High order sliding mode control for grid integration of photovoltaic systems

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ABSTRACT

The article suggests employing second-order sliding mode control (SOSMC) to manage photovoltaic systems (PVS) connected to the electrical grid. These systems face complexities due to non-linearities, variability, uncertainties, disturbances, and climate changes. The proposed control strategy utilizes two converters: one at the photovoltaic generator (PVG) side for maximum power point tracking (MPPT) to optimize energy generation and another at the grid connection point to regulate power injection into the grid and maintain the DC bus voltage (V_{dc}) while achieving unit power factor (UPF). Both converters are equipped with SOSMC controllers, enabling independent adjustment of active (P) and reactive (Q) power. This approach aims to enhance the energy efficiency and robustness of PVS under varying climatic conditions. The performance of the system is evaluated under standard and variable irradiation conditions using the MATLAB/Simulink environment. Simulation results indicate that SOSMC significantly improves system performance and efficiency compared to conventional vector control (CVC). Notably, it reduces active power overshoot by 100%, decreases V_{dc} response time, and lowers total harmonic distortion (THD) of the current to 1.19%, demonstrating its effectiveness across different irradiation levels.

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1. INTRODUCTION

In recent years, the advancement in renewable and green energy utilization has emerged as a key solution to environmental pollution caused by fossil fuels and the decline in energy production [1]. Renewable energy-based power generation systems are now crucial in global energy production. Among the available renewable sources, photovoltaic (PV) energy stands out as the most favorable option due to its widespread availability, environmental benefits, and cost-free nature [2]. Compared to other energy sources, PV systems are highly regarded for their durability and efficiency, establishing PV as a rapidly growing energy source worldwide. PV systems are expected to grow by 15% between 2020 and 2040 and have the potential to generate 9000 TWh, representing 26% of projected global demand [3]. This trend requires most photovoltaic power generation plants to make substantial changes to their operational and control structures. Consequently, many researchers have proposed various control configurations to improve the desired operational characteristics [4]. In the literature, most articles on grid-connected PV systems concentrate on inverter control. These methods typically employ proportional-integral (PI) controllers to regulate the V_{dc} and the current supplied to the grid, ensuring maximum active power transfer (P). For maximum power point tracking (MPPT) control, the perturb and observe (P&O) technique is commonly used due to its simplicity and satisfactory results [5]. However, it is important to note that this technique exhibits fluctuations around the operating point and can lose this point during rapid changes in irradiation, so for high-quality energy transfer, an alternative method for MPPT is required [6]. One method that fulfills this requirement is sliding mode control (SMC), particularly high-order sliding mode control (HOSMC). SMC is valued for its robustness against climatic fluctuations. HOSMC is introduced to overcome the challenges associated with first-order SMC, especially the significant issue of chattering around the sliding surface (σ) [7]. The development of grid-connected PV systems has led many researchers to study their robustness and stability. For instance, Debdouche *et al*. [8] propose a control strategy for grid-connected inverters that combines model predictive control with integral sliding mode control. Ali *et al*. [9] show that combining fuzzy logic control (FLC) with particle swarm optimization (PSO) algorithms enhances MPPT compared to P&O methods. While this technique offers robust performance in minimizing response time, it is complex to implement. Another MPPT method, introduced in [10], employs neuro-fuzzy logic (NFL) to improve output power and response time under varying climatic conditions. Zheng *et al*. [11] describe an MPPT strategy using a first-order plus integral plus derivative (FOPID) controller to eliminate disturbances affecting output voltage, demonstrating enhanced performance and dynamic response compared to traditional methods. In [12], an adaptive perturbing fuzzy Takagi-Sugeno sliding mode control (Fuzzy T-S SMC) approach is developed for accurate MPPT tracking and reducing oscillations around the MPP. Shahdadi *et al*. [13] present SMC control for a SEPIC boost converter, achieving precise MPP tracking and increased system robustness. Guo *et al*. [14] suggest using a second-order sliding mode control (SOSMC) configuration for a PV system with a single power converter, aiming to generate sinusoidal current for the grid and reduce harmonics, thus improving robustness against solar irradiance fluctuations. Beniss *et al*. [15] discuss fractional order SMC (FOSMC) to optimize power delivery and regulate DC voltage in permanent magnet synchronous generators (PMSG), showing fast response under variable wind conditions. Nonlinear integral backstepping (NIB) for PV systems, as presented in [16], proved efficient, though complexity issues can lead to higher energy costs. An intelligent MPPT approach combining neural networks and fuzzy logic (NN-FL) for PV control is detailed in [17], offering increased robustness and rapid dynamic response compared to conventional methods. Roy *et al*. [18] introduce an SMC controller using a two-power-law control method for PV systems and battery-powered DC microgrids, although chattering remains a major drawback. Various improvement methods, including the terminal SMC (TSMC) technique cited in [19], continuous nonlinear predictive control with integral SMC (ISMC) described in [20], and fuzzy SMC (FSMC) presented in [21], explore different strategies to enhance performance. While these strategies provide numerous benefits, they also come with drawbacks, such as power fluctuations and high levels of THD, which negatively impact overall power quality. Table 1 summarizes the advantages and disadvantages of some of these strategies.

