

Robust Second-Order Sliding-Mode Control for a Grid-Connected PV System

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Abstract- Photovoltaic Systems (PVS) connected to the electrical grid are characterized by strong non-linearity and multi-variability, involving numerous factors of uncertainty, disturbance and climatic change. That's why this article proposes the use of a Second-Order Sliding Mode Control (SOSMC) strategy to control a PVS via two conversion stages. The converter on the Photovoltaic Generator (PVG) side is employed to Track the Maximum Power Point (MPPT) to generate maximum energy from PVG. On the other hand, the grid-connected converter injects the power generated by PVG to the grid and regulates the DC bus voltage (V_{dc}) and is employed to attain the Unit Power Factor (UPF). The two converters use SOSMC controllers. The implemented regulation technique allows for independent adjustment of active (P) and reactive (Q) power through components of current in quadrature and direct, respectively. This study examines an SOSMC control approach to optimize the energy efficiency of a PVS and improve its robustness in the face of changing climatic conditions. The system's performance has been validated under standard and variable irradiation conditions. To implement and evaluate the proposed control over Conventional Vector Control (CVC) under different conditions, this study used Matlab/Simulink environment. The simulation results showed that the SOSMC contributes to improving the performance and efficiency of the system under different situations. The proposed control reduced the active Power overshoot by 100% and the V_{dc} response time by 50% compared with the CVC. In addition, it reduced the Total Harmonic Distortion (THD) of the current to 1.09%, compared with 2.19% for the CVC.

Keywords: Current Vector Control, DC–DC Boost Converter, Electrical Grid, Photovoltaic System, Second Order Sliding Mode Control.

1. Introduction

Over the past few years, progress in the utilization of renewable and green energies has proved to be the main solution to the problem of environmental pollution caused by fossil energy, and a reduction in energy production [1]. Power generation systems based on renewable energies play a major role in global energy production. Among the renewable energy sources available, photovoltaic energy emerges as the more favorable option due to its widespread availability, environmental friendliness, and free availability [2]. In comparison with other energy sources, Photovoltaic Systems (PVS) are recognized as a major renewable energy resource, primarily due to their high durability and efficiency. Consequently, PV has imposed itself as a rapidly

developing energy source in the world. It is anticipated that PVS could represent up to 30% of the global energy demand by 2030, with even greater prospects for the future [3]. Thus, this trend requires constant technological progress and continuous optimization, aimed at improving options for integrating energy into the power grid, reducing costs, and improving the performance of solar panels [4]. As a result, the majority of PV energy production installations have undergone significant modifications in their operational and control structures. Consequently, several researchers have proposed various control configurations to enhance the desired operational characteristics.

In the literature, the majority of articles on the subject of grid-connected PVSs focus on inverter control. These methods use Proportional-Integral (PI) controllers to control

the DC bus Voltage (V_{dc}) and the current supplied to the grid in order to ensure maximum active Power (P) transfer with Unit Power Factor (UPF) [5]. To ensure the Maximum Power Point (MPP) control, the Perturbation and Observation (P&O) technique is commonly used for its simplicity and acceptable results. But, it is important to note that this technique can exhibit fluctuations around the operating point and can lose this point during rapid irradiation changes [6]. Furthermore, the increasing integration of grid connected PVS has motivated numerous researchers to examine the robustness and stability of these systems. For example, in [7], the author proposed a control for grid-connected inverter using a Model Predictive Control (MPC). In [8], the combination of Fuzzy Logic Control (FLC) and PSO algorithms improved MPPT compared to P&O, this technique is a very robust strategy for minimizing response time but its inconvenience is the complexity of its realization. Another MPPT method, based on Neuro-Fuzzy Logic (NFL), was introduced in [9] to improve output power and minimize response time under variable climatic conditions. In [10], MPPT is based on a First-Order Proportional Integral Derivative (FOPID) controller to eliminate disturbances affecting the output voltage. The simulation results demonstrated the improved performance and dynamic response of the system with this strategy compared to classical command. In [11], Nonlinear Integral Backstepping (NIB) is employed to control a PVS. The results proved the efficiency of this strategy. However, persistence of complexity problems results in higher energy costs, which is undesirable. An intelligent MPPT approach, combining neural networks and fuzzy logic for PVS control is detailed in [12]. The advantage of this strategy lies in its increased robustness and rapid dynamic response compared to traditional methodologies. On the other hand, to control non-linear Variable Structure Systems (VSS) and reduce their complexity, First Order SMC (SMC) is widely recognized as a more efficient control tool. This type of control is particularly useful for PVS, due to its high accuracy and robustness. Also, power converters are part of VSS because their configuration is constantly changing due to switches [13]. The idea behind SMC is to force system states to converge on a predefined Sliding Surface (SS) that is independent of system parameters and disturbances but depends solely on the sliding coefficient. This simplifies the design and decouples the state variables. It is on this surface that system states exhibit desirable characteristics. Once the system reaches this surface, the controller keeps it there permanently [14]. However, the characteristics of the SMC are not fully guaranteed due to the need to discretize the control in discrete time, leading to reduced accuracy and losses in power converters. Thus, it is necessary to make improvements to the SMC, focusing on solving the above-mentioned problems [15]. For this reason, numerous improvements based on the classic SMC have been suggested, including terminal SMC [16], integral SMC [17] and SMC with observer [18] and SMC controller based on an adaptive perturbing Fuzzy T-S approach (Fuzzy T-S SMC) in [19]. [20] Presented SMC control for Single Ended Primary Inductor Converter (SEPIC) at precise MPP tracking and enhanced PVS robustness. The authors of [21] discussed

