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RESEARCH ARTICLE

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A novel maximum power point tracking technique based on Rao-1 algorithm for solar PV system under partial shading conditions

Laxman Bhukya | **Anil Annamraju** | **Srikanth Nandiraju**

Department of Electrical Engineering, National Institute of Technology, Warangal, Telangana, India

Correspondence
Laxman Bhukya, Department of Electrical Engineering, National Institute of Technology, Warangal, Telangana, India.
Email: blaxman@student.nitw.ac.in

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Summary

The performance of the Photovoltaic (PV) system is highly affected by fluctuating climatic conditions. Due to these changing climatic conditions, the irradiance diminishes, and it results in the non-linearity in voltage-power (P-V) curves of the PV system. Therefore, it is one of the reasons for the occurrence of the multiple peaks on P-V curves instead of a single peak. Therefore, it is challenging to track the global maximum power point tracking (MPPT) under these circumstances with traditional MPPT techniques viz. perturb and observe (P&O) and fuzzy logic control (FLC). Concerning global MPP tracking, this paper proposes a novel MPPT method based on a Rao-1 optimization algorithm. The proposed algorithm is used to overcome the drawbacks of the classical P&O, FLC, and PSO based MPPT techniques under partical shading conditions (PSCs) and rapidly changing atmospheric conditions viz. slow convergence speed and oscillation around the MPP. The proposed MPPT tracks the global MPP under any abnormal conditions like PSCs. To show the efficiency of the proposed MPPT a comparative assessment is performed with well-established MPPT methods in the literature. The simulation results witnessed that the proposed MPPT is more superior in improving the PV system performance under normal as well as under PSCs. The proposed MPPT over the PSO technique decreases the tracking time by 72.7% for pattern 1, 29.8% for pattern 2, 66.7% for pattern 3, 61.9% for pattern 5, 27.8% for pattern 6, and improves the tracking efficiency in all shading patterns.

KEYWORDS

global maximum, maximum power point tracking, partial shading conditions, photovoltaic system, Rao-1 algorithm

List of Symbols and Abbreviations: I_d, diode current (A); I_{SLC}, Sun light current (A); I_{SPVC}, solar PV cell output current; V_{SPVC}, solar PV cell voltage (V); R_{SH} and R_S, shunt and series resistance of PV cell (Ω); G, Sun irradiance (W/m^2); K_t, Temperature coefficient; T_r, Standard temperature (K); T_c, Cell temperature (K); V_t, Thermal voltage (V); I_o, diode reverse saturation current; D, duty cycle; V_{out}, Output voltage; V_{in}, PV voltage as input to the converter; q, Charge of an electron; K, The Boltzmann's constant; a, Diode ideality factor; ABC, artificial bee colony; ANN, artificial neural network; CS, cuckoo search; DRNN, deep recurrent neural network; FFA, fusion firefly algorithm; FL, fuzzy logic; FLC, fuzzy logic control; FP, flower pollination; GA, genetic algorithm; GHO, grasshopper optimization; GWO, gray wolf optimization; HC, hill climbing; INC, incremental conductance; MPP, maximum power point; MPPT, maximum power point tracking; P&O, perturb and observe; PV, Photovoltaic; PVS, photovoltaic system; PSC, partial shading condition; PSO, particle swarm optimization; RES, renewable energy sources.

1 | INTRODUCTION

The continuous decrease in natural resources and increasing demand for energy has lead research on alternative energy of renewable sources. Earnest renewable energy sources (RES) that are low running cost, less maintenance, and environmentally safe are required.[1,2] From the last decade, the solar photovoltaic system (PVS) based RES has gained great attention because of its advantages of unpolluted operation, low maintenance cost, unlimited power resource, and convenient utilization. PVS consists of many PV modules that are connected in series and parallel structure to enhance its capacity. The power generation from PVS predominantly depends on insolation and ambient temperature.[3] Consequently, partial shading condition (PSC) takes place if a part or whole PV modules receive non-uniform insolation.[4] Therefore, the voltage against power (P-V) curves of PVS produce multiple peaks with one global peak under PSCs, which is necessary to be tracked.

1.1 | Motivation

Due to the PV cell has limited efficiency, the PV systems are always required to operate close to the MPP to gain the maximum energy harvesting. Hence, to enhance the PVS power generation efficiency under PSCs, the maximum power point (MPP) essentially operated at a global peak. For uniform insolation, the P-V curve produces the only peak, and the conventional methods viz. incremental conductance (INC), hill climbing (HC), and perturb and observe (P&O) can track the MPP of PVS accurately.[5,6] The authors in Reference 7 proposed a P&O with genetic algorithm (GA) and cuckoo search (CS) optimization tuned Proportional-Integral-Derivative (PID) controller to track the MPP of a PV system. The GA and CS algorithms are used to tune the parameters of PID with various cost functions to find out the optimal MPPT technique. A significant number of improved or modified techniques have been proposed based on the INC or P&O to overcome the disadvantages in the past few years.[8] Under PSCs, the P-V curve has multiple peaks, and the MPP tracking using conventional methods can fall into the local peak and results in a reduction of efficiency of the PVS. Moreover, these P&O and HC methods produce oscillations at MPP due to constantly fluctuating perturbation in both directions, thereby, which leads the power loss in PVS. The conventional INC method reduces these oscillations but fails to remove them. Concerning the above issues, the PV system requires an efficient MPPT technique that tracks the global MPP. This paper purposes to provide an efficient MPPT technique to handle all abnormal conditions.

1.2 | Related works and key research gap

Many researchers introduced soft computing based MPPT methods viz. fuzzy logic control (FLC) and artificial neural network (ANN) for extracting the maximum power from the P-V array.[9,10] The authors proposed a new power differentials MPP tracking algorithm for the thermoelectric generators.[11] FLC based method is widely employed to enhance the reliability and efficiency of PVS under normal conditions. The authors proposed input current sensor-based fuzzy MPPT, in which the PV system requires only one sensor to measure the current. The major drawback of this method is that the FLC parameters are hard to design and require adequate analysis.[12] The authors in References 13–15 proposed an optimization-based FLC technique to increase the tracking speed under rapidly changing irradiances in which the membership functions scaling factors of FLC are optimized using meta-heuristics algorithms viz. particle swarm optimization (PSO), GA, and grasshopper optimization (GHO). However, these improvised FLC techniques enhance the performance of PVS under normal operating conditions but failed to track global MPP under abnormal (partial shading) conditions. In other studies, the authors proposed the combinations of FLC and ANN methods to track global MPP of PVS using irradiance level and cell temperature in the training process of ANN. However, these combinations of FLC and ANN methods increase the complexity of the system in the tracking process.[16] Furthermore, the authors proposed a deep recurrent neural network (DRNN) method to track global MPP under PSCs.[17] Although the DRNN technique successfully tracks the GMPP, it has a drawback that it requires retraining of the DRNN for any modifications in the PV system. In the last decade, the authors made many efforts to modify classical P&O, INC, and FLC methods to improve global MPP tracking.[18,19] However, these modified classical methods sometimes can be struck at local MPP under rapidly changing shading conditions and causes power loss. The authors proposed a sliding mode control method to extract the MPP of the PV system.[20,21] However, this method highly depends on the optimal selection of the sliding surface. The improper design of sliding surface leads to the unacceptable value. Therefore, the optimal selection of sliding surfaces is a complicated task.

To solve the above problem, the swarm intelligence based and bio-inspiring methods are applied in PVS for extracting maximum power (global peak) form the P-V curve. The use of swarm methods attracted more attention of interest to research in PVS and convincingly resolved the problem of global MPP extraction. Generally, swarm