In this context, the SOSTM and MPPT-SOSMC controllers are the major contributions of this paper. The results are compared with the conventional technique regarding dynamic response, overshoot and THD under two different irradiation profiles. Simulation results demonstrate its effectiveness compared to conventional control methods. Therefore, the principal contributions of this work are as follows:

- The SOSMC method reduces the chattering effects of traditional SMC;
- The MPPT-SOSMC method replaces the P&O to improve MPPT;
- The developed SOSMC method reduces the THD of the current injected to the grid; and
- Reduce P and Q overshoots and steady-state errors.

The structure of this article is: the first section presents the introduction to this work. The second section describes the photovoltaic generator (PVG) model, the DC-DC, DC-AC converter and its SOSMC control. The third section details the simulation results and analysis of the proposed SOSMC method, including a comparison with the conventional vector control (CVC) technique, while the fourth section presents a general conclusion of this study.

Table 1. Comparison of some strategies used in PV system control

Strategy Name	Advantage	Disadvantage
FLC and PSO [9]	Robust for minimizing response time	Complex hardware and programming required
NFL [10]	Rapid convergence	Oscillation near the operating point
FOPID [11]	Rapid dynamic response	Large overrun
SMC [13]	Simple and inexpensive	Chattering
NIB [16]	Good performance	Higher construction costs

2. PROPOSED SYSTEM

Figure 1 illustrates a diagram of a PV system connected to a grid through two power converters. The first converter, operating as a DC-DC converter in boost mode, is designed to regulate power on the PVG side. The second converter, functioning as a DC-AC inverter, is primarily responsible for maintaining a constant V_{dc} and ensuring a unity power factor (UPF).

2.1. Modeling of the PV generator

The PVG is composed of PV cells arranged in a series-parallel configuration to produce electricity directly from sunlight. Figure 1 shows the circuit diagram of a single-diode PV cell. Figure 2 shows the effect of temperature and irradiance on the PVG parameters (P-V). The PVG is modeled using (1) [21].

$$i_{pv}= i_{ph}\text{-}\, i_0\left[Exp\left(\frac{q}{A.k.T}\left(V_{pv}+i_{pv}.R_s\right)\right)\text{-}1\right]\ \text{-}\ \left(\frac{V_{pv}+i_{pv}.R_s}{R_{sh}}\right) \quad (1)$$

The photocurrent i_{ph}, influenced by the irradiance and cell temperature, is given by (2).

$$i_{ph}=[i_{sc}+K_i.(T\text{-}T_r)].\left(\frac{G}{G_r}\right) \quad (2)$$

Where: i_{sc} is short-circuit current, q is the electric charge, K is the Boltzmann constant, K_i is the current temperature coefficient, A is the cell's ideality factor, G is the irradiance, G_r is the reference irradiance, T is the temperature, T_r is temperature reference, V_{oc} is the voltage in an open circuit, E_g is the band gap energy, R_s and R_{sh} are the series and shunt resistors, and N_s is the number of series cells.

