PSO based MPPT for Partially PV Arrays

P. Sudheer

Abstract: ***Traditional MPPT algorithms such as P&O, Incremental conductance, Hill climbing are fail to track MPP (Maximum Power Point) when partial shading occurs for that purpose here introduce a new technique this is a combination of one traditional MPPT technique and one artificial intelligent is used this is called a hybrid MPPT it is a combination of P&O (Perturb & observe) with Particle Swarm Optimization (PSO) consequently, the conventional MPPT searches for the MPP in the estimated region. The proposed technique is modelled and simulated by using MATLAB R2011a/Simulink the results are compared with ANN based MPPT and PSO based MPPT for PV arrays under different shading patterns.***

Keywords: MPPT, Partial Shading Conditions (PSC), Perturband Observe, PV array, PSO

1. Introduction

Day by the usage of the usage of electricity greatly improves there are so many electrical energy resources are available these are non-renewable and renewable energy resources among these renewable energy resources are widely used all renewable energy resources are best way to generate electricity because these are reusable. So many renewable energy resources are available among all solar based PV arrays are mostly used. The PV array outputs are depends on the ambient temperature of the PV cell, solar irradiance on PV cell. The PV cell characteristics are usually described by using IV and PV curve. By multiplying the output current and voltage from IV curve, the output power can be calculated. There is an operating point where the output power is maximized, this point is called Maximum Power Point (MPP).Due to limited efficiency of the PV cell, and PV systems are always required to operate close to the MPP in order to gain the maximum energy. However the performances of PV cells can easily be affected by environmental conditions. The short circuit current depends on the solar irradiance level while the open circuit voltage shows a strong dependence of the cell temperature. As a consequence, the operating point which satisfies the MPP condition also varies with the environmental conditions. Thus it is essential to have a MPPT mechanism, which is a control algorithm that can track the MPP continuously during the operation in order to maximize the power production of the PV system [1], [2], [3], [4], [5], [6], [7] and [8].

PV cells are the combination of current source parallel with diode

Why its combination?

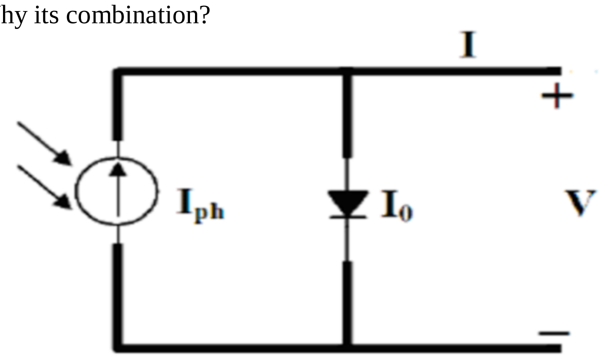


Figure 1: PV cell equivalent circuit diagram

Generally solar panels are PV cells which are made of semiconducting materials like silicon.

Whenever these cells are exposed to sunlight carriers in semi conducting materials are energised and result in flow of charge i.e. Current so solar cells are represented as current source.

Since this currents is flowing in panel made of semiconducting materials a diode is placed in parallel with current source.

PV modules are the combinations of PV cells are connected in series or parallel.

PV Arrays are the combinations of PV modules are connected in series or parallel.

If some of these cells are shaded due to passing out of clouds or adjacent trees or structure as shown in Fig.2 the shading pattern at some of the cellsthe unshaded cells produce more power compare to shaded cells this excess amount of power from unshaded cells it creates heat it will damages the PV cell partial shading condition. The characteristics also changes it will create many peaks. These are shown in Fig.3

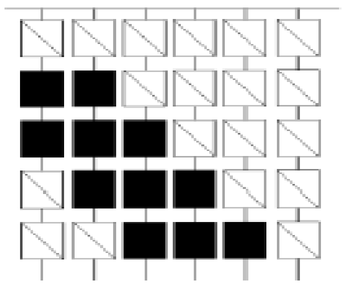


Figure 2: Photovoltaic arrays under different partial shading condition

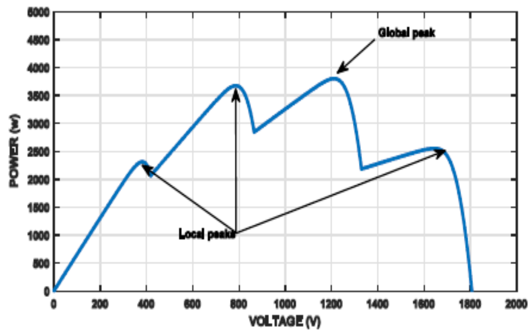


Figure 3: PV Array characteristics for different PSCs

All conventional MPPT fail to seek the global peak under PSCs [9], and [10]. Kobayashi *et al*. [11] have proposed a two stage method to track the GMP. In the first stage, the operating point of the PV system moves into the vicinity of the GMP by estimating the equivalent load line. Then the INC method is employed to converge to the MPP in the second stage. First stage is estimate under uniform insulation condition, some PSCs may cause an LMP to be tracked in second stage. A Fibonacci Search (FS) method was proposed [12]. However, as this is a linear search method, a GMP still cannot be guaranteed. The DIRECT (dividing rectangles) algorithm [13] Miyatake *et al*.[14] Have realized centralized MPPT control of PV modular PV systems, and used Particle Swarm Optimization(PSO) to determine the individual module voltage. Lian lian jiang *et al.* employed the artificial neural network (ANN) technique [15].

