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Optimized Third-Order Sliding Mode MPPT for Photovoltaic Systems in Variable and Realistic Weather Conditions

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A B S T R A C T

For optimal photovoltaic (PV) power-generation conversion, maximum power point tracking (MPPT) is essential. This study introduces a reliable and advanced third-order sliding mode control (TOSMC) based MPPT, aimed at addressing its main drawbacks such as chattering phenomena and voltage and power ripples. In order to demonstrate the capabilities of the proposed TOSMC control, a comprehensive study has been conducted. This study compares the TOSMC control with traditional perturb & observe and incremental conductance methods. Various factors such as tracking time, power oscillations, voltage and current ripples, robustness, and power efficiency have been taken into consideration. The verification of the recommended PV system is conducted using the MATLAB interface. Hence, diverse scenarios of atmospheric conditions have been applied such as fast fluctuation and realistic changing of irradiation across one day. The results obtained provide strong evidence for the effectiveness of the control method utilized, demonstrating superior performance.

التحكم في وضع الانزلاق المحسن من الدرجة الثالثة لأنظمة الطاقة الكهروضوئية في ظل ظروف الطقس المتغيرة والو اقعية

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الملخص

من أجل تحويل مثالي لتوليد الطاقة الكهروضوئية، فإن تتبع نقطة القدرة القصوى (MPPT) أمر ضروري. تقدم هذه الدراسة نظام تحكم في وضع الانزلاق من الدرجة الثالثة (TOSMC) موثوق ومتقدم، يهدف إلى معالجة عيوبه الرئيسية مثل ظاهرة التذبذب وتموجات الجهد والطاقة. من أجل إثبات قدرات التحكم في وضع الانزلاق من الدرجة الثالثة المقترح، تم إجراء دراسة شاملة. تقارن هذه الدراسة بين التحكم في وضع الانزلاق من الدرجة الثالثة وطرق الاضطراب والمراقبة التقليدية والتوصيل التدريجي. تم أخذ عوامل مختلفة في الاعتبار مثل وقت التتبع وتذبذبات الطاقة وتموجات الجهد والتيار والمتانة وكفاءة الطاقة. يتم إجراء التحقق من نظام الطاقة الكهروضوئية الموصى به باستخدام واجهة MATLAB. وبالتالي، تم تطبيق سيناريوهات متنوعة للظروف الجوية مثل التقلب السريع والتغيير الواقعي للإشعاع عبر يوم واحد. تقدم النتائج التي تم الحصول عليها دليلاً قوياً على فعالية طريقة التحكم المستخدمة، مما يدل على الأداء المتفوق .

1. Introduction

Renewable energy sources are becoming the dominant energy source since the beginning of the 21st century. Traditional energy sources are insufficient to satisfy the energy requirements of modern civilization including the industrial revolution. Furthermore, these sources generate inherent pollution, which poses a significant risk to human health. Nonconventional sources of energy can serve as a viable and prominent alternative in the advancement of human progress. Utilizing alternative energy sources is a crucial and accurate choice in the present day[1]. In recent years, there has been a significant increase in the study and manufacture of photovoltaic (PV) systems. Despite this noticeable progress, PV solar panels still demonstrate an extremely low conversion efficiency. Moreover, the PV module generates a power output that demonstrates nonlinearity and fluctuates in response to atmospheric conditions. The variations in performance reduce the operational efficiency of the PV panel, causing the operating power to deviate from the maximum power point (MPP) [2]. To deal with the aforementioned challenge, the PV system needed to be forced to operate at the optimal MPP. The latter technique refers to the maximum power point tracking (MPPT) algorithm, which is the main topic of this study. Over the past ten years, a multitude of MPPT methods have been implemented in academic publications. The two most renowned algorithms utilized are the perturb and observe method, as well as the incremental conductance technique. These approaches are simple to execute and