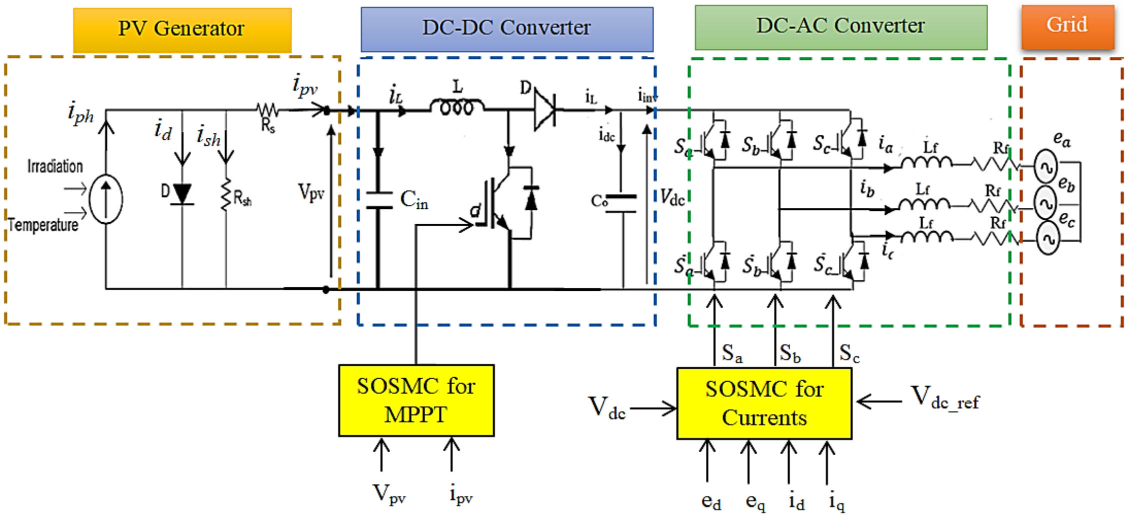
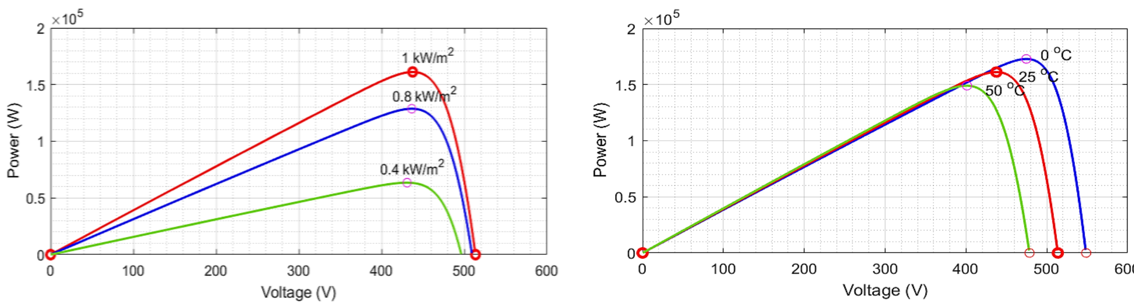


Figure 1. Topology of PVS connected to grid



(a) (b)

Figure 2. P-V characteristics of PVG according to (a) irradiation and (b) temperature

2.2. SOSMC controller design

In the SMC technique, the system trajectories are guided towards a specific surface known as the sliding surface (σ), where desirable characteristics are achieved. The controller ensures that the system remains on this surface at all times [22], [23]. However, this method can lead to persistent oscillations in the steady state, which is undesirable. In contrast, the SOSMC method is regarded as one of the most effective strategies for reducing chattering effects and enhancing the performance of the PV system [24]. The surface σ is expressed as (3).

$$\sigma = x_{ref} - x \quad (3)$$

Where x is the parameter to be regulated and x_{ref} its reference. The SOSMC controller (u_c) comprises two components: the equivalent control component (u_{eq}) and the SOSMC algorithm term (u_{SO}) [24].

$$u_c = u_{eq} + u_{SO} \quad (4)$$

The term u_{eq} is determined by (5).

$$\frac{d\sigma}{dt} = 0 \quad (5)$$

The u_{SO} term ensures that the PV system remains on the σ despite parameter variations and irradiation changes. The expression for u_{SO} is given by (6).

$$u_{SO} = u_1 + u_2 \quad (6)$$

Where:

$$\begin{cases} u_1 = \beta_1 |\sigma|^{0.5}.\,\mathrm{sign}(\sigma) \\ u_2 = \beta_2 \int \mathrm{sign}(\sigma).dt \end{cases} \quad (7)$$

Where β1 and β2 are the SOSMC gains.