PSO based MPPT (P &O) initially the P&O method is employed to identify the nearest local maximum. Starting from that point, the PSO method for the GMP. The advantage of this combination is to reduce the search space of the PSO is reduced and the time required for convergence can be greatly decreased.

The paper is organized as follows:
Section II: - Mathematical modelling of PV cell
Section III: - Partial Shaded PV arrays
Section IV: - PSO based MPPT
Section V: - Simulation Results
Section VI: -Comparison Study of the PSO based MPPT and ANN based MPPT.
Section VII: -Conclusion

2. Mathematical Modelling of PV Array

A PV cell can be represented by the circuit shown in Fig.4. The PV array current for a number of cells connected in series and/or parallel combination with each other is given by [16].

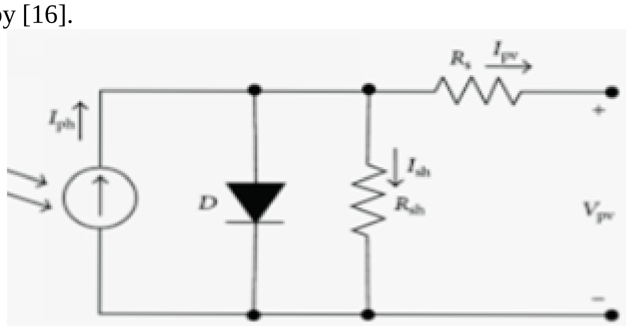


Figure 4: Equivalent circuit of the photovoltaic cell

$$I = I_{Photon} - I_d - I_{R_{sh}} \text{------------------------ (i)}$$

$$I_{photon} = I_{PV} N_p \text{---------------------------- (ii)}$$

$$I_d = I_0 N_p \left(e^{\frac{V + R_S\left(\frac{N_S}{N_P}\right) I}{V_t a N_S}} \right) \text{-------------------- (iii)}$$

$$I_{R_{sh}} = \frac{V + R_S\left(\frac{N_S}{N_P}\right) I}{R_P\left(\frac{N_S}{N_P}\right)} \text{--------------------------(iv)}$$

$$I = I_{PV} N_P - I_0 N_P \left(e^{\frac{V + R_S\left\{\frac{N_S}{N_P}\right\} I}{V_t a N_S}} \right) - \left[\frac{V + R_S\left\{\frac{N_S}{N_P}\right\} I}{R_P\left\{\frac{N_S}{N_P}\right\}} \right] \text{------ (v)}$$

Where
I_{PV}=current of pv array
I_0=saturation current of the diode
a=ideal factor of the diode
$R_{P\,(Sh)}$=shunt resistance(parallel resistance)
R_S=series resistance
N_P=No of parallel cells
N_S=No of series cells
V_t= thermal voltage
$V_t = \frac{N_S K T}{q}$
Where
q=electron charge =1.6×10^{-19} c
k=Boltzmann constant=$1.38\times10^{-23} j/k$
T=temperature of the PN junction in kelvin

$$I_{PV} = (I_{PV.n} + K_I)\frac{G}{G_n} \text{------------------------------ (vi)}$$

Where:
$I_{PV.n}$: Nominal condition PV current (1000w/m^2 and 25^{0}C)
G: irradiance at the panel surface,
G_n: Irradiance under nominal conditions,
K_I=cells short circuit current temperature coefficient,

$$\Delta T = T - T_n \text{-- (vii)}$$

Where: T: actual temperature
T_n: nominal temparature

$$I_0 : I_{0.n} \left(\frac{T_n}{T}\right)^3 e^{\left(\frac{qE_g}{ak}\left[\frac{1}{T_n} - \frac{1}{T}\right]\right)} \text{------------------ (viii)}$$

Where:
I_0: Diode saturation current,
$I_{0.n}$: Nominal reverse saturation current,
E_g: Band gap energy of the semiconductor (E_g at 25^{0}C=1.12Ev for polycrystalline Si)
Nominal reverse saturation current,

$$I_{0.n} = \frac{I_{sc.n}}{e^{\left(\frac{V_{ocn}}{aV_{tn}}\right)} - 1} \text{--------------------------------- (ix)}$$

Where:
$I_{0.n}$: Short circuit current under nominal conditions
V_{ocn}: Open circuit voltage under nominal conditions
V_{tn}: Array thermal voltage at the nominal temperatureT_n

The equations from (i) to (iX) are modelled and simulated by using MATLAB R2011a/Simulink. Based on that equations model simulate under different partial shading by connecting multiple PV arrays in series to track MPP obtaining by PV characteristics and steady state and dynamic response gives the results.

3. Partial Shaded PV Arrays

Partial shading occurs due to the clouds passing, trees shadow and bird waste likewise so many reasons some cells are under this condition means shaded cells and remaining are unshaded cells these are shown in fig.2.

In that situation unshaded cells produce excess amount energy this energy to heat this called hotspots in PV string.

By this hotspots will be created due to short circuit occurs at string the shaded cell will become reverse biased. All the forward biased voltages of unshaded cell will appear across the shaded cell this reverse bias could be very strong depending on the amount of partial (or) complete shadowing of the cell and the no. of cells in the series.

To avoid the destructive effect of hotspot (or) partial shading in series connected cells one device is used i.e bypass diode. This connects in parallel with solar cells with opposite polarity to that of a solar cell. Thus in normal condition, the bypass diode is operated in reverse bias connection, effectively open circuited. But if a series connected cell is shaded, reverse bias will act as forward bias for the bypass diode since it is connected with opposite polarity. The extra current generated by the non-shaded cells will be bypasses through the bypass diode, avoiding power dissipation in shaded cell and hence heat generated.fig.5.

