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EXTRCATING MAXIMUM POWER FROM SOLAR PANELS UNDER DIFFERENT PARTIAL SHADING THROUGH OPTIMIZED PERTURB AND OBSERVE TECHNIQUE

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ABSTRACT
Nowadays, the development of solar photovoltaic (SPV) technologies is shifting from prototype models and pilot demonstrations to comprehensive marketable products. However, poor power conversion efficiency of the solar panel is the key challenge in the solar industry since the panels only convert a small proportion of the accessible solar energy into electrical power. Hence, an effective maximum power point tracking (MPPT) system is inevitable to increase the power conversion performance of SPV cells. Recently, researchers have developed several MPPT approaches to overcome the key challenges in SPV-based renewable energy generation. The traditional power point tracking approaches such as incremental conductance and perturb & observe (P&O) methods easily trap into the local maximum power point. Also, these approaches fail to analyze the dynamic variations in radiance conditions and fetch large oscillation amplitude and poor convergence speed. In this context, this study proposes a Tuna Swarm Optimizer-based P&O approach (TSOPO) to decrease the oscillation amplitude, enhance the convergence rate, and increase the performance of the P&O technique over diverse partial shading (PS) patterns. This method can achieve the global maximum power point for various PS patterns. We evaluate the performance of the TSOPO approach by relating its maximum power, efficiency, and tracking speed with other advanced P&O variants using metaheuristic algorithms under four different PS patterns. The results prove that the TSOPO approach provides a better convergence rate, higher tracking efficiency, and extracts maximum power from SPV panels.

Keywords: fuel cell; MPPT; perturb and observe; renewable energy; solar PV array; wind turbine;

I. INTRODUCTION
Global energy consumption and unstable demands are growing exponentially due to increasing population, industrialization, and globalization. Promoting promising and green energy systems is the key solution to achieving Sustainable Development Goal 7 (SDG7) of continuous power supply for everyone. In economically developing nations, the progress toward SDG7 is considerably stagnated [1]. Governments struggle deliberately to decrease overdependence on conventional fossil fuels to achieve sustainability in the energy industry. With the frightening climatic crisis, scientists and researchers are looking for solutions to minimize greenhouse gas emissions and nonrenewable fuel ingestion. All countries are on a path toward the depletion of nonrenewable resources [2]. While that inevitable enervation has been reached, perhaps around the turn of century, any form of electric power used up by the people must be obtained from only unconventional sources. It reveals that the complex electric energy-on-demand to which we have been adapted, will be vanished soon [3].

Generating green energy is a basic requirement for the fiscal and viable growth of any economy [4]. At the same time, over 1B individuals worldwide live without electrical power in their homes, and 2.5B (around 40% of the inhabitants in the world) depend on unhealthy fuels and contaminating technologies to supply all their domestic electric loads [5]. However, due to environmental qualms, the demand for the generation of clean energy has been increasing and there is an inevitability to efficiently exploit the energy as there is limited availability of fossil fuel resources (e.g., gas, oil, and coal). India's installed renewable energy capacity has amplified by 396% in the past 8.5 years and reached over 159.95 GW, which is around 40% of the total capacity of the country as on 31st March 2022 [6]. India is making a move toward its goal of 175 GW of renewables by the end of the year 2023 to decrease the utilization of fossil fuels. In addition, the government has focused on a strategic plan to exploit solar and wind sources up to 100 GW and 60 GW, respectively [7].

The solar energy industry is poised for development with its indefinite copiousness and potential. Poor power conversion efficiency of SPV panels is the key challenge in the energy industry since the panels only transform a small amount of the existing light energy into usable electrical energy. The dependability of the SPV arrays is also an issue, particularly in those topographical regions where sunlight is not accessible in copiousness. To increase the power performance of the SPV array, various aspects including nonlinear characteristics, temperature, and PS conditions of the SPV must be completely taken into account. An effective MPPT approach can improve the power conversion performance of SPV arrays. These maximum power tracking

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approaches can be characterized into two categories including P&O and incremental conductance (IC) approaches [8].

The P&O approach works by persistently perturbing (i.e. increasing or decreasing) the cell current or terminal voltage and relating the yield with that of the earlier iteration. During its operation, the SPV cell produces maximum power at only one point which is known as Maximum Power Point (MPP). In the P&O approach, incrementing voltage leads to the power increasing when the perturbation is on the left-hand side of the maximum power point, and reducing the power if it is on the right-hand side of the MPP as given in Figure 1 [9]. The IC approach calculates the gradient of the power–voltage (P-V) characteristics, and the maximum power is followed by determining the amplitude of the power-voltage characteristics. The IC approach exploits the instantaneous conductance $\left(\frac{I}{V}\right)$ and the incremental conductance $\left(\frac{dI}{dV}\right)$ for tracking maximum power [10]. In this graph, the term V_{OC} denotes the open circuit voltage generated by a solar panel under no loaded condition at $I = 0$. The term I_{SC} denotes the short circuit current measured at $V = 0$. The terms V_{MPP} and I_{MPP} in the curve are the peak voltage and peak current of the SPV array, correspondingly.

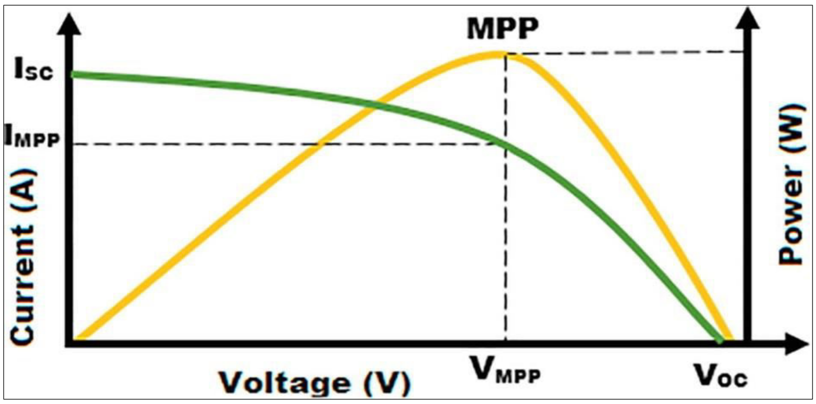

Figure 1: P-V and I-V and characteristics of SPV cell.

Generally, SPV arrays are working under two different scenarios, including uniform radiation and PS. During uniform conditions, all SPV panels get uniform radiation. Therefore, each cell can produce an equal amount of maximum power and increases the effectiveness of the system. In PS condition, a part of the SPV unit may be covered by passing clouds, tall trees, or buildings. Hence, each cell would generate different I-V characteristics, which lead to significant system losses. Moreover, the strength of irradiation gained by the unshaded area is more than the shaded one; therefore, it forms a hotspot problem in SPV arrays. Accordingly, it may damage the cells in the array. To alleviate this issue, bypassing diodes are used to generate an alternative current path during PS situations; however, they generate substantial losses and local MPP in the characteristics curve of the SPV arrays as given in Figure 2.

PS causes different current levels in I-V characteristics and multiple peaks in P–V curves, resulting in performance degradation in the solar panel. The energy reaped from the solar panel is decreased by PS condition significantly. The occurrence of PS condition in SPV unit is characterized by multiple peaks due to avoiding SPV arrays. The conventional MPPT methods trap into the local MPP and also they have ignored the dynamic variations in radiation patterns. Variations in the radiation level of SPV units can cause a large convergence time and upturn of the fluctuation magnitude. Several power tracking approaches have limitations including producing huge oscillation amplitude, demanding an extended convergence time, and being susceptible to trapping into local MPP.

