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Asymmetrical fuzzy logic control-based MPPT algorithm for stand-alone photovoltaic systems under partially shaded conditions

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DC-DC boost converter.

Abstract. Partial Shading Conditions (PSCs) in Photovoltaic (PV) system represent an inevasible situation that curtails the PV array output by exhibiting multiple peaks in its Power-Voltage (P-V) curve. The multiple peaks consist of a single Global Maximum Power Point (GMPP) and many Local Maximum Power Points (LMPPs). The presence of multiple peaks makes tracking of maximum power point quite difficult and demands an efficient controller to track the global peak of the P-V curve. In the present work, a novel intelligent Asymmetrical Fuzzy Logic Control (AFLC) based Maximum Power Point Tracking (MPPT) algorithm was proposed for tracking GMPP. The fuzzy membership functions of the proposed algorithm were optimized using a heuristic approach. The algorithm was designed, developed, and analyzed using MATLAB/simulink. Furthermore, to establish the superiority of the proposed AFLC algorithm, it was compared with conventional Perturb and Observe (P&O) algorithm and intelligent Fuzzy Logic Control (FLC) based algorithm for GMPP tracking and shading losses under Standard Test Condition (STC) and partially shaded conditions.

1. Introduction

Energy is a necessity for everyday life and due to depletion of fossil fuels, this demand may not be fulfilled by conventional power generation systems only. To overcome this major concern, renewable resources such as solar, hydro, wind, hydrogen fuel cell, biogas, etc. have taken the center stage of the emerging technology. Amongst these non-conventional energy resources, photovoltaic energy conversion is gaining widespread acceptance due to being green, abundant in nature, and relatively cheap [1]. Sun is a massive source of energy which can be converted into a utilizable form by means of Solar Photovoltaic (SPV) cell.

The performance of a SPV system highly depends on varying meteorological conditions like insolation, temperature, etc. PhotoVoltaic (PV) panels produce optimum output under Standard Test Condition (STC) (irradiation 1 kW/m^2 and temperature 25°C) and it can be negatively affected by partial shading. Shading is a condition in which PV array is not uniformly irradiated. Shading on solar PV array is formed because of dense clouds, nearby buildings, big trees, towers, dust, and panel aging or cracking. A major consequence of shading is that it exhibits multiple

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peaks in Power-Voltage (PV) and Current-Voltage (I-V) curves of PV array, which may account for conventional Maximum Power Point Tracking (MPPT) algorithms converging to Local Maximum Power Point (LMPP) instead of Global Maximum Power Point (GMPP), resulting in power loss. Hence, mitigating the effect of partial shading is a major practical challenge.

Several conventional MPPT techniques including perturb and observation, incremental conductance (INC), Fractional Open-Circuit Voltage (FOCV), etc. were reviewed and addressed in [2,3]. Among these conventional MPPT methods, Perturb and Observe (P&O) is widely used because of its simplicity and ease of implementation. However, its reliability is low under Partial Shading Conditions (PSCs) because the perturbation process makes the operating point lurch around the maximum power point, resulting in wastage of power. This challenge can be met by reducing the step size of perturbation; however, small perturbation size delays the MPPT [4,5]. Al-Majidi et al. proposed a novel MPPT algorithm in [6] in the performances of P&O and Fuzzy Logic Control (FLC) based MPPT for the grid-connected PV system were compared. The proposed algorithm accurately tracked maximum power with no drift problem.

INC algorithm offers improved tracking accuracy under steady-state and variable environmental conditions. The main advantages provided by INC algorithm over the P&O algorithm were dissected by Liu et al. [7]. The algorithm was formulated on the basis that the rise of the PV module power curve was zero at the MPP, positive on the left side, and negative on the right position of the MPP. The derivative algorithm was applied to find the MPP. This method puts a considerable computation burden on the controller because the differentiation process involves a relatively complex decision-making procedure [8,9]. Therefore, implementing INC algorithm increases the cost and complexity of the system and it may produce unsatisfactory results at a low-insolation level. Further, Reisi et al. [10] distinguished MPPT algorithms into two categories: direct and indirect methods. Indirect MPPT algorithms such as FOCV and short-circuit current cannot trace MPP in any given environmental condition, given that these methods require prior knowledge of P-V characteristics. Direct method [11] based algorithms do not require prior knowledge of P-V characteristics and can track MPP under any weather conditions. Authors in [12] compared the effects of different membership functions of FLC. Triangular membership function produced the best result, while Gaussian membership function generated poor performance in the considered cases. Asim et al. [13] carried out performance analysis for MPPT by different controllers such as P&O, FLC, neural network, ripple correction control current sweep, DC-Link capacitor droop control, etc. Ripple correction control proposed by by Esram et al. [14] enjoyed higher tracking efficiency under a uniform shading condition and its efficiency was significantly reduced under PSC as it took a longer time to search for GMPP.

Recently, Balasankar, et al. considered the deployment of P&O under a PSC [15]. In [16], MPPT algorithm based on an Adaptive Neuro-Fuzzy Inference System (ANFIS) was presented. ANFIS model for tracking MPP takes temperature and irradiation as input and duty cycle is the output. In [17], Sahoo detected the presence of PSC by examining the voltage at each PV module; however, this technique required an equal number of voltage sensors as the PV module in the array. Ishaque et al. [18] presented an impressive method based on Particle Swarm Optimization (PSO) algorithm. However, it is too complicated to be commercially applied as some parameters need to be set by the user. Karami et al. [19] applied Artificial Neural Network (ANN). The problem faced by ANN-based algorithm is that it is quite dependent on available training data under different environmental conditions; therefore, the data need to be revised again when array configuration changes. Authors in [20–22] reviewed algorithms such as an artificial bee, ant colony, PSO, flashing fireflies, and grey wolf algorithms. Although the genetic algorithm is characterized by better stability, its implementation is a significant challenge as it involves complicated calculation and equations and some data need to be set by the user.

In [23], the proposed system tracks maximum power utilizing differential evolution. The proposed technique appear to have a better response regarding fast convergence in both uniform and non-uniform shading conditions. It also eliminates fluctuations around MPP. Inputs such as insolation level and the temperature to SPV are ephemeral. Therefore, control algorithms need to be implemented to cope with the uncertainty in the quantities of interest. FLC technique, a soft computing tool, can deal with these uncertainties [24]. FLC can incorporate a conventional design to track MPP under ambient conditions, as suggested by Sundareswarm, et al. [25]. Verma, et al. [26] compared P&O with intelligent FLC algorithm under a partially shaded condition for stand-alone PV systems and simulation results illustrated that FLC could track maximum power with better tracking efficiency. Results also illustrated that conventional MPPT might track LMPP instead of GMPP under dynamic conditions.