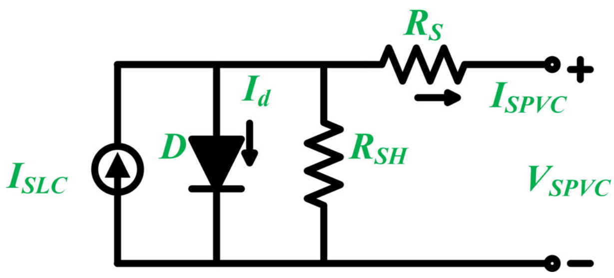

FIGURE 1 One diode photovoltaic cell model

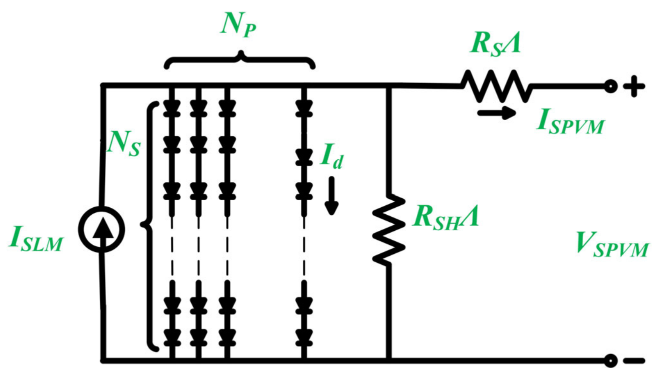

FIGURE 2 PV module

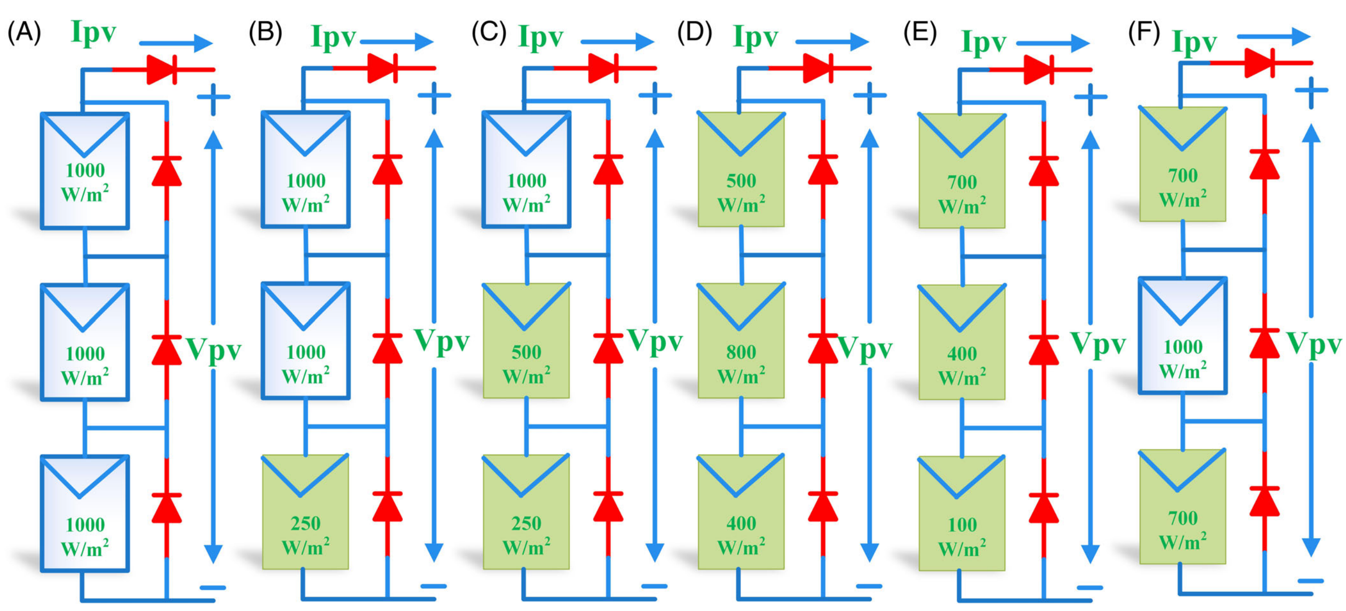

FIGURE 3 3S Structure of PVS with PSCs A, Pattern1: 1.0, 1.0, and 1.0 W/m.2 B, Pattern2: 1.0, 1.0, and 0.5 W/m.2 C, Pattern3: 1.0, 0.5, and 0.25 W/m.2 D, Pattern4: 0.5, 0.8, and 0.4 W/m.2 E, Pattern5: 0.7, 0.4, and 0.1 W/m.2 F, Pattern6: 0.7, 1.0, and 0.7 W/m^2

intelligence algorithms developed from the collective social behavior of ant colonies, a flock of birds, and schools of fish.[22,23] The key advantages of these techniques are a) easy implementation, b) it starts with randomly search, and c) avoids the convergence to local minima. The PSO is the first implemented swarm algorithm in PV MPPT applications. However, PSO loses its diversity when the randomness is decreasing. In addition, the convergence is slow due to its dependency on the search agent's initial position.[22-24] Moreover, the PSO technique will most likely get trapped at local MPP under PSCs, if the initial value of the duty cycle is not determined appropriately.[25] To overcome this issue, the modified and improved PSO methods have been developed.[26,27] Though the performance of these techniques under rapidly changing shading conditions is unsatisfactory. However, the parameter initialization procedure is challenging to implement. A hybrid MPPT technique by combining the conventional FLC and elephant herding optimization is proposed to overwhelm the drawback of low tracking efficiency.[28] On the other hand, an improved cooperative ANN-PSO approach has been developed for maximizing the output power of the PV system. The ANN is used to predict the solar irradiation level and cell temperature followed by PSO to optimize the power generation and optimally track the solar power of the PV system under fluctuating climatic conditions.[29] Recently the bio-inspired techniques are convinced well in the field of MPPT in PV application. Some of the methods proposed to identify the global MPP among the several local MPPs at the PVS output under partially shaded conditions are gray wolf optimization (GWO), artificial bee colony (ABC), CS, flower pollination (FP), and fusion firefly algorithm (FFA).[3,30-33] Yet, these techniques have drawbacks such as long tracking time, slow response for changing irradiance as well as shading conditions and high complexity.

TABLE 1 Various shading patterns of PVS

Shading Pattern	Module 1 G1(W/m^2)	Module 1 G1(W/m^2)	Module 1 G1(W/m^2)
Pattern 1	1000	1000	1000
Pattern 2	1000	1000	250
Pattern 3	1000	500	250
Pattern 4	500	800	400
Pattern 5	700	400	100
Pattern 6	700	1000	700

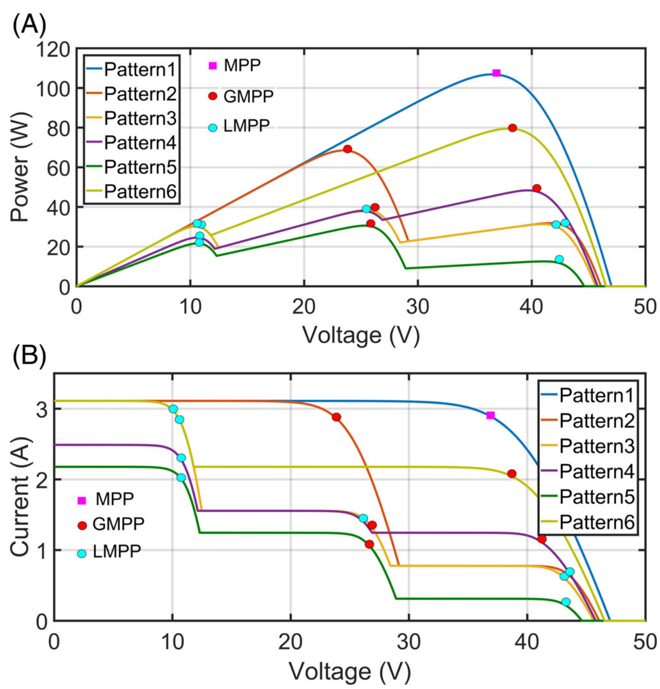

FIGURE 4 The PVS characteristics under various shading conditions A, V-P curves B, V-I curves

1.3 | Contribution

This paper proposes a unique soft computing method called the Rao-1 optimization algorithm-based MPPT for the PVS. The proposed Rao-1 algorithm-based MPPT detects the global MPP for all PSCs and rapidly changing shading conditions. The inspiration for the Rao-1 algorithm is, it does not require any algorithm-specific parameters and requires only common controlling parameters such as the number of generations and population size for its working. On the other hand, the existing algorithms require their own controlling parameters besides the common controlling parameters. For instance, GA requires selection operator, crossover probability, and mutation probability; PSO requires inertia weight, cognitive, and social parameters; GWO requires a vector $\overline{a}$, which is linearly decreasing from 2 to 0, etc. The improper tuning of these parameters increases the computational effort, number of iterations, and leads to converging at local MPP. The proposed Rao-1 algorithm efficiently converges to global MPP and cannot be struck to the local MPP under rapidly changing shading conditions. The effectiveness of the proposed MPPT for the PV system is validated and compared with conventional P&O, FLC, and PSO techniques using MATLAB/Simulink environment. The key contributions of this paper are:

1. A novel Rao-1 optimization-based MPPT technique is proposed to track the global MPP under PSCs, and its performance is compared with conventional P&O, FLC, and PSO.

2. The Rao-1 algorithm requires no tuning parameters, which also increases the exploration and exploitation process that reduces the computational effort and tracking speed.