the Fractional Order SMC control to optimize the performance of the power delivered by PMSG and regulate the V_{dc} . This technique exhibits fast time response under variable wind conditions. In reference [22], the author presents an SMC controller using a two-power-law control method, for PVS and battery-powered DC micro-grids. Despite its advantages, SMC is not widely used in some industrial applications due to the problem of chattering, which reduces control accuracy. Although various improvements have been proposed, a compromise between chattering and steady-state error persists. While these strategies offer many advantages, they also have disadvantages, including power variations and high levels of total harmonic distortion (THD). The advantages and disadvantages of some of the above strategies are summarized in Table 1.

Table 1: Comparison of some strategies used in PVS control.

Strategy Name	Advantage	Disadvantage
Fuzzy Logic Control (FLC) and PSO [8]	robust for minimizing response time	Complex hardware and programming required
Neuro-Fuzzy Logic (NFL)[9]	rapid convergence	Oscillation near the operating point
First-Order plus Integral plus Derivative (FOPID)[10]	rapid dynamic response	large overrun
Nonlinear Integral Backstepping (NIB)[11]	Good performance	higher construction costs
SMC[22]	Simple and inexpensive	chattering

In this context, the proposed Sliding Mode Control (SOSMC) control was used to solve these problems in order to optimize power management and improve the MPPT process. Thus, the application of the SOSMC strategy is the major contributions of this study. This controller is compared to the classical SMC in terms of several performance criteria (dynamic response, overshoot, chattering and THD) through different test scenarios. The simulation results demonstrate its effectiveness and robustness. Table 2 summarizes a comparative study of the additions made by SOSMC compared with classical SMC [16] [17] [18] [19] [20].

Table 2: Comparison of performance criteria for SOSMC and SMC classic

Criteria	SMC	SOSMC
Improved response time	-	+
Stability at steady state	-	+
Minimize overshoot	-	+
Eliminates chattering	-	+
robustness	+	+
Simple converter and filter design	+	+
Simplicité des calculs des gains	+	-

Note: (+) meets the criteria and (-) does not meet the criteria

Therefore, the principal contributions of this work are as follows:

- The proposed MPPT-SOSMC method integrates the SOSMC algorithm to replace the traditional P&O controller to improve the performance of MPPT technology under climatic conditions of the PVS.
- Reduction of THD and response time of the current injected into the grid using the SOSMC method developed.
- A comparison of results based on the proposed SOSMC method and traditional CVC under different conditions.
- The SOSMC method developed reduces the "chattering" effects of traditional SMC.

This article is organized as described in the following paragraph: the first section introduces the work by presenting its contribution and objectives. The PVG and PVS models are presented in section two. The third part presents the DC-DC converter and its SOSMC control system. The fourth section presents the DC-AC converter and its SOSMC control. The simulation results and analysis of the proposed SOSMC method are explained in the fifth section, including a comparison with the CVC technique. Finally, the sixth section summarizes the overall conclusions of this study.

2. Overview of Grid-Connected Photovoltaic Systems

Figure 1 presents a diagram of a PVS connected to the three-phase grid via two power converters. The first one, functioning as a DC-DC converter in boost mode, is specifically designed for regulating the power on for PVG side. The second converter, a DC-AC converter acting as an inverter, is mainly responsible for maintaining constant V_{dc} , synchronizing the power produced by the PVG and the grid, while ensuring a UPF. The capacitor decoupling allows for independent control of each power converter.

The PVG is formed by a set of PV cells linked together in a series-parallel configuration. Its main function is to generate electricity directly from sunlight. The corresponding circuit of a single diode PV cell is shown in Figure 2. The PVG is modelled using the following equations [23]:

$$I_{pv} = I_{ph} - I_d - I_{sh} \quad (1)$$

The I_d flowing through the diode is given by:

$$I_d = I_0 \left[\exp \left(\frac{q}{A \cdot k \cdot T} (V_{pv} + I_{pv} \cdot R_s) \right) - 1 \right] \quad (2)$$

The equation 3 presents the saturation current I_0 :

$$I_0 = I_{rs} \left[\frac{T}{T_r} \right]^3 \cdot \exp \left[\left(\frac{q \cdot E_g}{A \cdot K} \right) \left(\frac{1}{T_r} - \frac{1}{T} \right) \right] \quad (3)$$

The expression for current I_{rs} is given by:

$$I_{rs} = \frac{I_{sc}}{\exp \left[\frac{q \cdot V_{oc}}{N_s \cdot A \cdot K \cdot T_r} \right] - 1} \quad (4)$$

