PV System Analysis Under Partial Shading Using a Sine Model

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Abstract- A photovoltaic panel exhibits highly non-linear P-V and I-V characteristics, further its Maximum Power Point Tracking (MPPT) operation becomes difficult during partial shading for high performance. During partial shading condition, the P-V array characteristics have more than one maxima point and the PV array panel models employed to locate for Global Maximum Power Point Tracking (GMPPT) analysis becomes complex. In this paper, the effects on PV system characteristics under possible shading conditions are analyzed. A 450 W, PV array system modeling is carried out for different shading conditions with sinusoidal functions. The problem is analyzed for PV panel connection to produce maximum power output. The results from the developed Sine model for the partial shading for GMPPT using Matlab/Simulink software platform is simulated. The effective GMPPT operation is done to validate the sine model.

Keywords Photovoltaic (PV) panel, Global Maximum Power Point Tracking (GMPPT), Global Maximum Power Point(GMPP), Partial Shading, Sine Model, Particle Swarm Optimization (PSO).

1. Introduction

The ever-increasing demand for electrical energy is the reason for exhausting fossil fuel sources. The use of renewable sources worldwide is an alternative to meet this gap. The solar energy is gaining an edge over other form of renewable energy because of following advantages like: (1) no moving parts, (2) absence of air-pollution, (3) absence of noise-pollution and (4) less maintenance is required. The main drawback with PV power generation is its limited availability during the day-time only, but there are certain applications like water pumping, office activities, some factory activities, etc. which may need power during the day only. Moreover, the power generated by PV panels can also be fed to the grid. One should remember that each watt of power added helps in overcoming the deficiency in the present demand of electrical power.

Generally, a PV generation system consists of -- (i) the solar panel (ii) a dc-dc converter which may be step-up, step-down or both and (iii) a dc-ac converter stage, if load is ac. The dc micro-grid systems will not have a 3rd stage of dc-ac conversion. Fig. 1(a) shows a PV system with Boost converter. In photovoltaic systems, a PV array is formed by connecting large number of PV panels in series and parallel configuration, which is affected by partial shading phenomenon. The partial shading on PV panels may be there due to -- (1) the change in earth's inclination due to revolution of earth; (2) presence of tall buildings, trees etc. structures in vicinity of PV array; 3) movement of clouds. In an array due to partially shading, PV panel may be damaged due to the formation of hot spots, and this can be prevented by connecting bypass diodes in parallel with each panels. These diodes prevent reverse current flow through the shaded panel. The solar insolation varies non-uniformly during the day time. Few panels may be under the shadow because of the presence of trees, buildings, towers, near the PV array. This shading causes a difference in the generated voltage of panels in each string thereby decreasing the efficiency of PV system. This loss depends upon location and shaded area on the given PV array.

The I-V and P-V characteristics obtained from the diode model clearly depict their non-linear behavior. Some researchers have discussed [1-2] the modeling and technique for parameter identification for PV systems that introduces single diode model. Ramos J. S. et.al. [3] has shown the PV based water pumping systems can be efficiently used in villages or fields. The partial shading on PV panels hampers its performance and therefore the investigations related to partial shading of PV panels become important [4-6].

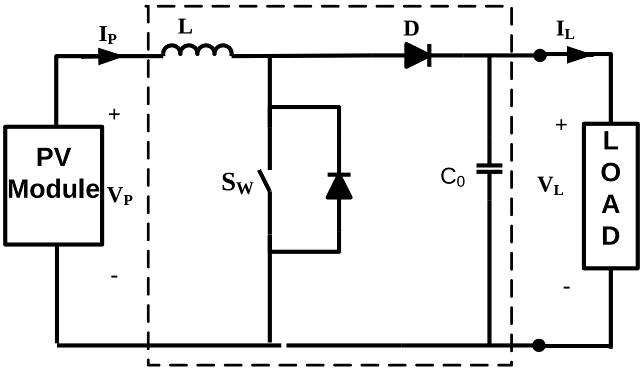

Fig. 1(a). Boost converter configuration for matching load and source.

