New MPPT Control for PV Systems Using the Equilibrium Optimizer Algorithm

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ABSTRACT

This paper proposes an efficient maximum power point tracking (MPPT) strategy based on the Equilibrium Optimizer (EO) algorithm for photovoltaic (PV) systems operating under both uniform and partial shading conditions. The PV generator is interfaced through a DC–DC Boost converter, whose voltage is regulated using a cascade PI–sliding mode controller to ensure fast and accurate tracking of the reference voltage. The EO algorithm is employed to identify the optimal operating voltage corresponding to the global maximum power point (GMPP) across different shading patterns. Simulation results demonstrate that the proposed EO-based MPPT scheme achieves rapid convergence, outperforming conventional methods particularly in complex multi peaks scenarios. Under partial shading, the algorithm successfully avoids local maxima and converges to the GMPP within 0.25 s, while maintaining stable voltage and power responses. The cascade control structure further enhances dynamic performance, as confirmed by time-domain indicators such as the integral absolute error (IAE). The combined use of an advanced Metaheuristic optimizer with a robust voltage controller significantly improves energy harvesting efficiency, making the proposed approach a promising solution for PV systems subject to irradiance variations.

I. Introduction

Photovoltaic (PV) systems have become a key component in modern renewable-energy infrastructures due to their sustainability, modularity, and declining production costs. Their electrical behavior is inherently nonlinear and strongly dependent on irradiance and temperature[1-3]. As a result, power conditioning through DC–DC converters is essential to regulate voltage and ensure optimal energy extraction[4]. These converters interface the PV generator with the load or storage element and play a central role in achieving high system efficiency. Indeed, the overall system behavior depends also to the climatic condition [5, 6]. A major challenge in PV system control arises under partial shading conditions, where non-uniform irradiance leads to a multimodal power–voltage (P–V) characteristic. This phenomenon produces multiple local maxima, making it difficult for conventional MPPT algorithms to identify the true global maximum power point. Consequently, advanced optimization-based and intelligent algorithms are required to achieve reliable tracking under such complex conditions.

In real-world applications, whether in grid-connected or standalone PV systems, Maximum Power Point Tracking (MPPT) is essential to ensure that the PV array continuously operates at the point where power generation is maximized. MPPT algorithms adjust the duty cycle of the DC–DC converter to maintain this optimal operating point in the presence of environmental variations. The effectiveness of the MPPT controller has a direct impact on the overall efficiency of the energy conversion process, particularly under rapidly changing irradiance or partial shading conditions, where fast dynamic response and high tracking accuracy are required.

Over the past decade, numerous Metaheuristic optimization algorithms have been investigated for MPPT and they can generally be classified into two main categories. The first category includes current-oriented MPPT techniques, as reported in [7-12]. The second category comprises voltage-oriented MPPT approaches, which are the most widely adopted in practical applications [13]. In this latter category, a significant number of studies have applied Meta-heuristic algorithms to search for the optimal voltage corresponding to the maximum power point. Approaches such as Particle Swarm Optimization (PSO)[14], Genetic Algorithms (GA)[15], Gray Wolf Optimizer (GWO)[14], and Cuckoo Search (CS) [16]have been proposed to overcome the limitations of conventional MPPT methods. These algorithms provide enhanced global search capabilities and improved robustness against multiple local maxima. However, their convergence speed and stability may deteriorate under highly dynamic environmental conditions. Therefore, the development of more efficient metaheuristic-based MPPT strategies remains an active and relevant research direction.

In this context, the present work proposes a new MPPT strategy based on the Equilibrium Optimizer (EO) Algorithm, a physics-inspired algorithm characterized by strong exploration–exploitation balance and fast convergence toward optimal solutions. The EO algorithm is employed to compute the optimal duty cycl of a DC–DC converter, ensuring accurate and robust tracking of the global maximum power point under various operating conditions. The remainder of this paper is organized as follows: Section 2 describes the photovoltaic system model and the Boost converter configuration. Section 3 discusses the partial shading scenarios and formulates the problem statement. Section 4 presents the EO-based MPPT strategy and its implementation. Section 5 reports the simulation results and comparative performance analysis. Finally, Section 6 concludes the paper.

II. Photovoltaic System

Figure 1 illustrates the PV system considered in this study, in which three panels connected in series supply a boost DC-DC converter to generate the DC voltage. The boost converter consists ofL, C_1, C_2,D and the switch S. the overall system is controlled through this switch S which enables adjustment of the operating voltage and thus facilitates Maximum Power Point Tracking.

