Optimized Cascade Fractional Order Controller for PV Systems

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ABSTRACT

Controlling and managing PV systems has been an open research subject for two decades. Regulating the operating point of a PV system requires acceptable closed-loop dynamic behavior. This paper proposes a cascade fractional order proportional integral derivative (FOPID) controller for voltage regulation of PV systems. The controller is optimized using the particle swarm optimization (PSO) algorithm, with the integral square error (ISE) as the fitness function. Excellent results were obtained, demonstrating that the proposed controller has the capability to operate in different working regions, especially in the constant current region where the oscillatory response must be reduced. The cascade controller has a significant impact on improving the dynamics of the PV system, as it can handle internal disturbances caused by the nonlinear relationship of PV current.

I. Introduction

Photovoltaic (PV) systems are a renewable energy technology that converts sunlight directly into electricity using semiconductor materials. The fundamental building block of a PV system is the solar cell, usually made from silicon. When exposed to sunlight, these cells generate direct current (DC) electricity through the photovoltaic effect. In fact, using a PV generator requires an association with a static converter, which allows for control and switching between different operating points. Hence, the nonlinearity present in the widely used boost converter, along with the unconventional nature of the PV source, makes controlling such a system a significant challenge in the field of control engineering [1, 2]. The main issue in controller design is that the plant exhibits variable behavior depending on the operating regions, which are commonly categorized into three types: voltage source (VSR), current source (CSR), and power source (PSR)[3]. In particular, the current source region, which represents the largest operating region, is the most challenging to control and exhibits oscillatory dynamics that can adversely affect any maximum power point tracking algorithm [4].

In the literature, various control techniques have been applied to PV systems, which can be divided into two main categories: linear controllers and nonlinear controllers. On one hand, nonlinear controllers, including Sliding Mode controllers [4, 5], feedback linearzation controllers as in [8] and adaptive controllers as [6], have demonstrated very good performance with reasonable control laws. However, these strategies depend on the plant's model. For any implementation, the designer must have precise knowledge of the model and all existing system uncertainties to ensure a robust closed-loop control. In the other hand, linear controllers are designed based on a linearized model around the operating point, such as the small signal models presented in [7] and [8]. This model may not remain valid for large deviations from the considered point, which can result in unpredictable system behavior. Additionally, linear controllers are generally highly dependent on the system's parameters, which complicate the controller design task [2, 9] . In the present work, another approach is used the address this problem, where the Meta-heuristic algorithm Particle Swarm Optimization [10] is applied to tune the fractional order PID controller. Fractional order control has demonstrated its efficiency, flexibility, and robustness over the past two decades. A cascade control strategy has been considered to reduce the effects of disturbances, as the PV current is directly related to solar irradiation.

The remainder of this paper is organized as follows: Section 3 describes the PV system connected to the boost converter and the issues associated with its voltage control. Section 4 presents the proposed controller and its tuning using a Meta-heuristic algorithm. Simulation results and their discussion are also presented in Section 4. Finally, the conclusion is provided in Section 5.

II. System Description

Figure 1 show the PV system used in this study, where three series panels are connected to a boost DC-DC converter to generate the required voltage. The boost converter is composed of passive elements L, C_i, C_o and active elements D and switch S. the overall system is controlled through this switch S allwing any change in the operational voltage.