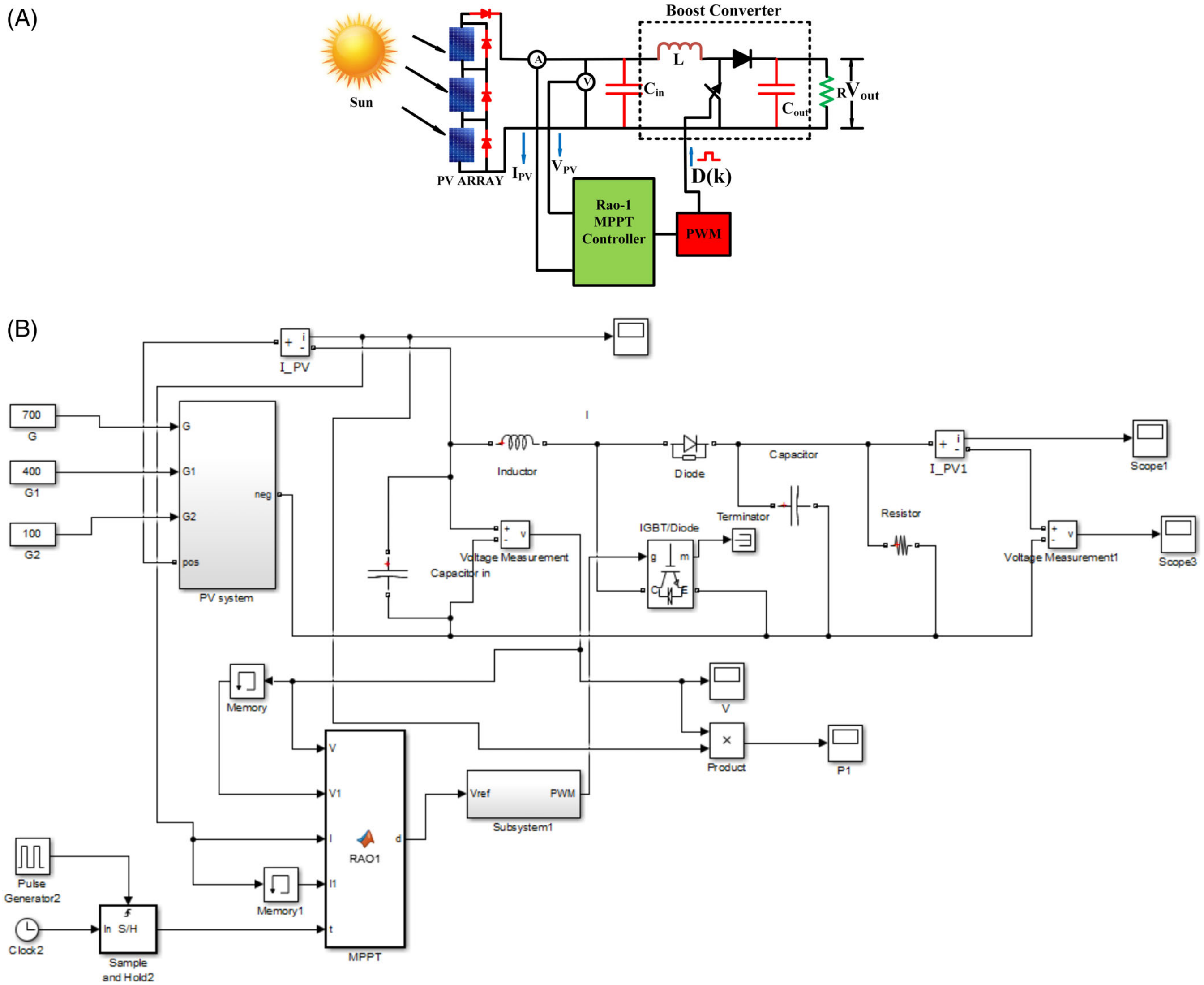

FIGURE 5 A, PV system connected Boost converter B, Simulink diagram of PV system

3. The performance of the MPPT of the PV system is examined under various PSCs. The proposed MPPT is enough to handle the output power of the PV system for any abnormal conditions in irradiance and temperature.

4. The proposed MPPT decreases the tracking time 72.7% for pattern 1, 29.8% for pattern 2, 66.7% for pattern 3, 61.9% for pattern 5, 27.8% for pattern 6, and improves the tracking efficiency in all shading patterns.

5. The proposed MPPT improves the convergence speed, tracking efficiency, and decreases the steady-state oscillations, which improve the PV system efficiency.

1.4 | Paper organization

The remaining sections of the paper are organized as follows: the next section describes the PV system modeling and its characteristics. Section 3 deals with the energy conversion unit. Section 4 describes the proposed MPPT scheme and

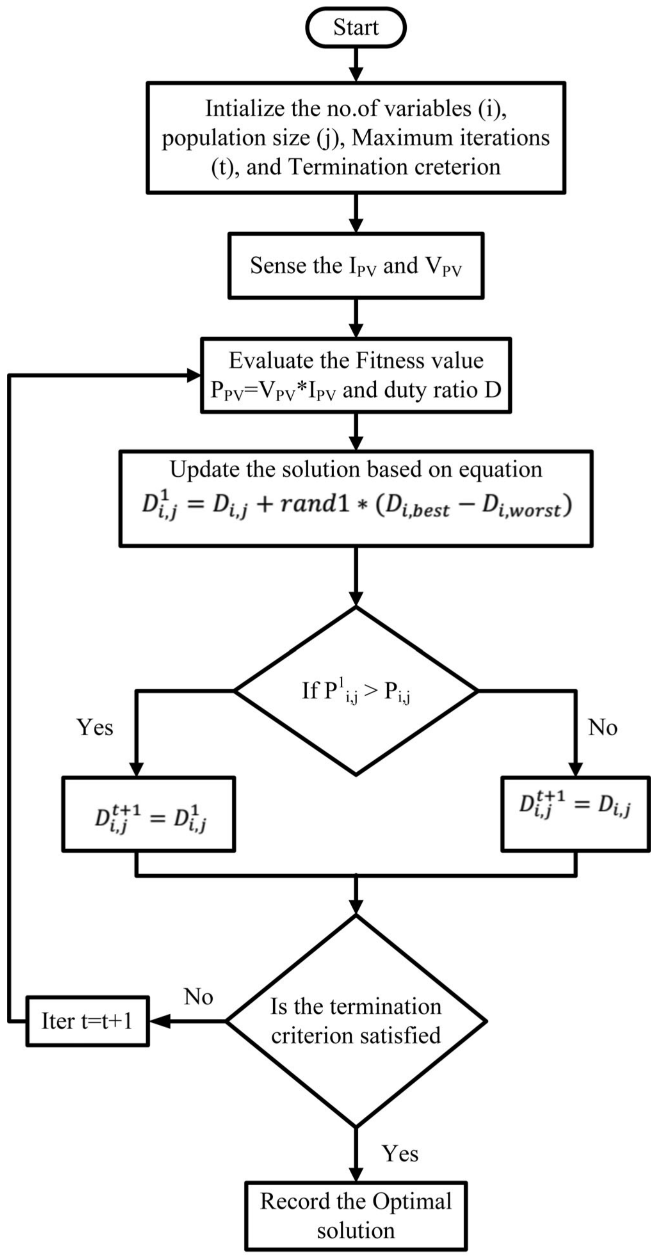

FIGURE 6 Flow chart of Rao-1 algorithm

Rao-1 algorithm. In Section 5, the results and discussions are presented. Finally, the conclusions are provided in the last section.

2 | PV SYSTEM MODELING

2.1 | PV cell

The single diode equivalent circuit model of the PV cell, which consists of source current I_{SLC}, antiparallel diode D across the source current, and a series-shunt combination of resistances R_S and R_{SH} is shown in Figure 1.

Using KCL, the solar PV cell output current of Figure 1 can be obtained as[34]:

TABLE 2 The PV system and Boost converter parameters

PV Parameters	Values
Maximum Power (P_{max})	36.3 W
Voltage at P_{max}	12.35 V
Current at P_{max}	2.93A
Open Circuit Voltage (V_{OC})	16 V
Short circuit Current (I_{SC})	3.11A
Series Resistance (Rs)	0.55 Ω
Shunt Resistance (Rp)	310.0248 Ω
Ideality factor of PV diode	1.3
Temperature co-efficient of I_{SC}	1.3 × 10-3 A/K
Reference Temperature (T_{ref})	250 C
Reference solar intensity (Ins_{ref})	1000 W/m2
Boost converter Parameters	*Values*
Input Voltage (VPV)	12.35 V
Input Current (IPV)	2.93 A
Output Voltage (VO)	41.8 V
Input Inductor (L)	10 mH
Input Capacitor (Cin)	100 μF
Input Capacitor (Cout)	300 μF
Load resistance (R)	50 Ω
Switching frequency (fsw)	2 kHz

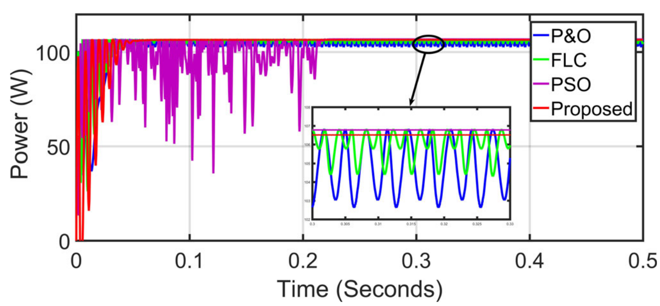

FIGURE 7 The output power of PVS with P&O, FLC, PSO, and Proposed Rao-1 for Pattern1

