

Sliding Mode MPPT for Grid-Connected Photovoltaic System Associated with Shunt Active Power Filter

Lyes MEZGHICH¹, Hichem LAIB¹, Djamel SAKRI¹, and Nouredine GOLEA¹

⁽¹⁾ Laboratory of Electrical Engineering and Automatic, LGEA, Larbi Ben M'hidi University, Oum El Bouaghi, Algeria

Email of the corresponding author: lyes.mezghich@univ-oeb.dz

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Abstract—This article focuses on grid-connected photovoltaic systems (GCPVS) coupled with a shunt active power filter (SAPF) based on sliding mode control (SMC). These strategies improve the photovoltaic system's performance in the face of weather variations and optimize the active filter by compensating for reactive power and eliminating harmonic currents induced by nonlinear loads. For maximum power point finding (MPPT) of the photovoltaic generator, MPPT and SMC are combined in the boost converter, and a sliding mode controller is applied to the DC bus voltage to ensure a fast and accurate response. The SAPF control, which manages the injection of power produced by the photovoltaic generator and the harmonic currents, is based on instantaneous power quality (PQ) theory. Comprehensive simulations, performed with MATLAB-SIMULINK, cover a wide range of operating scenarios and ensure the system's feasibility and robustness under different loads and irradiance (G) variations.

Keywords—Shunt active power filter (SAPF), Sliding Mode Control (SMC), PQ theory, harmonic currents

I. INTRODUCTION

Electricity is one of the most widely used forms of energy in the world and plays a crucial role in the socio-economic development of nations. However, the heavy reliance on fossil fuels poses a major challenge to environmental sustainability. This is why the development of renewable energies, such as wind and solar power, has become essential for the transition to more sustainable development. Photovoltaic power generation is one of the main ways to harness solar energy. The two operating modes of a photovoltaic generating system are grid-connected and independent. The application scale for the grid-connected operation mode is growing, and it is developing pretty quickly. As the interface device of renewable energy sources generating system and power grid, the three-phase voltage inverter have played a key role [1, 2, 3].

Integrating photovoltaic systems into local power grids introduces nonlinear loads, which degrade the power factor and cause power quality problems affecting other connected loads. With the increasing prevalence of nonlinear loads due to technological advancements, these problems are becoming more and more common.

With technological advancements, the degradation of electrical power quality is becoming a major problem for businesses that rely on a reliable, high-quality power supply. To maintain their diverse systems, commercial and industrial users place great importance on electrical signal quality, with harmonics being the primary issue associated with nonlinear loads [4, 5, 6, 7, 8, 9]. Shunt active power filters (SAPFs) effectively mitigate this problem by injecting compensating harmonic currents that oppose those generated by nonlinear loads.

Most grid-connected photovoltaic systems use a two-stage power conversion topology [10, 11]. To increase the voltage produced by the solar panel system above the grid peak voltage, a boost converter operating on the DC/DC conversion principle is first used. The maximum power point tracking (MPPT) algorithm is integrated into this converter via sliding mode control (SMC). The efficient transfer of energy captured by the first converter to the electrical grid is then ensured by the second converter, operating on the DC/AC conversion (VSI) principle.

Maximum power point tracking (MPPT) algorithms, essential for DC voltage regulation and efficiency optimization in photovoltaic systems, have been the subject of

various control strategies in recent research. The authors of references [15] and [16] proposed the use of a fuzzy logic MPPT in a boost converter, combined with PI controllers, to control the DC voltage.

Instantaneous PQ theory, which is one of the most widely used methods for controlling SAPF, has proven effective in many studies, some of which are mentioned [17, 18].

The objective of this article is to use a parallel active filter based on instantaneous power quality theory, coupled to a photovoltaic system, to inject the maximum power generated by a photovoltaic generator while ensuring better power

quality. The topology adopted for this purpose is illustrated in Figure 1. It consists of:

- A photovoltaic generator equipped with a DC-DC adaptation stage, controlled by an MPPT algorithm based on sliding mode control.
- A three-phase voltage inverter used as SAPF and providing the interface between the photovoltaic system and the electrical grid, controlled by instantaneous PQ theory with sliding mode control for the bus voltage.