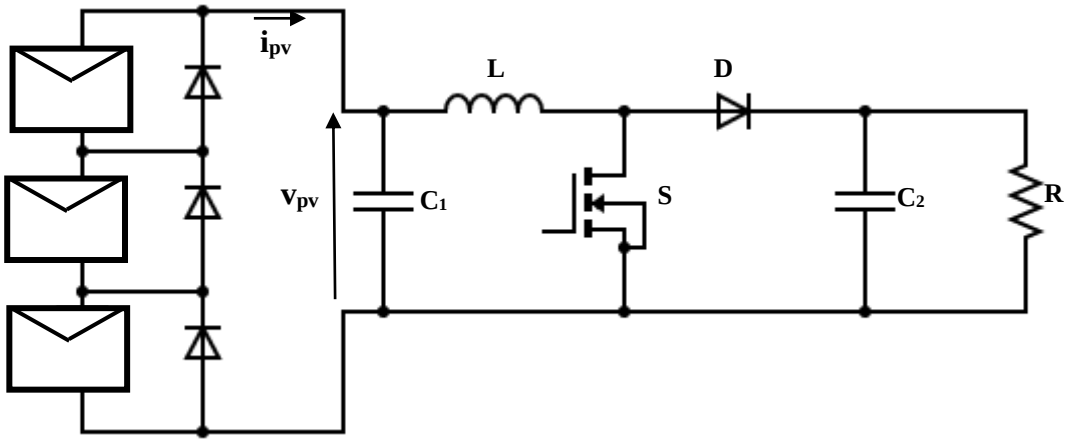

Figure 1. Used PV System and DC-DC converter.

The dynamic model of the boost converter combined to the PV system is given by:

$$\begin{cases} \frac{di_L}{dt} = \frac{v_{pv}}{L} - (1-u)\frac{v_o}{L} \\ \frac{dv_{pv}}{dt} = \frac{i_{pv}}{c_i} - \frac{i_L}{c_i} \end{cases} \quad (1)$$

Where *vo* is the boost output voltage 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.

PV panel is characterized by its current generated as [1]:

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

Where $I_{ph}$is the photocurrent and Io is the reverse saturation current.

The PV module used in this study is the Kyocera KC200GT, whose electrical and thermal parameters are summarized 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

III. Partial Shading

Partial shading occurs when solar irradiance is unequally distributed across the PV modules due to obstacles such as clouds, buildings, or vegetation. Under these conditions, each module receives a different amount of solar energy, leading to unbalanced electrical characteristics within the PV string. Consequently, the overall current–voltage (I–V) and power–voltage (P–V) curves of the PV system become nonlinear and exhibit multiple local maxima, as illustrated in Figure 2.

This multimodal behavior severely affects the performance of conventional MPPT algorithms, which are generally designed to track a single maximum power point. Under partial shading, such algorithms may converge to a local maximum instead of the global one, resulting in significant energy loss. Therefore, advanced optimization-based MPPT techniques are required to reliably identify the Global Maximum Power Point (GMPP) and ensure optimal energy extraction under rapidly changing shading patterns.

As shown in Figure 2, three operating scenarios are considered. The first corresponds to Standard Test Conditions (STC) with irradiance levels of (1000–1000–1000) W/m², yielding a maximum power of 600 W at V_{mp}=79 V. The second scenario, P1, represents heterogeneous irradiance conditions of (900–700–500) W/m², producing a maximum power of 331 W at V_{mp}=83 V. The third scenario, P2, corresponds to irradiance levels of (800–500–200) W/m², with a maximum power of 214 W at V_{mp}=54 V.

The presence of multiple peaks makes the search for the reference voltage significantly more complex, thereby necessitating the use of advanced Metaheuristic algorithms capable of overcoming the limitations of classical MPPT methods.