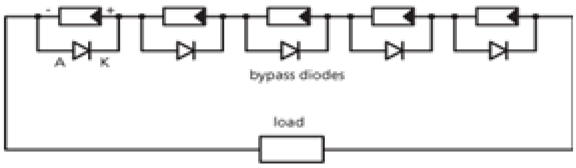


Figure 5: Bypass diode in parallel with PV cell

4. PSO based MPPT

Particle Swarm Optimization (PSO)
Particle: A particle is a small localized object can be several physical (or) chemical properties such as volume (or) mass.
Swarm: Collection of something that move somewhere in large numbers flock, crowd, flood.
Optimization: The action of making the best (or) most effective use of a situation (or) resource.

Flow chart of PSO

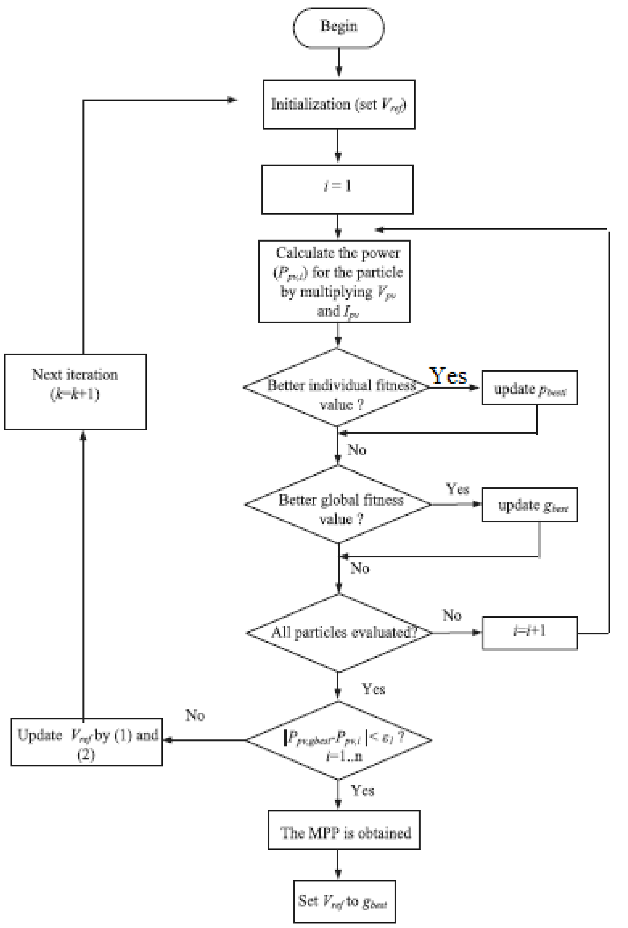


Figure 6: Flow chrt for the PSO

PSO Algorithm can be expressed mathematically by two equatiobns which specify the velocity and position update of a particle i.

$$V_i^{t+1} = WV_i^t + C_1 r_1 (P_{besti}^t - X_i^t) + C_2 r_2 (G_{besti}^t - X_i^t) \quad (1)$$

$$X_i^{t+1} = X_i^t + V_i^{t+1} \quad (2)$$

Where
V_i^{t+1}:-velocity of iteration of individual ‘i’ at iteration‘t+1’
V_i^t : - velocity of iteration of individual ‘i’ at iteration ‘t’
W: - Inertia weight

It is employed to control the effect of the previous velocities on the current velocity

$$W = W_{max} - \left(\frac{W_{max} - W_{min}}{iter_{max}}\right) iter$$

C_1: - Cognitive parameter
C_2: - Social parameter

The C_1, C_2 are accelerating constants represent the weighting of the acceleration term that pulls each particle towards P_{best}, G_{best} positions. By trial and error it is found that acceleration constants equal to 2 gives good results but it is not a usual value.
P_{best} :- Personal best position associated with the particle ‘i’ .
G_{best} :-Single best position in a swarm is called the global best
Based on above two equations entire PSO algorithm and programme is designed from these two equations
PSO algorithm

Step 1 Initialize
Initialize a population of particles with random position and velocities in problem space, confine the search space by specifying the lower and upper limits of each decision variable. The populations of points are initialized with the velocity and position set to fall into the allowed range and satisfying the equality and inequality constraints.

Step 2 Velocity Updating
At each iteration the velocities of all particles are updated according to the equation of

$$V_i^{t+1} = WV_i^t + C_1 r_1 (P_{besti}^t - X_i^t) + C_2 r_2 (G_{besti}^t - X_i^t)$$

The first part of the equation i.e $[WV_i^t]$is the momentum part of the particle. The inertia weight ‘W’ represents the degree of the momentum of particles.

The second part of the equation i.e$[C_1 r_1 (P_{besti}^t - X_i^t)]$ is the cognition part which represents the independent thinking of the particle itself.

The third part of the equation i.e. $[C_2 r_2 (G_{besti}^t - X_i^t)]$ is the social part which represents the collaboration among the particles.