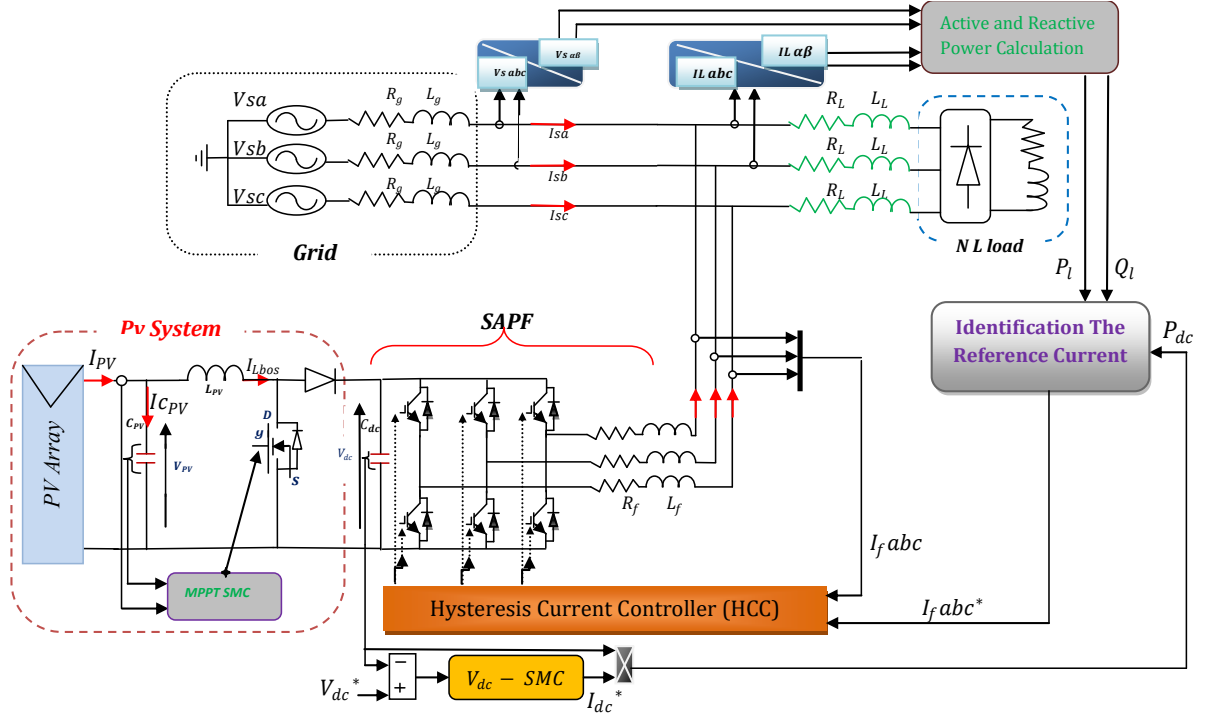


Fig. 1. Control scheme of the grid-connected PV system.

II. SYSTEM DESCRIPTION

The electrical system, composed of four main blocks, is illustrated in Figure 1. The first block is the three-phase network, followed by a variable nonlinear DC load (L_L, R_L) with an uncontrolled three-phase rectifier; the third block is the photovoltaic system, and the fourth is a two-level three-phase voltage source inverter (VSI), acting as a parallel active filter (SAPF). To this end, the grid-connected photovoltaic system, with its associated parallel active filter, is managed by different controllers:

- An MPPT algorithm based on sliding mode control governs a DC-DC boost converter.
- A DC-bus voltage controller by a SMC.
- The SAPF is controlled by the hysteresis current controller (HCC) after obtaining the reference current in the instantaneous active and reactive power theory.

III. MPPT ALGORITHM BASED ON SLIDING MODE CONTROL

The adaptation stage, represented by a DC-DC converter, aims to maximize the power produced by the photovoltaic system through an appropriate control mechanism. Several MPPT approaches have been developed and validated in the literature. Here, we focus on a sliding mode control approach.

Based on the equivalent circuit of each phase of the PV system, which constitutes the third main block in Figure 1, the equations of the boost converter can be given as follows:

$$\frac{dV_{PV}}{dt} = \frac{1}{C_{PV}} I_{PV} - \frac{1}{C_{PV}} I_{Lbos} \quad (1)$$

$$\frac{dI_{Lbos}}{dt} = \frac{1}{L_{PV}} V_{PV} - \frac{1}{L_{PV}} (1-D)V_{dc} \quad (2)$$

To determine the reference duty cycle D for the operation of the DC-DC boost converter, the two

sliding mode controllers are designed using equations (1) and (2).

A. Sliding surface design for PV voltage boost control

The selected sliding surface S_{PV} , is determined by:

$$S_{PV} = e_{PV} \quad (3)$$

Where e_{PV} represent the error between the output voltage of the photovoltaic panel V_{PV} and its reference voltage V_{PV}^* .

$$e_{PV} = V_{PV} - V_{PV}^* \quad (4)$$

The sliding surface first derivative $\dot{S}_{PV}$ can be written as follows:

$$\dot{S}_{PV} = \dot{e}_{PV} = \dot{V}_{PV} - \dot{V}_{PV}^* \quad (5)$$

By substituting equations (1) into equation (5), we obtain equation (6):

$$\dot{S}_{PV} = \frac{1}{C_{PV}} I_{PV} - \frac{1}{C_{PV}} I_{Lbos} - \dot{V}_{PV}^* \quad (6)$$