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rely on the abrupt adjustment of the duty cycle or voltage [3]. However, the lack of robustness of conventional MPPT against the intermittent nature and weather shifting promoted academic researchers to develop new techniques to deal with this challenge. A novel framework for enhancing MPPT in solar panels by reducing the search space and deriving an irradiance-free relationship between open circuit and MPP voltage has been introduced in [4]. The study verifies the suggested algorithm's effectiveness on three prevalent solar panel variants and showcases its improved performance in response to varying weather circumstances. The authors in [5] introduced an enhanced INC-based MPPT strategy for optimizing PV systems in remote areas. The suggested technique incorporates adaptive perturbation step adjustments in response to weather variables and integrates a drift avoidance method to ensure reliable tracking. A hybrid MPPT algorithm using particle swarm optimization (PSO) and conventional methods to optimize PV output power across varying climatic conditions was presented in [3]. The approach integrates PSO with P&O and INC methods, dynamically adapting the step size according to solar irradiation to enhance efficiency. Alternatively, Artificial Intelligence techniques are also employed to serve in this topic. In Ref.[6], Fuzzy Logic served as an MPPT and as a consequence the system efficiency reached 97 % as well as the power fluctuations were reduced. In order to handle the nonlinearity of PV systems and overcome the uncertainty resulting from unstable weather changes, nonlinear robust control algorithms have been widely used in the literature [7], [8], [9]. The study in [10] proposes a new hybrid approach to maximize the PV system's power output and improve energy quality by combining robust sliding mode control (SMC) and INC algorithm. Thus, this control technique effectively tackled problems that included chattering and control dynamics. Various studies have explored the integration of SMC with different control strategies to enhance MPPT performance. For instance, a study in [11] proposed a Backstepping SMC (BSMC) method with a fuzzy inference system and PSO optimizer for parameter fine-tuning, resulting in improved stability and power extraction capabilities under changing atmospheric conditions. Second-order sliding mode control (SOS-MC) has been suggested in numerous papers [12], [13], [14] to overcome the conventional SMC drawbacks, especially the chattering phenomenon. A robust super-twisting algorithm based on SOSMC was presented and discussed in [12]. The previously indicated technique exhibited rapid responsiveness and reduced chattering in comparison to the first-order SMC. A novel robust approach called Third-order sliding mode control (TOSMC) has been used widely in different systems to provide rapid convergence rates, precise tracking precision, and minimized chattering[15], [16], [17].

Based on an extensive review of the literature, it is observed that the persistent issues posed by varying atmospheric conditions, whether they are realistic and overcast or highly unstable, have not been well addressed. Therefore, this inspires the authors to develop a Maximum Power Point Tracking system that can efficiently operate under these circumstances. This research presents a new and strong tracking control method called Third-Order SMC for achieving maximum power output in solar photovoltaic systems. The suggested control technique is characterized by its straightforward design, effortless implementation, exceptional precision, and swift tracking capabilities.

The paper consists of five sections. Sect. 2 provides a comprehensive overview of the researched system. The proposed design for an MPPT controller is presented in Section 3. Section 4 includes an elucidation of the simulation results and a discussion. Section 5 addresses the final findings and conclusions of the work.

2. General Description

A standard stand-alone photovoltaic (PV) system consists of a PV array, a dc/dc converter to adapt the power generated by the PV supplier, a controller to manage disruptions, and a load, as shown in Figure 1. The PV array demonstrates a non-linear characteristic that varies considerably with the operating conditions, posing challenges in accurately predicting the optimal outputs required to ensure maximum power generation, this explains the importance of the MPPT controller in the studied system.

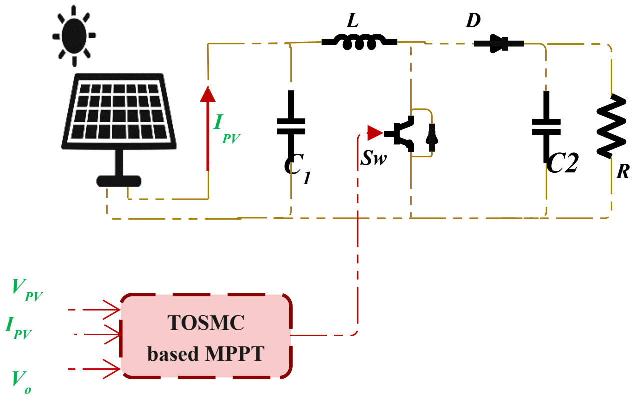

Fig. 1 :PV generator with MPPT control.