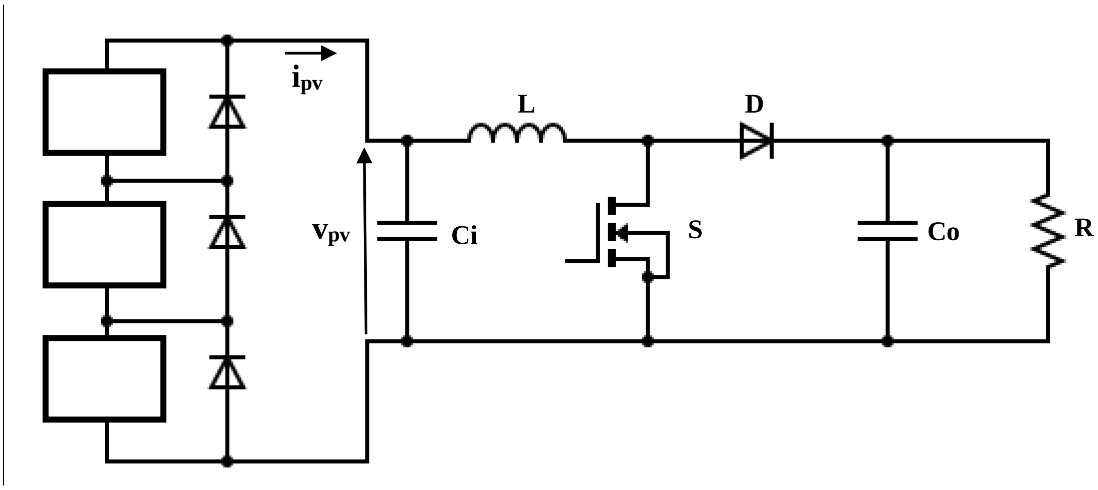

Figure 1. Association PV array/boost DC-DC converter.

The system shown in Figure 1 is represented by the following dynamic model:

$$\begin{cases} \dot{i}_L = \frac{v_{pv}}{L} - (1-u)\frac{v_o}{L} \\ \dot{v_{pv}} = \frac{i_{pv}}{C_i} - \frac{i_L}{C_i} \end{cases} \quad (1)$$

Where *vo* is the boost output voltage which is considered as an auxiliary state. *u* is the system input which is within the range [0 1] and *Vpv* is the system output to be controlled.

The current generated by the system is given by:

$$\mathrm{i_{pv}} = \mathrm{I_{ph}} - \mathrm{I_o}\left(\mathrm{e}^{\frac{\mathrm{v_{pv}+R_S i_{pv}}}{\mathrm{nN_S V_{th}}}} - 1\right) - \frac{\mathrm{v_{pv}+R_S i_{pv}}}{\mathrm{R_p}} \quad (2)$$

Where the photocurrent I_{ph} depends on the irradiation and temperature, and Io is the reverse saturation current.

From the nonlinear relationship (2), the PV current is highly denpending to the climatic conditions which need an appropriate controller that's ensuring better disturbance attenuation. In this work, the cascade control is proposed in order to reduce this distrbance effect.

The PV system employed in this study is the Kyocera KC200GT, and its parameters are listed in Table 1.

Table 1 Kyocera KC20GT PV panel characteristics at STC

Maximum power, P_{max}	200W (+10% / -5%)
Open circuit voltage, V_{oc}	32.9 V
Short circuit current, I_{SC}	8.21 A
Temperature coefficient of current, K_i	3.18e-3 A°C
Temperature coefficient of voltage, K_v	-1.23e-1 V/°C
Maximum power voltage	26.3V
Maximum power current	7.61 A

The characteristic I-V curve is shown in Figure 2, illustrating that the PV source differs from conventional sources with its three operating regions: CSR (Current Source Region), VSR (Voltage Source Region), and PSR (Power Source Region). The open loop response of this plant is illustrated by figure (3) where a significant change in the system dynamic behavior is observed. An oscillatory response increases in the (CSR) and decreases in (VSR). Traditional controller design concepts, which focus on the PSR (Power Source Region), often fail to provide acceptable performance across all operating regions. The challenge is how to control this multi-dynamic system using linear control methods.