P&O is the least complex than the IC approach but its basic versions carry the steady state fluctuations at the MPP which have been eliminated in the proposed TSOPO algorithm by controlling the exploration space of the MPP. This work utilizes the TSO algorithm, as a novel metaheuristic approach with an improved convergence speed, to optimize the P&O approach. Besides, the TSO has the benefits of few parameters and comparatively better stability. Furthermore, the optimizer has inordinate capacity for enhancement in tracking speed and convergence time. It can efficiently decrease the oscillation amplitude. It also has the ability to fine-tune the dynamic characteristics.

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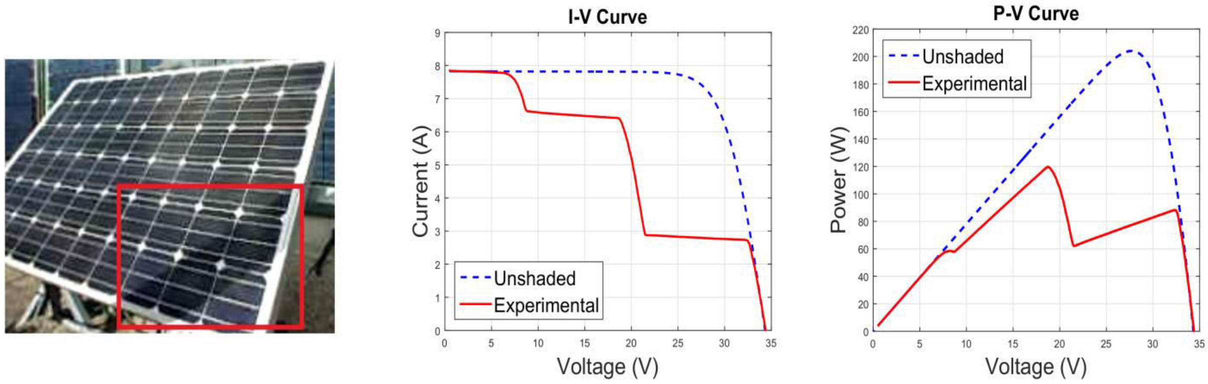

(**a**) Shaded PV module (**b**) Experimental I–V curve (**c**) Experimental P–V curve

Figure 2: Performance of SPV under partially shaded conditions.

Integrating the TSO algorithm with P&O can successfully solve the problems of traditional power tracking algorithms trapping into local MPP and further speed up the convergence rate of the P&O method. The TSOPO algorithm executes in two phases: (i) implements the TSO since it has a huge exploration range and the potential to jump out of local MPP. This approach switches to the subsequent phase once the number of runs satisfies the predefined constraints; (ii) employs the P&O method for correct tracking. The proposed TSO is applied for a huge exploration range in the initial phase, and P&O is employed for minor step tracking over a small extent. This strategy can successfully avert the approach from trapping into local optima and continuous oscillations. This method increases tracking performance in the second phase, guaranteeing that the approach can efficiently track variations in the level of radiation by determining algorithm resume constraints. When the radiation of the SPV module varies considerably, the procedure is resumed. The key contributions of this work are four fold.

- This work proposes a novel TSO algorithm to increase the performance of the P&O approach.
- We model a single-diode solar cell and verify the performance of the developed approach using three diverse PS patterns.
- The stability of the TSOPO in tracking GMPP is assessed against the abrupt variations in irradiation patterns.
- We evaluate the effectiveness of the TSOPO by comparing the numerical results of basic P&O and other advanced P&O variants using metaheuristic algorithms under four different PS patterns.

This paper is organized as follows: Section 2 presents pertinent studies aiming to apply meta-heuristic algorithms in MPPT control. Section 3 presents mathematical modeling of SPV cells, the controlling principle of the SPV system, and the modeling of PS conditions. Section 4 discusses the basic working mechanism of basic P&O approach. We confer the intended TSOPO algorithm to excerpt peak power from the solar panels under different PS patterns in Section 5. Section 6 delivers the experimentation outcomes. We conclude this work in Section 7.

II. LITERATURE SURVEY

Hitherto, the meta-heuristic algorithms-assisted MPPT approach for extracting maximum power from SPV arrays under PS condition is a comparatively matured technology and has been extensively explored [11, 12, 13, 14]. Mohamed et al. introduced a lucrative control approach for autonomous batteryless SPV arrays. This work utilizes a fuzzy-based MPPT algorithm which has the ability to preserve higher power performance under diverse loads and weather conditions [11]. Mohanty et al. developed a new cohesive MPPT method using Grey Wolf Optimizer (GWO) and the P&O method for effective excerption of peak power from a SPV module exposed to swift changes in radiation and PS patterns [12]. This work employs GWO in the first phase of the MPPT method followed by the utilization of the P&O approach at the second phase for realizing quicker convergence towards the GMPP. Ebrahim et al. proposed a Whale Optimization Algorithm (WOA) to optimize the MPPT approaches of a grid-tied SPV module [13].

Yang et al. proposed a new bio-inspired optimizer called the memeplex salp swarm optimization [14]. It is established by modifying the basic salp swarm optimization with several sovereign salp chains, consequently, it can achieve an extensive searching phase and deeper exploitation under the memeplex processing model. To increase the algorithm robustness, a virtual population-based reform process is used for the global synchronization across diverse salp chains. Yousri et al. applied the flower pollination algorithm (FPA) to

ISSN 2394 - 9554

extract maximum power from a SPV system and realized better outcomes [15]. Ali et al. applied a cuckoo search algorithm to improve the performance of the power tracking controller [16]. Su et al. developed an improved GWO by integrating a Levy flight scheme [17]. The authors use the concept of Levy flight to select the leader location, then applies the random walk and the group tuning of the Levy flight to enhance the searching accuracy and speed of the power tracking controlling mechanism.

Majad et al. developed the tunicate swarm optimization in a power tracking method to tackle the PS issue [18]. This optimization algorithm with an exploration and skipping method is used to reduce the search area and tracking time. This method can remove the deficiency related to the voltage range of GMPP and considerably increase the processing speed. Therefore, tracking efficiency, tracking time, and reliability can be improved significantly. There is one basic limitation of these population-based optimization algorithms is that they all search for the optimal results in an arbitrary manner and it is unlikely to determine the global optimal solution in a particular iteration [14]. Its intrinsic deficiency of robust uncertainty makes it vulnerable to trapping into low-quality sub-optimum results, leading to considerable dynamic power loss [11].

III.SYSTEM MODEL

This section briefly discusses the mathematical modeling of SPV cells, the controlling principle of the SPV system, and the modeling of different PS conditions.

3.1Modeling of SPV System

The SPV array directly transforms the solar irradiation into DC power. Indeed, the power produced by a single SPV cell is inadequate to supply large load demands; hence, the SPV module is developed by involving multiple cells in series/ parallel or both. The efficiency of the SPV module also hinges on its accurate mathematical modeling of SPV systems. Due to its non-linear features, the simulation of the SPV system is a perplexing task. Hence, numerous researchers employed various SPV system modeling with single, 2-, and 3-diode methods. Among these, single-diode modeling has been extensively employed to provide better accuracy.