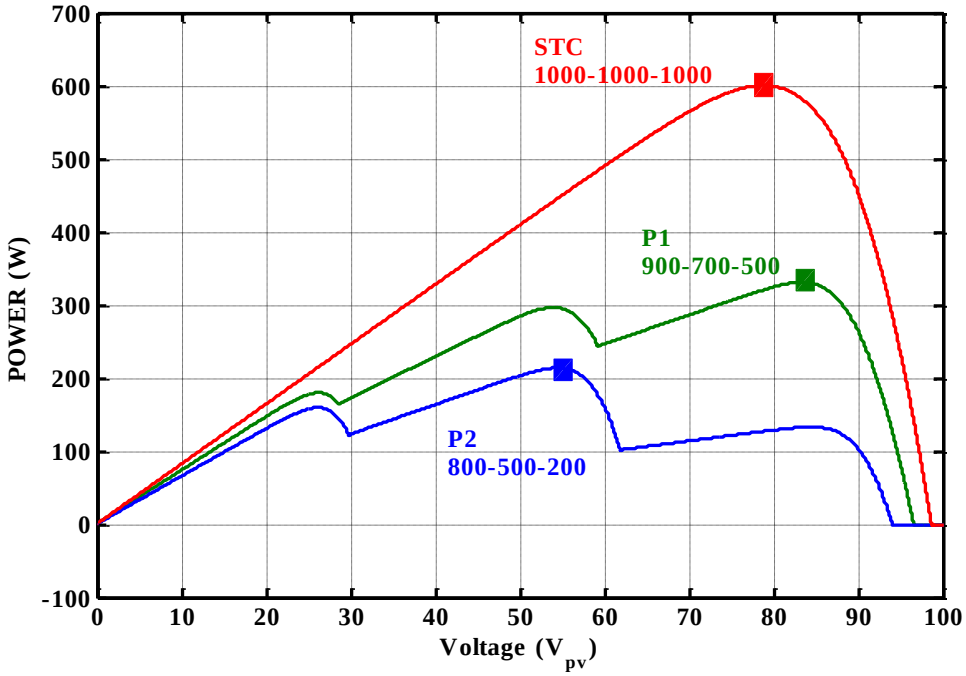

Figure 2. Characteristics P-V for three used scenarios.

VI. Proposed EO-based MPPT Algorithm

VI.1) Equilibrium Optimizer (EO) algorithm

A recently developed Metaheuristic method, known as the Equilibrium Optimizer (EO), has emerged as a promising optimization framework. EO is derived from the concept of dynamic mass balance, where candidate solutions evolve toward equilibrium states based on source–sink mechanisms. Since its introduction in [17], the algorithm has attracted growing attention due to its simple structure, strong exploration–exploitation balance, and competitive performance across a wide range of optimization problems[18-20].

The EO algorithm begins by initializing a population of NNN candidate solutions. The *i*-th particle in the *d*-th dimension is generated using:

$$X_i^d = X_{min} + rand_i^d(X_{max} - X_{max}) \quad i = 1,2,\dots,N \; and \; d = 1,2,\dots,D \tag{3}$$

where $X_i$denotes the position of the i^{th} particle, D is the dimensionality of the search space, and $rand_i^d$ is a uniformly distributed random number in [0, 1]. The variable X_{min} and X_{max} represent the admissible lower and upper bounds of each dimension, respectively. N represents the number of particles. The $X_{eq,pool}$ is the equilibrium pool that contains the best 4 candidates $X_{eq(i)}$ with its average $X_{eq(ave)}$. To guide the population toward promising regions, EO constructs an equilibrium pool composed of the four best individuals and their mean value:

$$X_{eq,pool} = \{X_{eq(1)},\ X_{eq(2)},\ X_{eq(3)},\ X_{eq(4)},\ X_{eq(ave)}\} \tag{4}$$

with the average equilibrium state defined by:

$$X_{eq(ave)} = \frac{(X_{eq(1)} + X_{eq(2)} + X_{eq(3)} + X_{eq(4)})}{4} \tag{5}$$

At each iteration, particles update their positions by selecting one of the equilibrium candidates at random. The convergence dynamics are influenced by an exponential factor F, given by:

$$F = Bsign(r - 0.5)[\exp(-\lambda t) - 1] \tag{6}$$

where *r* is a random number in [0, 1], λ is a uniformly distributed random vector, and *t* is a time-dependent parameter computed as:

$$t = \left(1 - \frac{Iter}{MaxIter}\right)^{\left(\alpha \frac{Iter}{MaxIter}\right)} \quad (7)$$

This dynamic formulation allows EO to maintain a suitable trade-off between exploration and exploitation.

The generation rate G is expressed as:

$$G = G_0 \exp\left(-\lambda(t - t_0)\right) = G_0 F \quad (8)$$

where G_0 and $t_0$are constant parameters governing the magnitude of exploration.

The particle position is updated according to:

$$X = X_{eq} + \left(X - X_{eq}\right)F + \frac{G}{\lambda V}(1 - F) \quad (9)$$

With *V* representing a control parameter influencing the diffusion effect.

The EO algorithm is summarized as follows:

VI.2) Proposed strategy

In the proposed MPPT scheme, the Equilibrium Optimizer (EO) is employed to determine the optimal operating voltage V_{mp} under partial shading. The algorithm searches for the global maximum of the PV power–voltage characteristic by iteratively updating a population of candidate voltages according to the EO dynamics.