I_{sh} current is defined by:

$$I_{sh} = \frac{V_{pv} + I_{pv} \cdot R_s}{R_{sh}} \quad (5)$$

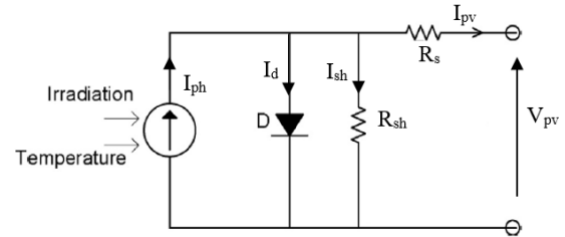
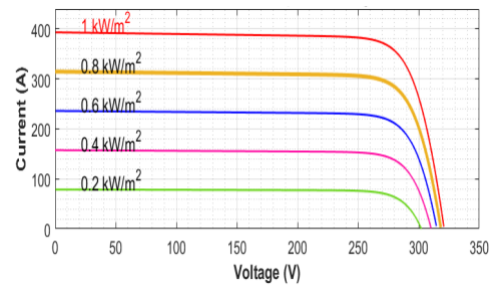


Figure 1. Topology of PVS connected to Grid



By replacing Eq. (2) and Eq. (5) with Eq. (1), the I_{pv} is calculated by [24]:

$$I_{pv} = I_{ph} - I_0 \left[\exp \left(\frac{q}{A \cdot k \cdot T} (V_{pv} + I_{pv} \cdot R_s) \right) - 1 \right] - \left(\frac{V_{pv} + I_{pv} \cdot R_s}{R_{sh}} \right) \quad (6)$$

The photocurrent I_{ph} , influenced by the irradiance and cell temperature, is given by:

$$I_{ph} = [I_{sc} + K_i \cdot (T - T_r)] \cdot \left(\frac{G}{G_r} \right) \quad (7)$$

Where; I_{ph} and I_{sc} are the photocurrent and short-circuit current, respectively (A), q is the electric charge, K is the Boltzmann constant, K_i is the current temperature coefficient ($A/^\circ C$), A is the cell's ideality factor, G is the irradiance at the module surface (W/m^2), G_r is the reference irradiance ($G_r = 1000 W/m^2$), T is the module temperature (K), T_r is temperature reference (293K), V_{oc} is the voltage in open circuit (V), E_g is the band gap energy (eV), R_s and R_{sh} are the series and shunt resistors (Ω), respectively. N_s is the number of series cells.

The I_{pv} generated by the PVG when several identical modules are linked in parallel (N_{pp}), series (N_{ss}) or series-parallel ($N_{ss} \cdot N_{pp}$) is defined as follows:

$$I_{pv} = N_{pp} \cdot I_{ph} - N_{pp} \cdot I_0 \left[\exp \left(\frac{q}{A \cdot k \cdot T} \left(\frac{V_{pv}}{N_{ss}} + \frac{I_{pv} \cdot R_s}{N_{pp}} \right) \right) - 1 \right] - \frac{N_{pp}}{R_{sh}} \left(\frac{V_{pv}}{N_{ss}} + \frac{I_{pv} \cdot R_s}{N_{pp}} \right) \quad (8)$$

Figure 3 shows the effect of temperature and irradiance on the PVG parameters (I-V) and (P-V).

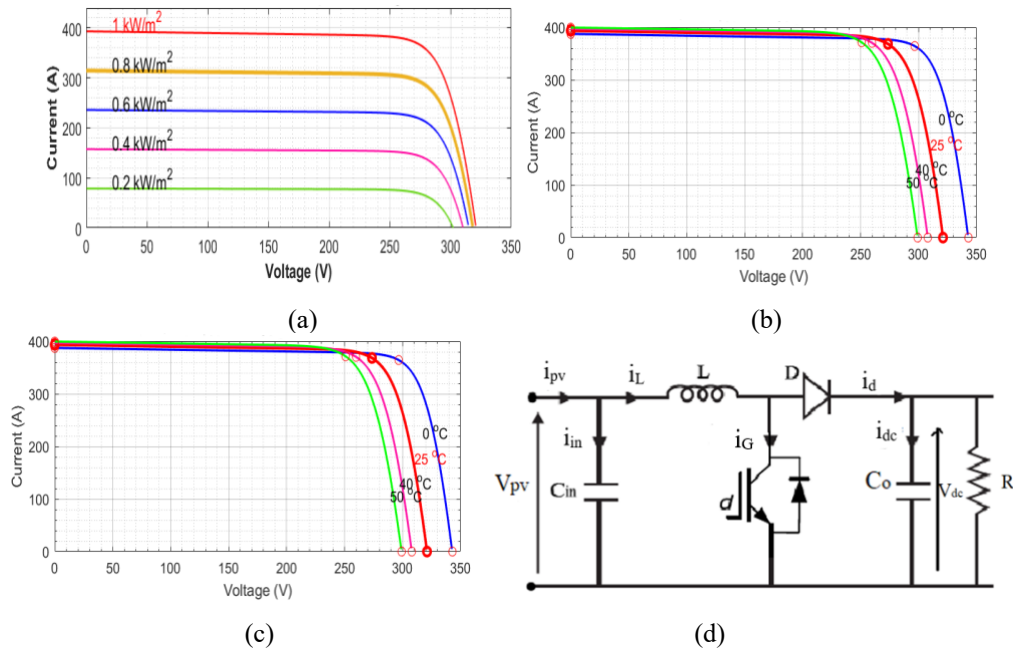


Figure 3. P-V and I-V characteristics of PVG according to irradiance (a, b) and temperature (c, d)

