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Performance Evaluation of Sliding Mode Control and Model Reference Adaptive Control based-MPPT for Photovoltaic Systems

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ABSTRACT

This study focuses on optimizing the power output produced via photovoltaic systems. The nonlinearity of the solar generator's operation and its changeable output characteristic during varied climatic circumstances create a strong need for maximizing the output energy. Due to the high demand for extracting maximum energy, numerous methods have been offered to ensure efficient operation at the optimal power for solar systems. The aim of this research is to examine two resilient techniques, sliding mode control and robust adaptive control, used for extracting the maximum power supplied by solar sources. The MPPT algorithms are designed mathematically and then validated using MATLAB/Simulink software. The simulation was conducted to verify the effectiveness against rapidly changing climatic conditions. The MPPT algorithms demonstrate exceptional tracking efficiency, rapid response time, little oscillation around the maximum power point (MPP), and reduced voltage and current ripple.

تقييم أداء التحكم في الوضع المنزلق والتحكم التكيفي المرجعي للنموذج القائم على MPPT للأنظمة الكهروضوئية

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Photovoltaic
MPPT
MRAC
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MIT Rule.

الملخص

تركز هذه الدراسة على تحسين إنتاج الطاقة المنتجة عبر الأنظمة الكهروضوئية. إن عدم خطية تشغيل المولد الشمسي وخصائصه المتغيرة أثناء الظروف المناخية المتنوعة تخلق حاجة قوية لاستخراج أقصى قدر من طاقة الخرج. ونظرًا للطلب المرتفع على استخراج أقصى قدر من الطاقة، فقد تم تقديم العديد من الطرق لضمان التشغيل الفعال عند الطاقة المثلى للأنظمة الشمسية. والهدف من هذا البحث هو فحص تقنيتين مرنتين، التحكم في وضع الانزلاق والتحكم التكيفي القوي، المستخدمان لاستخراج أقصى قدر من الطاقة التي توفرها مصادر الطاقة الشمسية. تم تصميم خوارزميات MPPT رياضيًا ثم التحقق من صحتها باستخدام برنامج MATLAB / Simulink. تم إجراء المحاكاة للتحقق من الفعالية ضد الظروف المناخية المتغيرة بسرعة. تظهر خوارزميات MPPT كفاءة تتبع استثنائية ووقت استجابة سريع وتذبذب ضئيل حول نقطة القدرة القصوى (MPP) وانخفاض تموج الجهد والتيار.

1. Introduction

The Paris Agreement on Climate Change implicitly necessitates the preservation of the majority of fossil fuel reserves underground in order to achieve the goal of reducing average global warming within the range of 1.5 to 2 degrees Celsius above pre-industrial levels[1]. In this context, using alternative sources instead of fossil fuels for electrical power production became necessary. Nowadays, renewable energy sources are the most recommended solution by many researchers because of their benefits such as free power production and being environmentally friendly[2]. Photovoltaic (PV) is one of the largest widely spread sources in the world. Photovoltaic energy production is of great importance due to its lack of greenhouse gas emissions and its ecologically benign nature. It can be utilized in locations where supplying energy via electrical grids is not possible. However, there are many challenges with producing energy through solar PV panels such as weather fluctuations which lead to produce unstable power during the different seasons. Accordingly, the maximum power point tracking (MPPT) controller is the most important device for any PV system which ensures that the PV system operates at the maximum power point (MPP). The designing of an MPPT algorithm requires two objectives things have to be considered, the first one is to achieve the desired operation point (the MPP) as quickly as feasible. Secondly, minimize the number of oscillations in the power output[3]. As stated in reference [4], MPPT strategies can be categorized into four groups according to their tracking methodologies: conventional techniques, intelligent techniques, optimization techniques, as well as hybrid approaches.