2.3. Modeling and control design of the boost converter

The boost converter is used to adjust the voltage between the PVG and the inverter. The proposed control objectives are to maintain MPP and increase output voltage [25]. The diagram of the boost converter used is shown in Figure 1. The characteristic equations of the boost converter are given by (8).

$$\begin{cases} \frac{di_{pv}}{dt} = \frac{1}{L}.\left[V_{pv} - (1-\alpha).V_{dc}\right] \\ \frac{dV_{dc}}{dt} = \frac{1}{C_0}.\left[(1-\alpha).i_L - \frac{V_{dc}}{R}\right] \end{cases} \quad (8)$$

Where α is the duty cycle α.

Based on the P-V and I-V profiles of the PVG presented in Figure 2, it can be deduced that when operating at MPP:

$$\frac{dP_{pv}}{dV_{pv}} = \frac{d(V_{pv}.i_{pv})}{dV_{pv}} = i_{pv} + V_{pv} \cdot \frac{di_{pv}}{dV_{pv}} = 0 \quad (9)$$

the surface σ is determined according to (10) to reach the MPP [26].

$$\sigma = \frac{dP_{pv}}{dV_{pv}} \quad (10)$$

The equivalent control term u_{eq} of the SOSMC controller is determined by (10).

$$u_{eq} = 1 - \frac{V_{pv}}{V_{dc}} \quad (11)$$

From the (4), (6), (7), and (11), the final expression for the proposed control signal is given by (12).

$$u_C = 1 - \frac{V_{pv}}{V_{dc}} + \beta_1 \times |\sigma|^{0.5} \times \text{sign}(\sigma) + \beta_2 \times \int \text{sign}(\sigma) \times dt \quad (12)$$

2.4. Modeling and control design on the grid side with SOSMC

The inverter's role is to maintain a constant V_{dc} and regulate the P and Q injected into the grid to ensure a UPF. In this study, a two-loop control scheme is used: the internal loops regulate the quadrature (i_q) and direct (i_d) currents, while the external loop controls V_{dc} and generates the reference current ($i_{d\text{-}ref}$). The circuit diagram of the inverter connected to the grid is shown in Figure 1. The Park transformation is applied to convert the inverter's three-phase coordinates into two synchronous d-q rotational coordinates [27].

$$\begin{cases} \frac{di_d}{dt} = \frac{1}{L_f} \cdot \left(V_d - R_f.i_d - e_d\right) + L_f \omega i_q \\ \frac{di_q}{dt} = \frac{1}{L_f} \cdot \left(V_q - R_f.i_q - e_q\right) - L_f \omega i_d \end{cases} \quad (13)$$

When the tension vector is aligned on the d-axis, the P and Q are given with:

$$\begin{cases} P = \frac{3}{2}.V.i_d \\ Q = \frac{3}{2}.V.i_q \end{cases} \quad (14)$$

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. The objective of SOSMC inverter control is to eliminate the chattering phenomenon by adding an integral term to the current error. The σ can be described as (15) [15].

$$\sigma_{dq} = i_{dq\text{-}ref} - i_{dq} \quad (15)$$

u_{eq} is determined from the (5), (13), and (15) as (16).

$$\begin{cases} u_{d\text{-}eq} = \frac{di_{d\text{-}ref}}{dt} + R.i_d - L\omega i_q + e_d \\ u_{q\text{-}eq} = R.i_q + L\omega i_d + e_q \end{cases} \quad (16)$$

The final expressions of the proposed commands are given as (17).

$$\begin{cases} u_d = \frac{di_{d\text{-}ref}}{dt} + R \times i_d - L\omega i_q + e_d - \lambda_1 \times |\sigma_d|^{0.5} \times \text{sign}(\sigma_d) - \lambda_2 \times \int \text{sign}(\sigma_d) \times dt \\ u_q = R \times i_q + L\omega i_d + e_q - \lambda_3 \times |\sigma_q|^{0.5} \times \text{sign}(\sigma_q) - \lambda_4 \times \int \text{sign}(\sigma_q) \times dt \end{cases} \quad (17)$$