The present work focuses on the tracking of global peak out of multiple peaks under PSC. Solar photovoltaic panels under PSCs are not uniformly irradiated, which makes P-V characteristic exhibit more than one peak. Out of these multiple peaks, there is only one peak exhibiting maximum power, i.e., GMPP. The conventional algorithm may not be able to track GMPP and lurch around LMPP. To overcome the drawbacks of a conventional algorithm, FLC was implemented so as to enhance the performance of MPPT by tracking GMPP. The MPPT tracking efficiency was further enhanced using a novel, intelligent asymmetrical fuzzy logic controller-based algorithm. For asymmetrical FLC, the authors optimized the universe of discourse by fine-tuning it at the center for effective implementation of MPPT. The proposed asymmetrical FLC MPPT algorithm distinguishes between GMPP and LMPP and contributes towards global peak tracking. By using an asymmetrical fuzzy controller, the tracked power is higher than other conventional algorithms, thus proving the superiority of the proposed algorithm. Moreover, shading losses are reduced using Asymmetrical Fuzzy Logic Control (AFLC) algorithm. The proposed MPPT algorithm excelled in both steady state and dynamic conditions. The relatively new idea of asymmetrical FLC-based MPPT algorithm under PSCs for stand-alone PV systems can be applied to large solar farms. These studies shall be helpful for system designers.

1.1. System configuration

Figure 1 presents the block diagram of a stand-alone PV system. To track maximum available power in a given environmental condition, MPPT technique is utilized by adjusting the duty ratio of a boost converter. The proposed asymmetrical FLC-based MPPT algorithm was designed, developed, and validated to track the global peak from multiple peaks of the P-V curve under partially shaded conditions, which may not be efficiently traced by other conventional approaches. The components of the proposed system are explained in the following sections.

2. Solar PV cell

Solar cell works on the principle of PV effect. It is an active transducer that converts energy from sunlight (photons) into electricity (current). The voltage produced by the solar cells is minimal (0.5 V to 0.8 V) to achieve the desired output so that they can remain connected in series. Solar cells connected in series make PV module and PV module connected in a series-parallel configuration, as per power requirement, makes PV array [27]. Figure 2 presents the ideal and practical equivalent circuits of the single-diode model used in the proposed system.

The output current $I_{o/p}$ of PV cell is given in Eq. (1):

$$I_{o/p} = I_{cs} - I_{sat} * \left[\exp\left(\frac{q(V_{o/p} + I_{o/p} * R_s)}{N_s A k T_{ac}}\right) - 1\right] - \frac{V_{o/p} + I_{o/p} R_s}{R_{sh}}, \tag{1}$$

where $I_{o/p}$ is the output current of PV cell, I_{cs} is the photon current, I_{sat} is the diode saturation

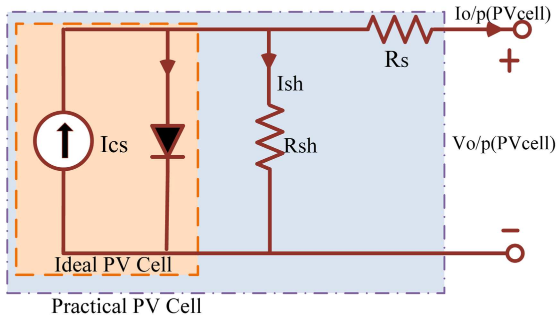


Figure 2. Equivalent circuit of a single-diode model of a Photovoltanic (PV) cell.

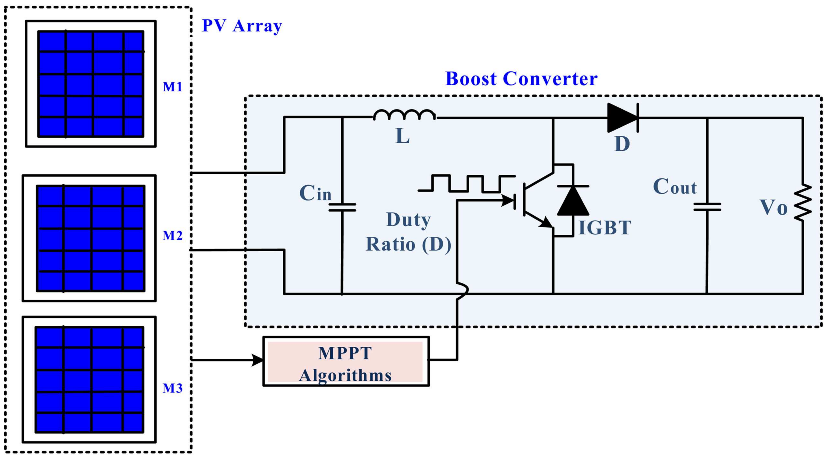


Figure 1. Block diagram of a stand-alone Photovoltanic (PV) system.

current, q is the elementary charge (1.602^*10^{-19} C), $V_{o/p}$ is the output voltage of a PV cell, N_s is the number of series cell, A is the ideal factor of the cell dependent on PV technology, K is the Boltzmann constant (1.38^*10^{-23} J), and T_{ac} is the actual operating temperature.

In the present work, sun power solar panel $X22-360$ PV module is used. Table 1 shows the sun power solar panel specifications used for simulating and modeling PV module. An array of (3×1) PV modules viz. M1, M2, M3, each characterized by 360 W, connected in series is considered, as shown in Figure 1, and is simulated using MATLAB/simulink. The maximum power obtained by the array is (360×3) 1.08 kW.

Figure 3 shows the effect of irradiation and temperature on the I-V and P-V characteristics of PV array. I-V and P-V curves show that with a change in temperature, voltage changes appreciably and change in irradiation causes appreciable variations in current. Also, according to Figure 3, when modules are uniformly irradiated, there is only one maximum.

Table 1. Specification of sun power Photovoltanic (PV) Module.