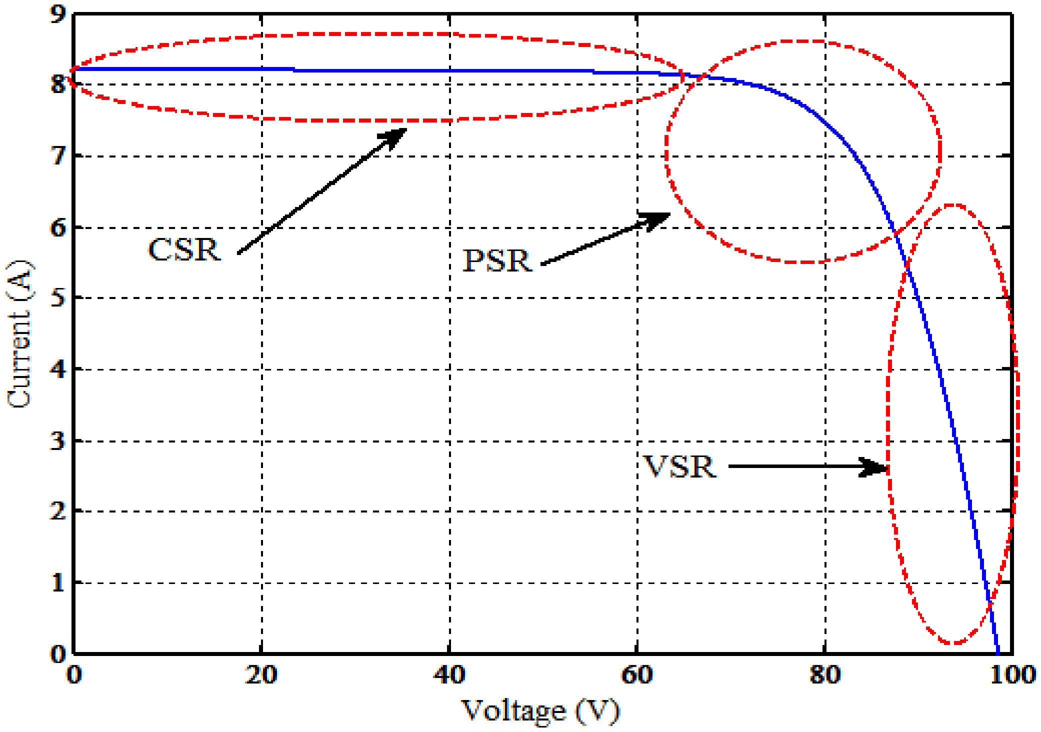

Figure 2. Characteristic (I-V) curves in standard test conditions STC.