Step 3 Position Updating
Between successive iterations the position of all particles are updated according to the equation.

$$X_i^{t+1} = X_i^t + V_i^{t+1}$$

Check all the imposed constraints to ensure the feasibility of all the potential solutions.

$$X_i^{t+1} = \begin{cases} X_i^t + V_i^{t+1} & \text{if} \quad X_i^{min} \leq X_i^t + V_i^{t+1} \leq X_i^{max} \\ X_i^{min} & \text{if} \quad X_i^t + V_i^{t+1} < X_i^{min} \end{cases}$$

X_i^{max} if $X_i^t + V_i^{t+1} > X_i^{max}$

Step 4 Memory Upadating

$P_{besti}^{t+1} \longleftarrow X_i^{t+1}$ if $f(X_i^{t+1}) < f(P_{besti}^{t+1})$

$G_{besti}^{t+1} \longleftarrow X_i^{t+1}$ if $f(X_i^{t+1}) < f(G_{besti}^{t+1})$

Where f(X) is the objective function to be minimized compare particles fitness evaluation for $P_{besti}^{t+1}, G_{besti}^{t+1}$.

Step 5 Termination Criteria Examination

The algorithm repeats from step (2) to step (4) until sufficient good fitness (or) a maximum number of iterations are reached. Once terminated the algorithm outputs the points of $P_{besti}^{t+1}, G_{besti}^{t+1}$ as it solution.

PSO based MPPT flow chart

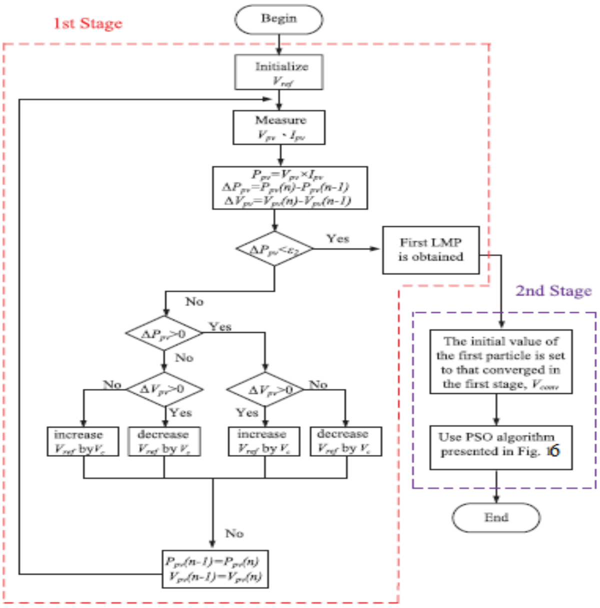


Figure 7: Flowchart for the PSO based MPPT (P&O)

Fig.7 illustrates the PSO based MPPT algorithm as a flowchart. The method consists of two stages.

In first stage the P&O method is employed to quickly search for the first local maximum. The operating voltage is perturbed by small amount (Vc) [17],[18] every control cycle to determine whether the algorithm is traveling up or down in the P-V curve. Note that convergence criterion needs to be introduced in the first stage of the proposed system to locate the first LMP and to pass it to the second stage.

In the second stage the PSO is activated to search for the GMP. The initial condition for the first particle is set to the converged value from the first stage Vconv. The initial conditions of the other particles are set to value ranging from Vconv to the upper bound of the search space. Because the number of particles remains the same but the search space is smaller, the hybrid method is expected to find the GMP in a shorter time than that taken by PSO method alone.

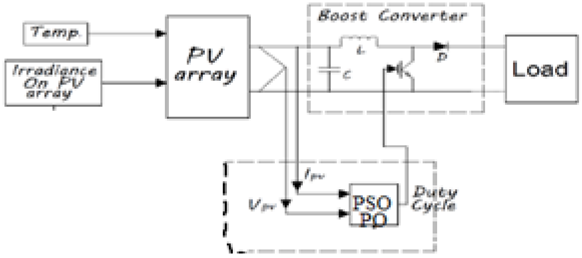


Figure 8: Schematic diagram of the PV system using PSOPO

Table1 lists the parameters of the PV module employed in each array. To emulate the effect of partial shading, the irradiances of the four PV arrays are set to different values. The mathematical model described in section II is modelled using MATLAB/Simulink (R2011a), and it is utilized to obtain the characteristics of the four series PV arrays under PSC.

Table 1: Photo Voltaic (PV) Panel Parameter

Parameter	Value
Maximum power	200W
Number of cells in each module	54
Open circuit voltage(V_{oc})	32.9V
Optimum voltage(V_{mp})	26.3V
Short circuit current(I_{sc})	8.21A
Optimum voltage(I_{mp})	7.61
Temp. coefficient of I_{sc} (K_I)	0.00318A/^{0}C
Temp. coefficient of V_{oc} (K_V)	-0.123V/^{0}C
Parallel resistance	601.3368 ohm
Series resistance	0.23 ohm

Fig.9 shows that there are four possible regions for the MPP voltage, as the PV string utilized in this consists of four PV arrays. The main idea of this MPPT technique is to identify the global MPP region. Consequently, one of the conventional MPPT methods such as P&O is utilized in this region to obtain the Local Maximum Power Point (LMP). To obtain the GMP (Global Maximum Power Point) the PSO technique is employed to recognize the region owing the global peak. In addition with the P&O technique is utilized to allocate the optimal operating voltage inside the recognized region by controlling the duty cycle of the boost converter, as shown in Fig.8.