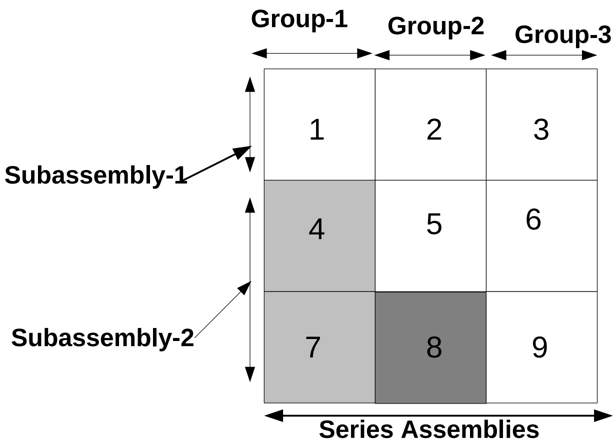

Fig. 1(b). Grouping of partial shaded PV array

Patel. H et.al. [4-5] has described the different shading patterns under rapidly changing insolation and also MATLAB based model is proposed to analyze the effects of shading on the characteristics of PV array. The authors have divided partial shaded PV array into various parallel connected groups having different shading pattern. Each group is divided into series assemblies connected in parallel having same PV characteristics, and each assembly is formed by connecting many subassemblies in series. A subassembly by connecting different PV panels in series/parallel is formed, having same insolation level. One such partial shaded array is shown in Fig 1(b). The authors [5] have also proposed the scheme for tracking the global peak power point under non-uniform shading condition. The code for PV arrays by Patel. H et.al. [4] is in the public domain (link:http: //www.ee.iitb.ac.in/ uma/phiren/) and can be used for analysis. The model needs the information of a large number of coefficients as input to make it effective. It helps in predicting the P-V characteristics of large system for different insolation-level, temperature-range and shading pattern.

During testing, all the panels in a PV array are normally subjected to constant temperature and insolation levels. The P-V characteristics in such case will have only one maximum as shown in Fig. 2. But under partial shading conditions, the PV systems show multiple peaks [7-10] in the P-V characteristics. These multiple peak points in the PV characteristics create confusion for tracking Global Maximum Power Point (GMPP). The PV system work stably on local maximum and not at GMPP if the controller is not designed properly. Some techniques for tracking GMPP have been researched [8-26], however, in the influence of shading presence and the performance of control algorithm also need improvement.

The researchers have not given the mathematical representation for partially shaded P-V characteristics and therefore there is a need to develop the model. Sine model was proposed in [27] for representing PV system, however the authors have not done investigation for partial shading conditions. This paper investigates effect of shading in a PV power generation system having nine (3×3) PV panels as shown in Fig. 2. The way of novel representation of characteristics and its analysis that shall be highly beneficial for development of flexible controller during shading conditions. Finally, this characteristic is compared with that from MATLAB-based model [4] under different shading conditions.

This paper mainly presents a mathematical model for representing PV panel under shading conditions. The non-linear model involves the determination of number of coefficients from data generated /recorded. To achieve this, a method is to be used to decompose the curve data with arbitrary frequencies. Prony [28] has invented a method before Fourier's discovery that can address this challenge to a certain extent but suffers from the difficulty of numerical implementation. Therefore, Particle Swarm Optimization Technique is investigated in this paper for arriving at the result in a standard way. The least squares (LS) method on large sets of data exhibits limits on implementation accuracy and gives results that are highly unsatisfying therefore this paper proposes a different objective function for enabling the coefficient determination for model.

2. System Modeling

A. PV Cell Model

A 3×3 PV array consists of three PV panels connected in series to form a string and these 3 strings are further connected in parallel. A 50 W PV panel is used for formation of a PV array is described in [1] and is used for analysis purpose.

A PV panel model comprises of a light-generated current source which is in parallel with shunt resistance, a diode and series resistance. The PV panel voltage-current relationship is given by well known equation as:

$$I = I_L - I_0\left(e^{\frac{V+IR_s}{b}} - 1\right) - \frac{V+IR_s}{R_{sh}}, \qquad (1)$$

where $$b = \frac{N_s \gamma KT}{q}, \qquad (2)$$

I_L is current generated by sun light,
D is diode,
q is charge of electron (1.6×10^{-19} C),

K is Boltzmann's constant (1.38×10^{-23} J/K),
γ is ideality factor (its value varies within 1-2),
N_S is the number of series cells,
T is temperature of PV panel (K),
I_0 is the diode reverse saturation current,
R_s and R_p are the series and shunt resistances of single diode model.

Table 1. 50 W Panel Specifications

S. No.	Electrical Characteristics of Panel	BP-350
1	Maximum power point (P_{max})	50 W
2	Voltage at maximum power (V_{mp})	17.3 V
3	Current at maximum power (I_{mp})	2.89 A
4	Panel short circuit current I_{sc}	3.17 A
5	Panel open circuit voltage V_{oc}	21.8 V

The output power supplied by a PV panel depends upon-- (i) the insolation level, (ii) Temperature of panel, (iii) Angle of sun's incidence, iv) Partial shading condition and (v) Electrical load resistance. The specifications of a 50 W PV panel are listed in Table 1 [1]. Eqn. (1) is a mixed equation which is difficult to solve and not valid for partial shading. The iterative methods can solve Eqn. 1 with the help of suitable assumptions.