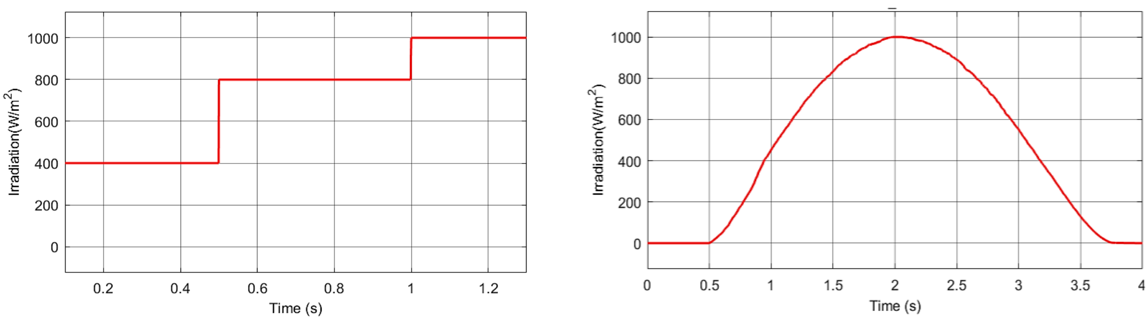
3. THE RESULTS AND DISCUSSION

In this study, the PVG used provides a maximum power of 160 kW at G=1000 W/m^2. A comparative analysis between SOSMC and conventional CVC is conducted to demonstrate the effectiveness of the proposed technique. The irradiation profile utilized is depicted in Figures 3(a) and 3(b). The simulation results are presented in Figures 3 through 7. Table 2 gives the PVS parameters.

Figure 4 illustrates the P and Q injected into the grid using both the SOSMC control and CVC method for step (Figure 4(a)) and real (Figure 4(b)) irradiation changes. It is evident that P quickly converges to its MPP with high precision during irradiation variations. At G=1000 W/m^2, P reaches its maximum value of 160 kW supplied by the PVG, with the overshoot reduced to zero, while Q remains at zero. Figure 5 shows the dynamics of V_{dc}, demonstrating that it closely follows its reference value in a very short time, with minimal steady-state error for the SOSMC controller. Figure 6 presents the current injected into the grid during the first phase, which has a sinusoidal waveform at 50 Hz, indicating a low rate of current harmonics. This figure also shows that the grid voltages and currents are in phase, confirming the absence of reactive power injection and ensuring a UPF. Figure 7 displays the THD of the first-phase current connected to the grid for both CVC (Figure 7(a)) and SOSMC (Figure 7(b)) controllers. The THD for SOSMC is reduced to 1.19%, compared to 2.28% for CVC, indicating that the CVC technique is more affected by irradiation variations. The developed method significantly reduces ripple, demonstrating its robustness under fluctuating climatic conditions.

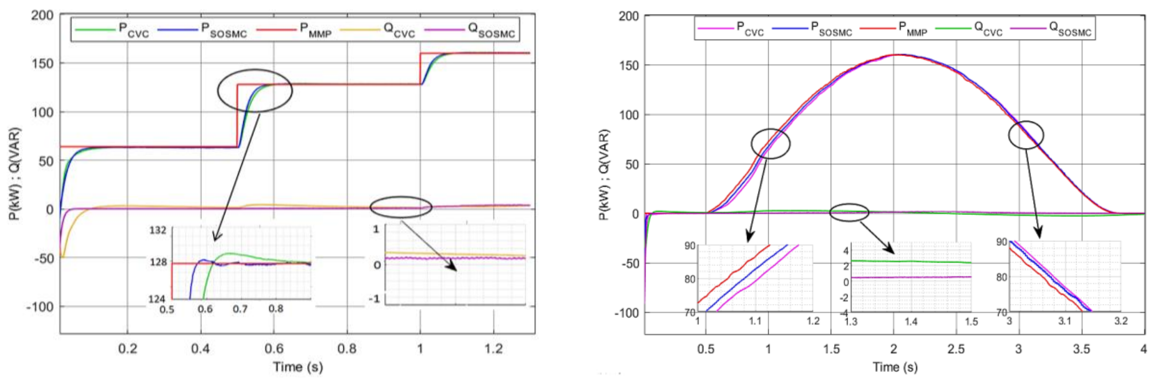
Table 2. The PVS parameters

Parameter	Symbol	Value
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)	Fs	5
Inverter inductance (mH)	L_f	3
Inverter switching rate (kHz)	F_{sh}	5
DC bus voltage reference (V)	V_{dc_ref}	700



(a) (b)

Figure 3. Irradiation variations in W/m^2: (a) stepped profile and (b) real profile



(a) (b)

Figure 4. Active and reactive power for (a) step irradiation and (b) reel irradiation

