection to the network (Figure 14).

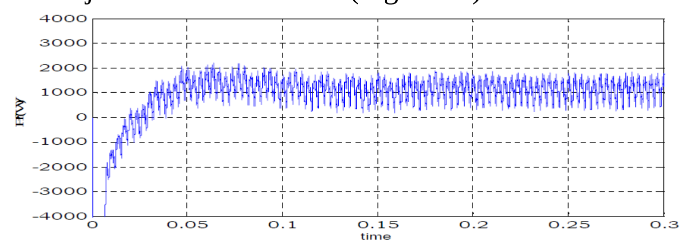



Figure 14: waveform of the active power injected into the grid by the PV Generator (DPC).

## 5. Conclusion

In this work, the association between a PV solar generator and an active filter is validated and allows simultaneous delivery of functionalities or services to the distribution network at the injection site without the addition of specific equipment. The results confirm the feasibility of the system and validate the various functionalities assigned to the voltage inverter, namely the compensation of harmonic pollution, reactive power and the transfer of the energy flow from the solar PV to the electricity grid. We exposed the results of the two control strategies. They are characterized by current control and direct power control.

We have developed an adaptation algorithm, based on the incremental conductance technique, of the reference voltage of the continuous bus, which has proved its efficiency.

The simulation results obtained in the various cases considered are satisfactory and confirm the theoretical study, and in particular the efficiency and robustness of the proposed system: a quasi-sinusoidal current absorption with a factor close to unity.

In the case of the hysteresis control of SAPF, we observed a good signal quality in terms of harmonic distortion THDi = 2.51% of the currents and voltages of the three-phase source. Nevertheless, this current control technique induces at the spectrum level a wide frequency band due to the switching of the semiconductors, which is difficult to filter.

While D.P.C control technique, in addition to its simplicity, a better control of instantaneous active and reactive power control is achieved. As well as a significant improvement in the current and voltage distortion rates relative to the hysteresis control THDi = 1.61%.

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