3. Modeling and Control of the Boost Converter

3.1. Modeling the Boost Converter

The boost converter is used as an interface to adjust the voltage between the PVG and the inverter. The proposed control objectives are to maintain MPP and increase output voltage. Figure 4 presents the schematic of the used boost converter, where C_{in} , L , C_0 , and R denote PVG rated capacitance, inductance, DC bus capacitance and load, respectively. The control determines the duty cycle α used for switching the boost switch, as follows:

$$\alpha = \frac{V_{dc} - V_{pv}}{V_{dc}} \quad (9)$$

The characteristic equations of the boost converter, in terms of current and voltage, are expressed[25]:

$$\begin{cases} \frac{dI_{pv}}{dt} = \frac{1}{L} \cdot [V_{pv} - (1 - \alpha) \cdot V_{dc}] \\ \frac{dV_{dc}}{dt} = \frac{1}{C_0} \cdot [(1 - \alpha) \cdot I_L - \frac{V_{dc}}{R}] \end{cases} \quad (10)$$

Where, V_{pv} is the voltage delivered by PVG.

Equations (11) and (12) provide the expressions for the capacitance C_0 and the inductance L , respectively [26].

$$L = \frac{\alpha \cdot V_{dc} \cdot (1 - \alpha)}{\Delta I_{pv} \cdot F_s} \quad (11)$$

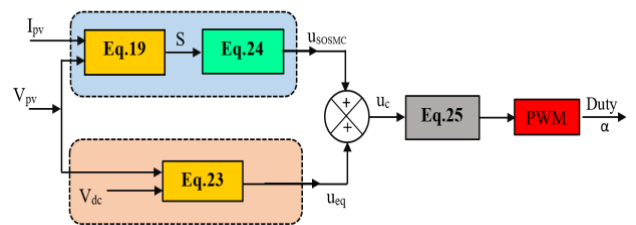


Figure 4. Boost Converter

$$C_0 = \frac{\alpha \cdot V_{dc}}{\Delta V_{dc} \cdot F_s} \quad (12)$$

Where ΔI_{pv} and ΔV_{dc} are the ripples in input current and voltage, respectively. F_s is the boost switching frequency.

3.2. SOSMC Controller Design

The objective of SOSMC is not only to reduce the SS surface to zero, but also to cancel successive derivatives of the relative degree (n) of SS with respect to the control input [27]. The SS is expressed mathematically as follows:

$$\begin{cases} SS = x_{ref} - x \\ SS = \frac{dSS}{dt} = \frac{d^2SS}{dt^2} = \dots = \frac{d^{n-1}SS}{dt^{n-1}} = 0 \end{cases} \quad (13)$$

Where x is the parameter to be regulated and x_{ref} its reference

Well-known SOSMC algorithms include Torsion, Super Torsion (STA), among which STA stands out because it offers the possibility of using fixed switching frequencies [27]. The SOSMC controller control, u_c , is made up of two components: the equivalent control component u_{eq} and the SOSMC algorithm term u_{SOSMC} .

$$u_c = u_{eq} + u_{SOSMC} \quad (14)$$

Solving equation 15 allows us to determine the equivalent control term u_{eq}

$$\frac{dSS}{dt} = 0 \quad (15)$$

The expression for the term u_{SOSMC} is given by:

$$u_{SOSMC} = u_1 + u_2 \quad (16)$$

Where:

$$\begin{cases} u_1 = \beta_1 |SS|^{0.5} \cdot \text{sign}(SS) \\ u_2 = \beta_2 \int \text{sign}(SS) \cdot dt \end{cases} \quad (17)$$

The tuning constants of the SOSMC controller, denoted as β_1 and β_2 , will be selected to ensure optimal operation of the PVS.

3.1 SOSMC for Boost Converter

Starting from the P-V and I-V profiles of the PVG shown in Figure 4, we can deduce that, when operating at maximum power:

$$\frac{dP_{pv}}{dV_{pv}} = \frac{d(V_{pv} \cdot i_{pv})}{dV_{pv}} = i_{pv} + V_{pv} \cdot \frac{di_{pv}}{dV_{pv}} = 0 \quad (18)$$

The surface SS is determined according to equation (19) to reach the MPP [28].

$$SS = \frac{dP_{pv}}{dV_{pv}} \quad (19)$$

The equivalent control term u_{eq} of the SOSMC controller is determined by solving the following equation:

$$\frac{dSS}{dt} = \frac{dSS}{di_{pv}} \cdot \frac{di_{pv}}{dt} = 0 \quad (20)$$

The equation (10) can be written:

$$\dot{x} = f(x) + g(x) \cdot u_{eq} \quad (21)$$

Where :

$$x = \begin{pmatrix} i_{pv} \\ V_{dc} \end{pmatrix}; f(x) = \begin{bmatrix} \frac{V_{pv} - V_{dc}}{L} \\ \frac{R \cdot i_L - V_{dc}}{C_o \cdot R} \end{bmatrix} \text{ and } g(x) = \begin{bmatrix} \frac{V_{dc}}{L} \\ \frac{-i_L}{C_o} \end{bmatrix} \quad (22)$$