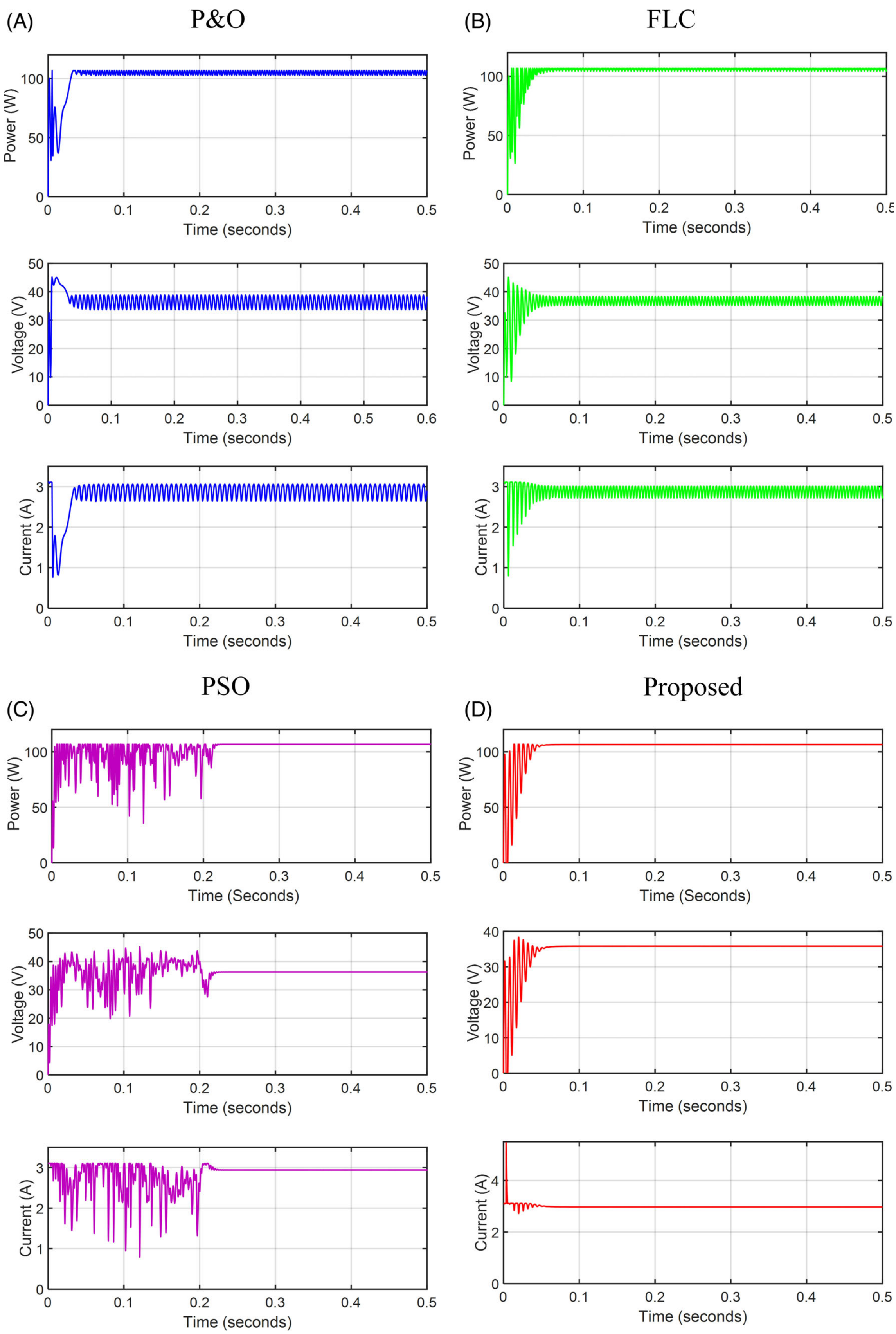

FIGURE 8 Pattern1 output power, voltage, and current curves of PVS for A, P&O, B, FLC, C, PSO, and D, Proposed Rao-1 method

$$I_{SPVC} = I_{SLC} - I_d - \frac{V_{SPVC} + R_S \times I_{SPVC}}{R_{SH}}, \quad (1)$$

where,

I_d: diode current (A), I_{SLC}: Sun light current (A), I_{SPVC}: solar PV cell output current, V_{SPVC}: solar PV cell voltage (V), R_{SH} and R_S: shunt and series resistance of PV cell (Ω).

The Sun light-current, I_{SLC} of the solar PV cell can be expressed as[34]:

$$I_{SLC} = \frac{G}{G_r}[I_{SLCr} + K_t(T_c - T_r)], \quad (2)$$

where,

G: Sun irradiance (W/m^2), K_t: Temperature coefficient, T_r: Standard temperature (K), T_c: Cell temperature (K), and $G_r = 1000\ W/m^2$.

The diode current, I_D can be written as:

$$I_d = I_o\left(e^{\frac{V_{SPVC}+R_S \times I_{SPVC}}{V_t}} - 1\right), \quad (3)$$

where, V_t: Thermal voltage (V), I_o = diode reverse saturation current.

The diode reverse saturation current is obtained as[34]:

$$I_o = I_{o,ref}\left(\frac{T_c}{T_r}\right)^3 \exp\left[\left(\frac{q\varepsilon_G}{a.K}\right)\left(\frac{1}{T_r} - \frac{1}{T_c}\right)\right], \quad (4)$$

q: Charge of an electron, K: The Boltzmann's constant, and a: Diode ideality factor.

2.2 | PV module

The PV module is an arrangement of several series and shunt connected PV cells to increase the output power of the solar system as presented in Figure 2. The output current, I_{SPVM} of solar PV module can be determined as:

$$I_{SPVM} = N_p I_{SLM} - N_p I_o\left[\exp\left(\frac{V_{SPVM} + I_{SPVM} \times R_S\Lambda}{N_s V_t}\right) - 1\right] - \frac{V_{SPVM} + \Lambda R_S \times I_{SPVM}}{\Lambda R_{SH}}, \quad (5)$$

where,

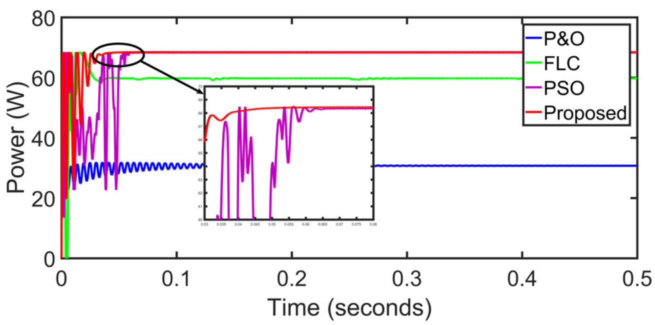

FIGURE 9 The output power of PVS with P&O, FLC, PSO, and Proposed Rao-1 for Pattern2

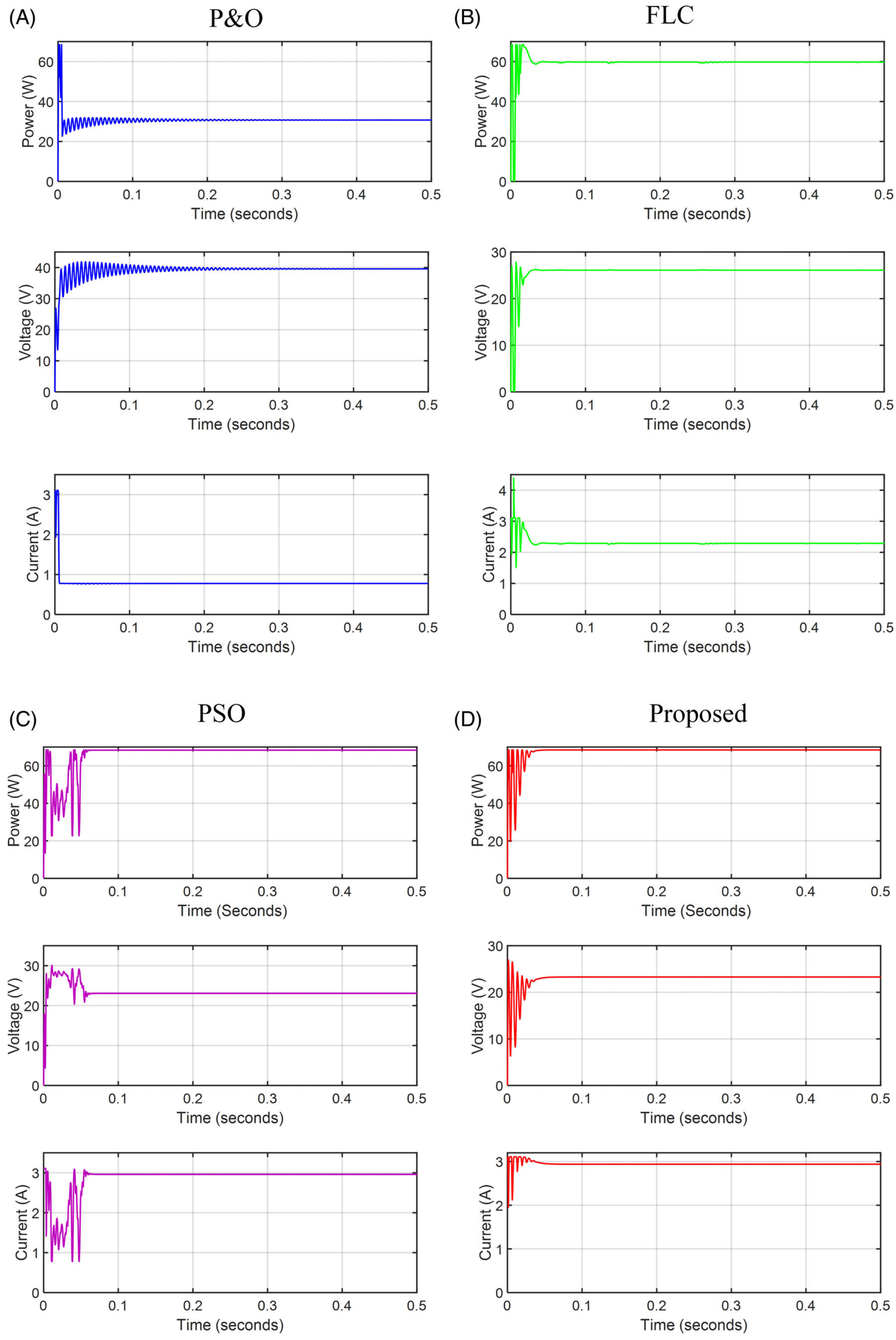

FIGURE 10 Pattern2 output power, voltage, and current curves of PVS for A, P&O, B, FLC, C, PSO, and D, Proposed Rao-1 method

$$\Lambda = \frac{N_s}{N_p}. \tag{6}$$

2.3 | PV system characteristics under PSC

The solar PV system (PVS) consists of numerous PV modules that are connected in series and parallel to come across the energy demand. The output power of the PVS mainly depends on ambient temperature and sun irradiances. Hence, the PVS produces a single peak on P-V curves if the irradiances are equally distributed in all PV modules. Consequently, there are multiple peaks on P-V curves for unequal irradiances on PV modules, and this phenomenon is called PSCs. A procedure to differentiate between partial and uniform shading faults is proposed.[35,36] To demonstrate the PSC of PVS a string of series-connected three modules (3S) with four shading patterns are considered. Figure 3 represents the 3S configuration with bypass and blocking diodes. The bypass and blocking diodes are used to prevent hotspot formation and to avoid the current reversal.