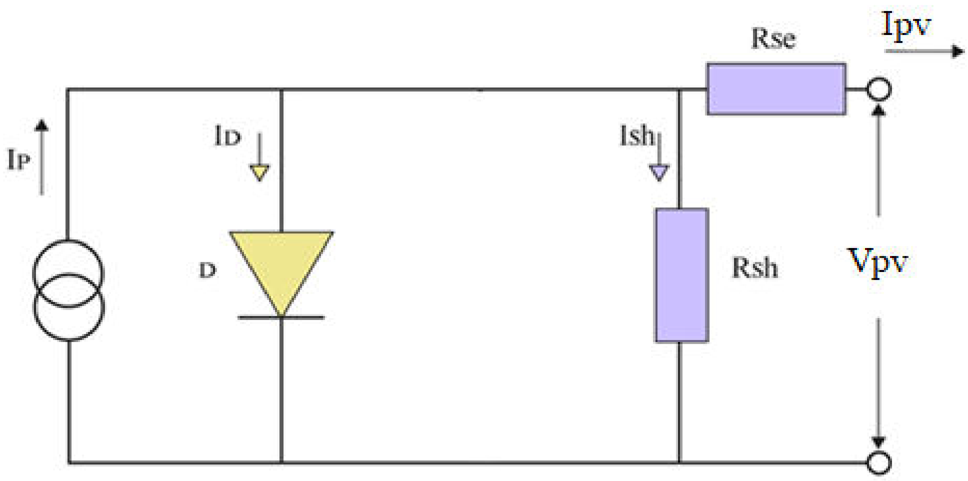

Figure 3: Modelling of SPV cell

Figure 3 represents the equivalent circuit of the SPV unit using the single-diode method. The current supplied by the cell I_{pv} is measured from the photocurrent I_p. This current relies on the level of radiation, the shunt (R_{sh}), and series resistors (R_{se}). Equation (1) defines the current supplied by the SPV unit.

$$I_{pv} = I_p - I_{p(STC)}\left(e^{\frac{q(V_{pv}+I_pR_{se})}{kT_c}}\right) - \left(\frac{V_{pv} + I_pR_{se}}{R_{sh}}\right) \quad (1)$$

where $I_{p(STC)}$ denotes photocurrent supplied at reference test condition (RTC) (i.e., 1000W/m^2 radiation at 25ºC); V_{pv} denotes the output voltage of the cell; q denotes the of unit charge (1.6x10^{-19}C); k denotes Boltzmann`s coefficient (1.38x10^{-23} j/K); T_c represents panel temperature (K). The output voltage of the cell is measured as given in Equation (2).

$$V_{pv} = V_d - I_{pv}R_{se} \quad (2)$$

$$V_{tot\_pv} = N_{cell} \times V_{pv} \quad (3)$$

ISSN 2394 - 9554

where V_{tot_pv} is the total output voltage of the SPV system, and N_{cell} is the number of cells in the system. The performance of the SPV system is usually evaluated under RTC, where an average sun irradiance spectrum at AM 1.5 is employed, the level of radiation is standardized to RTC. This work employs MSX-60 solar panels. The design parameters associated with the above equations are normally available in the manufacturer datasheet. Table 1 lists the specification of this array [19].

Table 1: Specification of MSX-60 SPV unit

Description	Value
Terminal voltage	29V
Short circuit current	7.84A
Open circuit voltage	36.3V
Rated power	213.15W
Voltage at MPP	29V
Current at MPP	7.35A
Temperature constant of current	-0.36099 %/°C
Temperature constant of voltage	0.102%/°C
Number of cells/unit	48

3.2 Control Principle of SPV System

Figure 4 shows a SPV with MPPT control strategy. The SPV module is applied with a boost type DC–DC power converter, which is employed to regulate and control the output of the SPV module. The GMPPT regulates the switching of the converter through the duty cycle. The purpose of driving the SPV module using the MPPT control mechanism is to reap the maximum power at any time. Conversely, the dynamic working environments, temperature, radiation level, and covered by clouds, etc. lead to nonlinearity and uncertainty in the performance of the SPV module, triggering challenges and difficulties for the MPPT controlling mechanism.

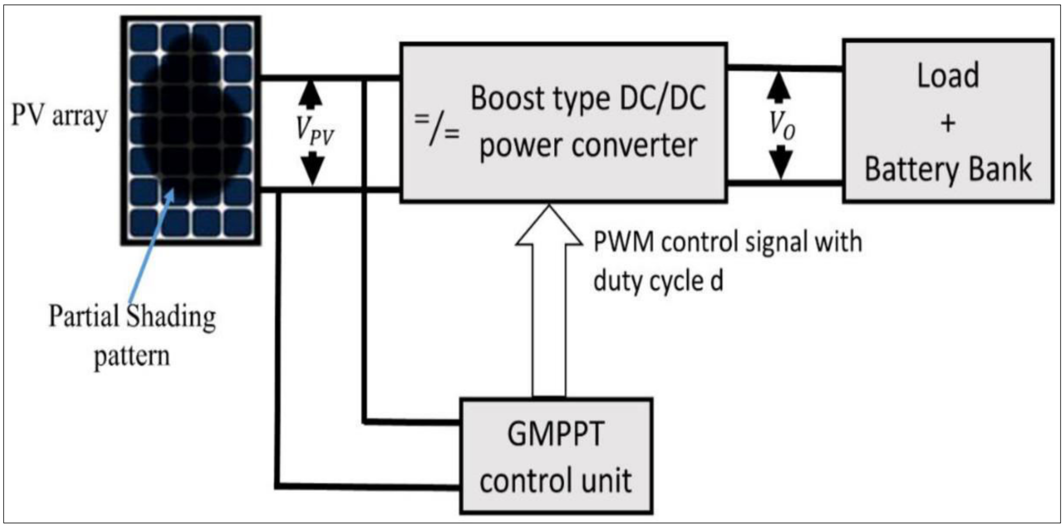

Figure 4: A Solar PV array with MPPT control.

3.3 Modeling of SPV Array at Partial Shading Conditions

In an ideal working environment, the characteristic curves of SPV arrays are given in Figure 5. But, the function of SPV arrays under real-time environments will be influenced by different parameters. SPV arrays are completely or moderately covered by nearby trees, structures, and passing clouds. Under PS conditions, the P-V characteristics of SPV arrays will become more intricate and have several MPPs. The maximum point is known as the GMPP whereas the other points are named local MPPs (LMPP).