In steady state, $\dot{S}_{PV}=0$ which gives:

$$I_{Lbos}^* = I_{PV} - C_{PV} \dot{V}_{PV}^* + K_{PV} \text{sing}(S_{PV}) \quad (7)$$

• Stability analysis

Let us take the Lyapunov's function as follows:

$$V_{PV} = \frac{1}{2} S_{PV}^2 \quad (8)$$

The time derivative of this function is given by:

$$\dot{V}_{PV} = S_{PV} \dot{S}_{PV} \quad (9)$$

By inserting equations (6) and (7) into equation (9), we obtain equation (10):

$$\dot{V}_{PV} = S_{PV} \left[\frac{1}{C_{PV}} I_{PV} - \frac{1}{C_{PV}} (I_{PV} - C_{PV} \dot{V}_{PV}^* + K_{PV} \text{sing}(S_{PV})) - \dot{V}_{PV}^* \right] \quad (10)$$

After simplification, equation (10) yields:

$$\dot{V}_{PV} = -K_{PV} \text{sing}(S_{PV}) = -K_{PV} |S_{PV}| < 0 \quad (11)$$

$$\Rightarrow K_{PV} > 0$$

Therefore, K_{PV} must be a positive constant.

B. Sliding surface design for current boost control

The selected sliding surface S_D , is determined by:

$$S_D = e_D \quad (12)$$

Where e_D denotes the error between the inductor current I_{Lbos} and its reference value I_{Lbos}^* from equations (7).

$$e_D = I_{Lbos} - I_{Lbos}^* \quad (13)$$

The sliding surface first derivative $\dot{S}_D$ can be written as follows:

$$\dot{S}_D = \dot{e}_D = \dot{I}_{Lbos} - \dot{I}_{Lbos}^* \quad (14)$$

By replacing equations (2) into (14), we get the equation (15):

$$\dot{S}_D = \frac{1}{L_{PV}} V_{PV} - \frac{1}{L_{PV}} (1-D) V_{dc} - \dot{I}_{Lbos}^* \quad (15)$$

In steady state, $\dot{S}_D = 0$, which leads to:

$$D^* = \frac{L_{PV}}{V_{dc}} \dot{I}_{Lbos}^* - \frac{V_{PV}}{V_{dc}} + 1 + K_D \text{sing}(S_D) \quad (16)$$

• Stability analysis

Consider the Lyapunov function defined as follows:

$$V_D = \frac{1}{2} S_D^2 \quad (17)$$

The time derivative of this function is given by:

$$\dot{V}_D = S_D \dot{S}_D \quad (18)$$

By inserting equations (15) and (16) into equation (18), we arrive at equation (19):

$$\dot{V}_D = S_D \left[\frac{1}{L_{PV}} V_{PV} - \frac{1}{L_{PV}} \left(1 - \frac{L_{PV}}{V_{dc}} \dot{I}_{Lbos}^* + \frac{V_{PV}}{V_{dc}} - 1 + K_D \text{sing}(S_D) \right) V_{dc} - \dot{I}_{Lbos}^* \right] \quad (19)$$

After simplification, equation (19) results in:

$$\dot{V}_D = K_D S_D \text{sing}(S_D) = K_D |S_D| < 0 \quad (20)$$

$$\Rightarrow K_D < 0$$

Therefore, K_D must be a negative constant.

IV. SMC-PROVIDED DC-BUS VOLTAGE CONTROLLER

The DC bus voltage must be regulated. The reference active power P_{dc}^* required by instantaneous PQ theory to obtain the reference current of the shunt active power filter (SAPF) can be accurately determined by efficient control. The sliding mode control strategy is used for this purpose due to its recognized advantages, including its robustness to external disturbances and parametric uncertainties, as well as its ability to provide good control performance, particularly in terms of accuracy and response time.

A. Sliding surface design

To determine the sliding surface, the general form is given as:

$$S(t) = \left(\lambda + \frac{d}{dt} \right)^{n-1} e(t) + K_1 \int_0^t e(t) dt \quad (21)$$

Where $e(t)$ is the error between the reference and controlled values:

$$e_{dc}(t) = V_{dc}^*(t) - V_{dc}(t) \quad (22)$$

λ, K_1 are the strictly positive constants, n is the relative degree, which corresponds to the number of differentiations required for the output, until the control appears. In our case, n is set to 1, which gives the following sliding mode surface of DC-link voltage:

$$S_{dc}(t) = e_{dc}(t) + K_1 \int_0^t e_{dc}(t) dt \quad (23)$$

The sliding surface first derivative $\dot{S}_{dc}$ can be written as follows:

$$\begin{aligned} \dot{S}_{dc} &= \dot{e}_{dc} + K_1 e_{dc} \\ \dot{S}_{dc} &= \dot{V}_{dc}^* - \dot{V}_{dc} + K_1 (V_{dc}^* - V_{dc}) \\ \dot{S}_{dc} &= \dot{V}_{dc}^* - \frac{1}{C} I_{dc} + K_1 (V_{dc}^* - V_{dc}) \end{aligned} \quad (24)$$