The V-P and V-I curves of PVS under various shading patterns shown in Table 1 are represented in Figure 4.

3 | ENERGY CONVERSION SYSTEM

The energy conversion system is used in PVS to increase the reliability, stability, and to improve the PV output power quality. As discussed in the literature, the PVS has a unique operating point (at which the maximum power available) in its V-P and V-I curves. To operate the PVS at this operating point an energy conversion unit (DC-DC converter) is employed. In general, the boost type DC-DC converter is used in PVS to boost the output voltage. The advantage of boost type DC-DC converter is simple structure, raised voltage gain, and higher efficiency.[37,38] Here, the DC-DC converter is connected in parallel to the PVS depicted in Figure 5A. In this, the duty cycle of the converter is regulated at the appropriate output voltage of PVS using the MPPT technique. The structure of the boost converter consists of an inductor, a capacitor, a switch (MOSFET), and a diode. The MOSFET is repeatedly turned on and turned off with variable duty-cycled' and an operating frequency. The boost converter has mainly two working modes based on switch ON and switches OFF. The analysis of the converter made using Kirchhoff laws. The relation between input and output voltages expressed as:

$$\frac{V_{out}}{V_{in}} = \frac{1}{1-D}, \tag{7}$$

where,

D = duty cycle, V_{out} = Output voltage, and V_{in} = PV voltage as input to the converter.

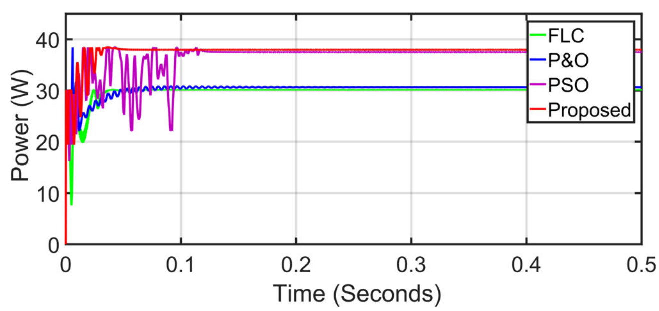

FIGURE 11 The output power of PVS with P&O, FLC, PSO, and Proposed Rao-1 for Pattern3

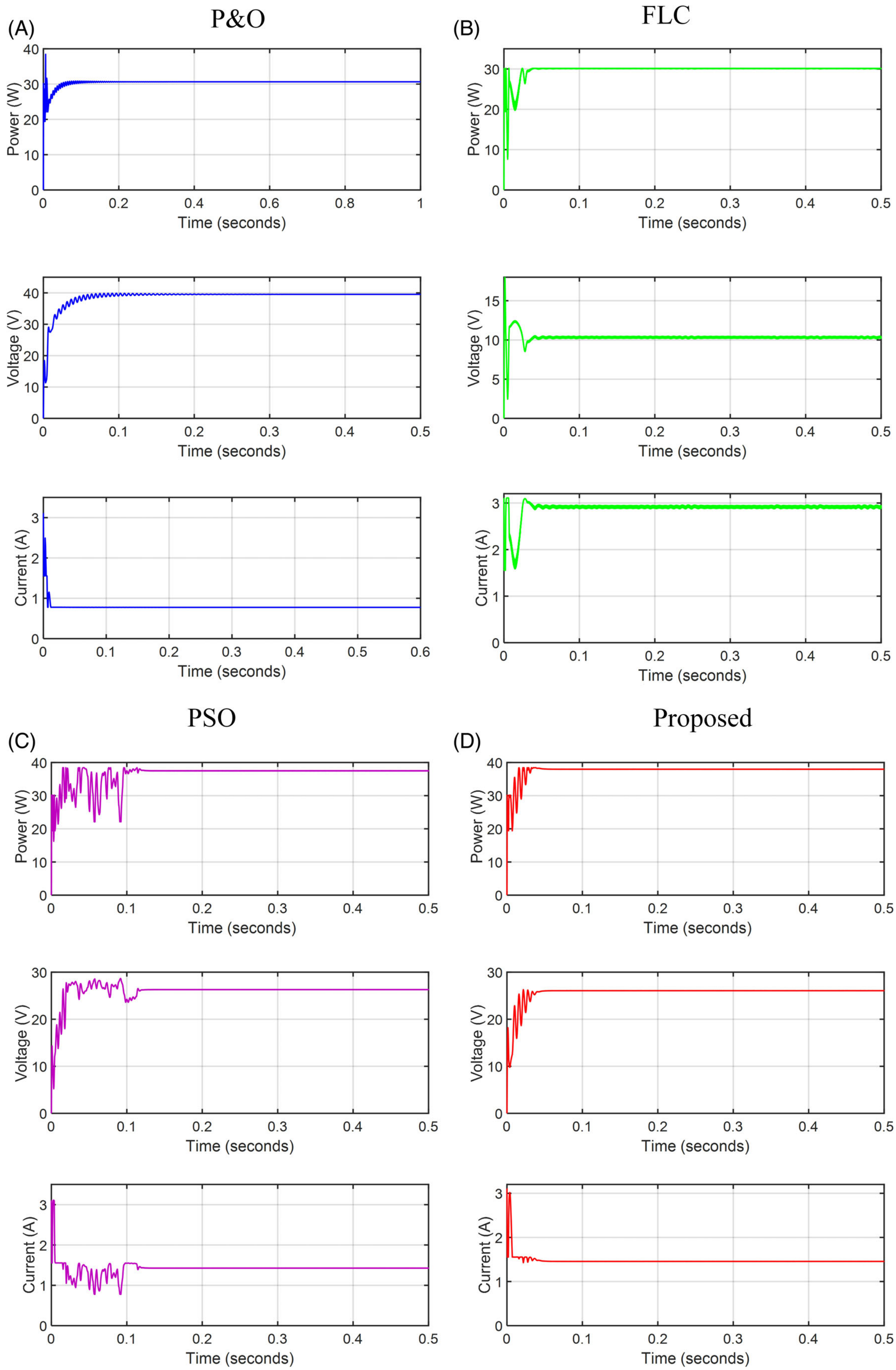

FIGURE 12 Pattern3 output power, voltage, and current curves of PVS for A, P&O, B, FLC, C, PSO, and D, Proposed Rao-1 method

4 | PROPOSED MPPT

In the literature, several authors proposed MPPT techniques based on various swarm and heuristic algorithms for extracting maximum power available from PVS under uniform and partially shaded conditions.[3,26,30-33] However, the major drawback of these algorithms is their performance highly depends on the algorithm-specific parameters. For instance, PSO has inertia weight, cognitive, and social components; GA has selection, crossover, and mutation. Similarly, the other algorithms viz. GWO, FP, ABC, CS, etc. need the proper tuning of their control parameters. The improper tuning or selection of these control parameters either leads to convergence at local optima or increases the computational efforts. To address this issue, a metaphor-less heuristic search method named Rao-1 algorithm is adopted to extract the maximum power available from PVS.

4.1 | Rao-1 algorithm

The Rao-1 optimization algorithm is a recently developed metaphor less search algorithm by Rao in 2019.[39] This algorithm was proposed to overcome the unnecessary complex nature of swarm intelligence or heuristic techniques. This Rao-1 algorithm works based on "get the best by removing all worst." In this, the search agents move toward the best solution by avoiding the worst solution. The main advantage of the Rao-1 algorithm with other heuristic techniques is that it is free from algorithm-specific parameters and uses only two parameters viz. population size and the number of iterations; and moves forward in a single step (ie, by avoiding worst solution moving to the best). The basic principle of this technique first identifies the best and worst solutions, and then in every iteration, pushes all other solutions away to the worst solution and updates the most lower solution as the worst solution obtained in that iteration. Hence, in the next iteration, all the solutions are better than the previous iteration's worst solution. Here, all search agents of the Rao-1 algorithm aim to find the best solution compared to the previous worst solution, and this behavior describes the Rao-1 algorithm can track the global best solution quickly.