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The traditional approaches such as Perturb and Observe (P&O) [5], Incremental Conductance (INC)[6], and the Constant Voltage approaches, are simply applied because of their accessibility. They achieve optimal performance when exposed to a consistent level of irradiation. Nevertheless, they hardly struggle against the intermittent nature of the weather conditions. In order to address the challenge of swift variation in solar irradiance, and temperature in addition to load fluctuation [7] has been suggested a new variable step-size INC algorithm which was evaluated and investigated under MATLAB/Simulink environment. Ref. [8] proposed an innovative MPPT in order to address the constraints of traditional P&O techniques as well as reduce the computing load related to step-size computations in adaptive (P&O) methods. Intelligent techniques based-MPPT are also widely employed and considered one of the most optimal solutions. Fuzzy Logic Control (FLC) has been recommended in [9] for the reason of enhancing the tracking performance as well as increasing the power efficiency which was valued up to 97 % in the aforementioned study. According to [10] sliding mode control is also categorized as an intelligent control technique for MPPT applications. An enhanced method for designing an SMC technique for the PV system has been introduced in [11]. This controller ensures that the PV voltage tracks a reference value generated by a separated MPPT algorithm. Additionally, it effectively reduces the disturbances produced by variations in irradiance. A robust optimization algorithm based on conventional SMC was presented in [12] to manage the uncertainty in PV systems resulting from fluctuations in weather conditions and changes in electrical demand. Another attractive robust MPPT technique has been widely used in the literature which is called model reference adaptive control (MRAC)[13]. In MRAC, the control signal is simultaneously inputted into both the reference model in addition to the plant model (i.e. actual system). Subsequently, the controller adjusts the gains in order to align the behavior of the actual system with that of the reference system, while simultaneously minimizing the discrepancy between the two outputs[14]. In [15], two loops of control have been employed, wherein the first level provides the MPP voltage reference whereas MRAC is used in the second stage to track the reference voltage.

This study presents a model of a PV array and a boost converter that is associated with a resistive load. Therefore, to enhance power production in the face of variable weather fluctuations, two types of robust maximum power point tracking controllers are employed. The first MPPT algorithm is the sliding mode controller, whereas the subsequent one is the MRAC-based MPPT. In order to investigate the effectiveness and robustness of the aforementioned methods, a comparative analysis study was established in terms of their dynamic performance.

The rest of this paper is organized as follows: section 2 presents the description of the system including mathematical modeling. The mathematical design of the suggested MPPT controllers is detailed in section 3. Simulation results under MATLAB environment and analytical discussion are outlined in section 5. Section 5 provides the paper's conclusion.

2. System Description

3. The system depicted in Figure 1 comprises a photovoltaic array, a power converter, a maximum power point tracking controller, and a resistive load. The DC-DC converter uses the duty ratio to regulate the operating voltage of the PV array. The primary objective of the MPPT controller in the first control level is to determine the optimal reference voltage (V_{ref}) required to operate the PV array near its maximum power point. Meanwhile, the second loop control tracks the reference provided by the outer loop. The specific parameters employed to simulate the photovoltaic (PV) array are presented in TABLE I.

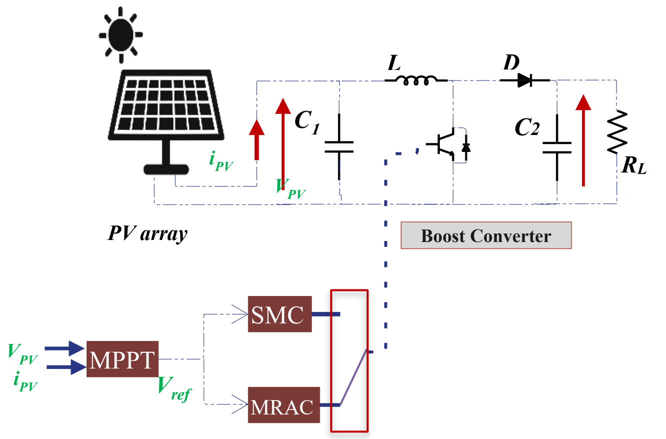

Fig. 1 PV system with MPPT control.

Table 1: System's specifications.