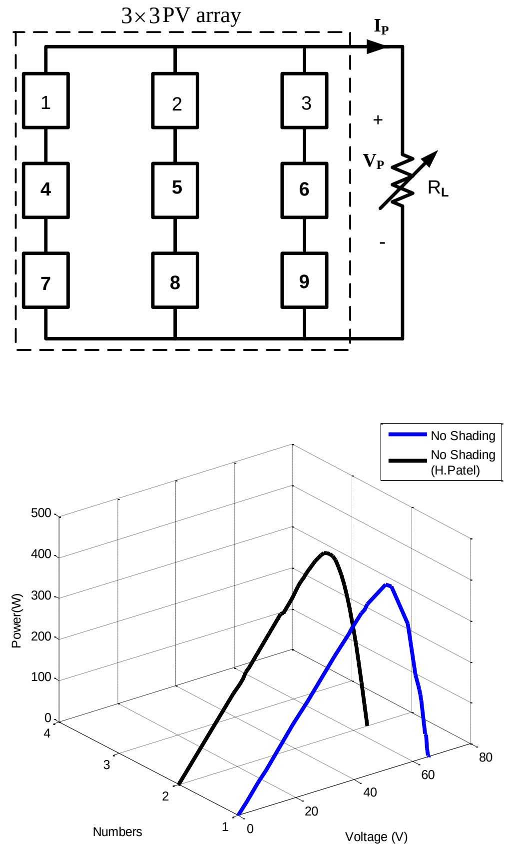

Fig. 2. PV array for nine panels (a) characteristics of different panels , CASE-A: All panels are subjected to constant insolation of 1000 W/m^2 at 25° C, comparison between the presented model and Patel's model.

A. PV array Configuration

A low power (450 W) 3×3 PV array is formed by connecting nine PV panels as shown in Fig. 2 (CASE-A). In this arrangement, the three columns are put in parallel and each column has three PV panels, put in series. Fig. 2 shows the characteristic under standard operating condition for 3×3 array of these PV panels.

Figures 3-7 shows the PV characteristics during partial shading for different cases (CASE B-F).

Blue curve is due to 100% of shading while black is the one obtained by Patel's model; green curve is due to 50% of shading while red is the one of Patel's model.

CASE B-F has multiple peaks in the characteristics shown. It is necessary to operate PV system at Global Maximum Power Point (GMPP) so that the whole of power produced could be fed to the loads. The matching of power demand of load and PV generation system is possible by use of intermediate dc converter, which must continuously control the current and voltage levels by changing the point of operation as described in the literature [6-8].

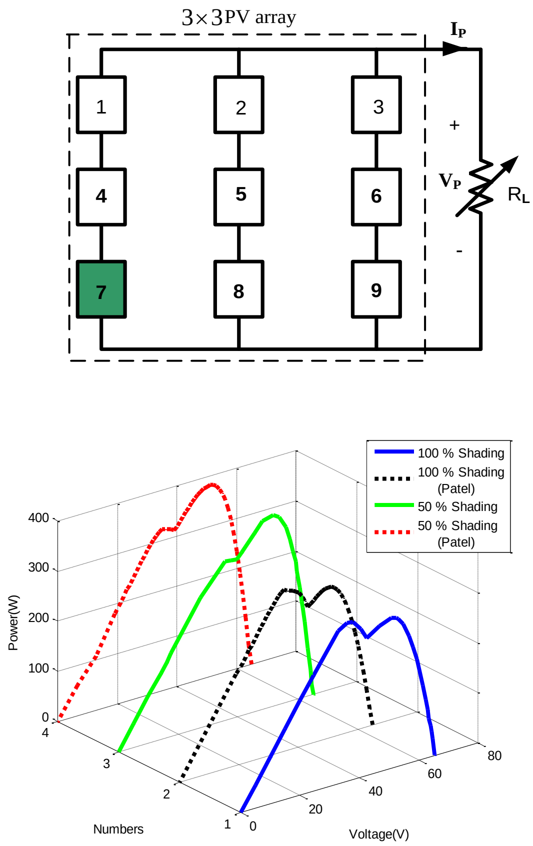

Fig. 3. CASE-B: PV panel number 7 is subjected for 100% and 50% shading.

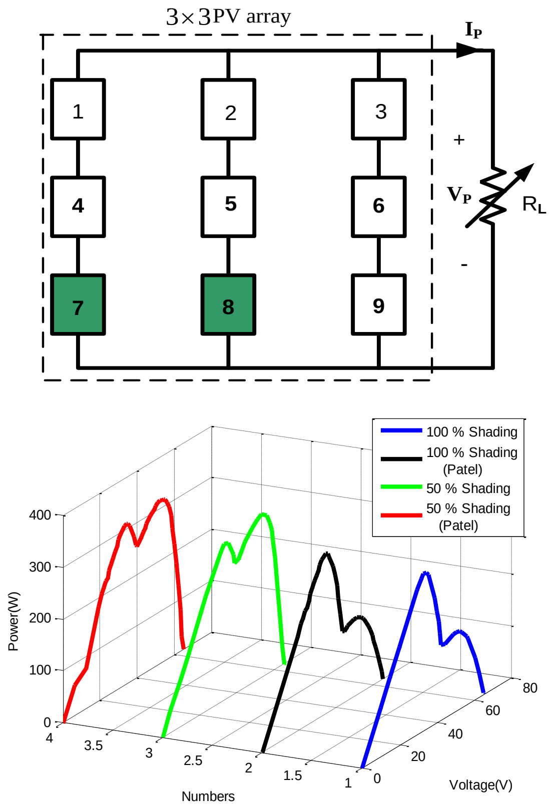

Fig. 4. CASE-C: PV panels 7 and 8 are subjected for 100% shading and 50% shading.