SPR-X22-360	
Power nominal (Max), P_{nom}	360 W
Rated voltage, V_m	60.6 V
Rated current, I_m	5.94 A
Open-circuit voltage, V_{oc}	69.5 V
Short-circuit current, I_{scc}	6.48 A
Total no. of cell in series, N_s	96

3. DC-DC converter

In the proposed PV system, the boost converter is used as a dc-dc converter (Figure 1). The main components of the boost converter along with IGBT switch are the series inductor and shunt capacitor, which are passive components. The values of an inductor, capacitor, duty ratio, and resistive load are calculated below, as given by Eqs. (2)–(5).

$$L = \frac{V_{o/p}\alpha}{(\Delta I_1 f_{sw})}, \tag{2}$$

$$\alpha = 1 - \left(\frac{V_a}{V_{o/p}}\right), \tag{3}$$

$$C = \frac{I_a \alpha}{(\Delta V f_{sw})}, \tag{4}$$

$$R_o = \frac{R_{in}}{(1-\alpha)^2}, \tag{5}$$

where $\Delta l_1$is the output ripple current and is considered as 10% of the input current, $V_{o/p}$ is the output voltage, f_{sw} is the switching frequency, α is the duty ratio, V_a is the input voltage, and I_a is the average output current. ΔV is the peak ripple voltage whose value is taken as 3% of the output voltage, R_{in} is the input resistance, and R_o is the load resistance which appears to be 122 Ω. The values of inductance, capacitance, and duty ratio are 1.1 mH, 500 μF, and 0.5–0.7, respectively.

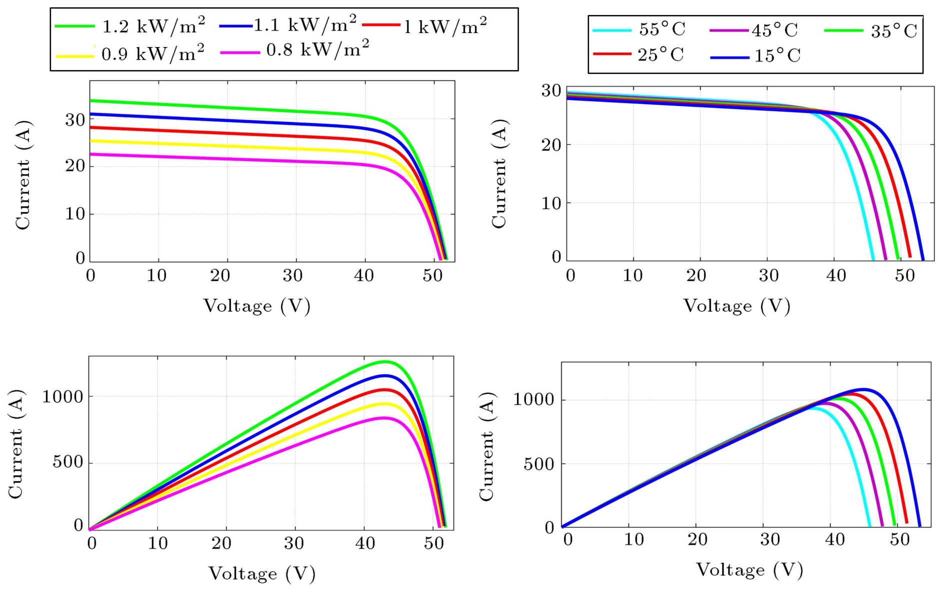


Figure 3. Current vs. voltage and power vs. voltage curves of the proposed Solar PV (SPV) system with (a) variable irradiation and (b) variable temperature.

4. MPPT techniques

4.1. Conventional algorithm (P&O algorithm)

The P&O maximum power point algorithm works on the condition that on the right side of the MPP, if voltage increases, power decreases and perturbation is made on the opposite direction, whereas towards the left side of MPP, if voltage increases, power also increases; then, perturbation is made in the same direction. Implementation of a P&O algorithm in the proposed PV system is shown Figure 4.

The main drawback of the P&O algorithm is its inability to track maximum power point due to the oscillations near MPP region under varying environmental conditions. To overcome these disadvantages, FLC-based algorithm is implemented that can minimize oscillations near the operating point; hence, energy wastage in a PV system is also minimized. Further, in the proposed AFLC-based algorithm, the output power is further enhanced by asymmetrical distribution of fuzzy membership functions.

4.2. Intelligent algorithm (AFLC)

Fuzzy logic is a logical system that does not require an accurate mathematical model. FLC uses "If...then..." command to frame a rule base. The fuzzy inference system can be Mamdani or Sugeno, and both can have symmetrical or asymmetrical membership functions [28,29]. The main drawback of conventional fuzzy logic algorithms is that they may not track GMPP. In the proposed work, the asymmetrical FLC-based control algorithm was designed. The input/output membership functions of symmetrical FLC were further fine-tuned by the heuristic approach with a carefully designed rule base to track MPP under PSCs.

In the proposed AFLC algorithm, the asymmetric distribution of input and output membership functions includes both convergent $(+\beta)$ and divergent $(-\beta)$ types of asymmetry for the fuzzy variables. The values of $[+\beta, -\beta]$ were tuned to achieve MPP without oscillations. Figure 5 shows the block diagram of the asymmetrical FLC-based control algorithm for MPPT.

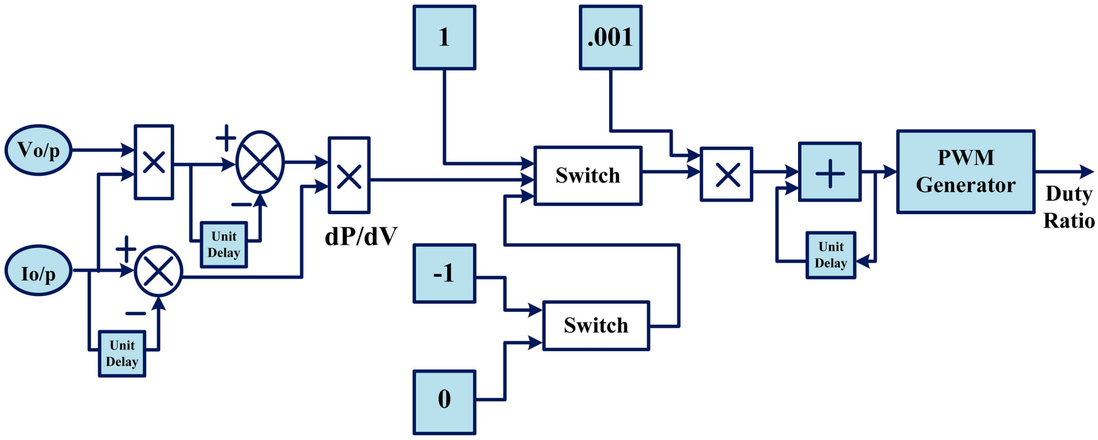


Figure 4. Block diagram of the P&O algorithm.