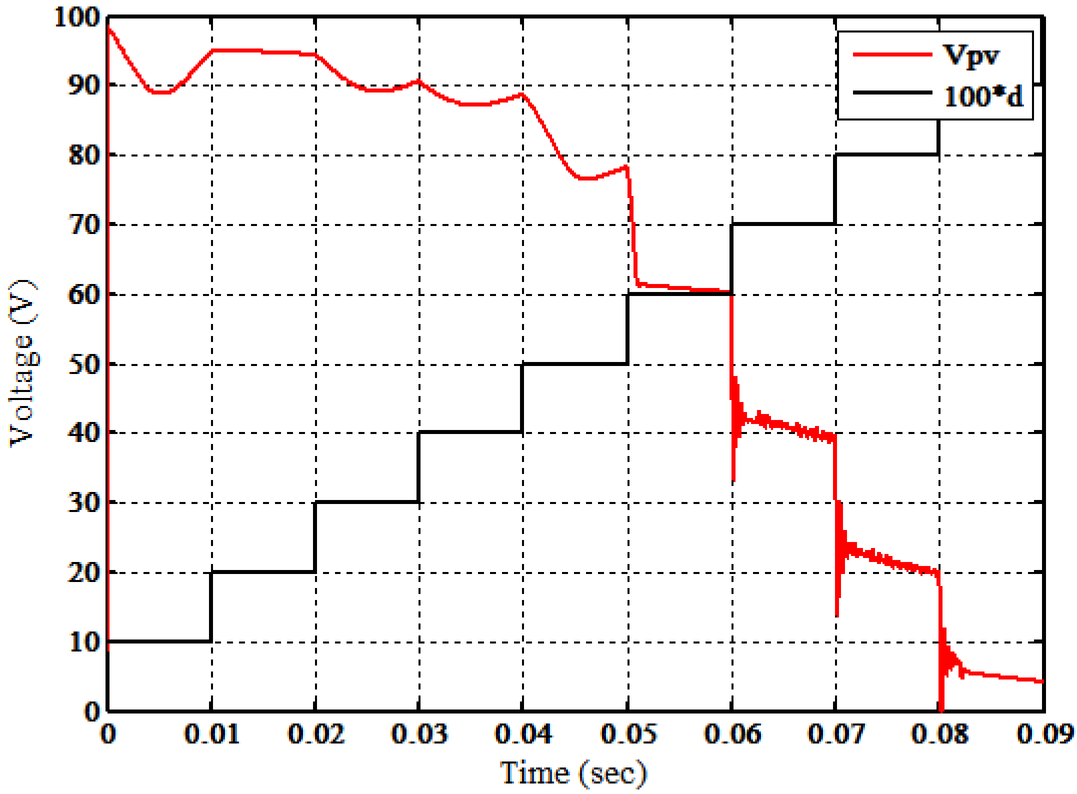

Figure 3 open loop response of the PV system

III. Proposed Controller

III.1) Fractional order proportional integral derivative controller

Over the last two decades, fractional calculus has emerged as a powerful tool in robust control design. The widely used structure is the one proposed by Poudloubny [11] which is which generalizes the classical PID control. The success achieved with the classical PID controller has opened research directions toward using fractional PID controllers, with many applications observed. For PV system [5, 12], using a fractional PID controller provides greater flexibility and enhances system dynamic performance, thereby improving maximum power point tracking (MPPT) algorithms.

$$u(t) = kc\, er(t) + Ti \int^{\lambda} er(t)dt + Td \frac{d^{\mu}}{dt^{\mu}}\, er(t) \quad (3)$$

Where er(t) and u(t) are the error and control signals respectively.

Figure (4) shows the structure of the fractional order PID used in this study. This controller has five parameters to tune instead of three gains of the classical PID. These parameters can be adjusted to ensure additional specifications in the closed loop system. However, the tuning of five parameters need more complicated algorithms which lead as to the well-kowen Meta heuristic program called Particle Swarm Optimization [10] (PSO).

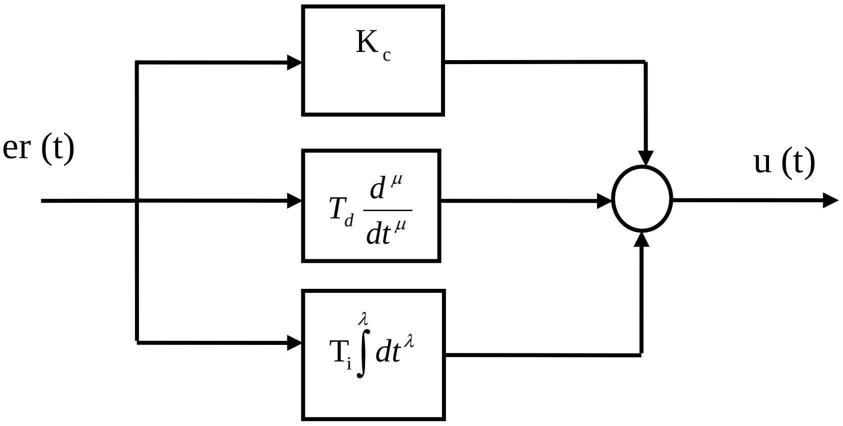

Figure 4 Structure of the fractional order controller (FOPID)

III.2) Tuning using the Particle Swarm Optimization (PSO) algorithm

Due to nonlinear model of PV associated boost converter, the controller design presents a challenging task where two main approach can be considered. The first approach is to consider the linearized model, from which the controller is designed based on the obtained transfer function. The second approach is to use the nonlinear model and optimize the controller parameters using a Meta-heuristic algorithm. In this study, the PSO algorithm is used to optimize the two cascade controllers, with the fitness function being the integral square error, given by:

$$ISE = \int_0^\infty er(t)dt \qquad (4)$$

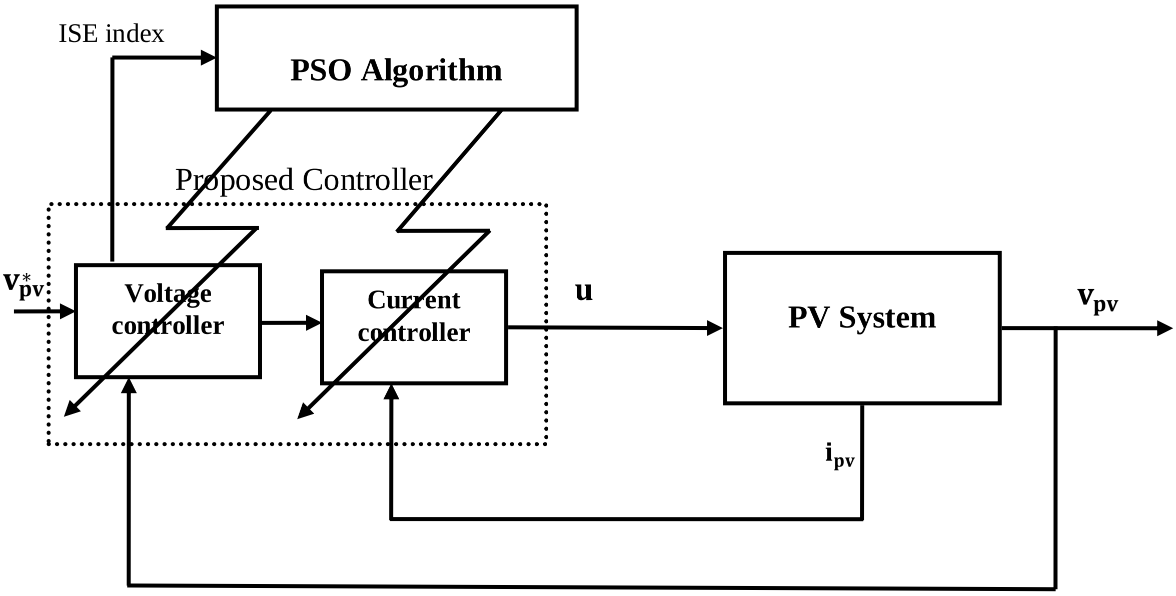

Figure 5. Proposed tuning strategy.

In the proposed tuning method, the PSO algorithm adjusts ten parameters (k_{c1}, T_{i1}, T_{d1}, λ_1, μ_1, k_{c2}, T_{i2}, T_{d2}, λ_2, μ_2) to minimize the Integral Square Error (ISE) index. The dynamic error considered is the differences between V_{ref} and V_{pv} across various operating regions, as shown in Figure 5.

IV. Simulation Results

The Particle Swarm Optimization (PSO) algorithm has been applied to tune the two cascade controllers, as shown in Figure 5, using 50 particles and 280 iterations.

It can be observed that the algorithm converges after approximately 140 iterations, with the final fitness function value equal to **0.1759**. The optimal parameters are as follows:

[k_{c1}	T_{i1}	T_{d1}	λ_1	μ_1	k_{c2}	T_{i2}	T_{d2}	λ_2	μ_2] =
[-1942.38	-2201.66	-1204.44	0.53	-0.399	220.28	21221.55	3543.59	0.978	-0.68]

It is clear that the obtained current and voltage controllers have a special structure of proportional control with two different integral orders $PI^{\lambda}I^{-\mu}$. The derivation of this structure, which has no equivalent in classical controllers, confirms the utility, efficiency, and adaptability of the fractional-order PI controller for such problems.