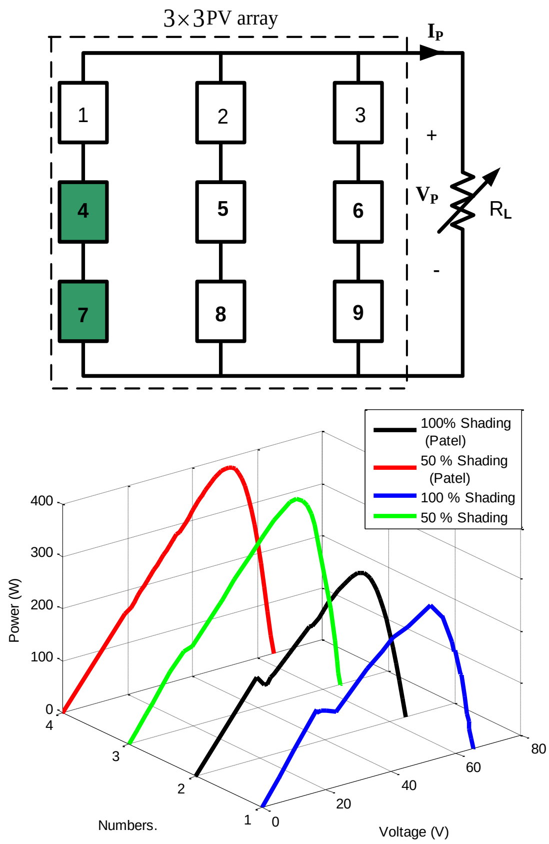

Fig. 5. CASE-D: PV panels 4 and 7 are subjected to 100% shading and 50% shading

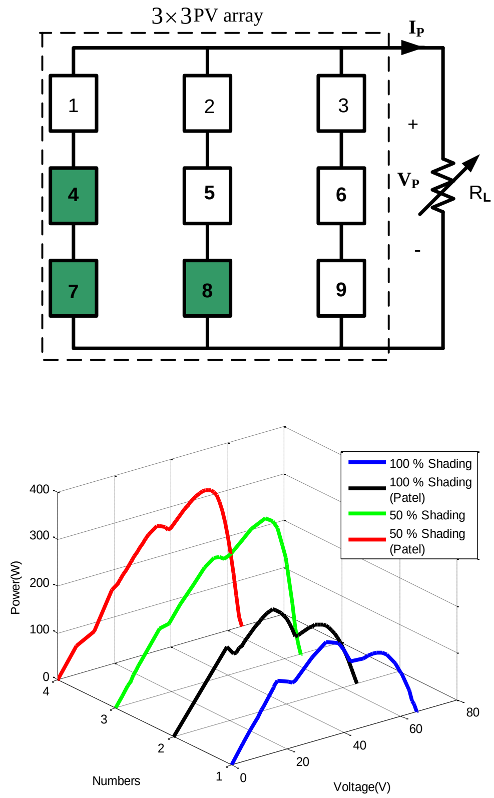

Fig. 6. CASE-E: The PV panels 4, 7 and 8 are subjected to 100% shading and 50% shading

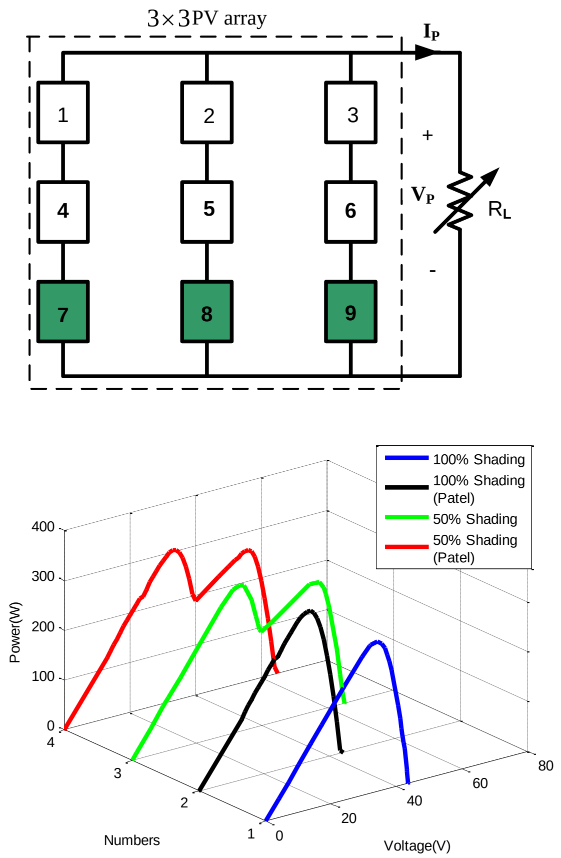

Fig. 7. CASE-F: The PV panels 7, 8 and 9 are subjected to 100% shading and 50% shading