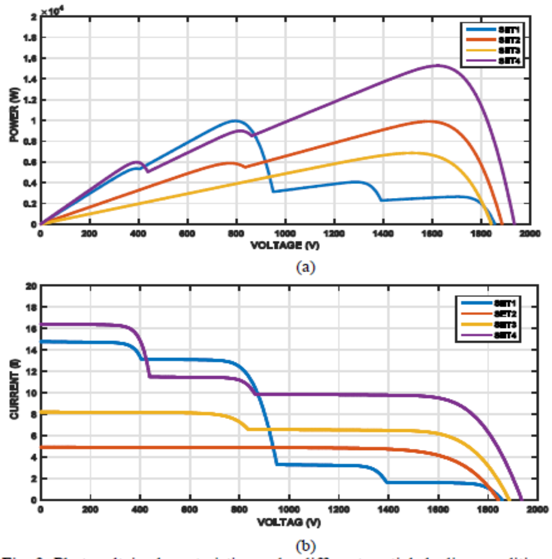


Fig. 9. Photovoltaic characteristics under different partial shading conditions (a) power–voltage curve; (b) current–voltage curve.

5. Simulation Results

PSO based MPPT technique is verified by various simulations under different partial shading patterns using MATLAB/Simulink (R2011a). In this three different shading patterns (SP1, SP2, and SP3) are considered for PV array under partial shading, while one SP under uniform irradiance (SP4) is considered, as listed in table. the case of uniform irradiance single peak , which leads to a simple detection for the MPP by directly utilizing any conventional method .however, in the other three cases of partial shading, there is a challenge in defining the global peak, as the PV curve changes from a single peak to multiple peaks.

Table 2: Shading Patterns (SPS) for Test Scenarios

Shading Parameter No	Irradiance on the Array in W/m^2			
	A_1	A_2	A_3	A_4
SP1	200	400	600	1000
SP2	400	500	800	800
SP3	600	600	1000	1000
SP4	1000	1000	1000	1000

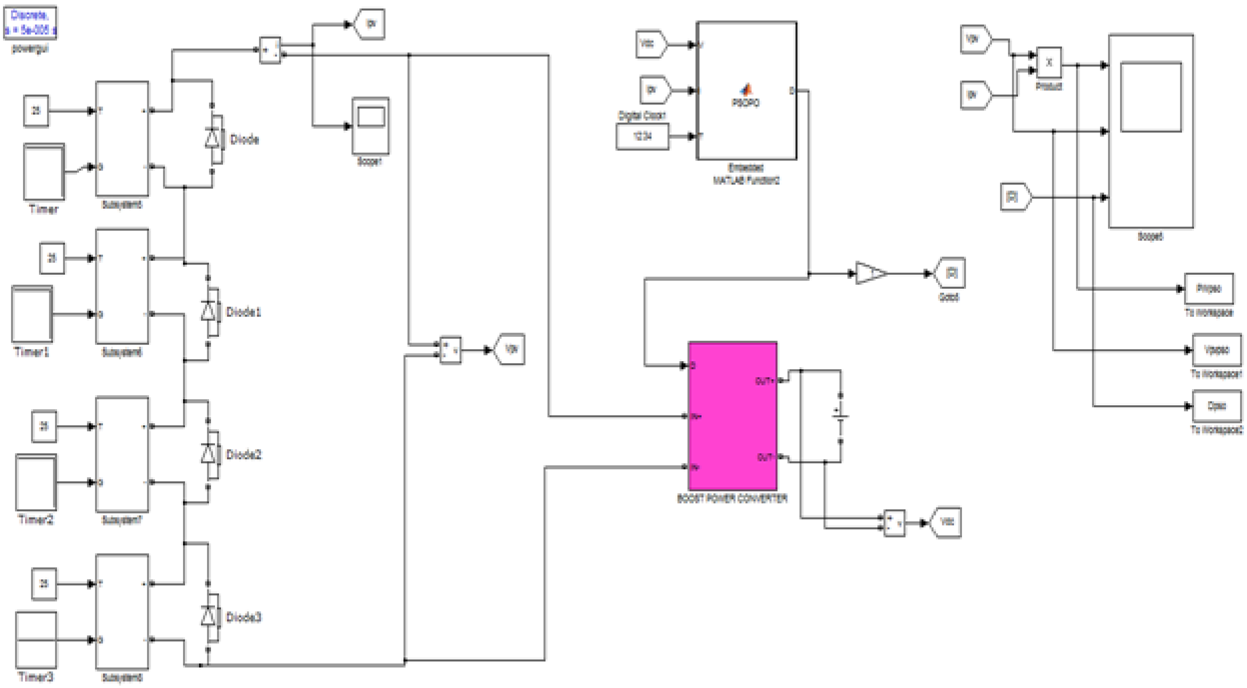


Figure 10: MATLAB/simulink model

To verify the proposed technique the system shown in fig.8 was modelled and simulated under different SPs. Each PV array consists of two parallel strings, each of which comprised 15 series modules. Therefore, the maximum power of each array at nominal conditions (25^{0}C and 1000W/m^2) was 6125W (6.125KW). Fig.10 displays the MATLAB/Simulink (R2011a) model for the system Fig.10.

First simulation was run to obtain the PV characteristics for the four SPs described in Table2. Fig.11. illustrates the PV characteristics under SP1 and SP4. Fig.12. illustrates the PV characteristics under SP2, SP3 and SP4.