2.1 PV cell model

1. The primary elements of a solar photovoltaic (PV) power system consist of PV panels, which are commonly interconnected in series and/or parallel configurations to enhance power output production or increase voltage. The PV cell can be described as a combination of a current source, a diode, a series resistance (Rs), and a shunt resistance (Rp), as shown in Figure 2.

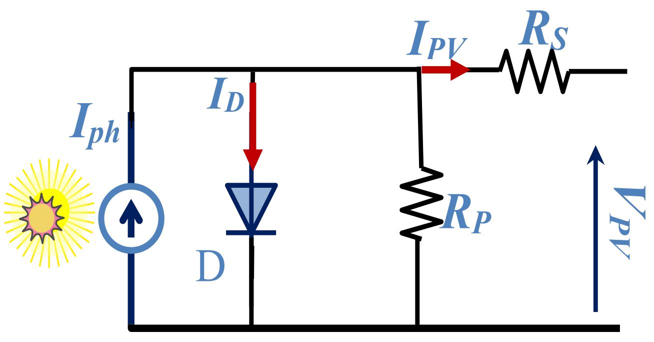

Fig. 2: PV Cell

2.2. Boost converter model

DC-DC converters are used as power conditioning units to regulate and increase the voltage from a solar source to the appropriate output voltage.

The nonlinear time-independent system of the converter can be expressed in a general manner as follows:

$$\dot{X} = f(X) + h(X)u \tag{1}$$

Where

$$X = [I_{PV} \quad V_o]^T, \quad u \in [0 \quad 1].$$

$$f(X) = \begin{bmatrix} \dfrac{V_{PV} - V_o}{L} \\ -\dfrac{V_o}{RC_2} + \dfrac{I_L}{C_2} \end{bmatrix} \quad \text{and} \quad h(X) = \begin{bmatrix} \dfrac{V_o}{L} \\ -\dfrac{I_L}{C_2} \end{bmatrix}$$

Thus, we obtain

$$\begin{cases} \dfrac{dI_{PV}}{dt} = \dfrac{V_{PV} - V_o}{L} + \dfrac{V_o}{L}u \\ \dfrac{dV_o}{dt} = \left(-\dfrac{V_o}{RC_2} + \dfrac{I_{PV}}{C_2} \right) \dfrac{V_o}{L}u \end{cases} \tag{2}$$

3. Controller Design

The TOSMC approach has recently appeared as a viable alternative to the SMC approach. It is a method that does not follow a linear pattern. The primary benefits of this approach, in contrast to various other tactics like feedback linearization control or backstepping control, are its simplicity and straightforward implementation. Furthermore, it is an efficient solution for uncertain systems that address the key limitations of the standard SMC technique discussed in the literature[15], [18].

In order to design any typical controller based on SMC, the first step is selecting the sliding surface in which the system state converges to it. However, in the studied case we aim to enforce the PV system to provide its maximum power output, for this reason, we select the sliding surface as follows [13] :

$$s(x,t) = \frac{\partial P_{pv}}{\partial V_{pv}} = \frac{I_{pv}}{V_{PV}} + \frac{\partial I_{pv}}{\partial V_{pv}} = 0 \quad (4)$$

The second step consists of defining the control input law (δ),which includes two main terms given by

$$\delta = \delta_{eq} + \delta_{TOSMC} \quad (5)$$

Where the term of the suggested TOSMC method is determined by the summation of three inputs, which are given as follows:

$$\delta_{TOSMC} = \theta_1 \sqrt{|S|} \cdot sign(S) + \theta_2 \int sign(S) + \theta_3 \cdot sign(S) \quad (6)$$

θ_1, θ_2 *and* θ_3 are arbitrary gains. Wherein the equivalent term δ_{eq} can be defined based on the following condition

$$\dot{s} = \left[\frac{dS}{dX}\right]^T \dot{X} = \left[\frac{dS}{dX}\right]^T (h(X)\delta_{eq} + f(X)) = 0 \quad (7)$$

Therefore, we obtain

$$\delta_{eq} = 1 - \frac{V_{PV}}{V_o} \quad (8)$$

4. Simulation Results:

This section assesses the performance of the TOSMC MPPT controller under varying environmental circumstances. In addition, the TOSMC controller has been compared to traditional MPPT methods such as P&O and INC to evaluate its comparative performance. Various atmospheric profiles have been selected to evaluate the suggested controller in the following subsections.