In steady state, $\dot{S}_{dc} = 0$ which gives:

$$I_{dc}^* = C_{dc} \dot{V}_{dc}^* + C_{dc} K_1 (V_{dc}^* - V_{dc}) + K_{dc} \text{sing}(S_{dc}) \quad (25)$$

Where K_{dc} is the positive constant and the function $\text{sing}(S_{dc})$ is defined as:

$$\text{sing}(S_{dc}) = \begin{cases} 1 & \text{if } S_{dc} > 0 \\ -1 & \text{if } S_{dc} < 0 \\ 0 & \text{if } S_{dc} = 0 \end{cases} \quad (26)$$

B. Stability analysis

Let us take the Lyapunov's function as follows:

$$V_{dc} = \frac{1}{2} S_{dc}^2 \quad (27)$$

The time derivative of this function is:

$$\dot{V}_{dc} = S_{dc} \dot{S}_{dc} \quad (28)$$

By replacing equations (24) and (25) into (28), we obtain the equation (29):

$$\begin{aligned} \dot{V}_{dc} &= S_{dc} \left[\dot{V}_{dc}^* - \frac{1}{C_{dc}} (C_{dc} \dot{V}_{dc}^* + C_{dc} K_1 (V_{dc}^* - V_{dc}) + K_{dc} \text{sing}(S_{dc})) + K_1 (V_{dc}^* - V_{dc}) \right] \\ &= -S_{dc} \frac{K_{dc}}{C_{dc}} \text{sing}(S_{dc}) = -\frac{K_{dc}}{C_{dc}} |S_{dc}| < 0 \end{aligned} \quad (29)$$

After simplification, the equation (28) leads to:

$$\begin{aligned} \dot{V}_{dc} &= -S_{dc} \frac{K_{dc}}{C_{dc}} \text{sing}(S_{dc}) = -\frac{K_{dc}}{C_{dc}} |S_{dc}| < 0 \quad (30) \\ &\Rightarrow K_{dc} > 0 \end{aligned}$$

Therefore, K_{dc} must be a positive constant.

V. ACTIVE POWER FILTER CONTROL BASED ON INSTANTANEOUS PQ THEORY

A. Instantaneous PQ theory

One of the most widely used methods for extracting harmonic current was initially proposed by Akagi [13] for three-phase systems. Its principle

consists of using the Concordia transformation to convert three-phase systems with simple line voltages and currents into two-phase (α, β) systems in order to calculate the instantaneous real and imaginary powers.

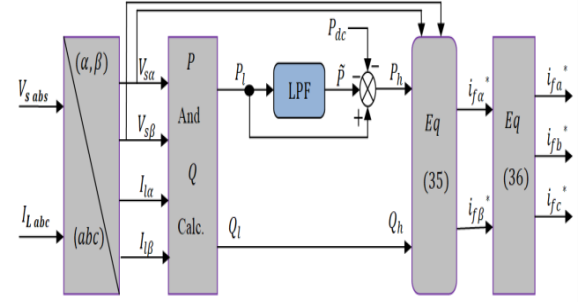


Fig. 2. Block diagram of instantaneous PQ theory.

Using Concordia Transformation (abc to $\alpha\beta$):

$$\begin{bmatrix} V_{s\alpha} \\ V_{s\beta} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} V_{sa} \\ V_{sb} \\ V_{sc} \end{bmatrix} \quad (31)$$

$$\begin{bmatrix} I_{L\alpha} \\ I_{L\beta} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} I_{La} \\ I_{Lb} \\ I_{Lc} \end{bmatrix} \quad (32)$$

Therefore, the Instantaneous active and reactive powers in (α, β) are given by:

$$\begin{bmatrix} P_l \\ Q_l \end{bmatrix} = \begin{bmatrix} V_{s\alpha} & V_{s\beta} \\ -V_{s\beta} & V_{s\alpha} \end{bmatrix} \begin{bmatrix} I_{L\alpha} \\ I_{L\beta} \end{bmatrix} \quad (33)$$

Furthermore, the instantaneous reference values of the active and reactive power of the active power filters, or what could be called the instantaneous reference values of the active and reactive power of the harmonics:

$$\begin{bmatrix} P_h \\ Q_h \end{bmatrix} = \begin{bmatrix} P_l - P_{dc} - \tilde{p} \\ Q_l \end{bmatrix} \quad (34)$$

Where $\tilde{p}$ is the Power low pass filter.