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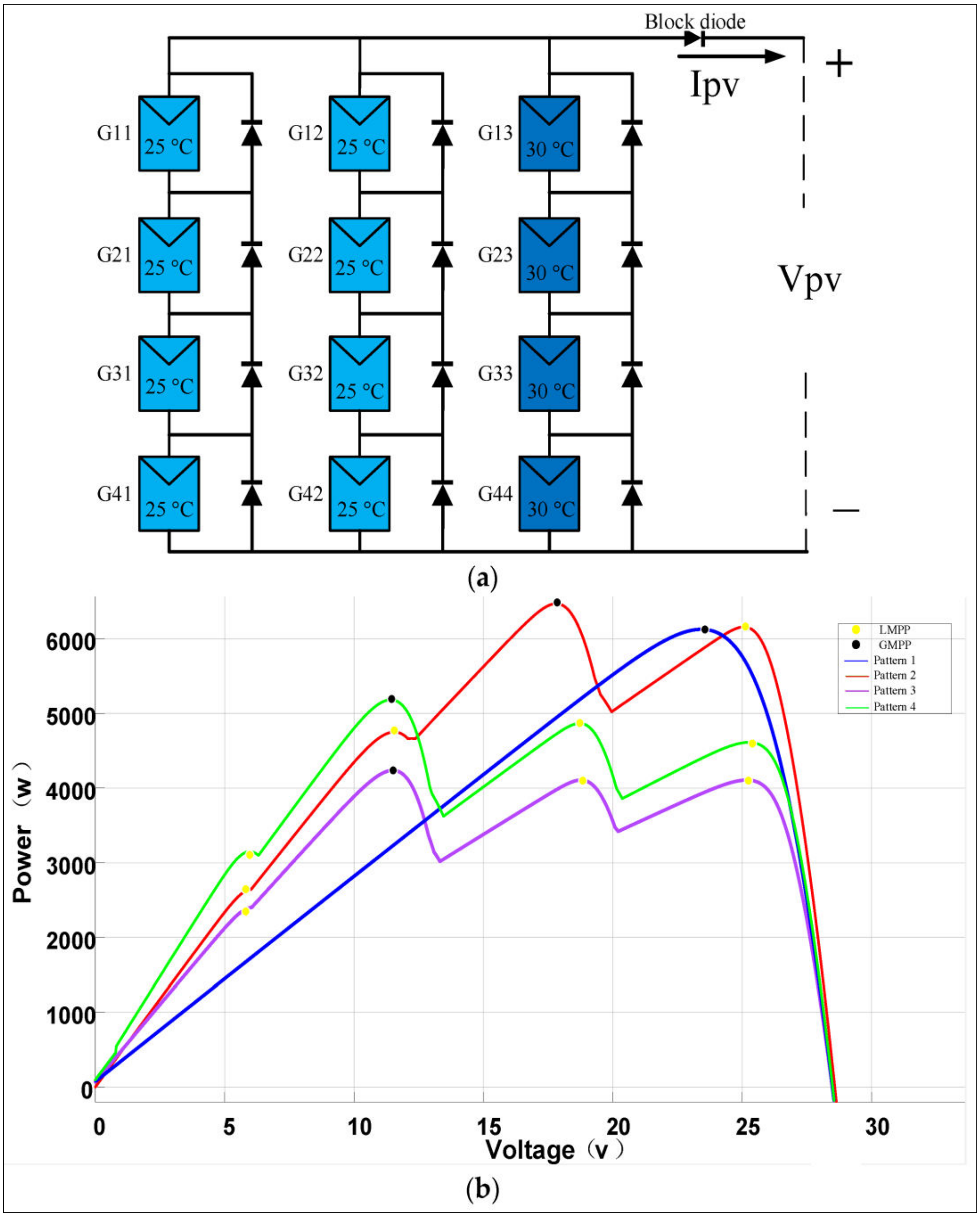

Figure 5: Analysis of PS patterns in the operation of the SPV module. (a) Shading configurations (b) P−V characteristics under PS condition.

In this work, a SPV is considered with 4 rows and 3 columns, and each unit contains 4 cells. Figure 5 shows the SPV module and P-V characteristics. The temperature of the cell is fixed to either 25 °C or 30 °C. Every SPV unit is interleaved into the anti-counterattack diode to guarantee the robust function of the cell. To evaluate the performance of the developed algorithms, we consider a uniform radiation pattern (P_1), and three different PS conditions (P_2, P_3, and P_4) are considered. The radiation level for these patterns is illustrated in Table 2. By setting various levels of radiation for each SPV unit (G11, G12, and G13), abrupt variations in solar radiation are controlled using step functions. P_1 has only one global MPP and no local MPP. It is noteworthy to mention that there are three local MPPs and one GMPP in P_2, three local MPPs and one global MPP in P_3, and three local MPPs and one GMPP in P_4.

Table 2: Radiation setting of SPV

Pattern	Radiation level (W/m^2)			MPP (KW)
P_1	G11=500	G12=500	G13=500	6.16
	G21=500	G22=500	G23=500	6.16
	G31=500	G32=500	G33=500	6.16
	G41=500	G42=500	G43=500	6.16

ISSN 2394 - 9554

P_2	G11=1000	G12=1000	G13=1000	6.47
	G21=1000	G22=700	G23=1000	6.15
	G31=700	G32=700	G33=700	4.75
	G41=500	G42=500	G43=300	2.64
P_3	G11=1000	G12=1000	G13=1000	4.72
	G21=1000	G22=700	G23=1000	4.57
	G31=300	G32=300	G33=300	4.57
	G41=500	G42=500	G43=300	2.64
P_4	G11=1100	G12=1200	G13=1100	5.18
	G21=1100	G22=300	G23=1100	4.86
	G31=300	G32=700	G33=300	4.60
	G41=600	G42=500	G43=300	3.11

IV. P&O-BASED MPPT APPROACH

The P&O algorithm begins its operation by perturbing the current or terminal voltage of the panel periodically and then it relates the present power output P(n) to the earlier output P(n-1). Since a power converter is mostly employed with a solar panel duty cycle perturbation will inevitably perturb the operating voltage. If the yield is increased after the perturbing of the terminal voltage $\left(i.e., \frac{\Delta P}{\Delta V} > 0\right)$, it should be retained in the same direction else it is changed to the reverse direction. This procedure is iterated till the MPP is gained $\left(i.e., \frac{\Delta P}{\Delta V} = 0\right)$. The step size of perturbation is reserved very small deliberately. It aids to preserve the power fluctuation trivial. If $\Delta P > 0$, then it verifies the ΔV value if it is also positive then it reduces the duty ratio (D) with constant step size (ΔD) and if $\Delta V < 0$, then it upturns the duty ratio with ΔD. Likewise, if $\Delta P < 0$, then it verifies the ΔV value if it is positive then it upturns the duty ratio value with ΔD and if $\Delta V < 0$, then it reduces the duty ratio with ΔD and repeats the process until it finds the MPP from the solar resource and provides the equivalent duty cycle.

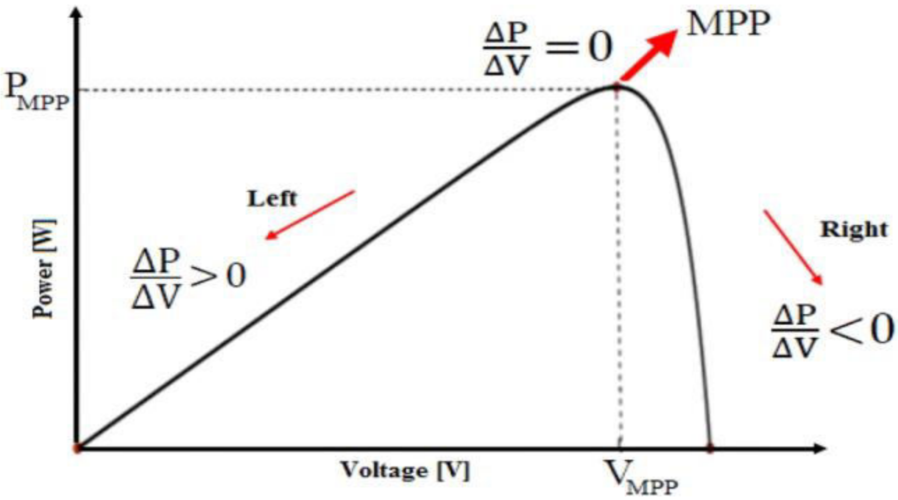

Figure 6: Performance of solar array with MPP

Figure 7 illustrates the solar panel with MPPT using the P&O method. The terms V_n and I_n denote the voltage and current of the solar unit at the n[th] iteration. $P_n = V_n I_n$ is the power output of the panel at the n[th] iteration. β is the step size of voltage perturbation and the selection of its value is most significant. Lesser β provides slow tracing and large β enables quick tracing however the fluctuation near the maximum power is more. To handle this problem, we select variable β. We assign a large value for β if the tracking process is far from the point of maximum power and its value reaches zippo as the tracking process approaches MPP. A quick speed convergence and nearly zero fluctuation at the MPP can be realized by selecting the value of β at the n[th] iteration ($\beta(n)$) as given in Equation (4).