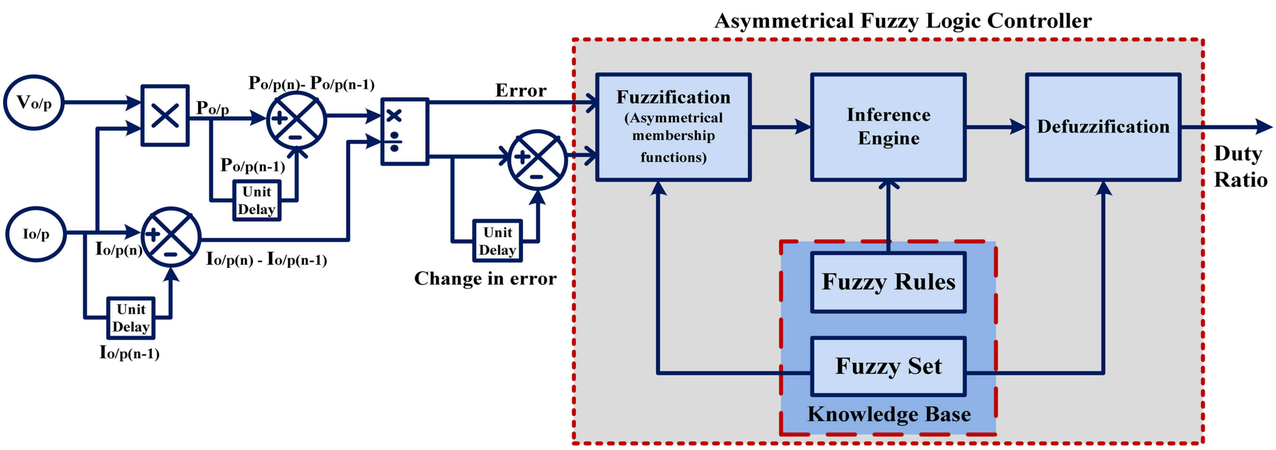


Figure 5. Block diagram of asymmetrical Fuzzy Logic Control (FLC)-based control algorithm for Maximum Power Point Tracking (MPPT).

First, fuzzification, inference method, and defuzzification are elaborated below.

4.2.1. Fuzzification

In the proposed asymmetrical FLC-based MPPT algorithm, two inputs include error and change in error. The power is calculated based on the sensed voltage and current. Error is then calculated using Eq. (6). Change in error is derived from the derivative of error and can be calculated through Eq. (7):

$$E_r(n) = \frac{P_{o/p^{(n)}} - P_{o/p^{(n-1)}}}{I_{o/p^{(n)}} - I_{o/p^{(n-1)}}}, \tag{6}$$

$$\Delta E_r\left(n\right) = E_r\left(n\right) - E_r\left(n-1\right), \tag{7}$$

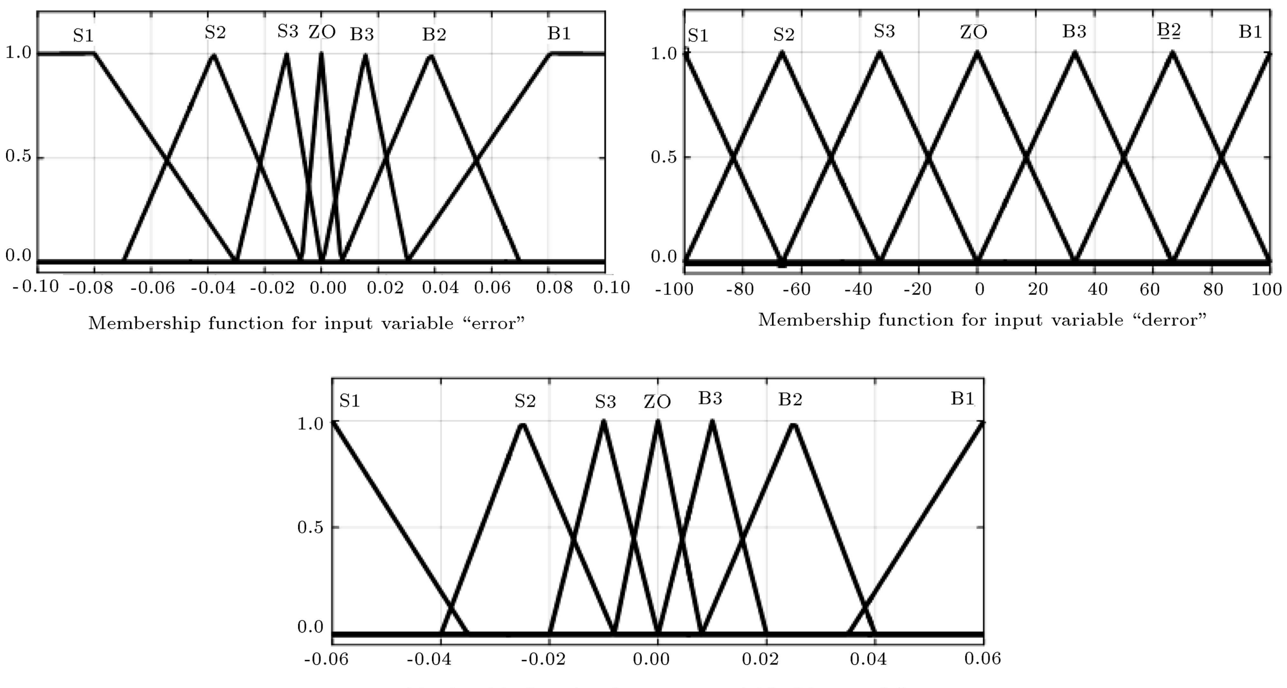
where E_r is the calculated error, $P_{o/p}$ and $I_{o/p}$ are the power and current output of the proposed PV system, and ΔE_r is the change in error.