In the next step, the reference current in (α, β) coordinates is calculated by this equation:

$$\begin{bmatrix} i_{fa}^* \\ i_{fb}^* \end{bmatrix} = \frac{1}{V_{s\alpha}^2 + V_{s\beta}^2} \begin{bmatrix} V_{s\alpha} & V_{s\beta} \\ V_{s\beta} & -V_{s\alpha} \end{bmatrix} \begin{bmatrix} P_h \\ Q_h \end{bmatrix} \quad (35)$$

In the last step, the reference current in coordinates (a, b, c):

$$\begin{bmatrix} i_{fa}^* \\ i_{fb}^* \\ i_{fc}^* \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{fa}^* \\ i_{fb}^* \end{bmatrix} \quad (36)$$

B. Hysteresis Current Control (HCC)

Hysteresis band current control has emerged as the most suitable approach for various applications

involving current-controlled voltage inverters within active filters. Characterized by its intrinsic stability, fast response time, and high accuracy [12], this method offers significant advantages.

Figure 3 illustrates the classic hysteresis band (HB) current control scheme used to regulate the line current of active power filters. This scheme includes a hysteresis band centered on the three reference line ($i_{fa}^*, i_{fb}^*, i_{fc}^*$) of the active power filter, with the actual line currents denoted (i_{fa}, i_{fb}, i_{fc}). This scheme enables the generation of the six (06) control signals of the voltage inverter (SAPF) so that it can inject the compensation currents (i_{fabc}) into the power grid in real time. [14]

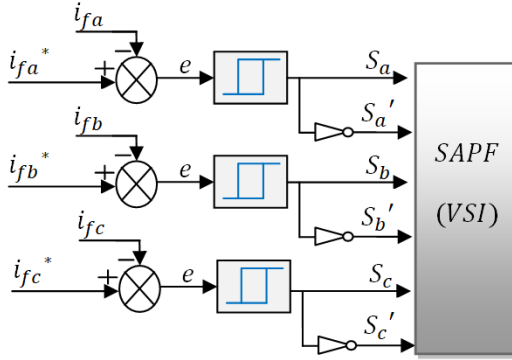


Fig. 3. Block diagram of Hysteresis Current Control (HCC) to SAPF

VI. SIMULATION RESULTS AND DISCUSSIONS

To demonstrate the efficiency and feasibility of the grid-connected photovoltaic system coupled with a parallel active filter, using the previously studied control based on instantaneous power quality theory and a sliding mode controller (SMC), and to confirm the efficiency of the MPPT algorithm based on the SMC, simulations were performed using MATLAB/Simulink, considering different scenarios.

The main parameters used in this configuration are listed in Table 1.

TABLE I. ELECTRICAL PARAMETERS SYSTEM AND CONTROL COEFFICIENTS.

Parameter	Value
Source voltage	230 V
System frequency	50 Hz
Source impedance R_g, L_g	$0.5 \Omega, 0.01 \text{ mH}$
Line impedance R_l, L_l	$0.01 \Omega, 1 \text{ mH}$
Dc-Bus voltage Capacitor C_{dc}	8 mF
Dc-Bus voltage reference V_{dc}^*	600 V
Load impedance R_L, L_L	$100 \Omega, 2 \text{ mH}$
Boost input capacitor C_{pv}	2 mF
Boost inductor L_{pv}	0.5 mH
APF impedance R_f, L_f	$0.01 \Omega, 0.01 \text{ H}$
MPPT (V_{opt}, MPP)	290 V, 8520 W

The first test aims to confirm the importance of instantaneous power quality theory with SMC for power quality improvement. The simulation results presented in Figure 4 demonstrate that implementing the SAPF filter and its controller for direct harmonic current injection leads to a significant improvement in the grid-side current waveform.

The DC bus voltage, demonstrating its speed, precisely follows its reference value, with satisfactory interference rejection. Regarding active and reactive power, Figure 5 shows that the presence of the SAPF filter significantly reduces power fluctuations. Reactive power is zero (0 W), while active power is approximately 1500 W.

To assess the robustness of the control system in maximizing energy extraction from the photovoltaic system, a test was conducted with a variable irradiation profile (G) and load. As shown in Figure 6, the test clearly demonstrates that the output power of the photovoltaic generator remains optimal, regardless of fluctuations in irradiation and load.