. $\beta(n) = N_{cell} log_{10} abs\left(\frac{\Delta P}{\Delta V}\right)$ (4)

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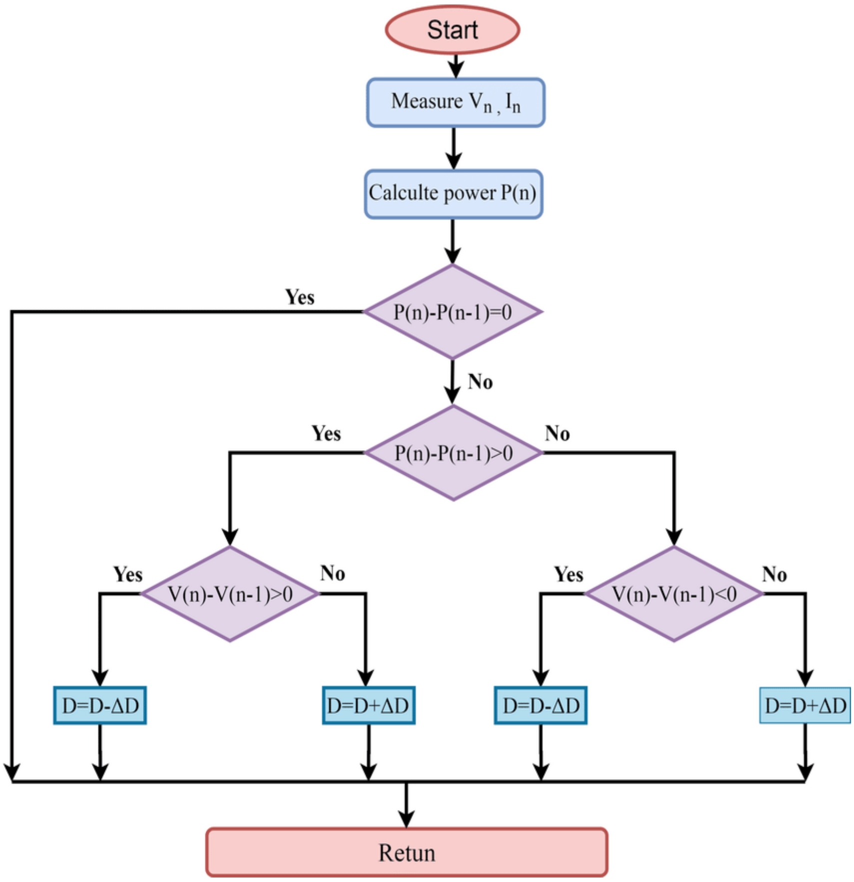

Figure 7: MPPT with P&O algorithm in a solar array

V. PROPOSED TSOPO ALGORITHM FOR MPPT

The TSO is an efficient meta-heuristic algorithm introduced with a huge exploration space and higher accuracy in resolving single-objective functions. TSO is motivated by the group hunting actions of tunas, and it contains two tactics: spiral hunting and parabolic hunting [20]. The TSOPO algorithm arbitrarily produces the initial population for the exploration area. The initialization process is defined by Equation (5).

$$P_i = rand\left(b^u - b^l\right) + b^l, \quad i = 1,2,3 \ldots . N \quad (5)$$

where P_i denotes the initial population; b^u and b^l are the upper and lower limits of the exploration area; and N is the total population. We enhance the initialization constraints for TSO by splitting the searching agents equally as defined by Equation (6).

$$P_0^k = \frac{k}{s+2} \qquad (6)$$

In Equation (6), s is the size of the swarm and P_0^k is the initial population (duty cycle). In the spiral hunting process, the bias terms ω_1 and ω_2 regulate the local and global search aptitude of the algorithm. These rudimentary weight factors are defined by Equations (7) and (8).

$$\omega_1 = \partial + (1 - \partial)\frac{t}{t_{max}} \qquad (7)$$

$$\omega_2 = (1 - \partial)\left[1 - \frac{t}{t_{max}}\right] \qquad (8)$$

A greater weight factor is favorable to the optimization procedure in getting a greater exploration area in the pre-iteration and mid-iteration phases. If it has a lower value, the algorithm can better perform exploitation in future runs and speed up the convergence level of the optimization process. We can avoid the TSO falling into the local optimum value at the initial phase of the run by adjusting the weight factors. To balance the local and global exploration abilities of TSO, ω_1, and ω_2 provide nonlinear enhancements, and the enhanced weight factors are given in Equations (8) and (9). These factors vary nonlinearly with ω_1, and ω_2. The variation range in the first half of ω_2 provides the global searching facility. Once the system approaches the second phase, ω_1 and ω_2 quickly shift to a constant value, supporting the algorithm to rapidly reach the optimum value and

ISSN 2394 - 9554

completely realize the local growth. Hence, the enhanced weight factor can balance the local and global exploration phases effectively.

$$\omega_1 = 1 - 0.3 \sin\left(\frac{t}{t_{max}} \times \frac{\pi}{2}\right)^2 \qquad (8)$$

$$\omega_2 = 0.3 \sin\left(\frac{t}{t_{max}} \times \frac{\pi}{2}\right)^2 \qquad (9)$$

where t denotes the current run and t_{max} denotes the maximum amount of runs, and The final spiral hunting process is defined by Equation (10).

$$P_i^{t+1} = \begin{cases} \omega_1(P_{rand}^t + \beta\left|P_{rand}^t - P_i^t\right| + \omega_2 P_i^t,\ i = 1 & \\ \omega_1(P_{rand}^t + \beta\left|P_{rand}^t - P_i^t\right| + \omega_2 P_{i-1}^t,\ i \geq 2, & if\ rand < \dfrac{t}{t_{max}} \\ \omega_1(P_{best}^t + \beta\left|P_{best}^t - P_i^t\right| + \omega_2 P_i^t,\ i = 1 & \\ \omega_1(P_{best}^t + \beta\left|P_{best}^t - P_i^t\right| + \omega_2 P_{i-1}^t,\ i \geq 2, & if\ rand < \dfrac{t}{t_{max}} \end{cases} \qquad (10)$$

where P_i^{t+1} is the position after completing the iteration; P_{rand}^t is an arbitrarily created standard point in the exploration area, and P_{best}^t denotes the current optimal value. The parabolic hunting nature of this algorithm is defined by Equation (11).

$$P_i^{t+1} = \begin{cases} P_{best}^t + rand\left(P_{best}^t - P_i^t\right) + \gamma\rho^2\left(P_{best}^t - P_i^t\right) & if\ rand < 0.5 \\ \gamma\rho^2 P, & if\ rand \geq 0.5 \end{cases} \qquad (11)$$

where γ is a arbitrary value of [−1, 1].