The PV system is studied for partial shading influence for non-uniform insolation levels of 1000 W/m^2 and 500 W/m^2 and operating temperature (25^{0}C). The partial shading conditions are under following six cases:

Figures 2 to 7 show Case-A to Case-F, where the shading on the panels is marked, and P-V characteristics are also shown.

The characteristics for Case-B to F cannot be represented simply by an exponential diode current equation like Eqn. (1). Therefore, for analysis and control of our PV system, a different mathematical representation is proposed in next section.

3. Proposed Mathematical Model for P-V Characteristics Under Partial Shading Condition

For a PV array, panels with or without partial shading as shown in CASES (A-F), the proposed relationship between V and P is as follows:

$$P = \{u(V) - u(V - V_{max})\} \sum_{x=1}^{6} \{\rho_x \sin(\omega_x V + \phi_x)\} \quad (3)$$

where:

V is the output voltage of PV array;

P is the output power from PV array;

V_{max} is the maximum possible value of voltage from PV system;

$\{u(V) - u(V - V_{max})\}$ is a gate function to enable signal existence between V=0 and V=V_{max} only;

ρ_x are the constants that have dimensions of power;

ω_x are the constants that have dimensions of radians/volt;

ϕ_x are the constants that have dimensions of radian.

This form of an equation is called 'Sine model' for PV array system in this paper where the value of ω_x is not integer number of some value of ω_0. It is suitable for analysis under partial shading provided the coefficients ρ_x, ω_x and ϕ_x are known correctly. The six sine terms in the model give sufficient accuracy and therefore the model identification is done if ρ_x , ω_x & ϕ_x are identified. The current (I), the power (P) and voltage (V) and are directly related therefore an equation between V and I can also be written similarly to represent its model. This form of an equation has an advantage over Eqn. 1 during partial shading condition. The 'Sine model' shall also reduce the complexity in control of power electronic converter fed from the array of PV panels. However, finding the coefficients of Eqn. (3) needs some standard technique.

A. Determining Sine model Coefficients (ρ_x, ω_x and ϕ_x) Employing PSO

The coefficients of Eqn. (3) are found from the data related to P-V curve panels. The determination of Sine model coefficients typically becomes a curve-fitting problem having eighteen unknowns. The number of points on this curve is more, and therefore, this becomes an over-determined system. This over-determined system is proposed to be identified by employing Particle Swarm Optimization (PSO).

PSO technique is used to determine the unknown coefficients of 'Sine model' for different shading condition. This effective method for solving non-linear equation is given in following steps:

- 1st Step: Initialization**:** The velocity and position of all particles are set randomly within the search space.
- 2nd Step: Fitness Function: The fitness $F(p_i)$ for each particle of the swarm is evaluated.
- 3rd Step: Velocity Update: The update of the velocity of particles is carried out at each of iteration.

$$V_{id(t+1)} = W * V_{id(t)} + K_1 * R_1 * \left(P_{id(t)} - X_{id(t)}\right) + K_2 * R_2 * \left(G_{id(t)} - X_{id(t)}\right) + K_3 * R_3 * \left(H_{id(t)} - X_{id(t)}\right) \quad (4)$$

Where

K_1 *is* cognitive-learning rate, K_2 is social-learning rate & K_3 is hybrid-learning rate.

The constants R_1, R_2 and R_3 are random numbers in the range from 0 to 1.

X_{id} is the position of particle

$P_{id(t)}$ is the local-best position

$G_{id(t)}$ is the global-best position,

$H_{id(t)}$ is the hybrid-best position,

$V_{id(t)}$ is the velocity of particle.

W is the 'inertia weight' required in velocity equation for balancing the global search and local search.

The velocity of each particle is lies in the range from V_{min} to V_{max}.

$$W = (W_{max} - W_{min}) * \frac{(Iter_{max} - Iter_{new})}{Iter_{max}} + W_{min} \quad (5)$$

- 4th Step: Position Update: The update of position of all particles is done between successive iterations as:

$$X_{id}(t+1) = X_{id}(t) + V_{id}(t+1) \quad (6)$$

After the update, these values must be checked and limited in the allowed range.