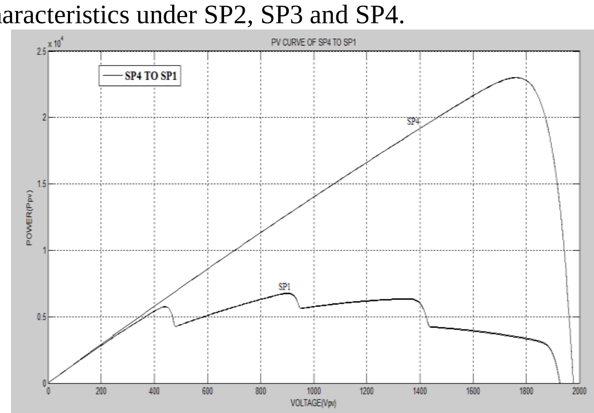


Figure 11: PV Characteristics under shading patterns SP4 to SP1

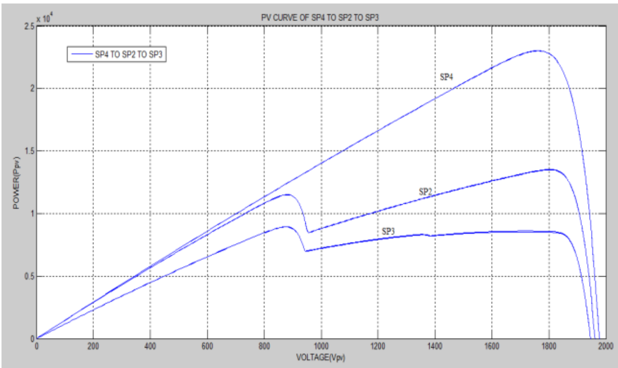


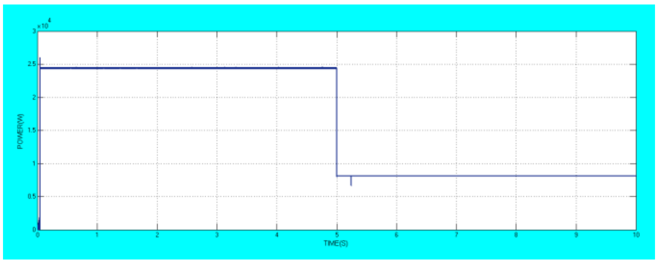
Figure 12: PV Characteristics under shading pattern SP2 to SP3 to SP4

Second the simulation was to obtain the Steady state and Dynamic behaviour of the system Fig.13. Illustrates for the changes of irradiances shading patterns from SP4 to SP1.

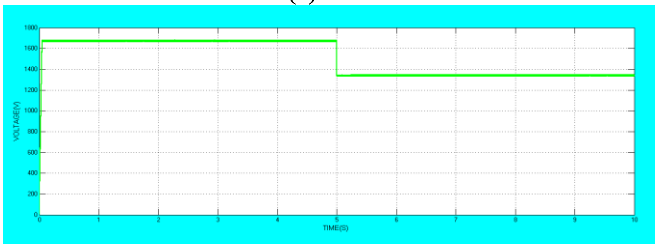
These are observed by the MPPT techniques

Shading Patterns	Power(W)	Volatge (V)	Duty Cycle
SP4 to SP1 (at t=0s to t=5s)	24500 to 8200	1665 to 1350	0.232 to 0.392

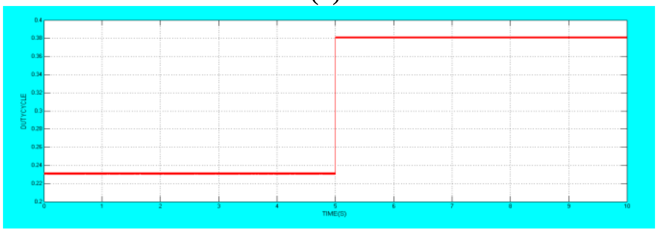
The PV characteristics of this SP 4 to SP1 is shown in fig.11.



(a)



(b)



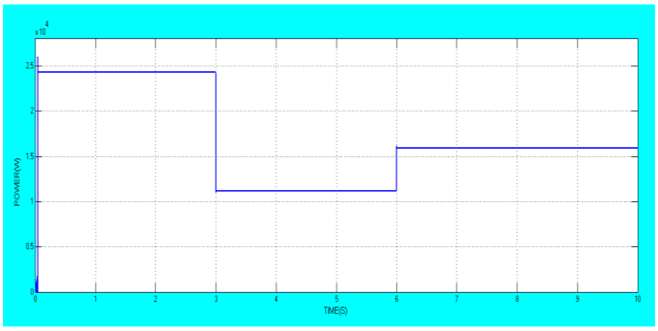
(c)

Figure 13: The simulation results of the changes from SP4 to SP1 ((a) power vs time, (b) voltage vs time, and (c) duty cycle vs time)

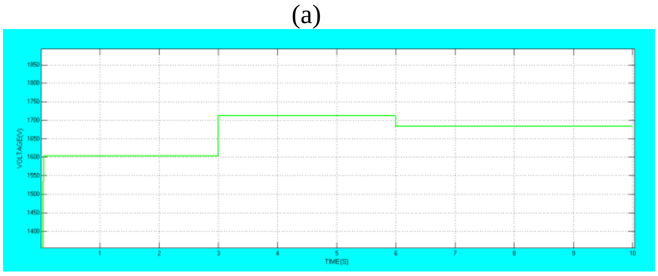
Another test scenario is considered in Fig 15 where the SPs was changed from SP4 to SP2 at t=3s and from SP2toSP3 at t=6S