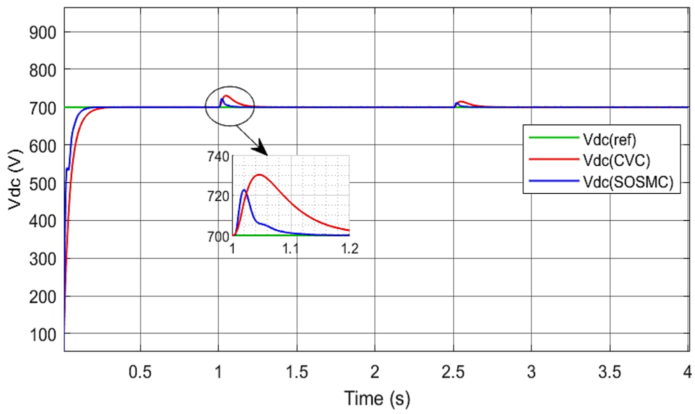


Figure 5. V_{dc} responses with SOSMC and CVC

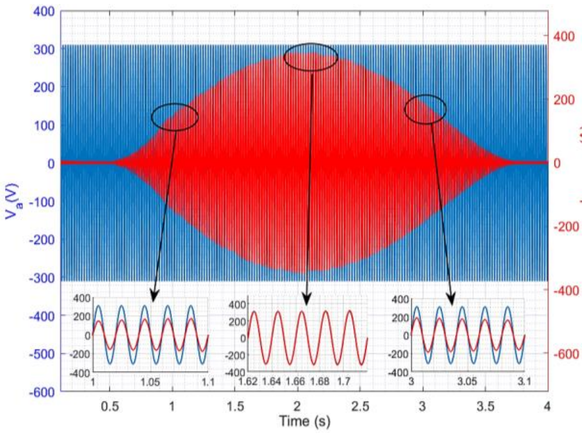


Figure 6. Current injected into grid for the first phase

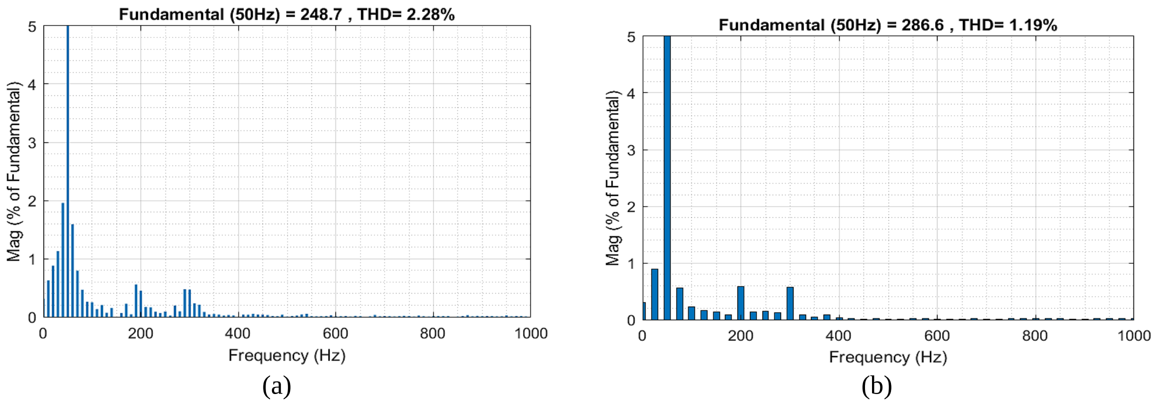


Figure 7. THD of the current with (a) CVC and (b) SOSMC

4. CONCLUSION

This article introduces a novel SOSMC controller for regulating a PV system in two distinct stages. Initially, on the direct current side, the controller focuses on maximizing the power generated by the PVG. Subsequently, on the alternating current side, the goal is to transfer this power to the grid with a unity power factor. The SOSMC-based strategy is designed to enhance PV system performance compared to traditional SMC by minimizing ripples in active and reactive power. Comparative results between the SOSMC and conventional CVC show a 100% reduction in active power overshoot during sudden irradiance changes, with minimized response time. Additionally, the THD of the current is reduced to 1.19% with SOSMC, compared to 2.28% with CVC. Thus, the SOSMC strategy demonstrates significant promise for improving the energy efficiency of grid-connected photovoltaic systems.

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