Parameters	Values
The Peak Power of the PV panel (W)	213.15
Open circuit voltage V_{OC} (V)	36.3
Short circuit current I_{SC} (A)	7.84
The voltage corresponding to the maximum power V_{MP} (V)	29
The current corresponding to the maximum power I_{MP} (A)	7.35
Parallel strings (NP)	2
Number of cells associated in Series (NS)	2

2.1 PV Array Model

PV cell representation based on a Single diode model as illustrated in Figure 2, is one of the most widely spread models used among researchers because of its simplicity furthermore it is considered as an accurate model. Thus, this model includes a current source I_{Ph}, one parallel diode, two resistors with parallel (R_P) and series (R_s) connecting, respectively.
The output current provided by a PV cell which is denoted as 'I_{PV}' can be given by

$$I_{PV} = I_{Ph} - I_s\left[\exp\left(\frac{V_{PV} + I_{PV} R_s}{\eta V_T}\right) - 1\right] - \frac{V_{PV} + I_{PV} R_S}{R_P} \quad (1)$$

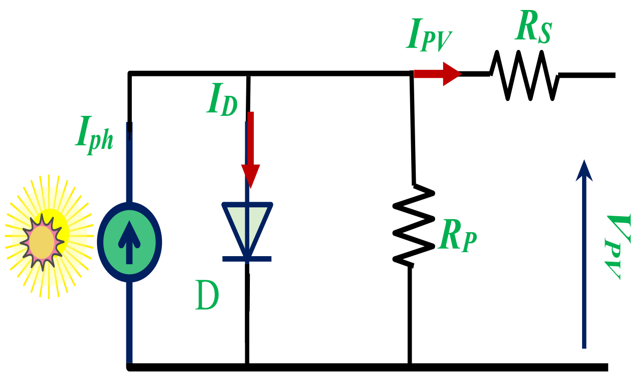

Fig. 2 PV cell representation

Where:
V_T : Thermal voltage.
V_{PV}: The output PV voltage.
I_S: saturation current.

3. Controller Design

3.1. Reference Voltage Generation

Typically, MPPT algorithms employ a constant step size that is selected based on trial and error taking into account the accuracy in addition to tracking speed. Increasing the step size in order to increase the response time leads to a drop in precision, resulting in relatively poor efficiency. The opposite is also true. This study utilizes a variable step size P&O technique to produce the maximum power point (MPP) voltage.

3.2. Sliding Mode Control

The crucial aspect of the SMC is the establishment of a zone of attraction centered around a predetermined switching manifold (Sliding Surface). This is achieved by implementing a discontinuous control strategy. The control performance requirements are incorporated into the switching manifold, which serves as the foundation for establishing an optimum sliding mode [16]. Therefore, the first step of the control design is choosing a sliding surface (Υ) as follows

$$\Upsilon = V_{ref} - V_{PV} \tag{2}$$

The control law u that is necessary to attain the desired reference may be described by Eq. (3).

$$u = \left(1 + Sign\left(\Upsilon\right)\right) \tag{3}$$

In another term, the aforementioned structure can be described as

$$u = \begin{cases} 1 & if \quad \Upsilon > 0 \\ 0 & if \quad \Upsilon < 0 \end{cases} \tag{4}$$

For stability analysis discussion and more information see [17], [18].

3.3. Model Reference Adaptive Control

Over the past few decades, there has been significant interest in the field of adaptive control research. The MRAC is well recognized as one of the most prominent methodologies in this particular discipline. This methodology employs a consistent model reference and aims to devise precise control parameters to ensure that the system dynamics mimic the model reference[19]. Figure 3 depicts the bloc diagram of system control using the MRAC strategy. Hence, The MRAC scheme consists of three main components: the reference system, the plant model or process with the controller, and the parameter adaptation block.

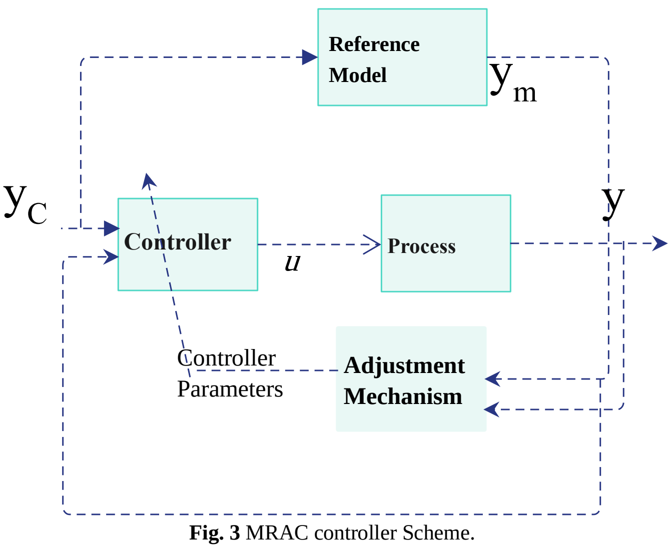

Fig. 3 MRAC controller Scheme.