Let "j" be the number of search agents (ie, population size, j = 1, 2.....p), and 'p' is the maximum number of search agents, 'i' be the number of variables (i = 1, 2....n), 'n' is the total number of variables, and 't' be the number of iterations (t = 1, 2.....m), 'm' is the maximum number of iteration. Let $D^t_{i,j}$ represents the i^{th} variable for j^{th} search agent during the t^{th} iteration. And $D^t_{i,best}$ best value in the entire search agents during t^{th} iteration for i^{th} variable, $D^t_{i,worst}$ worst value in the entire search agents during t^{th} iteration for i^{th} variable. Therefore, the updating equation for Rao-1 algorithm can be expressed as:

$$D^{t+1}_{i,j} = D^t_{i,j} + rand1 \times \left(D^t_{i,best} - D^t_{i,worst}\right) \tag{8}$$

The flow chat of Rao-1 algorithm for tracking MPPT of PVS is presented in Figure 6. The sequential steps of Rao-1 algorithm for MPPT tracking is described as follows:

Step 1. Initialization: Initialize the random values of search agents, population size, maximum iterations, and termination criterion.

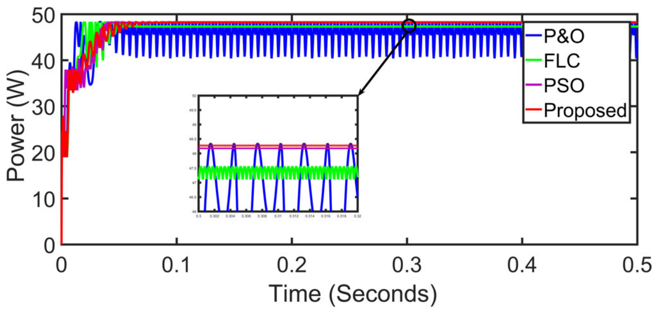

FIGURE 13 The output power of PVS with P&O, FLC, PSO, and Proposed Rao-1 for Pattern4

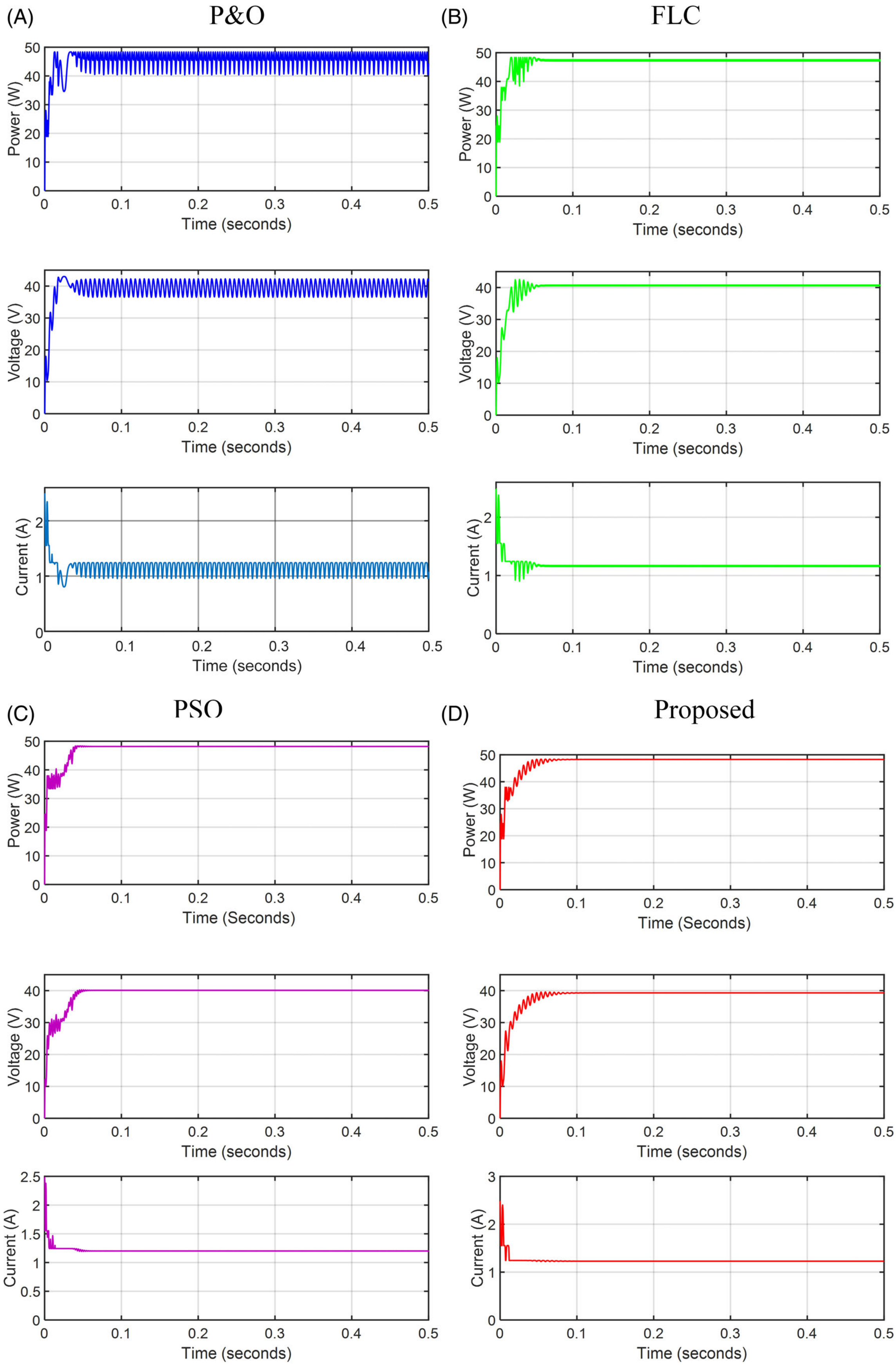

FIGURE 14 Pattern4 output power, voltage, and current curves of PVS for A, P&O, B, FLC, C, PSO, and D, Proposed Rao-1 method

Step 2. Fitness evaluation: Find the fitness values of each search agent using the Equation (9) and also find the corresponding duty ratio.

$$FF = Max\left\{ \int_0^{t_{sim}} t \times (V_{PV} \times I_{PV}) \times dt \right\}. \tag{9}$$

Step 3. Selection: Find the best and worst solution from the entire population.

Step 4. Update: Modify the position of every individual according to the Equation (8).

Step 5. Compare: If the fitness of the updated candidate is better than the previous fitness of that candidate, then accept the updated candidate for the next iteration or else keep the previous solution.

Step 6. Termination: if the termination criterion is satisfied, record the optimal solution, otherwise repeat step 2 to step 5.

5 | RESULTS AND DISCUSSIONS

A Matlab/Simulink (R2016a) software has been used for modeling and to validate the performance of the proposed MPPT technique of the PVS. The PVS model consists of a PV module, a resistive load, and a DC-DC converter with the MPPT technique presented in Figure 5A and its Simulink diagram is presented in Figure 5B. How better the performance of the proposed MPPT method in improving efficiency, tracking accuracy, and tracking speed with the other methods like the traditional P&O, FLC, and the PSO algorithm is validated with various shading patterns. The parameters used for modeling the PVS and DC-DC converter are presented in Table 2.

To validate the effectiveness of the proposed Rao-1 algorithm based MPPT the time-domain simulations have been carried out for all possible operating conditions viz. (i) uniform irradiance (Pattern1) and (ii) different irradiances, that is, PSCs (Pattern2 to Pattern4). For the case of uniform irradiance, the values of irradiance and temperature are kept constant, whereas, in the case of PSCs, the temperature is kept constant and the irradiance values of the PV modules are changed. How better the proposed Rao-1 based MPPT over the traditional P&O, FLC, and PSO, the results are examined under various aspects viz. speed of tracking, tracking efficiency, etc.

Pattern1: In this pattern, the irradiance considered for all the three PV modules is 1000 W/m^2. The P-V curve for this pattern is shown in Figure 4A has only peak with an MPP of 106.81 W. The output power of PVS with various MPPT methods is presented in Figure 7. Figure 8 presents the tracked power, PV voltage, and current. The traditional P&O MPPT tracks the MPP of 104.8 W with a tracking speed of 0.04 second. The conventional FLC MPPT tracks the MPP of 105.8 W with a tracking speed of 0.05 second. The PSO based MPPT method converges to the MPP of 106.79 W with a tracking speed of 0.22 second. The proposed Rao-1 based MPPT technique converges to the MPP of 106.5 W with a tracking speed of 0.06 second. It is observed from Figure 7 that the PSO algorithm tracking speed is slow with large initial oscillations. The traditional P&O and FLC have constant oscillations around MPP. The Proposed Rao-1 converges to MPP very fast and outperforms the P&O and FLC in terms of the efficiency and steady state oscillations, and PSO concerning to speed of tracking.