4.1 *Case 1: Fast-changing irradiance*

In this scenario, the intensity of radiation has been altered over time while maintaining the same temperature of 25 degrees Celsius. The irradiance was initially set at 800 W/m2, then dropped to 600 W/m2, and subsequently increased to a maximum value of 1000 W/m2. It was then decreased again to 800 W/m2, as depicted in Figure 3. This profile exhibits instances of highly fluctuating irradiance in the form of ramps. Figure 4 illustrates the power performance of the three controllers being studied. The initial state (occurring between 0 to 0.2 seconds) has been selected for analysis, as indicated in Table 1 and Figure 7. The settling time data have been recorded as 58 ms for the P&O method and 29 ms for the INC method, while the proposed TOSMC MPPT needed only 15 ms to achieve the MPP. Moreover, the responses of the PV voltage V_{PV} and PV current I_{PV} are represented in Figures 5 and 6, respectively. Accordingly, it has appeared that the innovative MPPT provided superior performance in terms of minimizing the voltage and current ripple as well as less fluctuation around the peak power point.

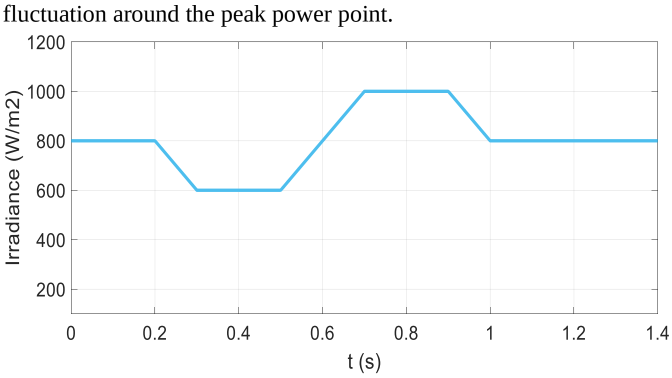

Fig. 3 : Irradiance Profile.

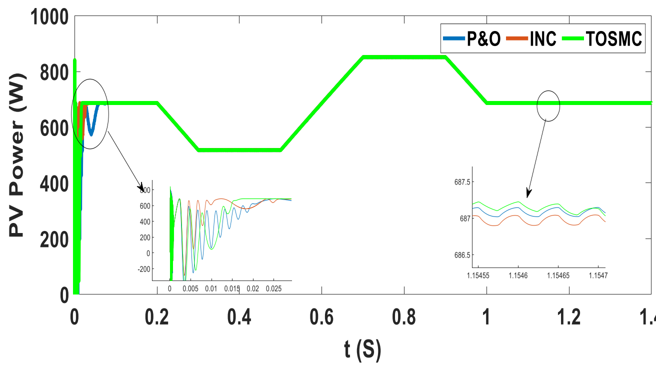

Fig. 4 : PV power performance under hard variation irradiance.

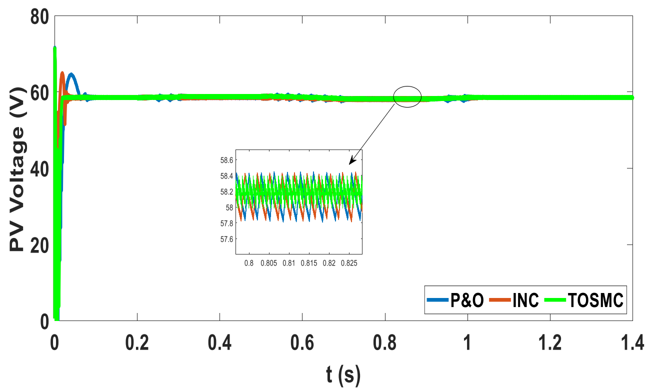

Fig. 5: PV Voltage performance under hard variation irradiance.