The universe of discourse or membership function is a curve that denotes how each point in the input space is mapped in between 0 and 1. Input and output universes of discourse of fuzzy sets consist of seven triangular membership functions. Figure 6 shows the asymmetrical distribution of fuzzy input and output membership functions used in the proposed system for tracking maximum power in a steady state and a dynamic condition. The universe of discourse for the input variable is divided into seven fuzzy sets: S1 (Small 1), S2 (Small 2), S3 (Small 3), ZO (Zero), B1 (Big 1), B2 (Big 2), and B3 (Big 3) [24]. In the proposed AFLC, the membership functions are denser at the centre to provide greater sensitivity in the region near the MPP. Input membership functions are normalized and suitable tuning gains are used to match the inputs to the respective universe of discourse.

4.2.2. Inference method

The inference method applies the rules to the fuzzy input to determine the fuzzy output. Rules are made based on the membership function of error and change in error. In the proposed system, the rules have been made using "If...then..." logic. For example, if an error is S1 and change in error is S3, then the duty ratio is ZO.

The idea behind making a rule base in the form of a matrix is to bring the operating point closer to the maximum power point with less fluctuations by increasing or decreasing the duty ratio as per the direction in which maximum peak occurs [30,31]. In Figure 7, the rule base for the proposed system is shown which consists of 49 fuzzy control rules. These rules can also be represented in a 3D graph known as a surface viewer, as shown in Figure 8. In the present work, Mamdani's Max-Min method is used for inference of fuzzy controller. The output membership function of each rule is given by the minimum operator, whereas collective fuzzy output (x) is provided by maximum operator [32].



Membership function for input variable "error"

Membership function for input variable "derror"

Membership function for output variable "duty cycle"

Figure 6. Membership functions for input variable 'error', error change', and output variable 'duty ratio' for asymmetrical Fuzzy Logic Control (FLC).

E / ΔE	S1	S2	S3	ZO	B3	B2	B1
S1	ZO	ZO	ZO	S1	S1	S1	S1
S2	ZO	ZO	ZO	S2	S2	S2	S2
S3	S3	S3	ZO	ZO	ZO	B3	B3
ZO	S3	ZO	ZO	ZO	ZO	ZO	B3
B3	B3	B3	ZO	ZO	ZO	S3	S3
B2	B2	B2	B2	B2	ZO	ZO	ZO
B1	B1	B1	B1	B1	ZO	ZO	ZO

Figure 7. Fuzzy rule base for computing the output variable called 'duty ratio' in the matrix form.

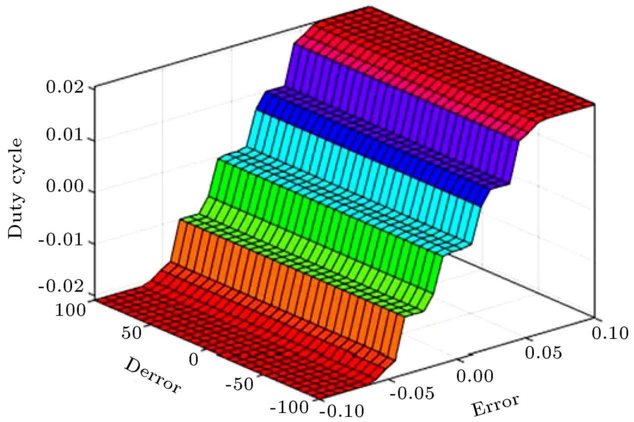


Figure 8. 3D surface view representation between two inputs (error and change in error) and output (duty ratio) generated by Asymmetrical Fuzzy Logic Control (AFLC) of the proposed Photovoltanic (PV) system.

4.2.3. Defuzzification

Defuzzification is used to convert the fuzzy inference output into crisp output which can be obtained through Eq. (8):

$$z_o = defuzzifier\ (x), \tag{8}$$

where x is the aggregate output and defuzzifier is the defuzzification operator.

Defuzzification can be done by using the center of area, the max criterion method, etc. In the present work, the center of the area defuzzifier operator is used and represented by Eq. (9):

$$x = \frac{\sum_{i=1}^{n} \mu\,(x_i)\, x_i}{\sum_{i=1}^{n} \mu x_i}, \tag{9}$$

where μx_i is the activation degree on rule 'i', x_i is the center of the Max-Min composition of the output membership functions, and x is the required output, i.e., duty ratio.

5. Simulation results and performance evaluation

The MATLAB/simulink environment is used to develop a stand-alone PV system and the proposed asymmetrical FLC-based MPPT algorithm is employed to track maximum available power under varying environmental conditions. The result of AFLC has been compared with those of P&O and FLC under three conditions: (i) STC, (ii) PSC, and (iii) dynamic conditions.

Moreover, the performance of the proposed algorithm has been evaluated and compared with respect to other algorithms on the basis of performance criteria viz. GMPP tracking and shading losses:

(i) *Maximum power*: The maximum power point is the point with maximum voltage and current. It can be determined by Eq. (10):

$$P_{MP} = V^{*}_{MP} I_{MP}. \tag{10}$$

(ii) *Shading losses*: In spite of technological advancement, the adverse effect of partial shading on the PV system results in power loss. The power loss due to shading is called shading loss. Shading loss is the difference in power between the maximum power obtained from an array under STC ($P_{MP,without\ shading}$) and the total maximum available power under PSCs ($P_{MP,\ shading}$) [33]. It can be represented by Eq. (11):

$$P_{MP,shading\ losses} = P_{MP,without\ shading} - P_{MP,\ shading}. \tag{11}$$

In the present study, all the three PV modules of the proposed system are connected in series and the maximum power obtained from this series arrangement is 1.08 kW. The modules are excited at different irradiation levels to give various shading patterns, as shown in Figure 9.

The following cases are considered:

Case 1: All the three PV modules (M1, M2, M3) are at STC, i.e., solar insolation at 1000 W/m^2 and temperature at 25°C. Case 1 is shown in Figure 9(a);

Case 2: PV module M1 is at 1000 W/m^2, M2 at 900 W/m^2, and M3 at 500 W/m^2. Case 2 is shown in Figure 9(b);

Case 3: PV module M1 is at 500 W/m^2, M2 at 400 W/m^2, and M3 at 700 W/m^2. Case 3 is shown in Figure 9(c);

Case 4: PV module M1 is at 450 W/m^2, M2 at 250 W/m^2, and M3 at 500 W/m^2. Case 4 is shown in Figure 9(d);

Case 5: PV module M1 is at 100 W/m^2, M2 at 100 W/m^2, and M3 at 200 W/m^2. Case 5 is shown in Figure 9(e).