3.4 Integration of P&O and TSO algorithm

Applying optimization algorithms for maximum power tracking is an important problem since out of several possibilities, only some configurations extract the maximum power successfully. The TSO algorithm is one of the influential techniques found in the literature for handling nonlinear stochastic optimization problems. The proposed TSOPO algorithm-based MPPT performs better regarding efficiency and performance for extracting performs power from the SPV modules under various shading conditions.

In this work, the concepts of spiral and parabolic hunting with flexible inertia weight are applied in the P&O approach to achieve maximum power. The proposed TSOPO algorithm with the population size of N and d dimensional search space is given in Algorithm 1. The initial population of (P_i) is selected arbitrarily and then P_0^k is determined by Equation (6). The best tuna is selected from P_i and P_0^k for the first iteration. In the TSOPO algorithm, each tuna updates the fitness value after assessing the fitness from the objective function. Then the tunas rank and update their locations using Equation (11).

Algorithm 1: TSOPO for MPPT
Input: Size of the population (SPV array) Output: Global maximum power point
1:Initialize P_i as given in Equation (5)
2:Update $P_{best}^t$of SPV array in each shading condition
3:Evaluation of the fitness function
4:Ranking process of tunas based on their fitness and finding the best
5: for i=1 to n for j=2 to n if fitness($rand < 0.5$) Update P_i^{t+1} position according to Equation (11)

ISSN 2394 - 9554

else go to Step 7
Step 6:Adjust weight factor based on the best tunas
Step 7:Calculte fitness and update the best
Step 8:if iteration<generation go to Step 4 else check for variation in radiation level if there is any change? go to Step 3 Display maximum power point
9: Stop

VI.RESULT AND DISCUSSION

In this work, we apply the proposed TSO on P&O to find out the optimum GMPP and excerpt peak power from the SPV panels. The performance of the intended approach is evaluated by relating the performance of the system with prevailing MPPT methods including original P&O [9], WOA-based P&O [13], and FPA-based P&O [15]. The group size considered for all the algorithms used in this study is 6.

5.1 Result of Pattern 1

We evaluate the performance of the TSOPO algorithm in handling MPPT problems for P_1. The numerical fallouts obtained from TSOPO are related to the original P&O and two optimized P&O techniques using WOA, and FPA. Figure 8 illustrates the power characteristics gained from the SPV panel using the WOA, TSOPO, FPA, and P&O. The maximum power of P_1 is 6.16 kW. Indeed, the stable state variation of power tracking method using TSOPO is minimum while realization MPP of 6.17kW. Related to the original P&O, WOA, and FPA, TSOPO reached the MPP at a very high speed, with an efficacy of 99.99%. The maximum power of P&O, WOA, and FPA approaches in P_1 are 6.13 kW, 6.16 kW, and 6.17 kW with the tracking efficiency is 99.62%, 99.91%, and 99.94%, correspondingly. Regarding tracking efficiency, these three approaches consume 0.412 s, 0.342 s, and 0.276 s, correspondingly. TSOPO only required 0.052 s to achieve GMPP, which is the fastest speed among all 4 approaches. As listed in Table 3, TSOPO had a higher tracking efficiency and lower tracking time than FPA, P&O, and WOA.

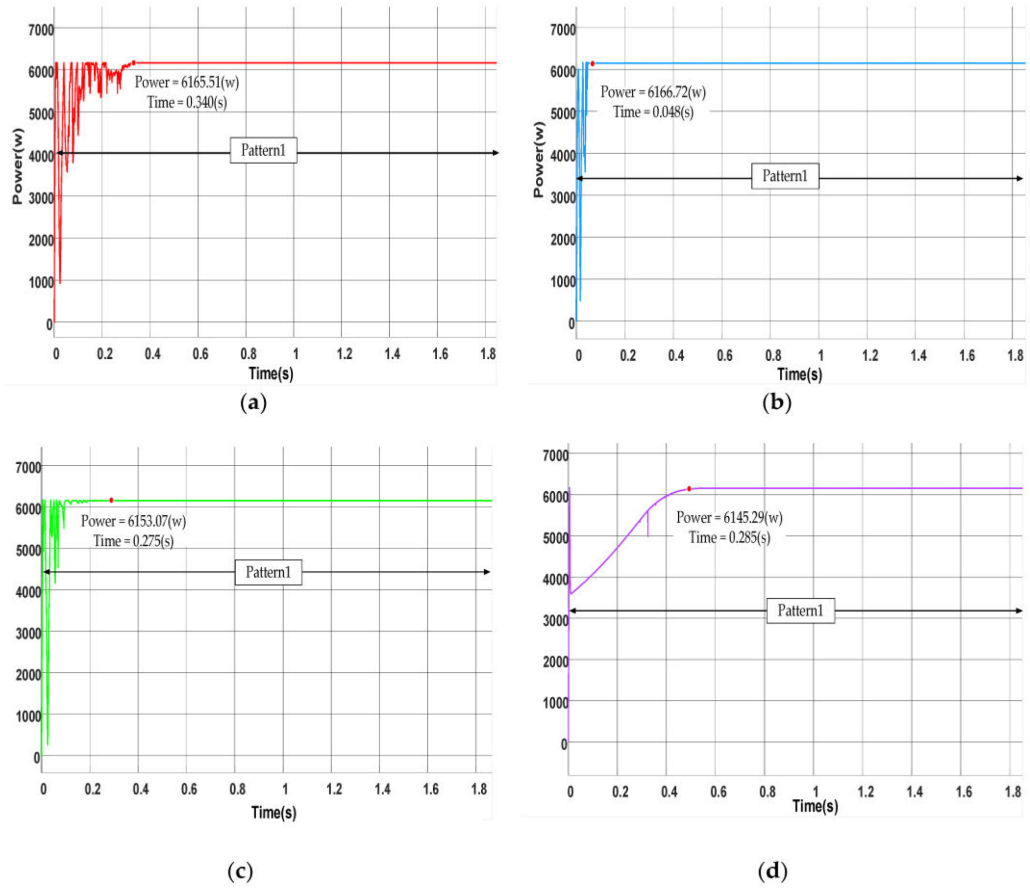

Figure 8: The power performance gained by the algorithms in uniform radiation pattern P_1 (a) WOA; (b) TSOPO; (c) FPA; (d) P&O

Table 3: Results of WOA, TSOPO, FPA, and P&O techniques in P_1

Method	MPPT method	Extracted Power (kW)	Efficiency (%)
P&O	6.13	99.62	0.412
WOA	6.16	99.91	0.342
FPA	6.15	99.94	0.276
TSOPO	6.17	99.99	0.052

Figure 9 illustrates the duty cycle characteristics gained from SPV using WOA, TSOPO, FPA, and P&O methods. It is witnessed that the approaches considered in this work can preserve zero steady-state operation after a definite time. Related to WOA and FPA, the TSOPO technique can swiftly preserve stability after a minor frequency fluctuation and converge towards the MPP. Hence, the robustness of the TSOPO algorithm is superior to P&O, FPA, and WOA in P_1.