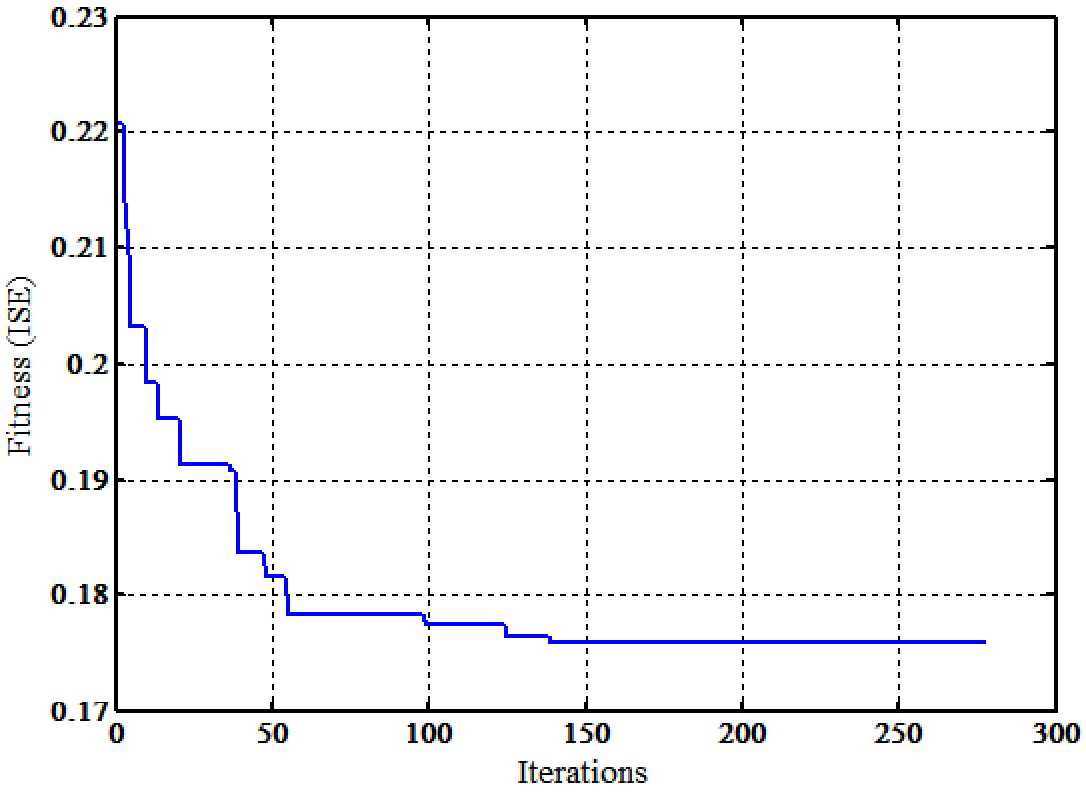

Figure 6. Convergence curve of the tuning algorithm.

The time response of the closed-loop system, simulated using the proposed cascade controller, is illustrated as follows: Figure 7 shows the voltage curve, Figure 8 shows the current curve, and Figure 9 shows the power curve. During the transient phases, a significant spike is observed in the current curve, which may be attributed to the initial charging conditions of the input/output capacitors and the inductance. However, this behavior can be disregarded as it is not relevant to control system design.

The presented responses confirm the existing oscillatory behavior, which increases as the operating point moves towards the CSR (Current Source Region). However, the proposed controller ensures acceptable performance across all operating ranges. Additionally, Figure 8 illustrates that the current controller performs excellently across the three operating regions, suggesting that the oscillatory behavior is primarily due to limitations in the outer voltage controller.