Plant model: In the context of MRAC controller design-based MPPT, it's necessary to find the correlation between the PV source output and the dynamic behavior of the DC-DC converter. For this reason, a small signal analysis was established in [13] to extract the correlation between the duty cycle and the PV voltage which can be described in S-domain as follows

$$\frac{V_{pv}(s)}{d(s)} = \frac{\frac{-V_o}{LC_1}}{s^2 + \frac{1}{RC_1}s + \frac{1}{LC_1}} \tag{5}$$

Equation (5) can be rewritten as

$$\frac{y(s)}{u(s)} = \frac{\boldsymbol{K_p}}{\boldsymbol{s^2 + a_p s + b_p}} \tag{6}$$

where

$\begin{bmatrix} y & u \end{bmatrix} = \begin{bmatrix} \hat{V}_{PV} & \hat{d} \end{bmatrix}$ and $k_p = -\frac{V_o}{LC_1}$, $a_p = \frac{1}{RC_1}$ and $b_p = \frac{1}{LC_1}$.

While the value of the input resistor (R) may be estimated by $\frac{1}{R} \approx \frac{-\Delta I_{PV}}{\Delta V_{PV}}$ [13].

Reference Model: The reference model that delineates the ideal response of the process output to the control signal *u(t)* is represented in Equation (7). In this model, y_m denotes the desired output, K_m signifies a positive gain, and the parameters a_m and b_m must be appropriately chosen. Consequently, the reference model prescribes the optimal response behavior.

$$\frac{y_m(S)}{y_c(S)} = \frac{\boldsymbol{K_m}}{\boldsymbol{s^2 + a_m s + b_m}} \tag{7}$$

Controller Architecture: In order to accomplish the control purpose, we employ the controller structure as defined by

$$u = \theta_1 y_c - \theta_2 y = \theta^T \omega \tag{8}$$

Where $\theta = [\theta_1, \theta_2]$ represent the gains of the controller's vector whereas ω may expressed as $[y_c, y]^T$.

Adjustment Mechanism: According to the published works in literature, there exist two famous main methods to design the adjustment of controller's parameters are: the gradient descent method also known as the MIT rule, and the second method is based on the Lyapunov approach. Noteworthily the aforementioned methods have been developed and enhanced to new and advanced structures. In this paper, the MIT rule has been selected for adaptation (adjustment) low. Accordingly, the objective function (ψ) given by

$$\psi(\theta) = \frac{1}{2}\varepsilon^2 \tag{9}$$

Where ε denoted to the error which is given by

$$\varepsilon = y - y_m \tag{10}$$

Where: y is the system output and y_m denotes to reference model output.

To be the formulation mentioned in (9) minimized, the MIT rule then provides the subsequent adaptation gains

$$\frac{d\theta}{dt} = -\gamma \frac{\partial \psi(\theta)}{\partial \theta} = -\gamma\varepsilon \frac{\partial \varepsilon}{\partial \theta} \tag{11}$$

Where:

γ : The adaptation parameters.