- 5th Step: Memory Updating: Update of values of particle's best position P_{best} and G_{best} are given as:

$$P_{best} = P_{id} \text{ if } F(P_i) < F(G_{best}) \quad (7)$$

$$G_{best} = G_{id} \text{ if } F(G_i) < F(G_{best}) \quad (8)$$

$$H_{id} = \frac{P_{id} + G_{id}}{2} \quad (9)$$

where $F(x)$ is the objective function subjected to minimization.

- 6th Step: Criteria for stopping: The algorithm repeats Steps 2 to 5 till the desired stopping condition is reached. It stops after a pre-defined number of iterations or a failure to make progress in fitness function. Once terminated, the algorithm shall report the value P_{best} and G_{best} as its solution.

The objective function to be minimized is the exponential of absolute value of error measured for the power calculated by the Sine model and diode model.

$$F(x) = Exp\left[\alpha + \frac{\text{abs}\{P_{est}(x) - P_{act}(x)\}}{\beta}\right] \quad (10)$$

Where:

$P_{est}(x)$ is the power calculated by the Sine model,

$P_{act}(x)$ is the power calculated by the diode model,

α and β are the two constants.

Using PSO algorithm the objective function given by in Eqn. (10) is minimized and the unknown coefficients of proposed model are found. The function is chosen for faster elimination of coefficients that give higher values of errors, during initial iterations.

B. Motivation for employing sine model

During partial shading condition, it becomes complex to track the global peak point as the multiple local peaks are present. Perturb & Observer (P&O) algorithm of MPPT controller can operate stably at any local maximum for the PV system. The dc-dc boost converter is a highly non-linear device which also adds complexity to track the GMPP. For a particular value of shading, once the Sine model coefficients are determined, the Sine model can be employed for simulation and the global peak shall be determined.

4. Simulation of Proposed PV System

Using MATLAB/Simulink along with SimPowerSystem toolbox the PV system is simulated. Fig. 8 shows the block diagram of the complete PV system. Table 2 shows the converter parameters that have been employed for simulation. DC-DC boost converter act as the power flow controller between PV panels and the load.

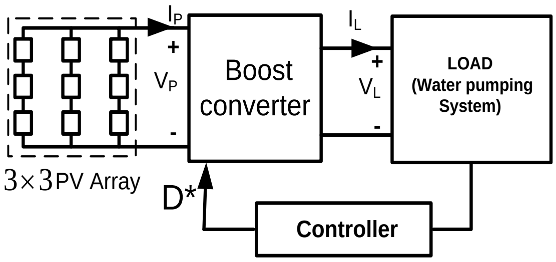

Fig. 8. Block diagram for arrangement of PV array, load and the boost converter.

Table 2. Design parameters of Boost converter

S. No.	Input voltage	V_i	10-65 V
1	Output voltage	V_o	15-200 [V]
2	Switching frequency	f_S	10 [kHz]
3	Boost Inductor	L	2 [m H]
4	Input capacitor	C_i	47 [µ F]
5	Output capacitor	C_0	470 [µ F]
6	Maximum Power output	P_{max}	450 W

The PV array operating point under various load conditions is governed by the duty ratio of boost converter. By changing the duty ratio, the desired load current and voltage is obtained. Fig. 1(a) shows the circuit of the converter employed for shifting the operating point on P-V panel characteristics. The output voltage of boost converter is a function of duty ratio of switching signal given by equation

$$V_{op} = \frac{1}{1-D} V_{ip} \quad , \quad (11)$$

where:

D is the duty ratio,

V_{ip} is the input voltage of converter,

V_{op} is the output voltage of converter.

A. Simulation of proposed model

All the characteristics for six different cases are plotted by varying effective load connected to output of the boost converter in the Simulink model and also compared with characteristics obtained from MATLAB code given by [4]. Table 3 recalls the performances of the array in the CASE E.

From the values of coefficients given in Table IV, the proposed Sine model is employed for Eqn. 3. The load is connected to sine model by interfacing it through boost converter. The simulation of sine model employing parameter from Table IV is shown in Fig. 9. For the diode model and proposed model, simulated P-V curves (for Case-E) are plotted and compared as shown in Fig. 10. Figure 11 show the P-V curves of case-E with three different insolation levels (G=1, G=0.5 and G=0).

Table 3. Values of current, voltage and power under varying load conditions for 3×3 PV array CASE-E 100% and 50% shaded.