Finally, from equations (21) and (22) in equation (20), we can deduce the equivalent term u_{eq} as follows:

$$u_{eq} = 1 - \frac{V_{pv}}{V_{dc}} \quad (23)$$

Integration of the term u_{SOSMC} ensures that the PVS stays on the SS despite parametric variations and external disturbances. Substituting equations (17) into (16), we get:

$$u_{SOSMC} = \beta_1 \cdot |SS|^{0.5} \cdot \text{sign}(SS) + \beta_2 \cdot \int \text{sign}(SS) \cdot dt \quad (24)$$

The final expression of the proposed control signal is given by:

$$u_c = 1 - \frac{V_{pv}}{V_{dc}} + \beta_1 \cdot |SS|^{0.5} \cdot \text{sign}(SS) + \beta_2 \cdot \int \text{sign}(SS) \cdot dt \quad (25)$$

Figure 5 shows the boost converter control diagram using the SOSMC method.

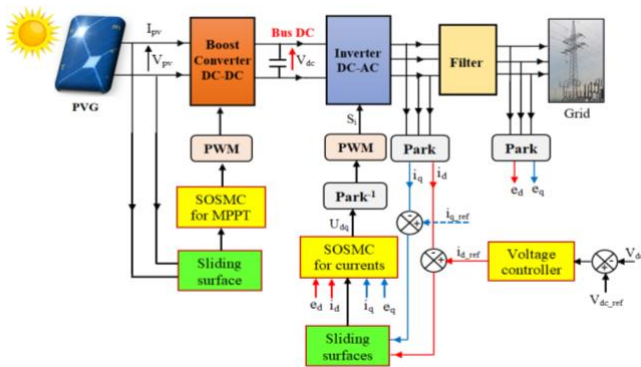
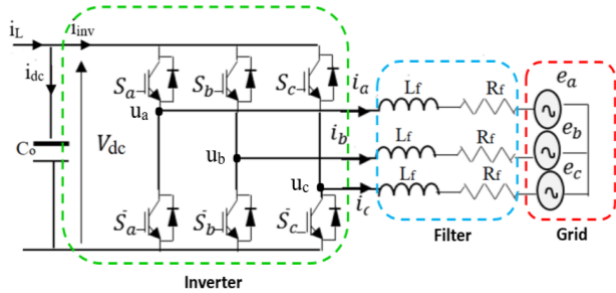
4. Modeling and Control Design on the Grid Side With SOSMC

4.1. Modeling of the Inverter

The function of the inverter is to maintain V_{dc} constant and to regulate P and Q injected into the grid in order to have a UPF in response to irradiation variations. Various strategies are employed for inverter control. In this article, the SOSMC command is used to control this inverter. A two-loop scheme is therefore adopted [29]. The internal control loops regulate the quadrature (i_q) and direct (i_d) currents, while the other loop regulates the V_{dc} and generate the reference source current i_{d-ref} . The circuit diagram of the inverter connected to grid is shown in Figure 6. The analytical model of the three-phase circuit is given by equation:

$$\frac{d}{dt} \begin{pmatrix} i_a \\ i_b \\ i_c \end{pmatrix} = \frac{1}{L_f} \left[\begin{pmatrix} u_a \\ u_b \\ u_c \end{pmatrix} - R_f \cdot \begin{pmatrix} i_a \\ i_b \\ i_c \end{pmatrix} - \begin{pmatrix} e_a \\ e_b \\ e_c \end{pmatrix} \right] \quad (26)$$

Where e_a , e_b and e_c represent the grid voltage components, while u_a , u_b and u_c denote the inverter system output voltages. Line currents are defined as i_a , i_b and i_c , L_f and R_f are the inductance and resistance of the filter.



The determination of the value of the inductance L_f is done as follows [30]:

$$L_f = \frac{\sqrt{3} \cdot m_a \cdot V_{dc}}{12 \cdot h \cdot f_s \cdot \Delta i_L} \quad (27)$$

Where, m_a is the modulation index, h is overload factor ($h=1.2$), f_s is the inverter switching frequency, Δi_L is the ripple of the nominal current (10%).

In a three-phase coordinate system, the variables undergo changes, creating interdependence between them. This poses challenges when designing the system controller. To resolve this situation, a Park transformation is used to transform the three-phase coordinates to two synchronous d-q rotational coordinates [29]. The transition from equation (27) to the d-q reference frame is as follows:

$$\begin{cases} \frac{di_d}{dt} = \frac{1}{L_f} \cdot (V_d - R_f \cdot i_d - e_d) + \omega i_q \\ \frac{di_q}{dt} = \frac{1}{L_f} \cdot (V_q - R_f \cdot i_q - e_q) - \omega i_d \end{cases} \quad (28)$$

With ω , the grid pulsation, i_d and V_d are the direct term of the current and voltage, i_q and V_q are the quadrature term of the current and voltage on the inverter side, e_d and e_q are the direct and quadrature term of the voltage on the grid side. The P and Q are given with:

$$\begin{cases} P = \frac{3}{2} (V_d \cdot i_d + V_q \cdot i_q) \\ Q = \frac{3}{2} (V_d \cdot i_q - V_q \cdot i_d) \end{cases} \quad (29)$$

Thus, the link current equation is defined by:

$$i_{dc} = i_L - i_{inv} \quad (30)$$

Where, i_{inv} is the current of the transmission line on the grid side, i_L is the current of the transmission line on the boost side, i_{dc} is the intermediate circuit current.