Table 2. Power at Global Maximum Power Point (GMPP) and Local Maximum Power Point (LMPP) under various shading patterns.

	Case 1	Case 2	Case 3	Case 4	Case 5
P_{GMPP} (W)	1080	630	425	250	78
P_{LMPP} (W)	–	332; 555	227; 347	141; 198	55

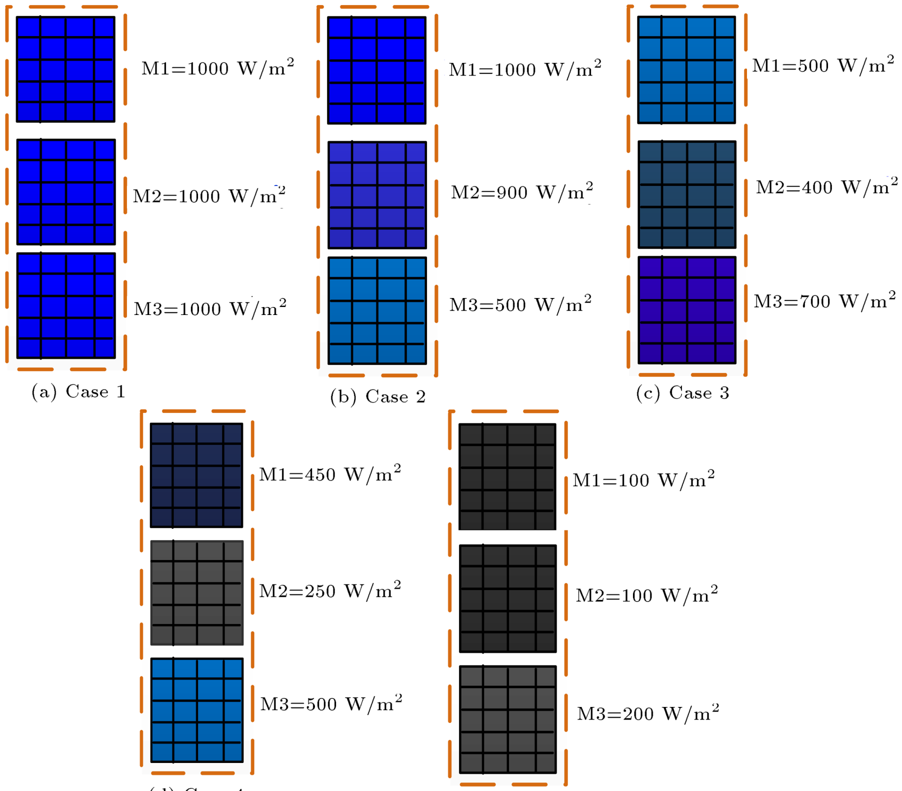


Figure 9. Shading patterns of Photovoltaic (PV) modules for the proposed system.

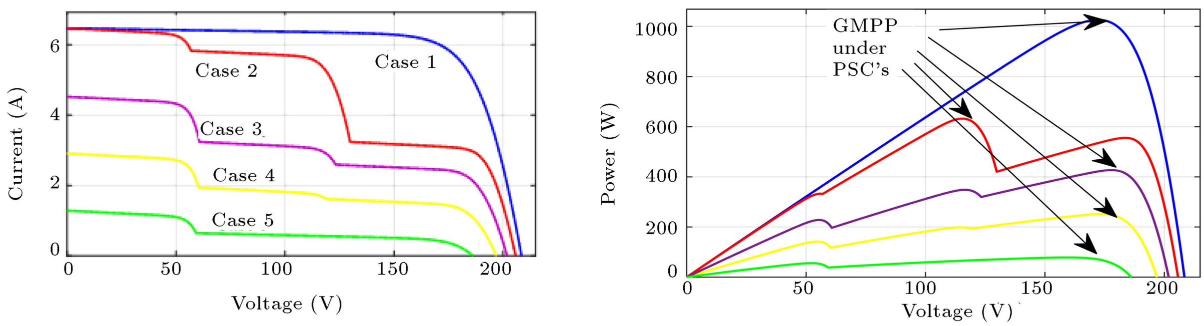


Figure 10. Simulated current vs. voltage and power vs. voltage curves for the different shading patterns of the proposed system.

Figure 10 shows the I-V and P-V characteristics of the proposed stand-alone PV system in different shading patterns considered. Table 2 gives the global and local maximum power rates in different shading patterns.

5.1. Steady-state response

Figure 11 compares the steady-state response of the proposed AFLC-based MPPT with those of P&O and FLC algorithms in different shading patterns. The results are tabulated in Table 3. Table 4 gives the corresponding shading losses.

Discussion of the considered cases are as follows:

Case 1: In this case, the highest maximum power is tracked by AFLC algorithm, which is 970.5 W, with