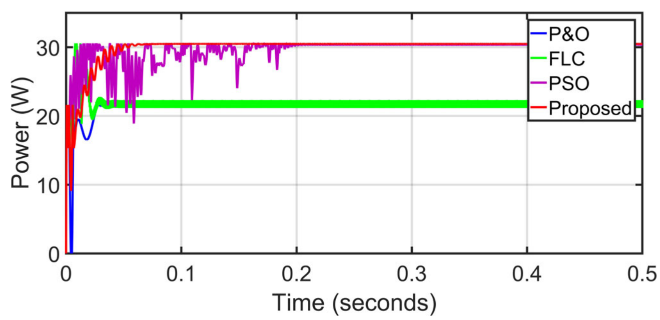

FIGURE 15 The output power of PVS with P&O, FLC, PSO, and Proposed Rao-1 for Pattern5

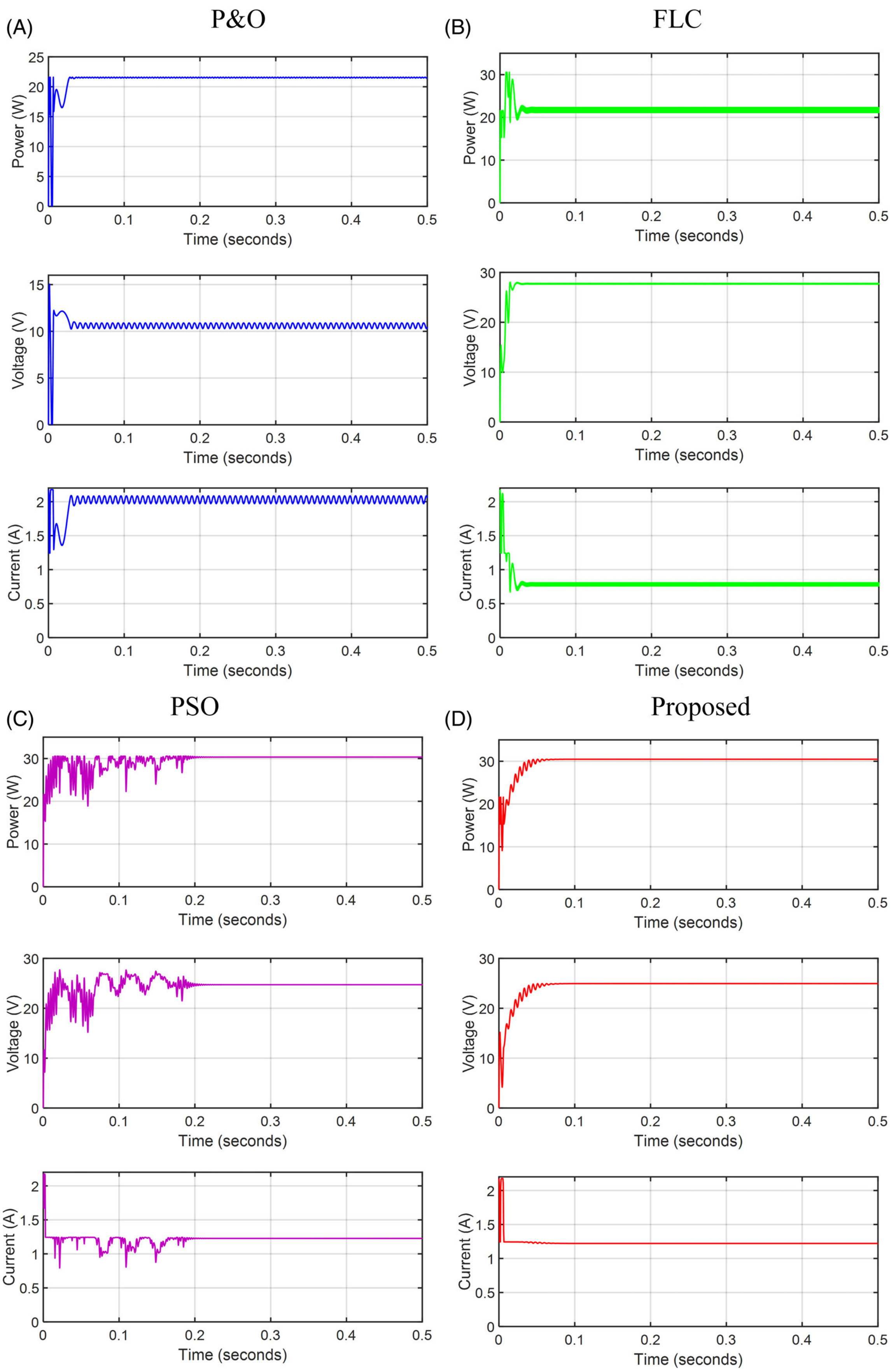

FIGURE 16 Pattern5 output power, voltage, and current curves of PVS for A, P&O, B, FLC, C, PSO, and D, Proposed Rao-1 method

Pattern2: In this pattern, the irradiance profile considered for all the three PV modules is 1000, 1000, and 250 W/m^2. The P-V curve for this pattern is shown in Figure 4A has two peaks (one local and one global MPP) with a global MPP of 68.47 W. The output power of PVS with various MPPT methods is presented in Figure 9. Figure 10 presents the tracked power, PV voltage, and current. The P&O MPPT tracks the local MPP of 30.72 W and fails to reach the global MPP. The conventional FLC MPPT tracks the MPP of 59.76 W with a tracking speed of 0.04 second. The PSO and proposed MPPT converges to the MPP of 68.32 and 68.44 W with a tracking speed of 0.057 second and 0.04, respectively. It is witnessed from Figure 9 that the proposed Rao-1 based MPPT efficiently converges to global MPP over P&O, FLC, and PSO concerning the efficiency, steady state oscillations, and tracking speed.

Pattern3: In this, the irradiances considered for the three PV modules are 1000, 500, and 250 W/m^2. In this case, the PVS produces multiple peaks (one global peak and two local peaks) on its P-V curve presented in Figure 4A with the global MPP of 38.435 W. The output power of PVS with various MPPT methods is presented in Figure 11. Figure 12 presents the tracked power, PV voltage, and current of PVS. The traditional P&O and FLC-based MPPT techniques are failed to reach global MPP and they track the local MPP of 30.64 W and 30.04 W with the tracking speed of 0.2 second and 0.04 second, respectively. The PSO based MPPT technique converges to the MPP of 37.48 W with a tracking speed of 0.12 second. The proposed Rao-1 based MPPT technique converges to the MPP of 37.96 W with a tracking speed of 0.04 second. It is confirmed from Figure 11 that the PSO algorithm tracking speed is slow with large initial oscillations. The Proposed Rao-1 converges to MPP very fast and outperforms the PSO concerning the efficiency and speed of tracking.

Pattern4: In this pattern, to study the performance of the proposed MPPT method, all three PV modules are considered to have the shading effect with irradiance profile as 500, 800, and 400 W/m^2. The P-V curve for this pattern is shown in Figure 4A has one global peak and two local peaks with an MPP of 48.35 W. The output power of PVS with various MPPT methods is presented in Figure 13. Figure 14 presents the tracked power, PV voltage, and current. The classical P&O and FLC based-MPPT tracks the global MPP of 45.57 W and 47.18 with a tracking speed of 0.05 second and 0.06 second, respectively. The PSO and proposed MPPT techniques converge to the MPP of 48.16 W and 48.27 W with a tracking speed of 0.05 second and 0.08 second, respectively. It is observed from Figure 13 that the proposed MPPT technique outperforms the P&O, FLC, and PSO concerning the efficiency and steady state oscillations, and speed of tracking.

Pattern5: In this, the irradiances considered for the three PV modules are 700, 400, and 100 W/m^2. In this case, the PVS produces one global peak and two local peaks on its P-V curve presented in Figure 4A with the global MPP of 30.562 W. The output power of PVS with various MPPT methods is presented in Figure 15. Figure 16 presents the tracked power, PV voltage, and current of PVS. The traditional P&O and FLC-based MPPT techniques are failed to reach global MPP and they track the local MPP of 21.54 W and 21.86 W with the tracking speed of 0.04 second and 0.045 second, respectively. The PSO based MPPT technique converges to the MPP of 30.35 W with a tracking speed of 0.21 second. The proposed Rao-1 based MPPT technique converges to the MPP of 30.48 W with a tracking speed of 0.08 second. It is confirmed from Figure 15 that the PSO algorithm tracking speed is slow with large initial oscillations. The Proposed Rao-1 converges to MPP very fast and outperforms the PSO concerning the efficiency and speed of tracking.

Pattern6: In this, the irradiances considered for the three PV modules are 700, 1000, and 700 W/m^2. In this case, the PVS produces one local peak and one global peak on its P-V curve presented in Figure 4A with a global MPP of 79.465 W. The output power of PVS with various MPPT methods is presented in Figure 17. Figure 18 presents the tracked power, PV voltage, and current of PVS. The traditional FLC-based MPPT tracks the local MPP of 30.12 W and

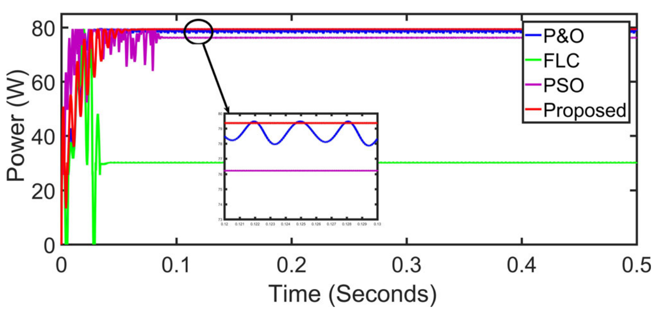

FIGURE 17 The output power of PVS with P&O, FLC, PSO, and Proposed Rao-1 for Pattern6