According to Eq. (29), we can rewrite Eq. (30) as follows:

$$C_0 \cdot \frac{dV_{dc}}{dt} = \frac{3}{2V_{dc}} (V_d \cdot i_d + V_q \cdot i_q) - i_{inv} \quad (31)$$

When the tension vector is aligned on the d-axis, then:

$$V_d = V \quad \text{and} \quad V_q = 0 \quad (32)$$

Therefore, we can rewrite Eq. (28-29) as follows:

$$\begin{cases} \frac{di_d}{dt} = \frac{1}{L_f} \cdot (V - R_f \cdot i_d - e_d) + \omega i_q \\ \frac{di_q}{dt} = -\frac{1}{L_f} \cdot (R_f \cdot i_q + e_q) - \omega i_d \end{cases} \quad (33)$$

$$\begin{cases} P = \frac{3}{2} \cdot V \cdot i_d \\ Q = \frac{3}{2} \cdot V \cdot i_q \end{cases} \quad (34)$$

P and Q can therefore be controlled by regulating i_q and i_d . Thus, the i_q reference (i_{q_ref}) is kept at zero to achieve UPF, while i_d reference (i_{d_ref}) is determined by the V_{dc} controller to regulate the P of the converter. The control method involves two control loops, allowing for independent regulation of P, Q and V_{dc} . The V_{dc} reference (V_{dc_ref}) is determined using the following equation [29]:

$$V_{dc-ref} = \frac{2\sqrt{2} \cdot V_{LL}}{\sqrt{3} \cdot m_a} \quad (35)$$

Where V_{LL} represents the line-to-line voltage of the grid.

4.2. SOSMC Controller Design

The aim of SOSMC control for inverter connected to grid is to eliminate the chattering phenomenon generated by conventional SMC thanks to an integral term of the current error is added. The SS can be described as follows [30]:

$$SS_{dq} = i_{dq-ref} - i_{dq} \quad (36)$$

To obtain switching close to the surface SS and ensure excellent performance, the command u_c is exeprired by [14]:

$$u_{c_dq} = u_{d,q,eq} + u_{d,q,STA} \quad (37)$$

Where $u_{d,q,eq}$ is computed from the equation:

$$SS_{dq} = \frac{dSS_{dq}}{dt} = 0 \quad (38)$$

By applying equation (33), the temporal derivatives of SS_d and SS_q can be evaluated as follows:

$$\begin{cases} \frac{dSS_d}{dt} = \frac{di_{d-ref}}{dt} - \frac{di_d}{dt} = \frac{di_{d-ref}}{dt} - \frac{1}{L_f} (R \cdot i_d + L\omega i_q + V - e_d) \\ \frac{dSS_q}{dt} = \frac{di_{q-ref}}{dt} - \frac{di_q}{dt} = \frac{di_{q-ref}}{dt} - \frac{1}{L_f} (R \cdot i_q - L\omega i_d - e_q) \end{cases} \quad (39)$$

From equation (39), u_{eq} can be calculated as follows:

$$\begin{cases} u_{d-eq} = \frac{di_{d-ref}}{dt} + R \cdot i_d - L\omega i_q + e_d \\ u_{q-eq} = R \cdot i_q + L\omega i_d + e_q \end{cases} \quad (40)$$

Furthermore, u_{STA} is employed to ensure the attraction of the controlled variable towards the switching surface. u_{STA} can be expressed as follows [30]:

$$\begin{cases} u_{STA} = -\lambda_1 \cdot |SS|^{0.5} \cdot \text{sign}(SS) + z \\ \dot{z} = -\lambda_2 \cdot \text{sign}(SS) \end{cases} \quad (41)$$

Where λ_1 and λ_2 are positive constants.

The final expressions of the proposed commands are:

$$\begin{cases} u_d = \frac{di_{d-ref}}{dt} + R \cdot i_d - L\omega i_q + e_d - \lambda_1 \cdot |SS_d|^{0.5} \cdot \text{sign}(SS_d) \\ \quad - \lambda_2 \cdot \int \text{sign}(SS_d) \times dt \\ u_q = R \cdot i_q + L\omega i_d + e_q - \lambda_3 \cdot |SS_q|^{0.5} \cdot \text{sign}(SS_q) \\ \quad - \lambda_4 \cdot \int \text{sign}(SS_q) \times dt \end{cases} \quad (42)$$

Figure 7 presents the block diagram of the inverter control using the proposed SOSMC method. The global diagram of the PVS connected to the grid via an inverter is illustrated in Figure 8, incorporating the advanced control methods proposed. The Table 3 gives the PVS parameters.