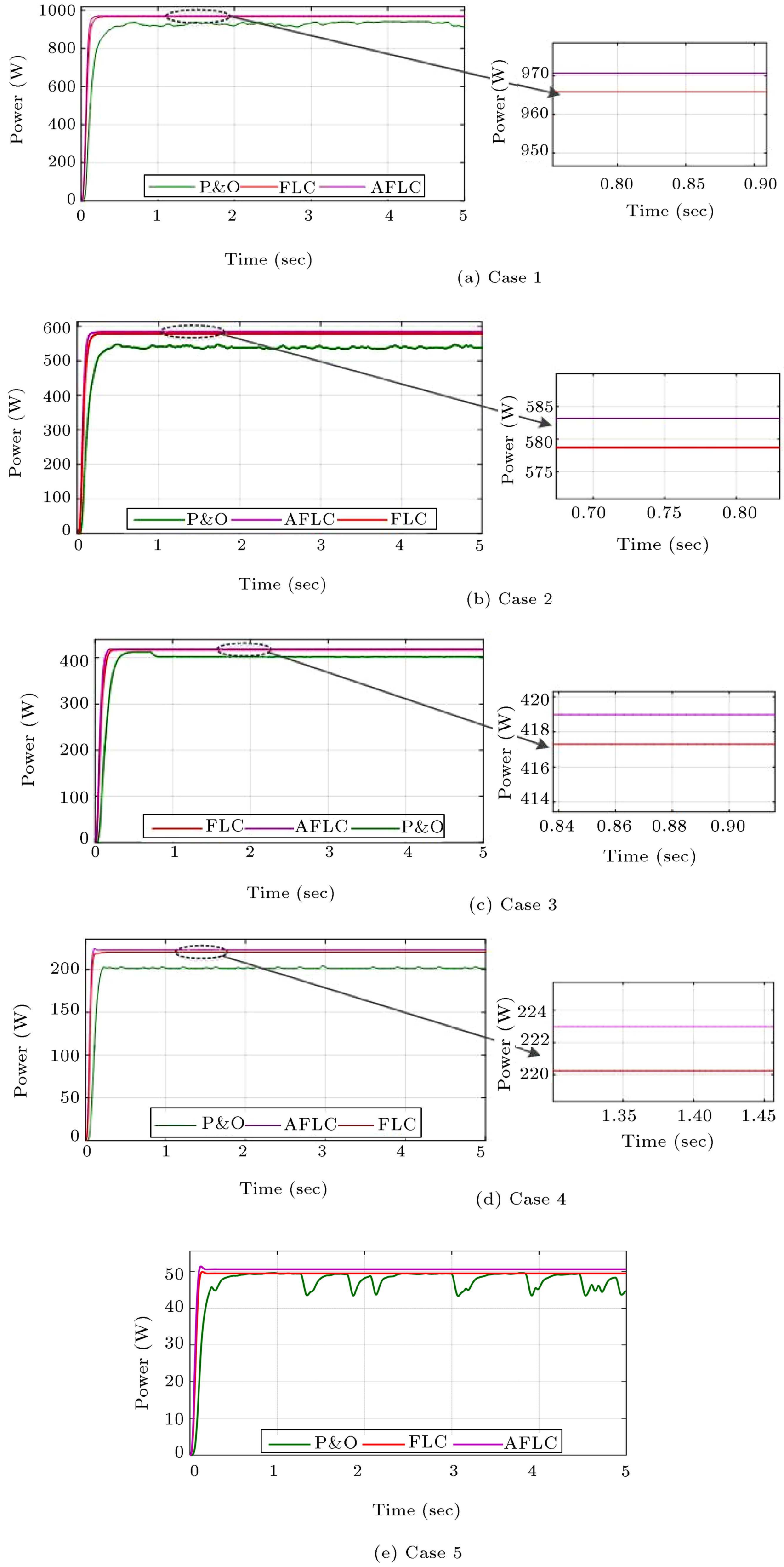


Figure 11. Simulated power vs. time plot of the three algorithms under the steady-state condition with different shading patterns.

Table 3. Steady-state response of various Maximum Power Point Tracking (MPPT) techniques under study.

MPPT techniques		Case 1	Case 2	Case 3	Case 4	Case 5
P&O	P_{MP} (W)	930	540	402	201	46
	V (V)	360	276	236.5	167	82.8
	I (A)	2.583	1.956	1.699	1.203	0.55
FLC	P_{MP} (W)	965.4	578.5	417.5	220.5	49.5
	V (V)	360	279.4	205	161.5	81.06
	I (A)	2.681	2.070	2.036	1.362	0.61
AFLC	P_{MP} (W)	**970.5**	**583.5**	**419**	**223**	**50.5**
	V (V)	360	280.8	204	172.5	80.25
	I (A)	2.695	2.080	2.053	1.380	0.62

Table 4. Shading loss (W) in various Maximum Power Point Tracking (MPPT) techniques under study.

MPPT techniques	Case 1	Case 2	Case 3	Case 4	Case 5
P&O	150	540	678	879	1034
FLC	114.6	501.5	662.5	859.5	1030.5
AFLC	**109.5**	**496.5**	**661**	**857**	**1029.5**

no fluctuations around GMPP. The shading losses are the lowest viz. 109.5 W. FLC tracks 965.4 W, while conventional P&O MPPT algorithm tracks only 930 W power, i.e., the lowest power and shading losses are the highest at 150 W;

Case 2: In this case, the proposed AFLC-based MPPT algorithm tracks the maximum power of 583.5 W and the shading losses of 496.5 W are least among the values obtained by other MPPT approaches. Moreover, in this case, the AFLC MPPT algorithm tracks power more accurately than other approaches;

Case 3: In this case, the highest maximum power is tracked by AFLC algorithm which is 419 W, with no fluctuations around GMPP. The shading losses are the lowest viz. 661 W. FLC tracks 417.5 W and Conventional P&O MPPT algorithm tracks 402 W power, i.e., the lowest power tracked and shading losses are also the highest at 678 W;

Case 4: In this case, the highest maximum power is tracked by AFLC algorithm which is 223 W, with no fluctuations around GMPP. The shading losses are also lowest viz. 857 W. FLC tracks 220.5 W and the conventional P&O MPPT algorithm tracks 201 W power, i.e., the lowest power tracked in this case and shading loss is high which is 879 W;

Case 5: In this case, the highest maximum power is tracked by AFLC algorithm which is 50.5 W, with no fluctuations around GMPP. The shading losses are also the lowest viz. 1029.5 W. FLC tracks 49.5 W and conventional P&O MPPT algorithm tracks 46 W power, i.e., the lowest power tracked with large perturbations. Shading losses are the highest at 1034 W.

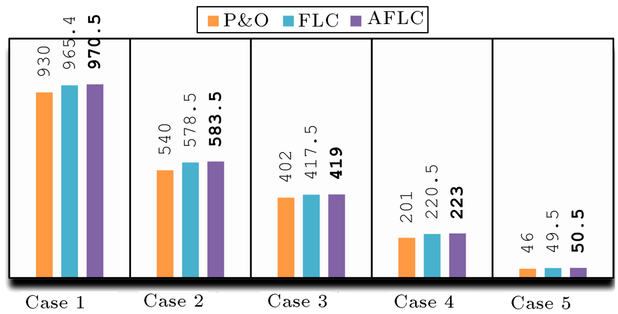


Figure 12. Comparative analysis of tracked power on the bar chart.

According to Tables 3 and 4, the power tracked is maximum and shading losses are minimum in the proposed asymmetrical FLC. In addition, according to Figure 11, it can be seen that P&O algorithm has large perturbations in the output. Figures 12 and 13 show the comparative analysis of tracked powers and shading losses on the bar chart, respectively.