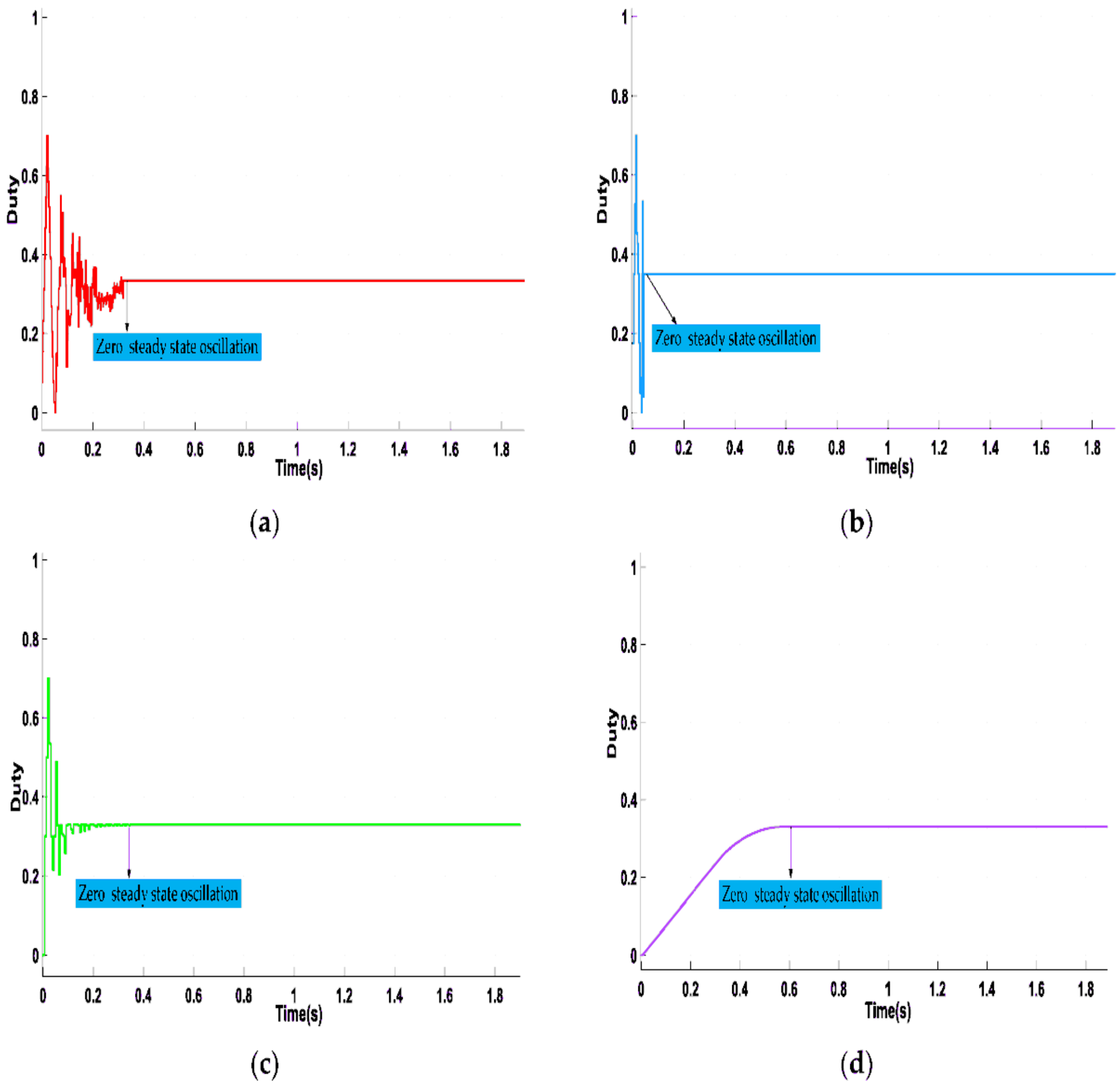

Figure 9: The duty cycle obtained by the algorithms for P_1. (a) WOA; (b) TSOPO; (c) FPA; (d) P&O

5.2 Result of Pattern Transitions

We analyze the strategy of the SPV array to handle dynamic variations in irradiance patterns (from P_2 to P_3) in this section. The numerical outcomes gained from four different approaches are given below. For P_2, it is observed from Figure 10 that P&O, WOA, FPA, and TSOPO are able to reach the MPP and preserve a zero steady-state characteristics, with peak power of 6.04 kW, 6.35 kW, 6.26 kW, and 6.47 kW, correspondingly. The basic P&O failed to preserve global peak owing to the huge oscillation magnitude, causing a mean power of 6.04 kW. These outcomes show that the performance of P&O method is inferior. With respect to convergence speed, the time taken by the P&O method to converge is 0.222 s, but during PS conditions, P&O does not conserve zero steady-state value.

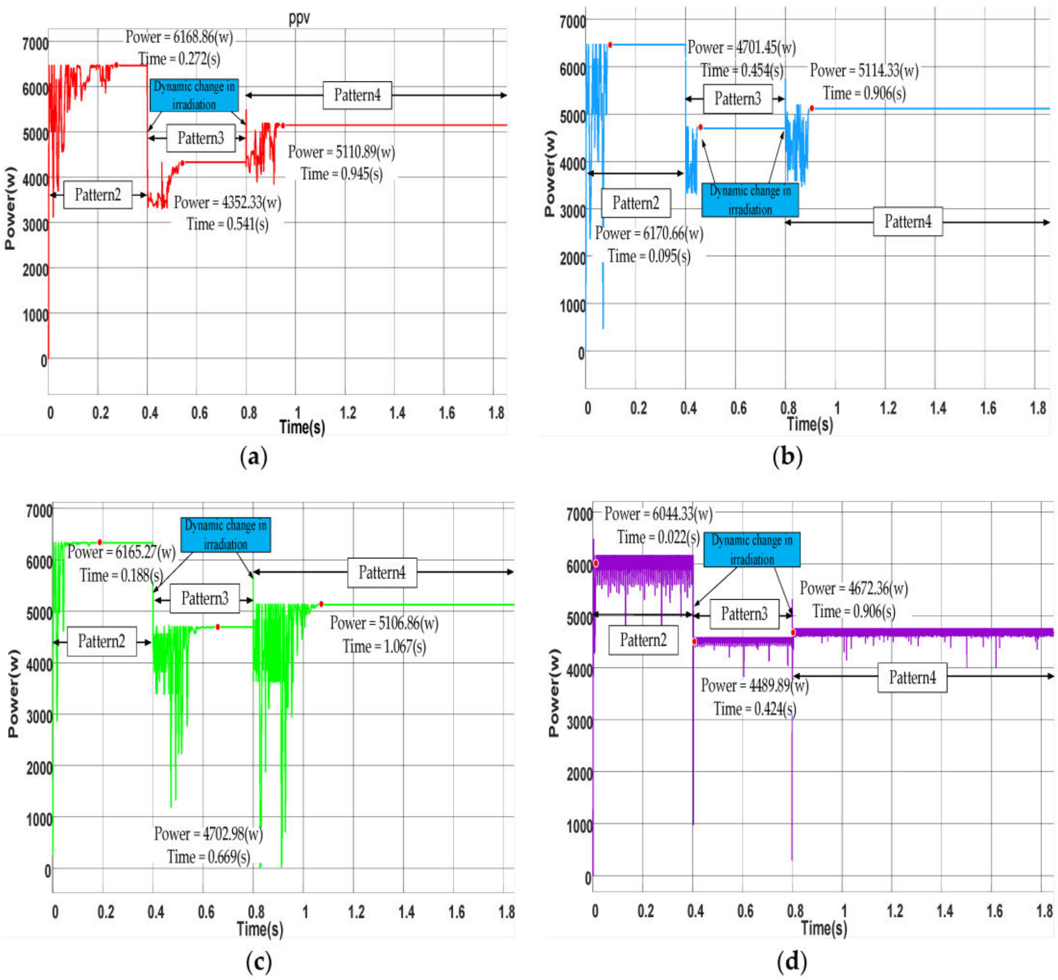

Figure 10: Efficiency of algorithms during step changes from P_2 and P_3. (a) WOA; (b) TSOPO; (c) FPA; (d) P&O

The convergence speed of basic P&O, WOA, and FPA algorithms are 0.222 s, 0.272 s, and 0.95 s, correspondingly. Conversely, the TSOPO consumes the shortest time (0.095 s) and generates small frequency fluctuations, which can guarantee stable performance in GMPP.