No Shading			**3-Panels Shaded (CASE E) 100 %**			**3-Panels Shaded(CASE-E) 50 %**		
V_P	I_P	P	V_P	I_P	P	V_P	I_P	P
0	9.51	0	0	9.51	0	0	9.51	0
3	9.51	28.53	4.0	9.62	38.55	2.36	9.51	22.443
7	9.51	66.57	6.6	9.51	63.55	4.31	9.51	40.988
9.51	9.51	90.44	9.1	9.42	86.33	6.31	9.51	60.008
19.02	9.51	180.88	10.	9.40	100.4	8.01	9.51	76.175
23.75	9.50	225.64	14.	9.45	140.37	8.94	9.51	85.04
28.52	9.50	271.13	16.	9.26	151.35	15.4	9.283	143.4
33.28	9.50	316.42	20.	7.16	143.84	18.6	7.939	147.7
38.02	9.50	361.26	21.	6.38	137.93	22.8	7.924	181.1
38.84	9.47	367.97	22.	6.28	141.17	27.2	7.913	215.5
42.5	9.44	401.37	28.	6.31	181.1	31.4	7.829	246.1
43.26	9.40	406.99	33.	6.07	204.2	34.6	7.531	260.5
44.45	9.43	419.25	37.	5.19	196.15	36.7	7.06	259.8
50.86	8.87	451.53	39.	4.44	176.93	38.3	6.594	252.7
52.72	8.42	444.21	42	3.51	147.79	40.6	6.336	257.5
58.23	5.82	339.07	48.	3.07	149.11	44.4	6.313	280.5
60.83	3.46	210.71	50.	3.01	150.76	47.9	6.254	299.5
62.02	2.92	181.59	51.	2.92	150.56	52.9	5.924	313.5
62.14	2.76	171.94	55.	2.53	139.41	55.6	5.452	303.3
62.58	2.51	157.63	57.	2.05	118.82	57.1	4.992	285.4
63.07	2.27	143.35	58.	1.99	115.67	60.0	3.594	215.7
64.4	0.91	59.11	60.	1.47	88.86	60.4	3.338	201.7
64.46	0.85	55.4	62.	0.77	48.91	63.6	0.964	61.35
65.04	0.32	21.15	64.	0.40	25.79	64.3	0.397	25.57
65.32	0.06	4.26	64.	0.27	17.78	65.3	0	0

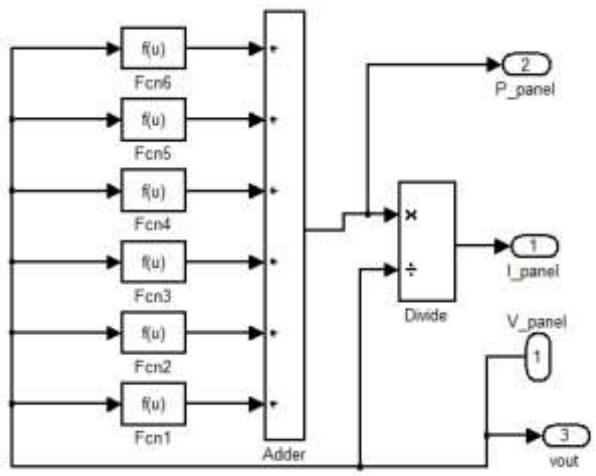

Fig. 9. Simulation of proposed sine model of PV array (CASE E) using Eqn. 3 and coefficients from Table IV

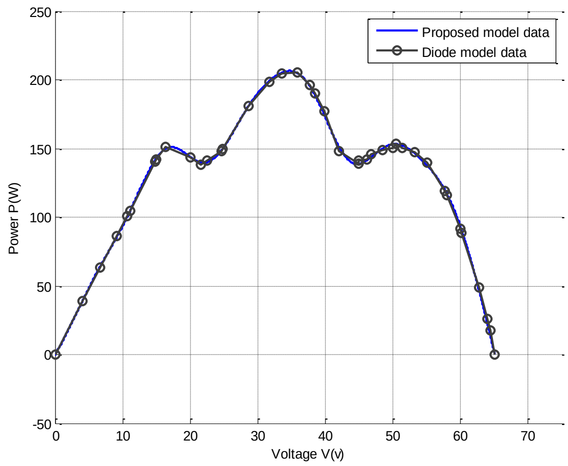

Fig. 10. Characteristics of PV array obtained from (i) Diode model and (ii) proposed sine model for the CASE-E as shown in Fig.6.

Table 4. Coefficients of Sine Model Computed For Power-Voltage (P-V) Characteristics For Case-E

Sine model coefficients	**CASE-E**		
	G=1	**G=0**	**G=0.5**
ρ_1	12.940	360.7	279.8
ω_1	0.254	0.064	0.0425
ϕ_1	5.5297	0.011	-0.1326
ρ_2	1.5327	448.9	54.15
ω_2	0.9464	0.096	0.2614
ϕ_2	9.9325	2.891	-5.224
ρ_3	50.1834	277.9	37.15
ω_3	0.1816	0.115	0.1384
ϕ_3	3.9209	5.751	0.9493
ρ_4	394.796	29.78	63.52
ω_4	0.0499	0.201	0.3073
ϕ_4	-0.1926	0.683	-3.106
ρ_5	141.679	15.53	125.3
ω_5	0.1124	0.343	0.3949
ϕ_5	-4.1970	8.717	-2.391
ρ_6	0.1244	3.946	107.7
ω_6	2.71E-09	0.586	0.4051
ϕ_6	-8.2238	-1.96	0.5095
RMSE	4.0441	4.03	4.023