$\frac{\partial \varepsilon}{\partial \theta}$: The sensitivity derivative

Thus, the sensitivity derivative $\frac{\partial \varepsilon}{\partial \theta_1}$ $and \frac{\partial \varepsilon}{\partial \theta_2}$ are obtained as [20]

$$\begin{cases} \frac{\partial \varepsilon}{\partial \theta_1} = \frac{k_p}{s^2 + a_p s + (b_p + k_p\theta_2)} y_c \\ \frac{\partial \varepsilon}{\partial \theta_2} = -\frac{k_p}{s^2 + a_p s + (b_p + k_p\theta_2)} y \end{cases} \tag{12}$$

To achieve an accurate tracking performance in this closed-loop process, we will use the assumption that the time behavior is identical to that of the reference model. This means that the system will mimic the reference model's time response. Therefore we can write

$$s^2 + a_p s + (b_p + k_p\theta_2) = s^2 + a_m s + b_m \tag{13}$$

Accordingly, the adaptation parameters of the control law can be written as the following formulate

$$\begin{cases} \frac{d\theta_1}{dt} = -\gamma \left(\frac{1}{s^2 + a_m s + b_m} y_c(t) \right) \varepsilon(t) \\ \frac{d\theta_2}{dt} = \gamma \left(\frac{1}{s^2 + a_m s + b_m} y(t) \right) \varepsilon(t) \end{cases} \tag{14}$$

4. Results and Discussion

The simulation is conducted using the MATLAB/Simulink tool. The photovoltaic module utilized has an ideal power output of 852 W (Reference: Soltech STH-215-P) under normal meteorological circumstances, characterized by an irradiation level of 1000W/m2 with a temperature of 25◦C. The above-mentioned discussed MPPT are evaluated under sudden shifting of irradiance across five diverse states as shown in Figure 4. The PV power performance results under the selected test is depicted in Figure 5. Therefore, it's clear that the applied methods provided a fast response to achieve the desired output power under each irradiance state. Nevertheless, the SMC method showed some undesirable results such as the high fluctuation around MPP, hence the main cause of this problem was the chattering phenomenon associated with the conventional SMC control. The PV voltage response is illustrated in Figure 6, while the PV Power-Voltage and PV

Current-Voltage characteristics are depicted in Figures 7 and 8, respectively. Therefore, the results presented below unequivocally illustrate the higher performance of the adaptive control method in terms of tracking time, current ripple, and voltage ripple. Table 2 provides a clear and concise analytical comparison of the dynamic performance across the studied MPPT techniques.

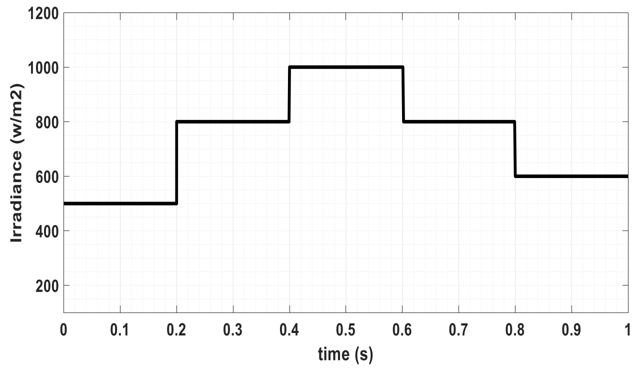

Fig. 4 Irradiance Profile.

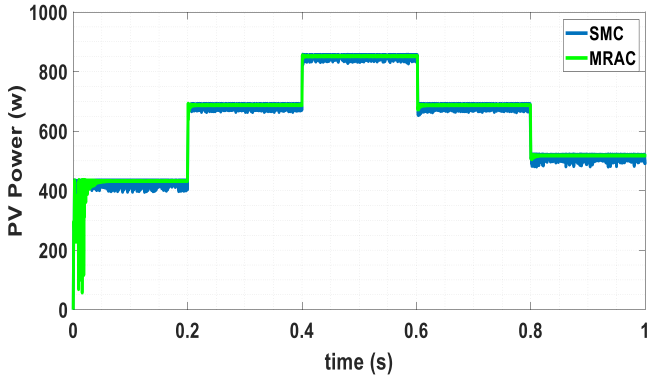

Fig. 5 PV power dynamic performance.