Table 4: Shading patterns change from SP4 to SP2 to SP3

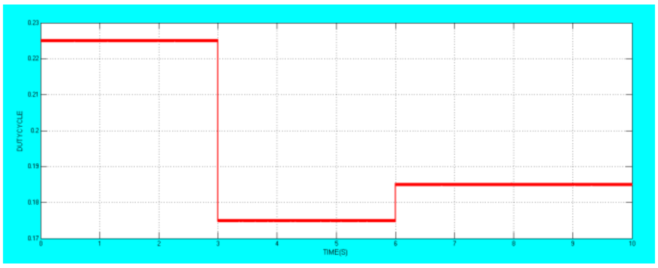
Shading Patterns	Power(W)	Voltage(V)	Duty Cycle
SP4 to SP2(at t=o to t=3s)	24500 to 11168	1602 to 1712	0.232 to 0.1752
SP2 to SP3(at t= 3s to t=6s)	11168 to 15891	1712 to 1683	0.1753 to 0.1853



(a)



(b)



(c)

Figure 14: The simulation results of the changes from SP4 to SP2 to SP3((a) power vs time, (b) voltage vs time, and (c) duty cycle vs time)

The PV characteristics for SP4 to SP2 to SP1 is shown in Fig.12.

$$D=1-\frac{V_i}{V_o} \qquad \text{--------------------- (X)}$$

Moreover the PSO based MPPT technique is succeeded in instantaneously controlling the duty ratio of the boost converter. As expected, the duty ratio was inversely proportional to the terminal voltage of the PV array.

Comparison Study of the PSO based MPPT and ANN based MPPT

In order to clarify the performance improvement of the PSO based MPPT technique, a comparative study between it and the ANN based MPPT technique which presents in [1] is carried out in this section. Consider two shading patterns (SP5 and SP6) as listed in TABLE 5.

Table 5: Shading patterns for test scenarios

Shading Parameter No	Irradiance on the Array in W/m^2			
	A1	A2	A3	A4
SP5	120	240	600	700
SP6	220	460	680	1000

The same Simulink model is described in this test scenarios but here change the shading patterns in different ways to compare ANN based MPPT and PSO based MPPT here ANN based MPPT is previous technique PSO based MPPT is newest technique here also compare with only ANN.

Knowing the optimum voltage leads to predict the desired duty cycle of the boost converter. The PV track during change of irradiance from SP5 to SP6.

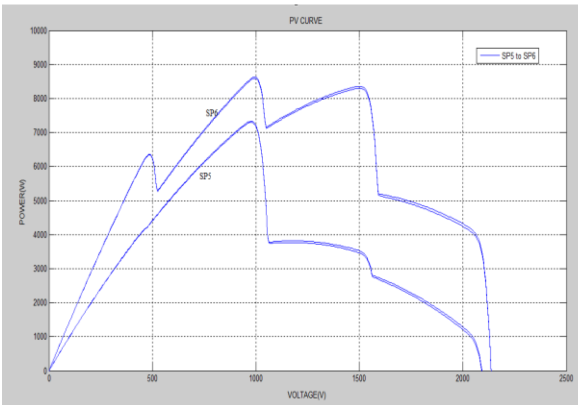
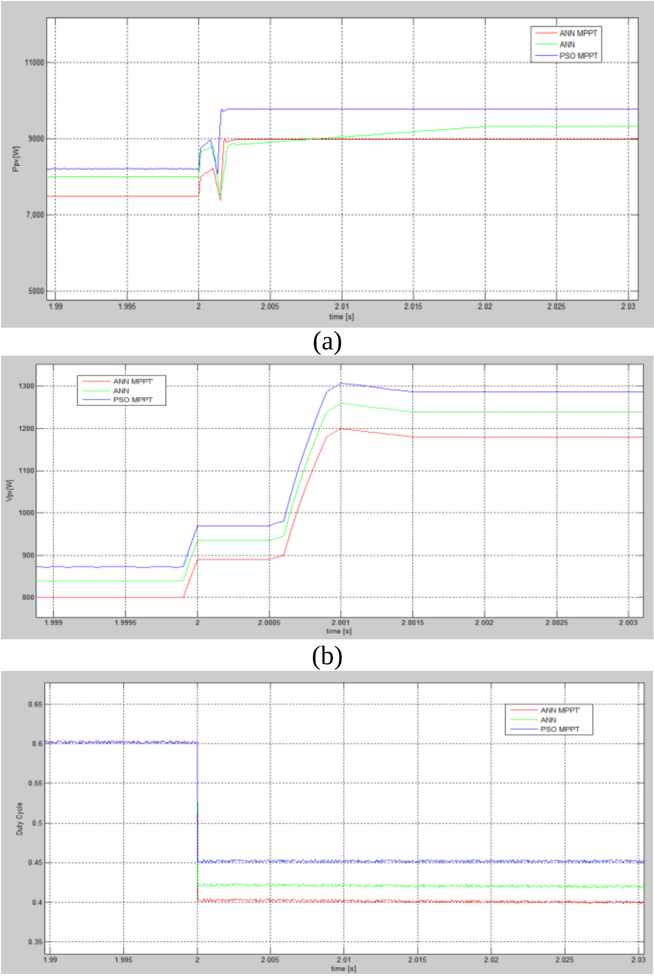


Figure 15: PV characteristics under shading patterns SP5 to SP6



(a)

(b)

(c)

Figure 15: Simulation results when changing from SP5 to SP6 considering the ANN, ANN based MPPT and PSO based MPPT techniques (a) output power of PV arrays (b) terminal voltage of the PV array (c) duty cycle of the boost converter.