For each pattern of Fig. 2, EO is initialized within the feasible PV voltage range and evaluates the corresponding power using the PV model. The algorithm then drives the candidate solutions toward the equilibrium state representing the global MPP. The final equilibrium concentration vector yields the optimal reference voltage V_{mp} , which is subsequently used as the control set point for the boost converter figure (3).

The voltage regulation loop employs a cascade PI–sliding mode controller, structured similarly to the approach presented in [6]. This architecture ensures robust tracking and stable operation across the different operating regions of the PV–boost converter system

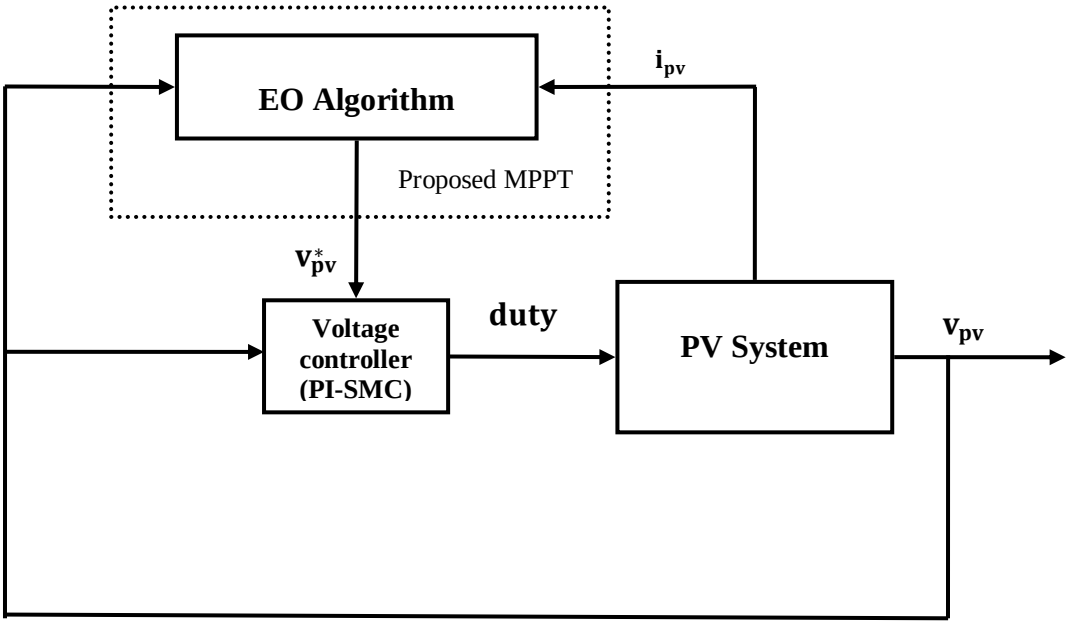

Figure 3. Proposed MPPT controller.

V. Simulation results

This section presents a comprehensive set of simulation results to validate the effectiveness of the proposed EO-based MPPT strategy under various partial shading conditions. The dynamic model of the boost-fed PV system is implemented in MATLAB/Simulink, and the EO algorithm is applied to extract the optimal operating voltage for

the three shading patterns introduced in Fig. 2. The obtained results are analyzed in terms of convergence speed toward the global MPP, stability of the voltage regulation, and accuracy in tracking the true maximum power point. Comparative performance with the classical P&O method is also provided to highlight the improvements achieved in transient and steady-state behavior. The corresponding time-domain responses are presented in the following figures.