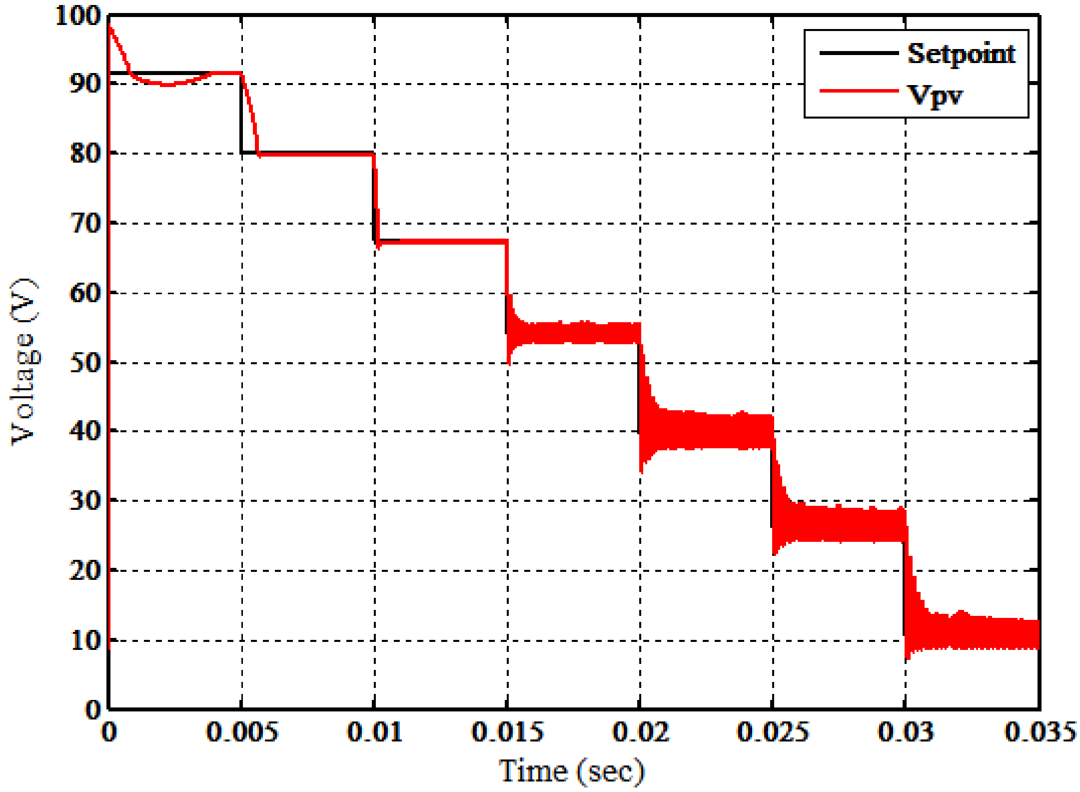

Figure 7. Controlled voltage of PV system.

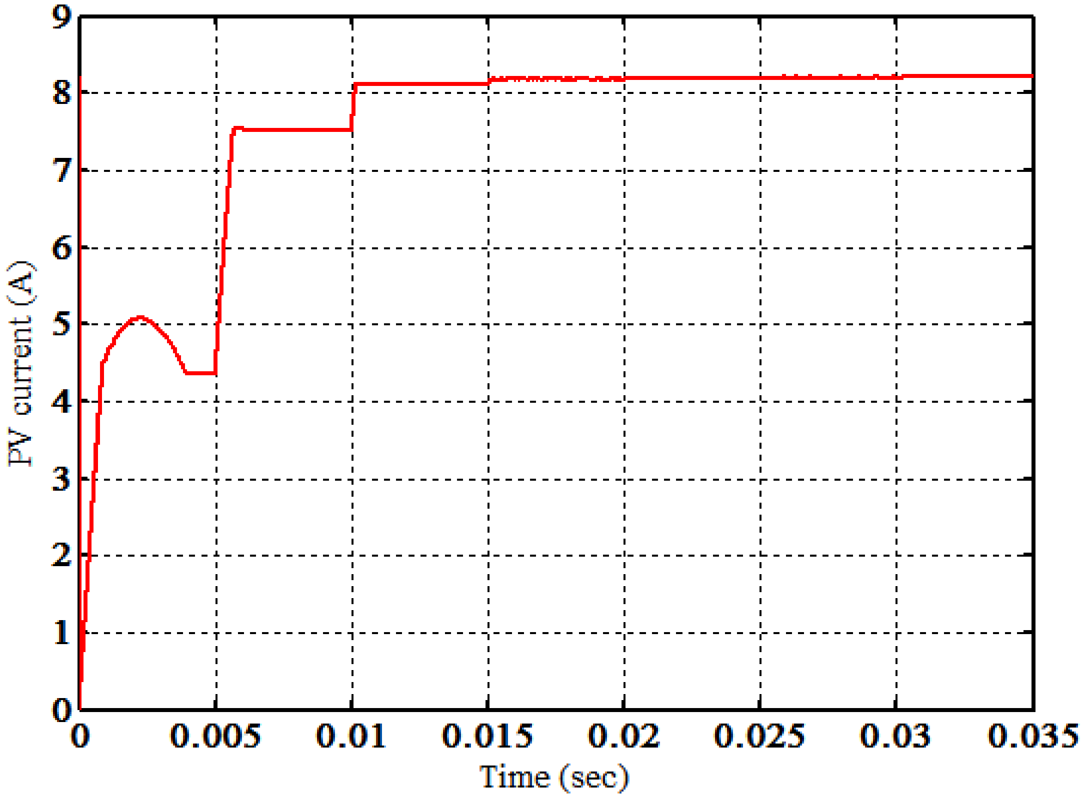

Figure 8. Current curve of the controlled PV system.