During dynamic changes in radiation in P_2, when radiation abruptly altered at 0.4 s, P&O trapped into LMPP with a value of 6.04 kW. The MPPT approaches such as WOA, TSOPO, and FPA achieved GMPP for a second time after the disruption. The salvage time of TSOPO after the disruption is 0.051 s, which demonstrates that the TSO has an improved stability. The MPPs of the P&O, WOA, FPA, and TSOPO in P_3 are 4.19 kW, 4.42 kW, 4.35 kW, and 4.71 kW, respectively. When the radiation pattern quickly changed at 0.8s, WOA, FPA, and P&O all revealed substantial oscillations. The TSOPO approach generates a minor oscillation amplitude and frequency, causing improved enactment. Concerning tracking efficiency, the TSOPO outdoes the other two algorithms. The basic P&O method could not be maintained near MPP. The tracking speed of the TSOPO is very high (0.052 s) as compared to P&O (0.274), WOA (0.141 s), and FPA (0.271 s). From Table 4, it is observed that the intended TSOPO has improved stability, efficiency, and tracking speed.

Table 4: Numerical results of WOA, TSOPO, FPA, and P&O methods in P_2, P_3, and P_4

Pattern	MPPT method	Extracted Power (kW)	Efficiency (%)	Tracking time (s)
P_2	P&O.	6.04	96.82	0.222
	WOA	6.35	99.97	0.272
	FPA	6.26	99.94	0.188
	TSOPO	6.47	99.99	0.095
P_3	P&O.	4.19	95.01	0.174
	WOA	4.42	99.48	0.141
	FPA	4.35	92.09	0.271
	TSOPO	4.71	99.48	0.051
P_4	P&O.	4.52	91.08	0.145

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	WOA	4.62	98.41	0.267
	FPA	4.60	98.50	0.106
	TSOPO	5.12	98.56	0.006

From Figure 11, we can observe that the algorithms such as WOA, FPA, and TSOPO could preserve zero steady-state values after and before disruptions in the algorithms. Though the basic P&O method had quick convergence time, it cannot continue robust action, and the characteristic curves sustained to fluctuate in constant magnitude. The TSOPO has the lower tracking time and the maximum tracking performance among the approaches used in this study that can predict zero steady states.

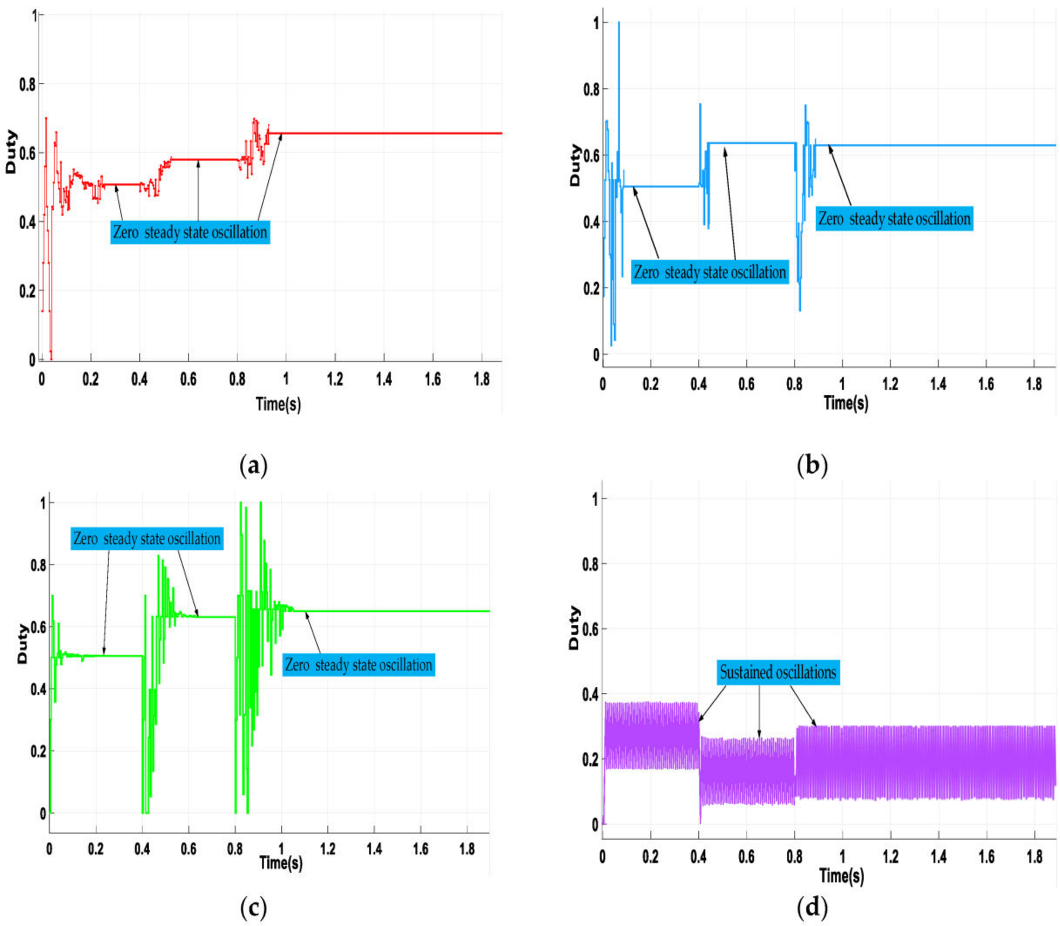

Figure 11: The duty cycle gained during the step variations from P_3 and P_4 (a) WOA; (b) TSOPO; (c) FPA; (d) P&O

VII. CONCLUSION

This paper develops a novel optimized P&O approach that integrates the TSO algorithm with the concept of the P&O approach to excerpt peak power from a SPV module under various PS conditions. The proposed TSOPO technique carries out maximum power tracking by fine-tuning the duty cycle of converter. In the modelling, the system contains a SPV module, a boost-type DC-DC power converter, and an MPPT control unit. The proposed system is implemented and results are obtained from the experimentation using the MATLAB software. Under 4 different PS conditions, TSOPO enables better tracking speed, stability, and tracking efficiency. TSOPO exhibits better enactment under constant and different shading patterns. The results proved that the tracking efficiency of the TSOPO approach is superior to basic P&O and other optimized P&O approaches (using WOA and FPA optimization algorithms) with respect to extracted power, power conversion performance, and tracking speed. The tracking speed of TSOPO is significantly increased related to the other three techniques. Under different PS conditions, the proposed approach provides improved tracking speed and efficiency. These results reveal that TSOPO is a good and reliable high-speed MPPT technique. Hence, it can be established that TSOPO provides the optimum result to find out GMPP for all kinds of radiation pattern.

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