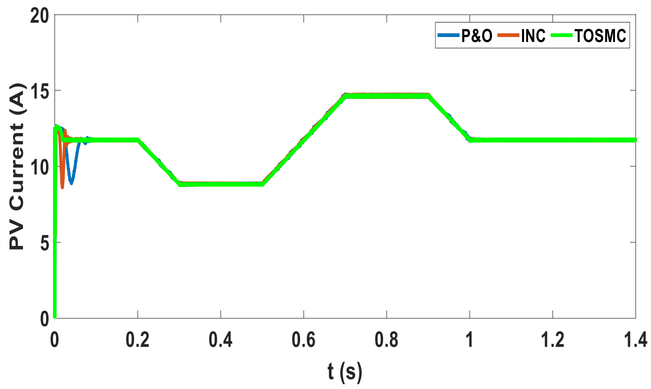

Fig. 6: PV Current performance under hard variation irradiance.

Table I : In-depth comparative examination.

	Index				
Period	*MPPT Method*	*Settling Time (ms)*	*P_{PV} Ripple (W)*	*V_{PV} Ripple (V)*	*I_{PV} Ripple (A)*
S [0--0.2]	P&O	58	2.38	0.68	0.53
	INC	29	0.42	0.65	0.25
	TOSMC	15	0.37	0.38	0.055

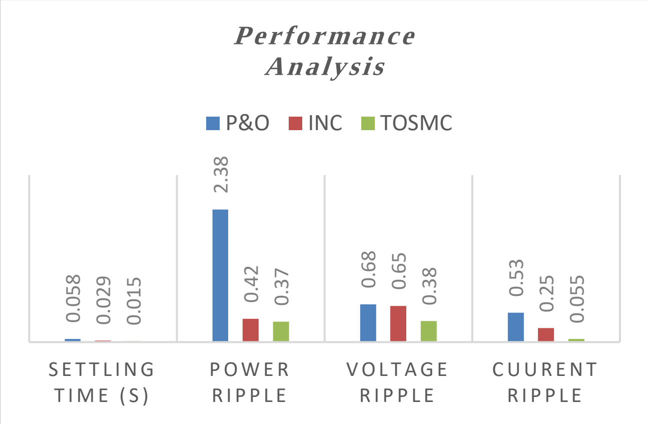

Fig. 7 : Graphical representation of performance analysis.

4.2 *Case 2: Realistic weather fluctuation*

This test case includes realistic data on irradiance fluctuation, as depicted in Figure 8. Figure 9 displays the photovoltaic (PV) power response of the developed TOSMC controller compared to both (P&O) and (INC) methods under realistic meteorological conditions. The suggested technique demonstrates efficient tracking of the MPP with minimal fluctuation and fast response, nevertheless, the perturb&Observe and incremental conductance (INC) exhibit noticeable fluctuations. Figures 10 as well as 11 illustrate the photovoltaic (PV) voltage and current, respectively. The results clearly showed the higher performance of the recommended MPPT algorithm in terms of power efficiency, robustness, tracking time, and greatly diminished oscillatory behavior.

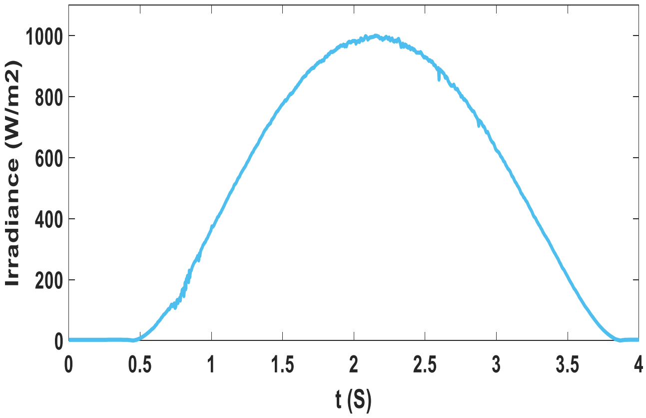

Fig. 8 : Realistic irradiation profile.