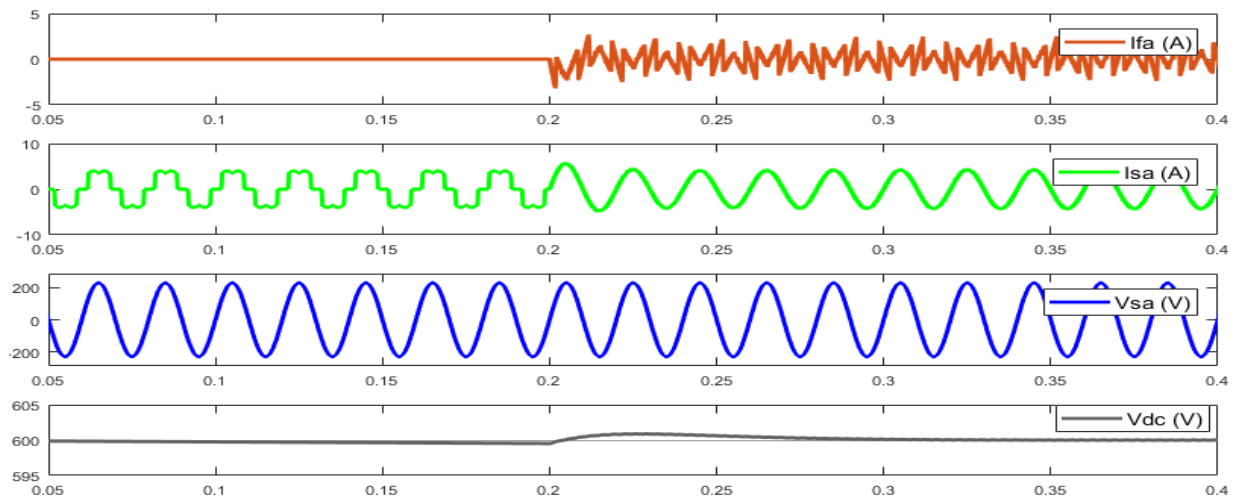


Fig. 4. Filter current, Grid current, voltage, and Dc-Bus voltage behavior before and after filtering.

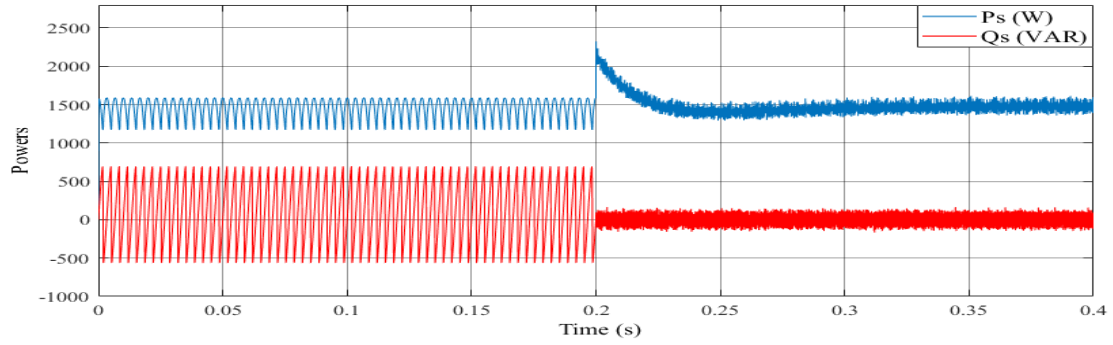


Fig. 5. Behavior of grid active and reactive powers before and after filtering..

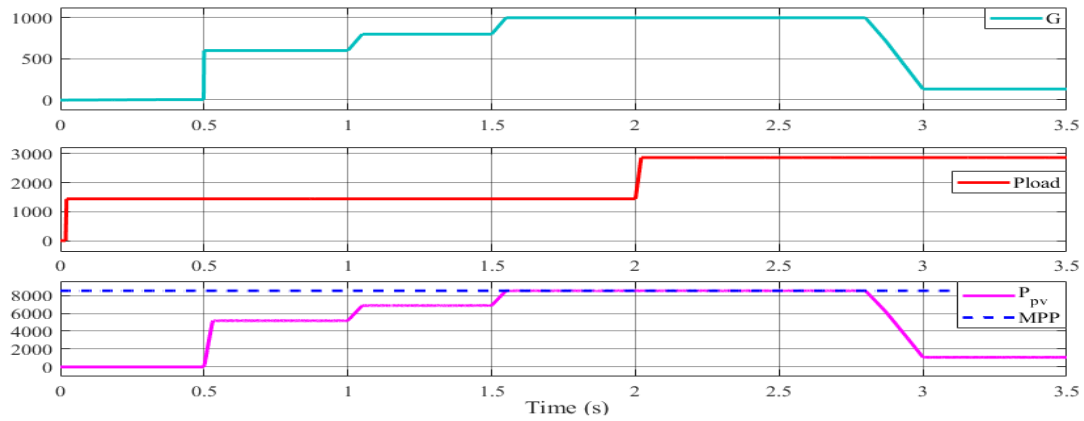


Fig. 6. Power of PV system under a variable irradiance profile.

The simulation results presented in Figures 4, 5, and 6 and Table 2 demonstrate that Instantaneous power quality theory, combined with SMC technology, enabled a significant improvement in power quality, with a satisfactory THD value after filtering.

TABLE II. TABLE OF THD VALUE BEFORE AND AFTER FILTERING.

Operating mode of SAPF	Not activated	Activated
THD [%]	28.85	4.73

The resilience of the energy management of the proposed topology is evaluated using a variable load that fluctuates between 100 Ω and 200 Ω at $t = 2$ s and the same irradiation profile (Figure 6).