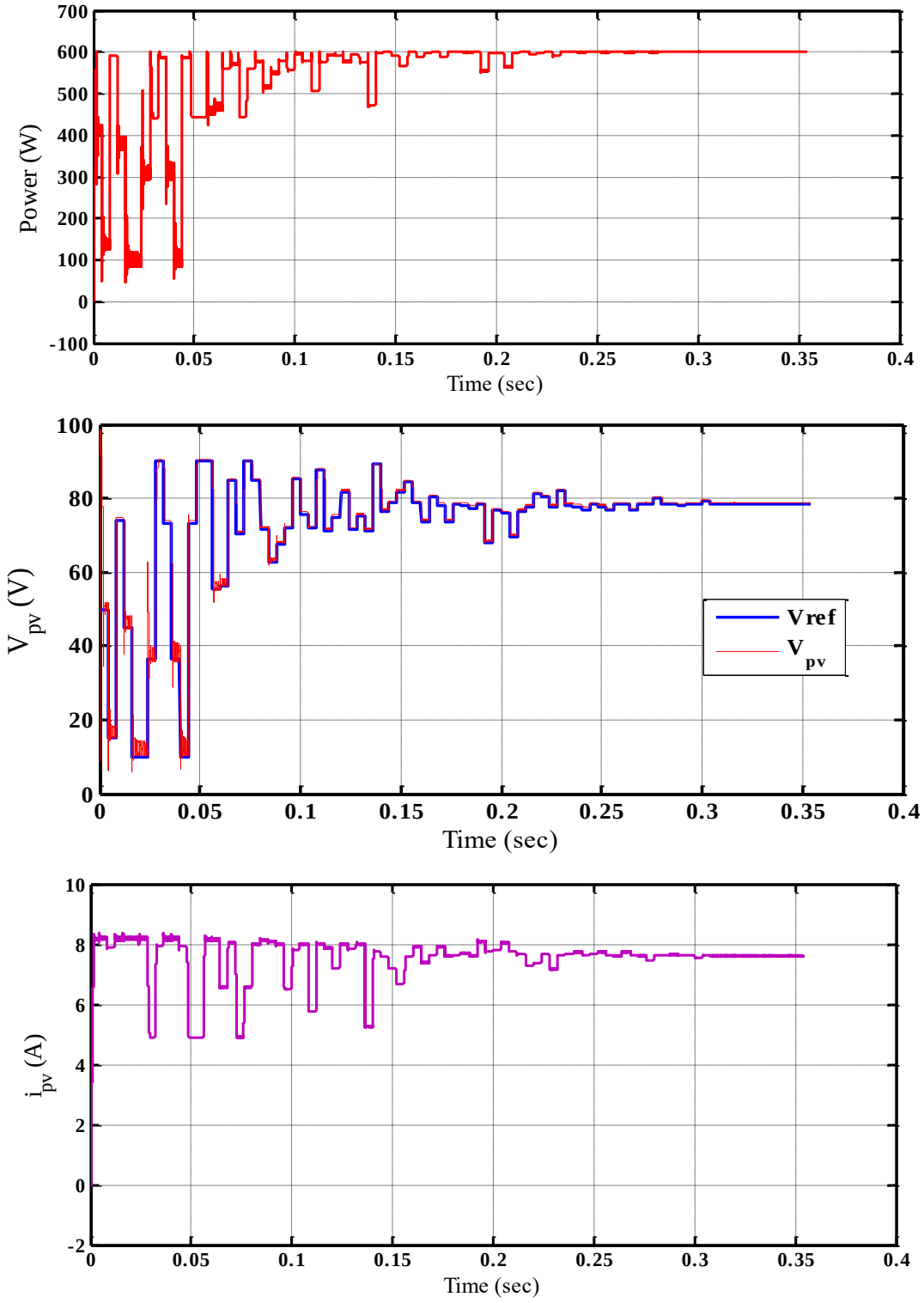

Figure 4. Time responses of the proposed algorithms in STC.