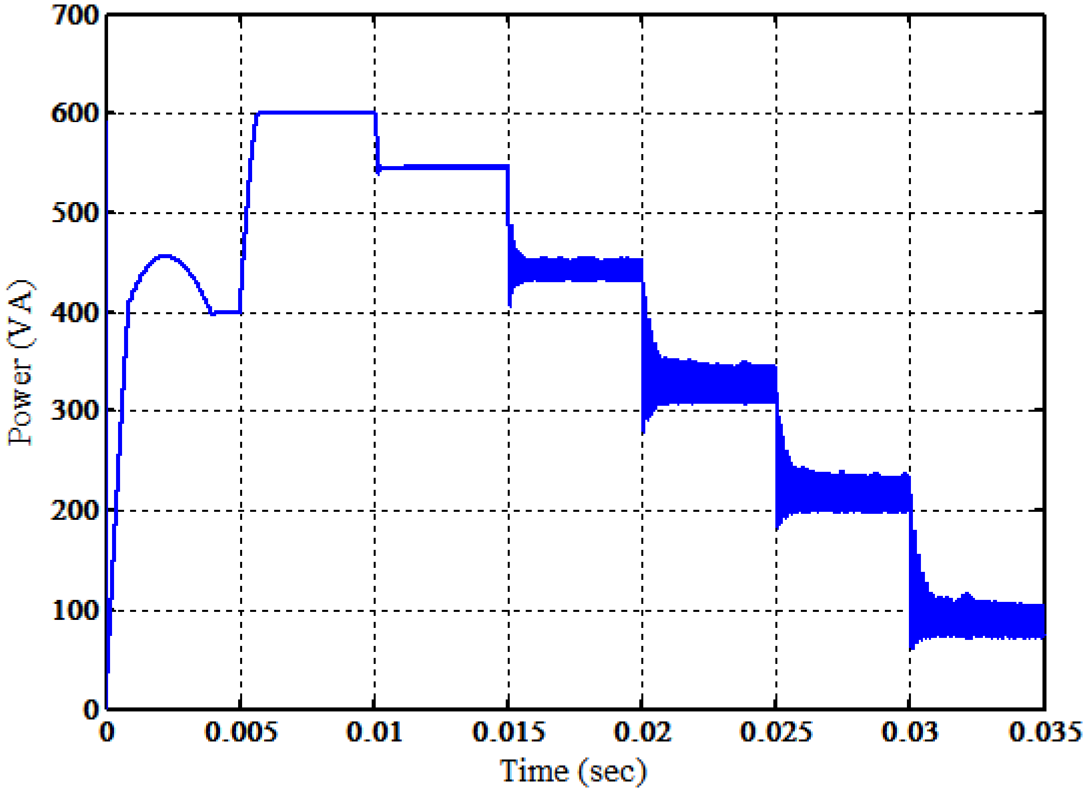

Figure 9. Power curve of the controlled PV system.

To study the effect of climatic conditions on PV system performance, the system has been simulated under varying values of solar irradiation and temperature. The performance indices, ISE and IAE, are presented in Table 2.

Table 2 Performance indices with variations in irradiation and temperature.

G	800	600	400	1000	1000	1000	800	600	400
T	25	25	25	35	45	50	30	35	40
ISE	0.2052	0.1975	0.2828	0.2144	0.2320	0.3190	0.2110	0.2162	0.4838
IAE	0.0501	0.0518	0.0628	0.0502	0.0559	0.0681	0.0506	0.0554	0.0819

It can be observed from Table 2 that the performance indices change significantly with decreasing irradiation and increasing temperature, especially when both parameters vary simultaneously. However, the proposed cascade controller has demonstrated robustness, achieving acceptable performance across different operating regions despite changes in climatic conditions.

V. Conclusion

The PV system presents an important nonlinear dynamic system with multiple behaviors, influenced both by the operating region and by climatic conditions. Considering these system characteristics during voltage controller design enhances system efficiency and ensures robust and precise operation at various operating points. The obtained results validate and demonstrate, on one hand, the efficiency of cascade control for such systems, and on the other hand, the robustness of the fractional order controller in terms of parameter changes. Key results from this study indicate that voltage control of a PV system presents significant challenges in the constant current region (CSR). Any proposed controller must be specifically designed, tested, and validated for this operating region. Additionally, all enhancements can be achieved through a thorough improvement of the voltage controller, which is crucial for addressing this control problem.

The Particle Swarm Optimization (PSO) algorithm has demonstrated its efficiency in solving nonlinear problems, particularly for controller tuning. The fractional order controller offers greater flexibility in control system design and can be effectively used for PV voltage regulation across different operating regions.

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