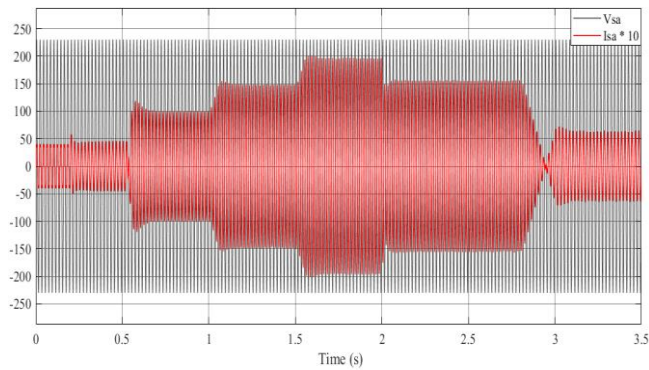


Fig. 7. Grid voltage and current waveforms.

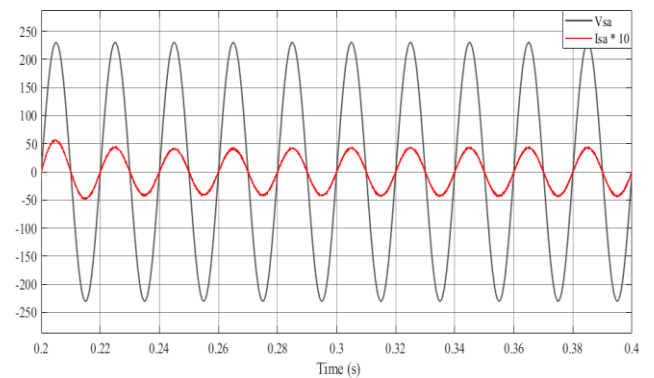


Fig. 8. Zoom of grid voltage and current waveforms when the electrical grid acts in generation mode.

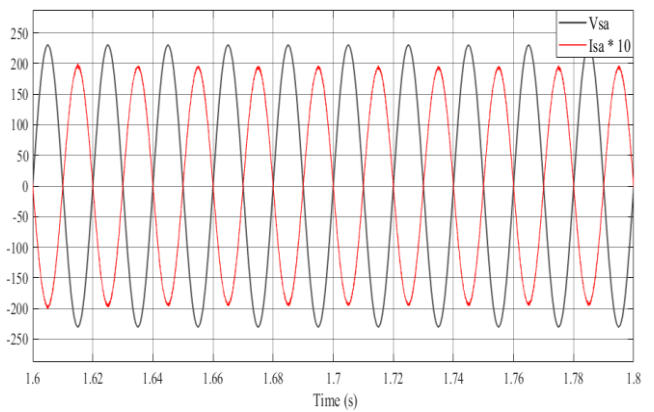


Fig. 9. Zoom of grid voltage and current waveforms when the electrical grid acts in reception mode.

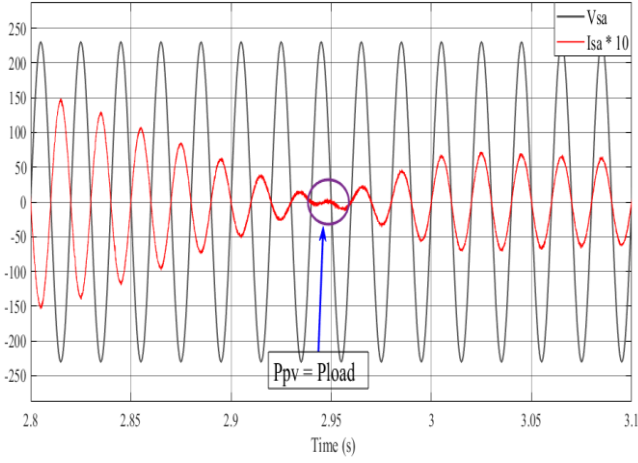


Fig. 10. Zoom of grid voltage and current waveforms when the electrical grid acts in zero power exchange mode

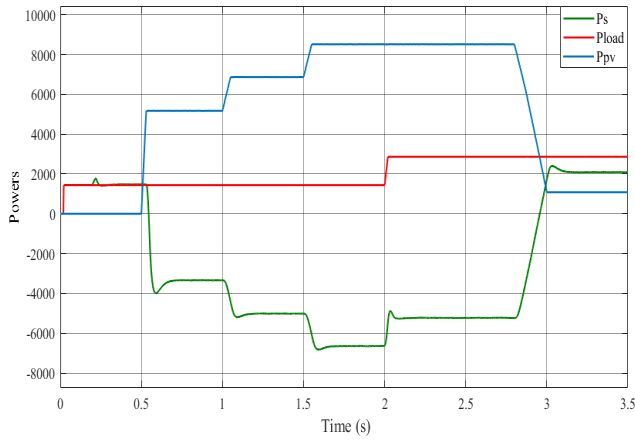


Fig. 11. Power flow under different load and irradiance conditions and different managed modes.