5.2. Transient response

The proposed asymmetrical FLC-based MPPT has

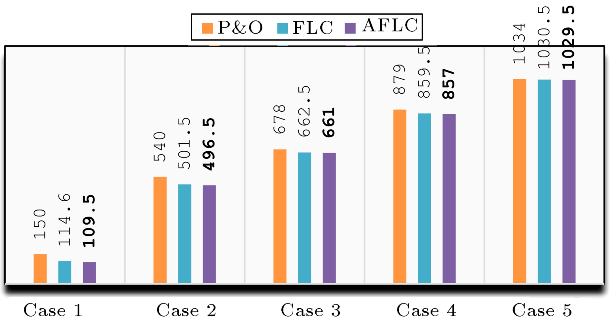


Figure 13. Comparative analysis of shading loss on the bar chart.

Table 5. Shading patterns of Photovoltaice (PV) Modules for transient response.

Shading pattern	Irradiation level (kW/m^2)	Time (sec)
SP1	$[M1: 0.9,\ M2: 0.7,\ M3: 0.6]$	$0-2.5$
SP2	$[M1: 0.5,\ M2: 0.8,\ M3: 0.3]$	$2.5-5$
SP3	$[M1: 0.6,\ M2: 0.3,\ M3: 0.1]$	$5-7$

been evaluated in transient conditions. The change in the insolation level for each PV module in a given time duration is shown in Table 5. Figure 14 shows the comparative analysis of the asymmetrical FLC-based MPPT algorithm and other approaches in transient conditions. Tables 6 and 7 show the results and the corresponding shading losses, respectively.

According to Tables 6 and 7, the power tracked is maximum and shading losses are minimum in the proposed asymmetrical FLC-based algorithm. In addition, the settling time of the proposed asymmetrical FLC is the shortest in all conditions, while P&O takes the longest settling time.

6. Conclusion

This paper proposed an intelligent asymmetrical Fuzzy Logic Control (FLC)-based Maximum Power Point Tracking (MPPT) algorithm for the stand-alone Photovoltanic (PV) system in partial shading conditions. To establish the superiority of the proposed algorithm, it was compared with other conventional and intelligent techniques viz. Petrob and Observe (P&O) and FLC. The proposed asymmetrical FLC algorithm was designed, developed, and validated to track the global maximum power under various shading scenarios including steady and dynamic states. Simulation results demonstrated that the asymmetrical FLC could effectively track the global maximum power point under various test conditions. Moreover, compared to other algorithms, the proposed asymmetrical FLC-based MPPT algorithm had less shading losses and took the shortest settling time to perform. The implementation of the asymmetrical FLC-based MPPT algorithm improved the overall steady state and dynamic behavior of the PV system under consideration. Therefore, there was low wastage of environment-friendly solar power. Furthermore, these studies should be useful to system designers.

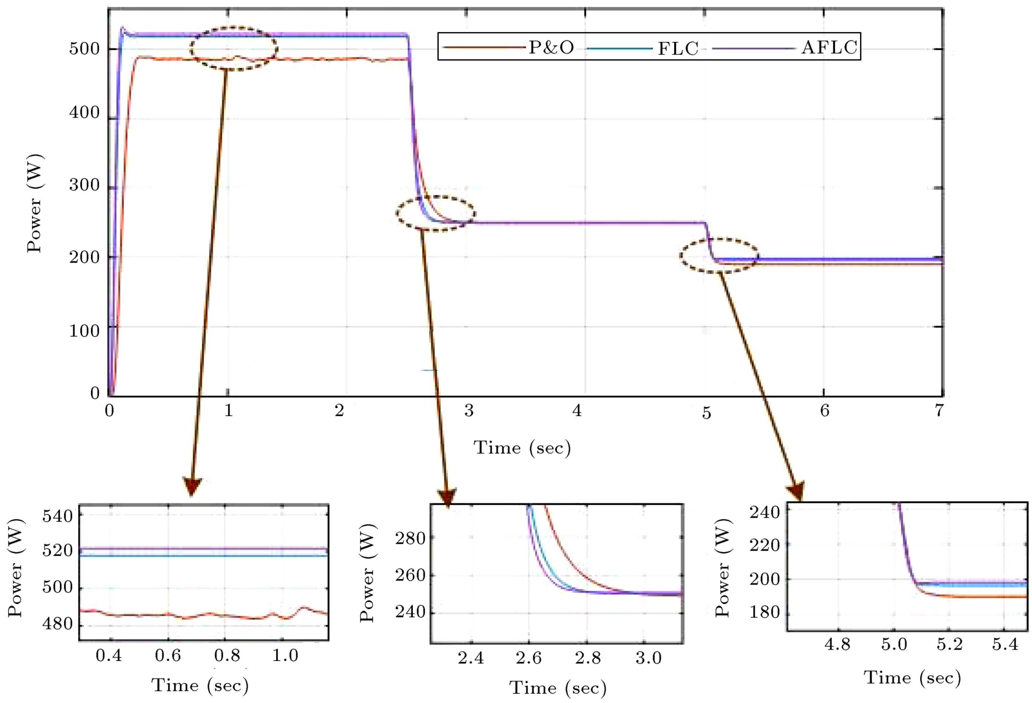


Figure 14. Simulated power vs. time plot of the three algorithms under transient conditions.

Table 6. Transient response of various Maximum Power Point Tracking (MPPT) techniques under study.

MPPT techniques	0–2.5 (sec)		2.5–5 (sec)		5–7 (sec)	
	Power (W)	Settling time (sec)	Power (W)	Settling time (sec)	Power (W)	Settling time (sec)
P&O	486	0.26	249	0.6	190	0.2
FLC	517.5	0.19	250.1	0.3	196.5	0.1
AFLC	**521.5**	0.19	**250.6**	0.3	**198.1**	0.1

Table 7. Shading loss (W) in various Maximum Power Point Tracking (MPPT) techniques under study.

MPPT techniques	0–2.5 (sec)	2.5–5 (sec)	5–7 (sec)
	Shading loss (W)	Shading loss (W)	Shading loss (W)
P&O	594	831	890
FLC	562.5	829.9	883.5
AFLC	**558.5**	**829.4**	**881.9**

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