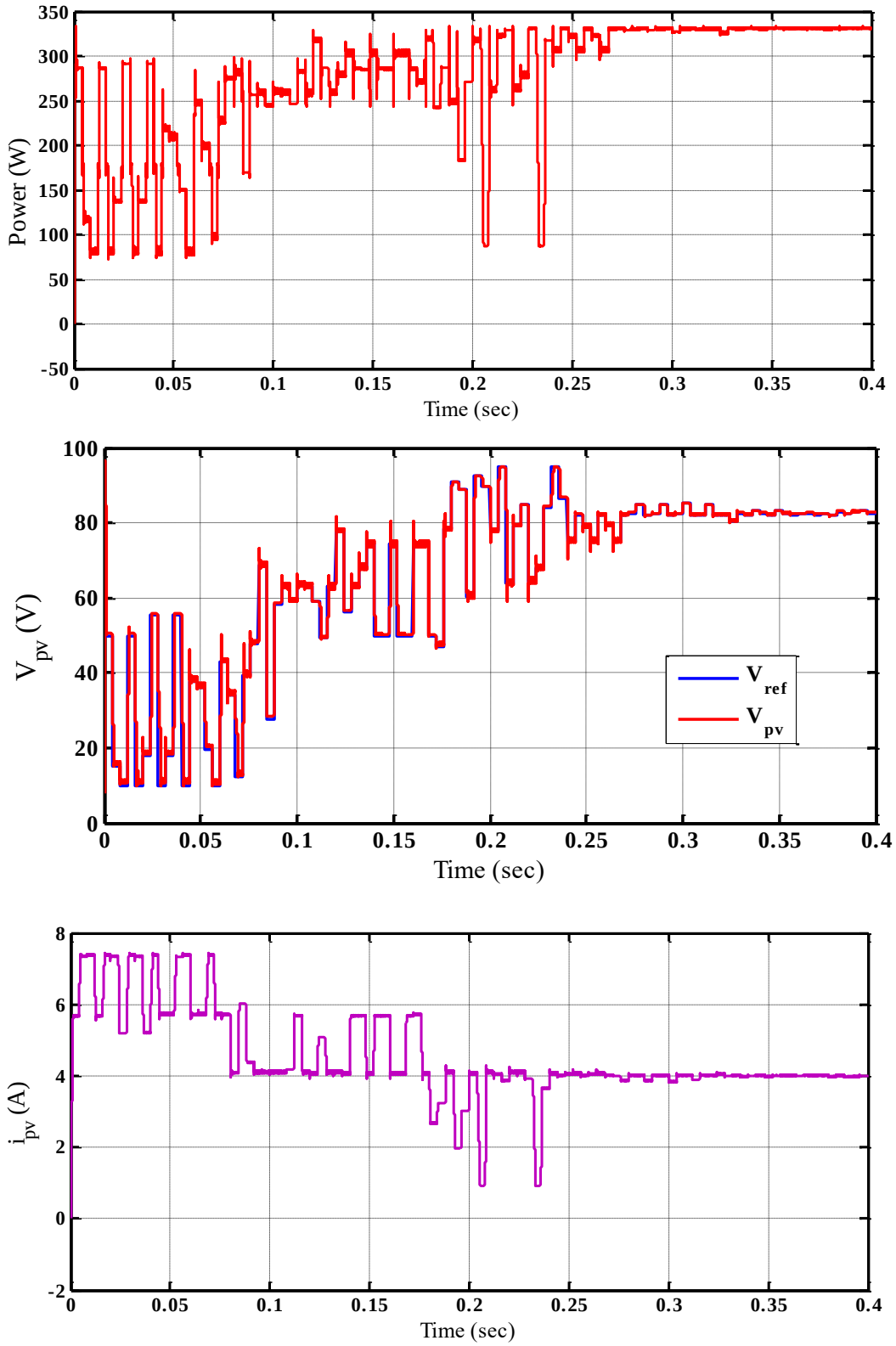

Figure 5. Time responses of the proposed algorithms in P1.