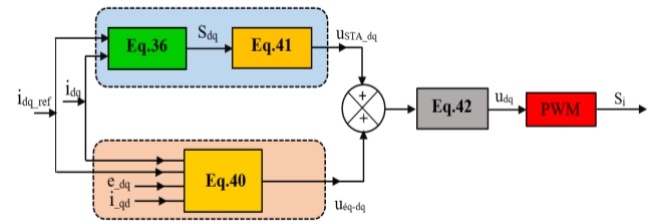


Figure 8. Global schematic of a PVS connected to the grid

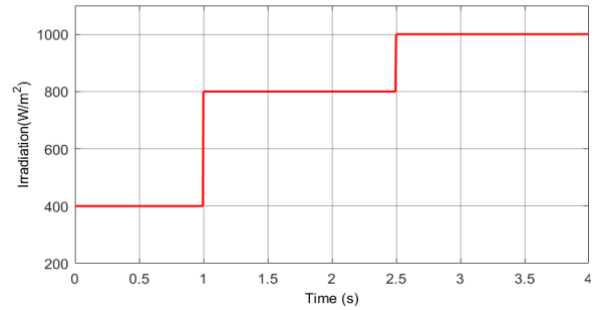


Table 3. PVS parameters

Parameter	Symbol	Value
Boost Converter		
Capacitor for DC bus (μF)	C_O	2000
Input capacitor (μF)	C_{in}	1000
Inductance of the boost (mH)	L	3,5
Switching frequency (kHz)	F_s	5
Filter		
Inverter inductance (mH)	L_f	3
Inverter switching rate (kHz)	F_{sh}	5
DC bus voltage reference (V)	V_{dc_ref}	700

5.The Simulation Results

The PVG used in this study is based on the "SunPower SPR-305-WHT" module. This PVG offers a maximum output of 100 kW at $G=1000W/m^2$ and $T=25^\circ C$. At a light intensity of $800 W/m^2$, the PVG's maximum power is 80 kW,

and at $G=400 \text{ W/m}^2$, the PVG delivers 40 kW as maximum power. Since temperature has a negligible impact on maximum power, it is kept constant at 25°C . Model of PVS is simulated using Matlab/Simulink under standard and real environmental conditions. In this section, a comparative study between SOSMC and conventional CVC is performed to demonstrate the efficiency of the proposed technique. The irradiation profile used is shown in Figure 9. The results for the two methods are presented in Figures 10 to 15.

The Figures 10 and 11 illustrates, respectively, the P and Q injected into the electrical grid using the SOSMC control and conventional CVC method. It can be seen that powers converge to its MPP value at each irradiation variation, with great precision and rapid response. At $G=1000\text{W/m}^2$ the P attains its maximum value supplied by the PVG (100 kW) and the overshoot is 100% reduced, while Q remains at zero ($Q=0 \text{ VAR}$).

Most grid-connected SPVs use the CVC method to control the power fed to grid. However, its disadvantage lies in the presence of oscillations around the PPM and its delayed response, resulting in energy loss. In contrast, the SOSMC method demonstrates high performance in terms of time to response, overshoot damping and reduction of steady-state error.

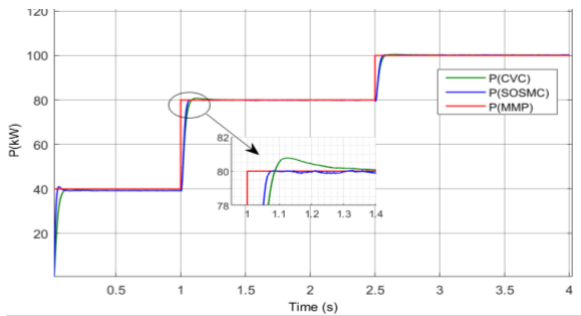


Figure 9. Irradiation variations in W/m^2

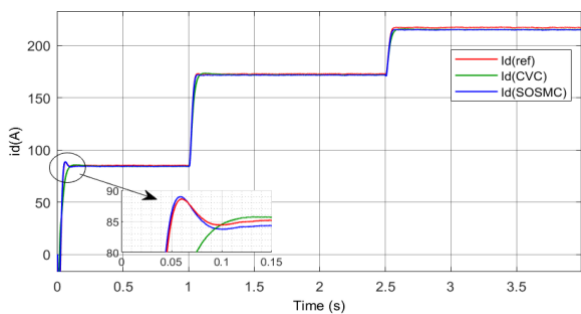


Figure 10. P with SOSMC and CVC under real conditions

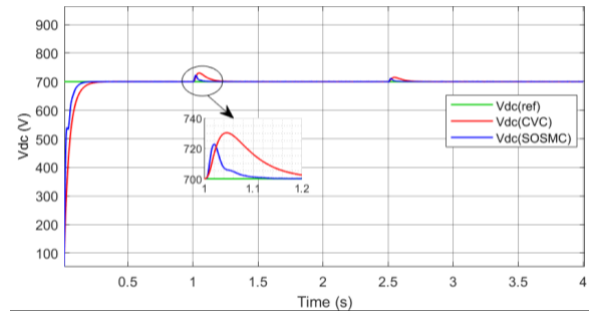


Figure 11. Q with SOSMC and CVC under real conditions

To ensure high-quality energy transfer from the PVG to the power grid, the V_{dc} is regulated by an external loop to maintain its reference value ($V_{dc_ref} = 700\text{V}$). Figure 12 shows the dynamics of V_{dc} during irradiation variations. It is clear that it precisely follows its reference value in a very short time, and that the steady-state error is minimal for the proposed SOSMC controller.