6. Conclusions

Traditional MPPT algorithms such as Perturbed and observed, Incremental Conductance, Hill climbing so many Traditional MPPTs are not succeeded while tracking MPP under different Partial Shading Conditions (PSCs) they are track instead of MPP, LMP is tracked to track MPP here additionally combined With traditional MPPT to other swarm (or) artificial intelligent is used to obtain the MPP. Here PSO based MPPT is used to track global MPP here MPPT (i.e. P & O) technique is firstly track the LMP is the first stage for the next stage it is PSO is activated and get the MPP. That's why it is simple and give more accurate MPP when compare to others for different partial shading conditions (PSCs) these are observed by simulation (MATLAB Simulink) steady state and dynamic, compare this PSO based MPPT with ANN based MPPT and ANN and observed that PSO based MPPT is better performance.

References

[1] Hadi M. El-Helw, Ahmed Magdy, Mostafa I. Marei A Hybrid Maximum Power Point Tracking Technique for Partially Shaded Photovoltaic Arrays.

[2] Y. H. Ji, D. Y. Jung, C. Y. Won, B. K. Lee, and J. W. Kim. (2009, Sept). Maximum power point tracking method for PV array under partially shaded condition. IEEE Energy Conversion Congress and Exposition.

[3] L. L. Jiang, D. R. Nayanasiri, D. L. Maskell; and D. M. Vilathgamuwa. "A hybrid maximum power point tracking for partially shaded photovoltaic systems in the tropics," Renewable Energy, vol. 76, pp. 53-65, Apr. 2015.

[4] L. M. Elobaid, A. K. Abdelsalam, E. E. Zakzouk. (2012, Oct.). Artificial neural network based maximum power point tracking technique for PV systems38th Annual Conference on IEEE Industrial Electronics Society.

[5] F. Chekired, C. Larbes, and A. Mellit. "Comparative study between two intelligent MPPT-controllers implemented on FPGA: application for photovoltaic systems," International Journal of Sustainable Energy, vol. 33, pp. 483-499, Dec. 2012.

[6] H. M. El-Helw, M. Al-Hasheem, and M. I. Marei. "Control strategies for the DAB based PV interface system," PLoS ONE, vol. 11, Aug. 2016.

[7] N. Patcharaprakiti, S. Premrudeepreechacharn, and Y. Sriuthaisiriwong. "Maximum power point tracking using adaptive fuzzy logic control for grid-connected photovoltaic system," Renewable Energy, vol. 30, pp. 1771-1788, Sept. 2005.

[8] M. S. Ngan and C. W. Tan. "Multiple peaks tracking algorithm using particle swarm optimization incorporated with artificial neural network," International Journal of Electrical, Computer, Energetic, Electronic and Communication Engineering, vol. 5, pp. 1320-1326, 2011.

[9] R. Subha, and S. Himavathi, (2014, Dec.). Neural network based maximum power point tracking scheme for PV systems operating under partially shaded conditions. International Conference on Advances in Green Energy.

[10] M. S. Ngan, and C. Wei Tan, (2011, April). A study of maximum power point tracking algorithms for stand-alone photovoltaic systems. IEEE Applied Power Electronics Colloquium.

[11] K.Kobayashi, I. Takano, andY. Sawada, "A study on a two stagemaximum power point tracking control of a photovoltaic system under partially shaded insolation conditions," in *Proc. IEEE Power Eng. Soc. General Meeting*, Jul. 2003, vol. 4, pp. 2612–2617.

[12] M. Miyatake, T. Inada, I. Hiratsuka, H. Zhao, H. Otsuka, and M. Nakano,"Control characteristics of a Fibonacci-search-based maximum power point tracker when a photovoltaic array is partially shaded," in *Proc. Int.Power Electron. Motion Control Conf.*, Aug. 2004, vol. 2, pp. 816–821.

[13] D. Nguyen and B. Lehman, "An adaptive solar photovoltaic array using model-based reconfiguration algorithm," *IEEE Trans. Ind. Electron.*,vol. 55, no. 7, pp. 2644–2654, Jul. 2008.

[14] M. Miyatake, M. Veerachary, F. Toriumi, N. Fujii, and H. Ko, "Maximum power point tracking of multiple photovoltaic arrays: A PSO approach,"*IEEE Trans. Aerospace Electron. Syst.*, vol. 47, no. 1, pp. 367–380, Jan.2011.

[15] L. L. Jiang, D. R. Nayanasiri, D. L. Maskell, and D. M. Vilathgamuwa. (2013, Nov.). A simple and efficient

hybrid maximum power point tracking method for PV systems under partially shaded condition. 39th Annual Conference of the IEEE Industrial Electronics Society.

[16] M. G. Villalva, J. R. Gazoli, and E. R. Filho. (2009, Ocy.). Modeling and circuit-based simulation of photovoltaic arrays. Brazilian Power Electronics Conference.

[17] W. Xiao, N. Ozog, and W. Dunford, "Topology study of photovoltaic interface for maximum power point tracking," *IEEE Trans. Ind. Electron.*,vol. 54, no. 3, pp. 1696–1704, Jun. 2007.

[18] M. Masoum, H. Dehbonei, and E. Fuchs, "Theoretical and experimental analyses of photovoltaic systems with voltage and current-based maximum power-point tracking," *IEEE Trans. Energy Convers.*, vol. 17, no. 4,pp. 514–522, Dec. 2002.