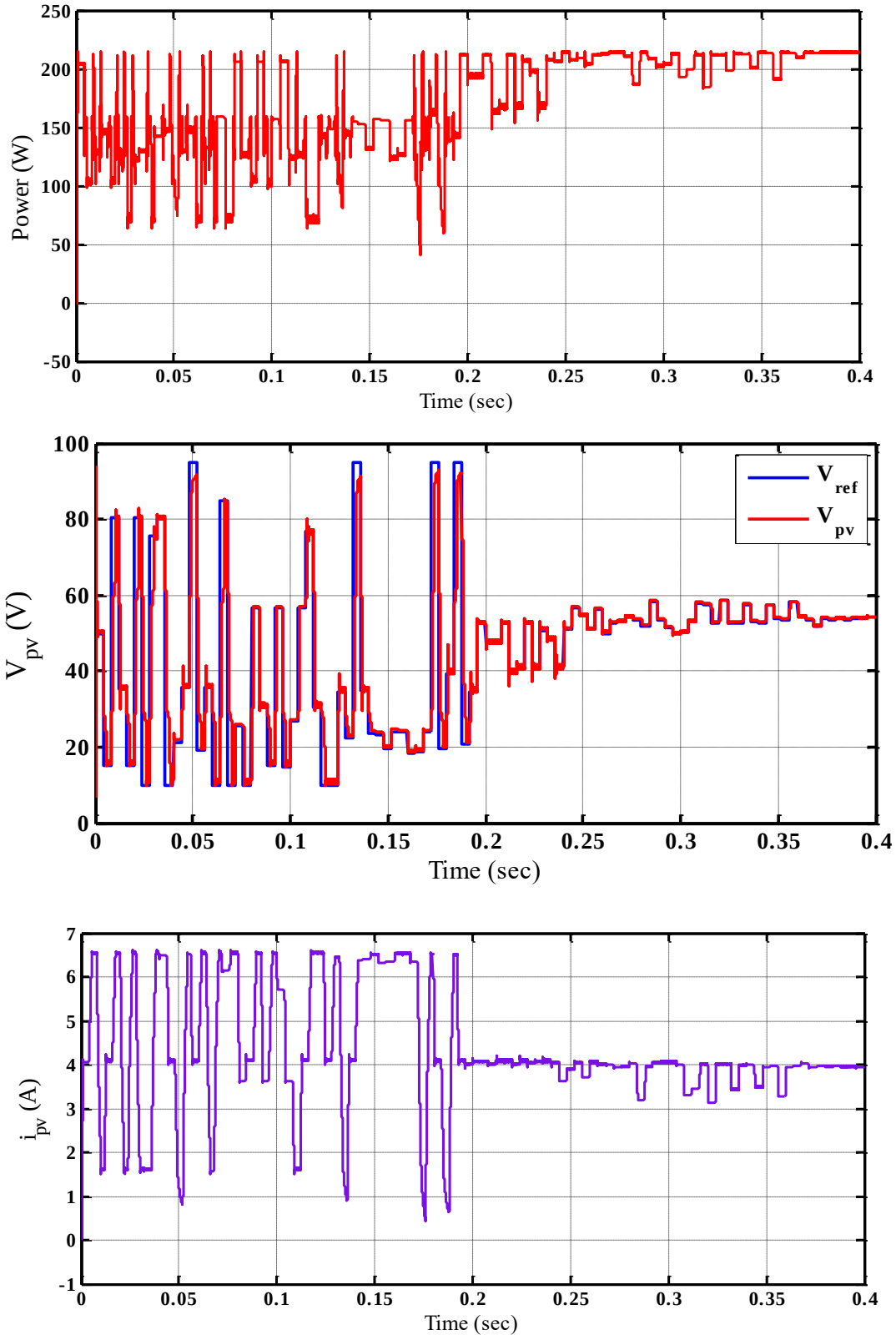

Figure 6. Time responses of the proposed algorithms in P2.

As illustrated in Fig. 4, the proposed algorithm demonstrates a superior convergence rate, attaining the optimal

operating point in approximately **0.15 seconds—a 40% improvement** over the two benchmark patterns (P1 and P2), which both converge at around 0.25 s. This accelerated response is attributed to the synergistic combination of the Equilibrium Optimizer (EO) and the cascade PI–sliding mode controller. The controller's architecture is pivotal, as the sliding mode component ensures robust handling of system nonlinearities and disturbances, thereby enabling the excellent transient performance observed. This results in highly accurate and reliable Maximum Power Point Tracking (MPPT) operation, with minimal oscillation around the peak power point. The quantitative superiority of the proposed method is further corroborated by the time-domain performance indices in Table 2. The significantly lower Integral Absolute Error (IAE) values for both voltage and power confirm the enhanced effectiveness of both the voltage regulation loop and the overall MPPT strategy, validating its precision and stability.

Table 2 Time characteristics using the proposed algorithm.

	IAE(V)	IAE (P)	Convergence time
Standard test condition (STC)	8.34 10^5	3.78 10^7	0.1415
Pattern (P1)	9.6 10^5	4.44 10^7	0.2403
Pattern (P2)	8.62 10^5	1.67 10^7	0.2411

V. Conclusion

This study presented a robust MPPT strategy based on the Equilibrium Optimizer (EO) algorithm, integrated with a cascade PI sliding mode voltage controller for a PV system interfaced through a Boost converter. Simulation results demonstrated that the proposed approach provides a significantly faster convergence to the maximum power point, achieving shorter response times in STC condition compared with the other tested patterns. Under varying irradiance levels and partial shading conditions, the EO algorithm exhibited strong exploration–exploitation capability, ensuring accurate identification of the optimal voltage V_{mp}. In parallel, the cascade control structure delivered excellent transient performance and precise voltage tracking, contributing to enhanced global system behavior.

Performance indices, including the integral absolute error (IAE), confirmed the superiority of the proposed method in terms of speed, stability, and MPPT tracking accuracy. Overall, the combination of a robust control scheme with a modern optimization algorithm proves to be an effective solution for PV systems operating under dynamic and uncertain conditions. Future work may include experimental validation and assessment of the proposed approach on large-scale or grid-connected PV installations.

References

[1] M. G. Villalva, J. R. Gazoli, and E. Ruppert Filho, "Modeling and circuit-based simulation of photovoltaic arrays," in *2009 Brazilian Power Electronics Conference*, 2009, pp. 1244-1254.

[2] H. J. El-Khozondar, R. J. El-Khozondar, K. Matter, and T. Suntio, "A review study of photovoltaic array maximum power tracking algorithms," *Renewables: Wind, Water, and Solar*, vol. 3, pp. 1-8, 2016.

[3] H. J. El-Khozondar, R. J. El-Khozondar, and K. H. Matter, "Simulation and Implementation of Incremental Conductance Maximum Power Point Tracking Algorithm for Photovoltaic System," *Journal of Mechatronics*, vol. 3, pp. 174-178, 2015.