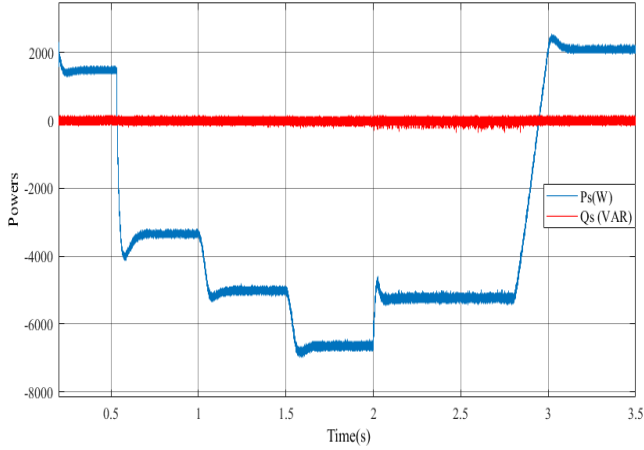


Fig. 12. Grid active and reactive powers under a variable irradiance profile.

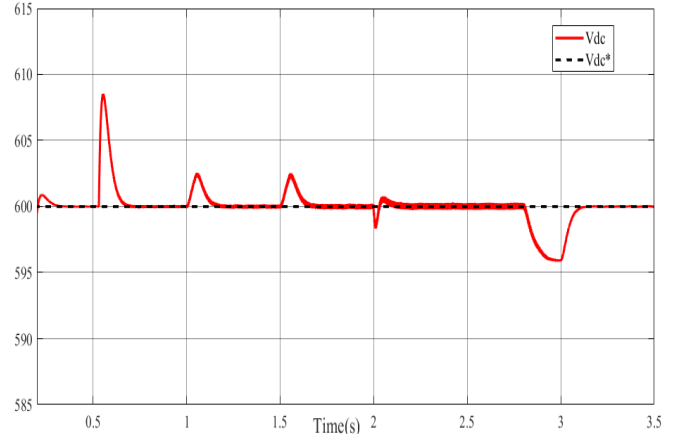


Fig. 13. DC-link voltage under different external disturbances.

Table 3 summarizes the numerical of THD and power factor results under the simulation conditions.

TABLE III. TABLE OF RESULTS.

Resistance Load [Ω]	Time interval [s]	Irradiation G [W/m ²]	THD [%]	Power factor
100	[0 ; 0.5[	0	4.73	1
	[0.5 ; 1.0[	600	2.20	1
	[1.0 ; 1.5[	800	1.54	1
	[1.5 ; 2.0[	1000	1.24	1
200	[2.0 ; 3.0[	1000	1.65	1
	[3.0 ; 3.5[	130	3.34	1

The following observations are made possible by the simulation results presented in Figures 7, 8, 9, 10, 11, 12 and 13:

- The instantaneous PQ theory combined with the SMC technology ensured full compensation of reactive power, while the active power is bidirectional, which is justified by the operating mode of the electrical grid.
- Instantaneous PQ theory combined with SMC technology has enabled complete compensation of reactive power, while active power is bidirectional, which is justified by the operating mode of the electrical network:
 - ✓ Generator mode in the case where there are no irradiation values, characterized by the current and voltage of the network in phase and ($P_s = P_{load}$).
 - ✓ When the photovoltaic generator produces more energy than it needs, it enters receiver mode, which is indicated by a current and network voltage in opposite phase and ($P_{pv} > P_{load}$).
 - ✓ In standby mode or zero power exchange mode, the grid neither supplies nor absorbs energy, resulting in perfect equality between the power produced by the photovoltaic system and the power consumed by the load ($P_{pv} = P_{load}$). In this case, the system is in equilibrium.
- The quality of the electrical power is characterized by a total harmonic distortion (THD) and a unity power factor. These results are satisfactory and comply with international standards.
- The SMC control technology used to regulate the DC bus voltage has proven to be efficient, high-performing, and robust, ensuring fast tracking of the reference value

in milliseconds, with negligible tracking error and low overshoot, even in the presence of various external disturbances.

VII. CONCLUSION

This study presents a design methodology for a grid-connected photovoltaic system coupled to a parallel active filter (SAFP) using sliding mode maximum power point tracking (MPPT). The judicious choice of control techniques for the proposed topology led to the following satisfactory results:

- Effective regulation of network management modes according to energy demand and/or variations in irradiation.
- Precise monitoring of active power based on changes in network operating mode.
- Achieving a unity power factor through complete reactive power correction.
- Achieve low total harmonic distortion (THD) values in accordance with international standards.
- Efficiency of the MPPT algorithm based on SMC to extract the power generated by the photovoltaic system, independent of irradiation variations.
- Effective DC bus voltage with sliding mode control even in the event of external disturbances.

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