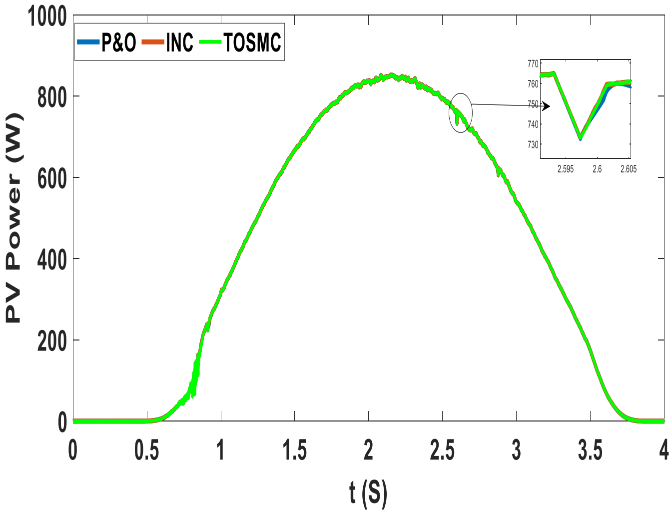

Fig. 9: PV power output under realistic irradiation test.

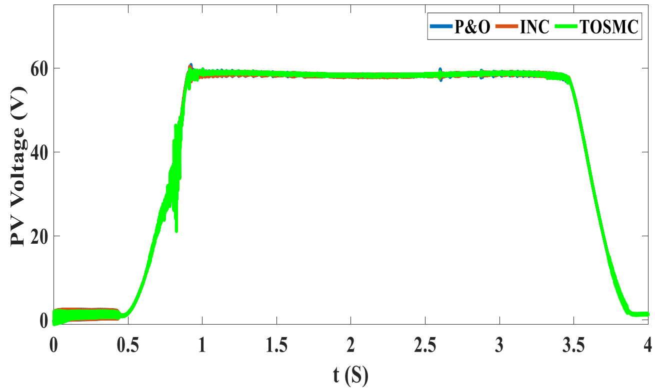

Fig. 10: PV Voltage output under realistic irradiation test.

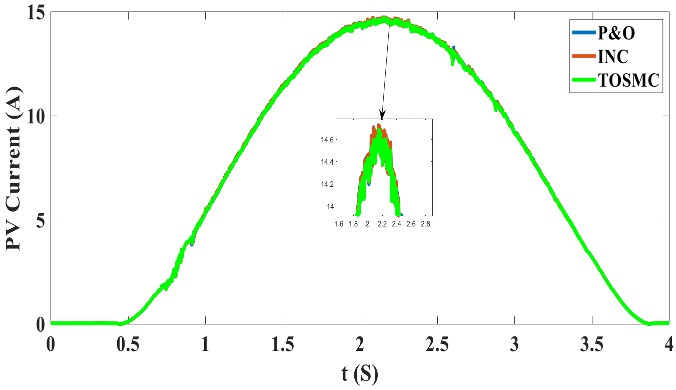

Fig. 11 : PV Current output under realistic irradiation test

5. Conclusion

This study examines the comprehensive development of a third-order sliding mode control (TOSMC) based MPPT controller for efficient attainment of maximum power response in Solar Photovoltaic (SPV) systems. The TOSMC controller was developed with the aim of achieving four key objectives simultaneously: a straightforward design that is easy to implement, minimizing oscillations around the MPP, robustness to uncertainty and fluctuating environmental circumstances, and demonstrating fast reaction. In order to evaluate the effectiveness of the controllers in achieving maximum power response, various performance metrics were employed. These metrics encompassed the settling time of the power, steady-state power variations, as well as voltage and current ripples. The findings obtained demonstrate that the suggested controller effectively addresses oscillations around the MPP and delivers improved performance in comparison to the incremental conductance (INC) and perturb and observe (P&O) methods.

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