[4] W. Xiao, W. G. Dunford, P. R. Palmer, and A. Capel, "Regulation of photovoltaic voltage," *IEEE Transactions on Industrial Electronics,* vol. 54, pp. 1365-1374, 2007.
[5] M. Aquib, S. Jain, and V. Agarwal, "A time-based global maximum power point tracking technique for PV system," *IEEE Transactions on Power Electronics,* vol. 35, pp. 393-402, 2019.
[6] M. S. Bouakkaz, A. Boukadoum, O. Boudebbouz, N. Fergani, N. Boutasseta, I. Attoui, A. Bouraiou, and A. Necaibia, "Dynamic performance evaluation and improvement of PV energy generation systems using Moth Flame Optimization with combined fractional order PID and sliding mode controller," *Solar Energy,* vol. 199, pp. 411-424, 2020.
[7] P. E. Kakosimos, A. G. Kladas, and S. N. Manias, "Fast photovoltaic-system voltage-or current-oriented MPPT employing a predictive digital current-controlled converter," *IEEE Transactions on Industrial Electronics,* vol. 60, pp. 5673-5685, 2012.
[8] M. Metry, M. B. Shadmand, R. S. Balog, and H. Abu-Rub, "MPPT of photovoltaic systems using sensorless current-based model predictive control," *IEEE Transactions on Industry Applications,* vol. 53, pp. 1157-1167, 2016.
[9] E. Bianconi, J. Calvente, R. Giral, E. Mamarelis, G. Petrone, C. A. Ramos-Paja, G. Spagnuolo, and M. Vitelli, "A fast current-based MPPT technique employing sliding mode control," *IEEE Transactions on Industrial Electronics,* vol. 60, pp. 1168-1178, 2012.
[10] G. A. Raiker and U. Loganathan, "Current control of boost converter for PV interface with momentum-based perturb and observe MPPT," *IEEE Transactions on Industry Applications,* vol. 57, pp. 4071-4079, 2021.
[11] D. Ounnas, M. Ramdani, S. Chenikher, and T. Bouktir, "An Efficient Maximum Power Point Tracking Controller for Photovoltaic Systems Using Takagi–Sugeno Fuzzy Models," *Arabian Journal for Science and Engineering,* vol. 42, pp. 4971-4982, 2017.
[12] S. Sousa, L. Gusman, T. Lopes, H. Pereira, and J. Callegari, "MPPT algorithm in single loop current-mode control applied to dc–dc converters with input current source characteristics," *International Journal of Electrical Power & Energy Systems,* vol. 138, p. 107909, 2022.
[13] S. Motahhir, A. El Hammoumi, and A. El Ghzizal, "The most used MPPT algorithms: Review and the suitable low-cost embedded board for each algorithm," *Journal of cleaner production,* vol. 246, p. 118983, 2020.
[14] J. Águila-León, C. Vargas-Salgado, D. Díaz-Bello, and C. Montagud-Montalvá, "Optimizing photovoltaic systems: A meta-optimization approach with GWO-Enhanced PSO algorithm for improving MPPT controllers," *Renewable Energy,* vol. 230, p. 120892, 2024.
[15] F. M. de Oliveira, M. H. M. Brandt, F. Salvadori, J. E. E. Izquierdo, M. R. Cavallari, and O. H. Ando Junior, "Development of an MPPT-based genetic algorithm for photovoltaic systems versus classical MPPT techniques in scenarios with partial shading," *Inventions,* vol. 9, p. 64, 2024.
[16] T. Mariprasath, C. H. Basha, B. Khan, and A. Ali, "A novel on high voltage gain boost converter with cuckoo search optimization based MPPTController for solar PV system," *Scientific reports,* vol. 14, p. 8545, 2024.
[17] A. Faramarzi, M. Heidarinejad, B. Stephens, and S. Mirjalili, "Equilibrium optimizer: A novel optimization algorithm," *Knowledge-based systems,* vol. 191, p. 105190, 2020.
[18] D. A. Elmanakhly, M. M. Saleh, and E. A. Rashed, "An improved equilibrium optimizer algorithm for features selection: Methods and analysis," *IEEE Access,* vol. 9, pp. 120309-120327, 2021.
[19] R. Rai and K. G. Dhal, "Recent developments in equilibrium optimizer algorithm: its variants and applications," *Archives of Computational Methods in Engineering,* p. 1, 2023.
[20] M. A. Al-Betar, I. Abu Doush, S. N. Makhadmeh, G. Al-Naymat, O. A. Alomari, and M. A. Awadallah, "Equilibrium optimizer: a comprehensive survey," *Multimedia Tools and Applications,* vol. 83, pp. 29617-29666, 2024.