In Figure 13, the current i_d accurately converges to its reference value (i_{d_ref}) more quickly under SOSMC control than under CVC control when irradiation varies. This follow-up means that current i_q is well maintained at its reference ($i_{q_ref} = 0$).

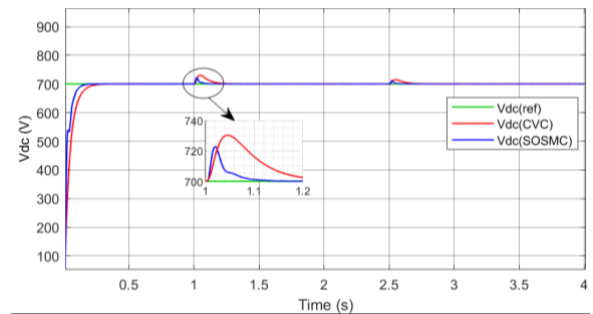


Figure 12. V_{dc} responses with SOSMC and CVC under real conditions

Figure 14 shows the current injected into grid for a first phase. It has a sinus wave form with a 50 Hz frequency, thus ensuring a low rate of current harmonics. The figure also shows that grid voltages and currents are in phase, confirming the absence of Q injection into the grid and ensuring a UPF. Figure 15 shows the results of Fast Fourier Transform (FFT) analysis of the first-phase current connected to the grid for the HVAC (Figure 15a) and SOSMC (Figure 15b) controllers. The THD of the current for the SOSMC is reduced to 1.09%, compared with 2.19% for the CVC. These THD values show that the CVC technique was affected by irradiation variations compared with SOSMC. The method we have developed achieves a significant reduction in grid current THD compared with improved SMC techniques (see Table 4), which justifies its robustness in the face of fluctuations.

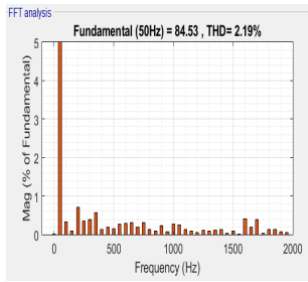


Figure 13. i_d responses with SOSMC and CVC under real conditions

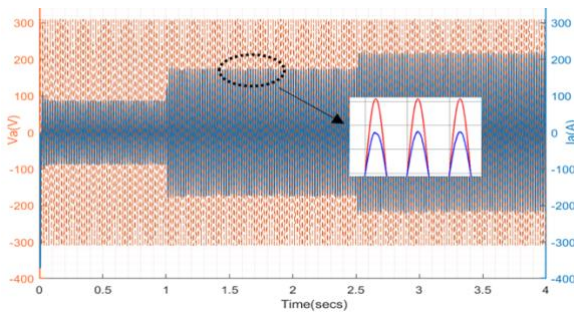


Figure 14. Current responses I_a of the first phase injected into the grid with SOSMC control

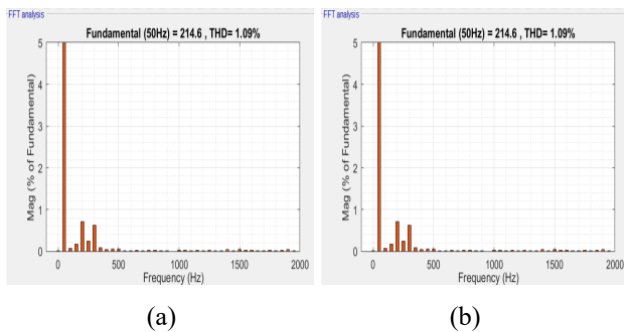


Figure 15. Fourier transforms analysis of grid-connected current with CVC (a) and SOSMC (b)

Table 4: a comparative study between results obtained from the proposed SOSMC and other methods already published

reference	technique	THD(%)
[14]	FOSMC (SMC)	4.4
[30]	IC-SMC	3.27
	FL-SMC	3.12
	RL-SMC	2.95
[28]	DM-SMC	3.3
[31]	SMC-IC-IPT	3.38
Proposed techniques	CVC	2.19
	SOSMC	1.09

5. Conclusion

This article presents a new SOSMC controller for regulating a PVS in two distinct stages. First, on the Direct Current (DC) side, the aim of the controller is to maximize the power produced by the PVG under both variable climatic conditions. Then, on the Alternating Current (AC) side, the aim is to transfer this power to grid as a UPF. The SOSMC controller based strategy is designed to improve PVS performance over the conventional SMC strategy, by reducing P and Q ripples. The results of the comparison between the SOSMC and the CVC show that P overshoot is reduced by 100% in the event of a sudden change in irradiance and response time is minimized. In addition, it reduced the THD of the current to 1.09%, compared with 2.19% for the CVC. Consequently, the SOSMC strategy appears to be a promising solution for increasing the energy efficiency of grid-connected photovoltaic systems.

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Author Contributions

All authors were responsible for the conceptualization, validation, resources, data curation, software development, and project administration. They jointly contributed to the methodology, formal analysis, investigation, original draft preparation, review and editing, visualization, supervision, and funding acquisition. All authors have read and agreed to the published version of the manuscript.

Conflict of Interest

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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