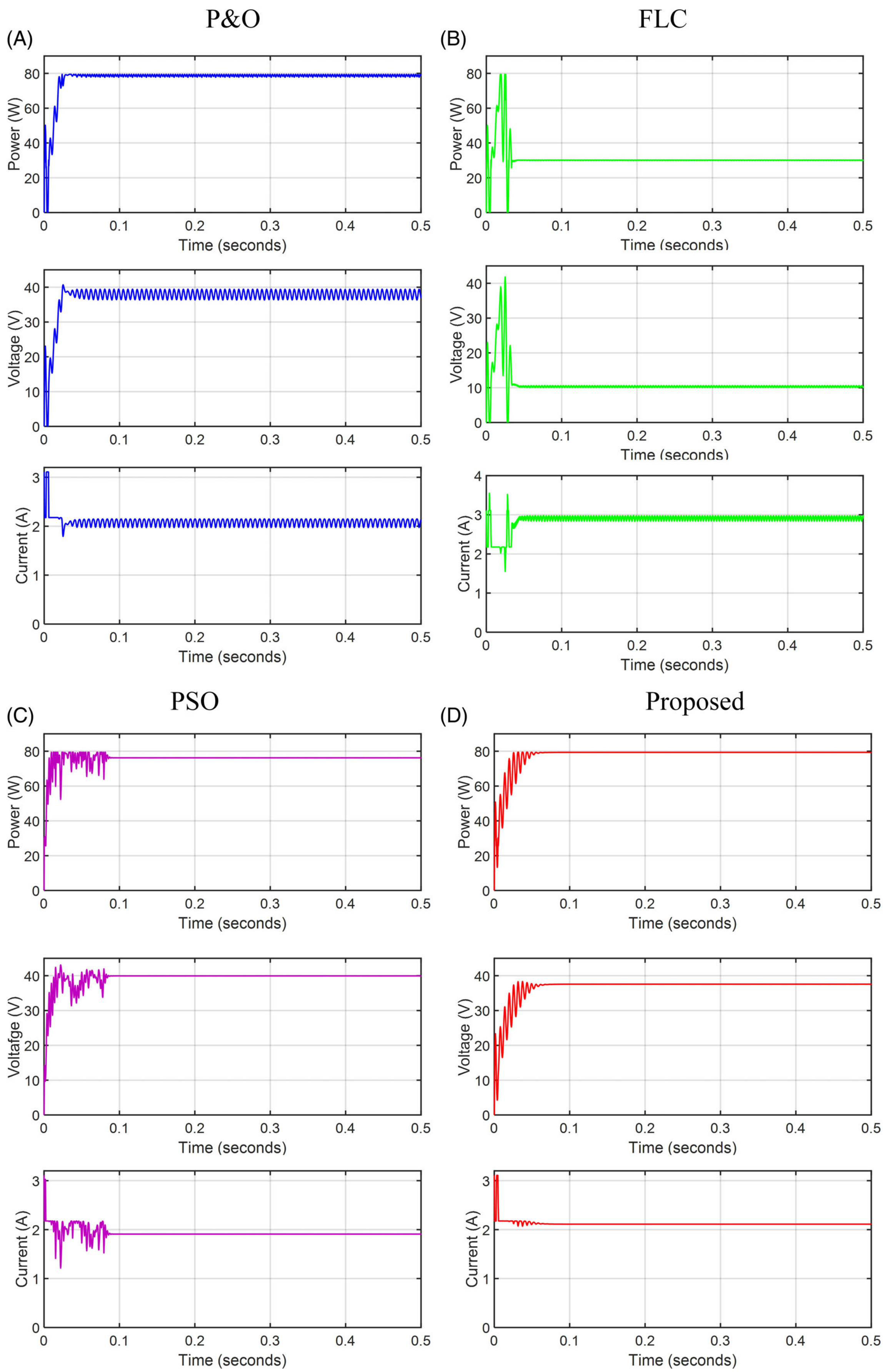

FIGURE 18 Pattern6 output power, voltage, and current curves of PVS for A, P&O, B, FLC, C, PSO, and D, Proposed Rao-1 method

TABLE 3 A quantitative comparison of MPPT techniques

Shading Patterns	Method	Maximum Power	Power at MPP (W)	Voltage at MPP (V)	Current at MPP (A)	Tracking time(sec)	Efficiency
Pattern1	P&O	106.81	104.8	36.47	2.894	0.04	98.11
	FLC		105.8	36.74	2.89	0.05	99.05
	PSO		106.79	36.3	2.941	0.22	99.98
	Proposed		*106.5*	*35.81*	*2.974*	*0.06*	*99.71*
Pattern2	P&O	68.47	30.72	39.59	0.7761	0.3	44.87
	FLC		59.76	26.1	2.289	0.04	87.27
	PSO		68.32	23.07	2.962	0.057	99.78
	Proposed		*68.44*	*23.28*	*2.94*	*0.04*	*99.95*
Pattern3	P&O	38.435	30.64	39.54	0.7751	0.2	79.71
	FLC		30.04	10.17	2.954	0.045	78.15
	PSO		37.48	26.3	1.425	0.12	97.51
	Proposed		*37.96*	*26.07*	*1.456*	*0.04*	*98.76*
Pattern4	P&O	48.35	45.57	39.7	1.152	0.05	94.25
	FLC		47.18	40.75	1.158	0.06	97.58
	PSO		48.16	40.12	1.201	0.05	99.6
	Proposed		*48.27*	*39.31*	*1.228*	*0.08*	*99.83*
Pattern5	P&O	30.562	21.54	10.6	2.03	0.04	70.48
	FLC		21.86	27.71	0.789	0.045	71.52
	PSO		30.35	24.72	1.227	0.21	99.30
	Proposed		*30.48*	*24.96*	*1.221*	*0.08*	*99.73*
Pattern6	P&O	79.465	78.79	37.94	2.078	0.045	99.15
	FLC		30.12	10.35	2.91	0.042	37.9
	PSO		76.22	39.95	1.908	0.09	95.91
	Proposed		*79.37*	*37.59*	*2.111*	*0.065*	*99.88*

TABLE 4 A qualitative comparison between proposed and existing MPPT techniques

Criteria	P&O	FLC	PSO	Proposed
Tracking speed	Fast	Medium	Low	Fast
Dynamic Performance	Poor	Good	Very Good	Very Good
Tracking accuracy	Moderate	Moderate	Accurate	Accurate
Steady state oscillations	Large	Medium	Low	Very Low
Tracking efficiency	Less	Medium	High	High

fails to reach the global peak. The conventional P&O MPPT tracks the global MPP of 78.79 W with a tracking speed of 0.045 second. The PSO based MPPT technique converges to the MPP of 76.22 W with a tracking speed of 0.09 second. The proposed Rao-1 based MPPT technique converges to the MPP of 79.37 W with a tracking speed of 0.065 second. It is confirmed from Figure 17 that the conventional FLC fails to track global MPP. The traditional P&O has constant oscillations around the MPP and the PSO algorithm tracking speed is slow with large initial oscillations. The Proposed Rao-1 converges to global MPP very fast over P&O, FLC, and PSO concerning the efficiency, steady-state oscillations, and tracking speed.

A quantitative comparison of simulation results for all shading conditions is shown in Table 3. From the simulation results, it is evident that the proposed Rao-1 based MPPT method outperforms the other techniques in the literature. The tracking efficiency shown in Table 3 is determined as the ratio of the actual output power of the PVS to the maximum power available from the PVS under certain shading conditions. The performance evaluation of the proposed Rao-1 based MPPT technique against P&O, FLC, and PSO techniques is presented in Table 4. In comparison with the traditional P&O and FLC, the proposed MPPT converges to the accurate MPP with fast-tracking speed, high tracking efficiency, and without steady-state oscillations. Moreover, in the FLC and P&O methods, the operating point moves away under PSCs. The proposed MPPT improves the tracking speed and tracking efficiency compared to the PSO. Moreover, the major drawback of PSO is its performance highly depends on the algorithm-specific parameters.

6 | CONCLUSION

In this paper, a novel MPP tracking technique based on the Rao-1 algorithm for the solar PVS is proposed to improve the performance under partial shading and normal conditions. The key conclusions of this paper are as follows:

1. The proposed MPPT technology addresses the shortcomings of traditional P&O, FLC-based MPPT methods, which fail to track global MPP in partially shaded conditions. In addition, the proposed method outperforms the PSO-based MPPT technique. The proposed MPPT decreases the tracking time 72.7% for pattern 1, 29.8% for pattern 2, 66.7% for pattern 3, 61.9% for pattern 5, 27.8% for pattern 6, and improves the tracking efficiency in all shading patterns.
2. It has been observed that the proposed Rao-1 algorithm provides a faster response as there are no control algorithm-specific parameters.
3. The proposed MPPT is particularly strong in tracking the global MPP under PSCs. The main aesthetic of the proposed MPPT method is elevated in these critical situations. Moreover, it can easily handle any abnormal conditions.
4. The simulation results are evidence that the proposed MPPT technique effectively improves the tracking efficiency, tracking speed, and reduces the steady-state oscillations. Therefore, further, the proposed method can be applied to solar-wind hybrid systems to achieve higher efficiency of energy conversion.

PEER REVIEW

The peer review history for this article is available at https://publons.com/publon/10.1002/2050-7038.13028.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study. All data are available in websites and provided in references.

ORCID

Laxman Bhukya https://orcid.org/0000-0003-3186-1252
Anil Annamraju https://orcid.org/0000-0001-9358-4348

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