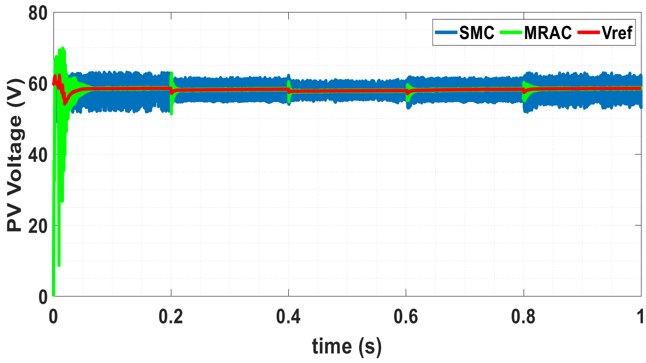

Fig. 6 PV Voltage dynamic performance.

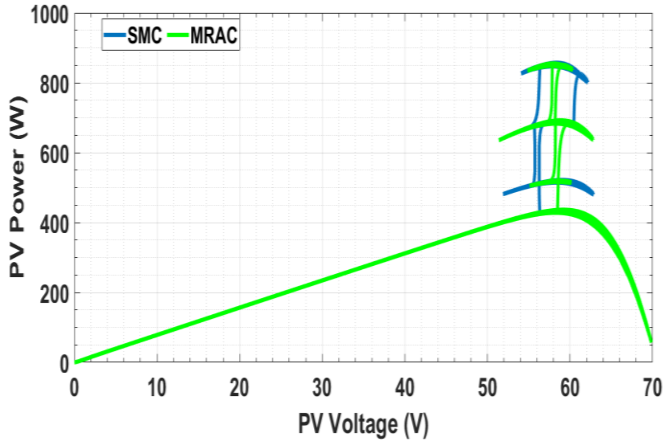

Fig. 7 Voltage- Power Characteristics

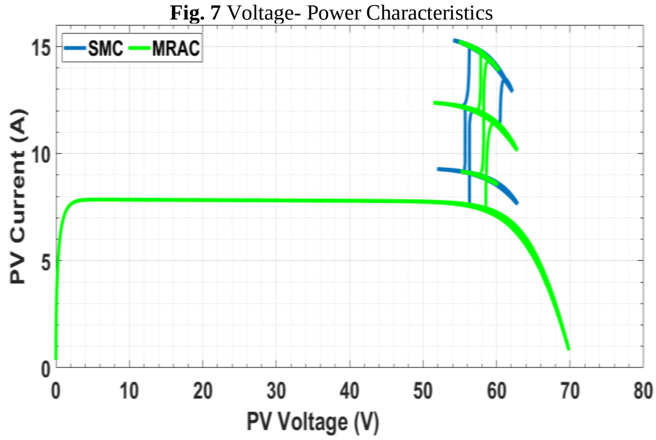

Fig. 8 Voltage-Current Characteristics.

Table 2 : In-depth comparative examination.

		Index				
Stage	**MPPT Method**	**η (%)**	**Power ripple**	**Voltage ripple**	**ITAE**	**IAE**
[0-0.2] (s)	SMC	96.9 (%)	38 (w)	9.9 (v)	0.24	2.69
	MRAC	96.3 (%)	0.67 (w)	0.52 (v)	0.038	3.19

$$\eta = \frac{\int_{t0}^{t1} P_{actual}}{\int_{t0}^{t1} P_{MAX}} \tag{15}$$

$$ITAE = \int t|e|\,dt \tag{16}$$

$$IAE = \int |e|\,dt \tag{17}$$

5. Conclusion

This work presents two renowned robust control methods for accurately tracking the maximum power of photovoltaic systems in the presence of frequently shifting meteorological circumstances. This study examines the effectiveness of sliding mode control (SMC) and model reference adaptive control (MRAC) in conjunction with adjustable perturb and observe (P&O) under various atmospheric conditions.

By utilizing the MATLAB/Simulink environment, the simulation results demonstrate that these algorithms can effortlessly attain maximum power, even in the presence of rapid atmospheric changes. The implemented MPPT algorithms have demonstrated exceptional performance, yielding highly efficient outcomes. However, the MRAC-based VSS-P&O exhibits superior performance in terms of reduced fluctuations around the maximum power point, decreased voltage, and current ripple, in addition to enhanced resilience and rapid reaction. Notably the fluctuation effect resulting from the SMC method was greatly caused by the chattering phenomena. However, all findings have been acquired to the highest level of satisfaction.

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