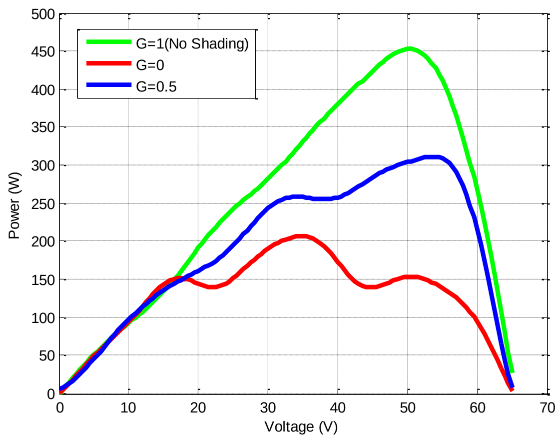

Fig. 11. P-V characteristic obtained from proposed sine model for the CASE E at three different insolation levels (G=1, G=0.5 and G=0). The condition G=1 means that panel (4, 5 and 6) shown in Fig. 1(b) are not shaded while G=0.5 means that panel (4, 5 and 6) are 50% shaded and G=0 means that panel (4, 5 and 6) are 100% shaded.

B. Simulation of GMPP tracking technique

This proposed GMPPT algorithm is simulated. Figure 12 shows the schematic diagram of simulation consisting of GMPP tracking algorithm. It consists of two subsystems, namely MPPT controller and the 'Sine model' to track the global peak point under different shading condition for case-E. Figure 13 shows the simulation model of the subsystem for MPPT algorithm used to control the reference voltage, where the reference voltage corresponds to peak point, either local or global peak. The variation in insolation is done in three steps for three conditions G=1, G=0.5 and G=0 for case E. The condition G=1 means that panel (4, 5 and 6) are not shaded, while G=0.5 means that panel (4, 5 and 6) are 50% shaded, and G=0 means that PV panel (4, 5 and 6) are fully shaded. The response for varying insolation is shown in Fig. 14

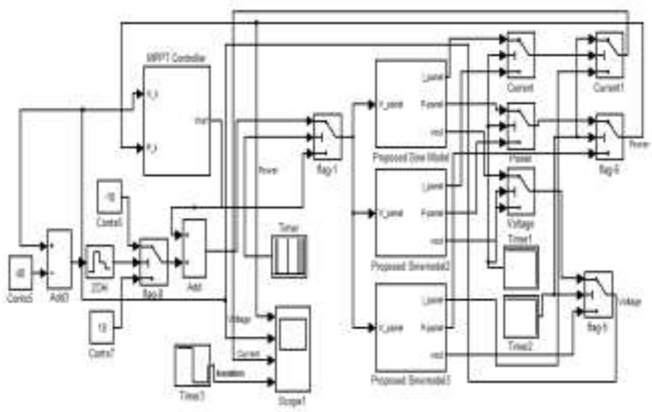

Fig. 12. Simulation of proposed GMPPT controller algorithm for a PV array, when three panels are shaded (Case-E).

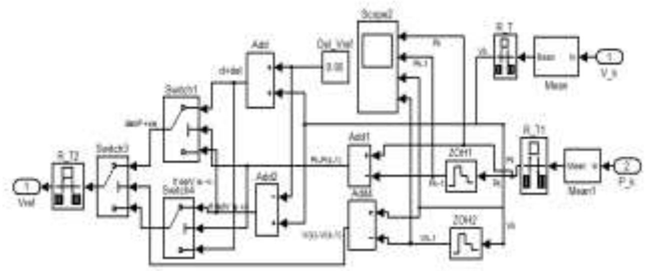

Fig. 13. Simulation of MPPT algorithm using P&O method.

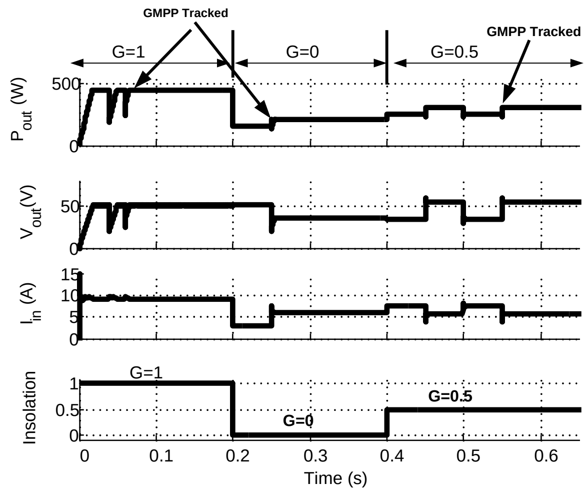

Fig.14. The response of proposed GMPPT controller at different insolation levels when three panels are under shading and remaining panels have 100 % insolation (Case-E).

C. Boost Converter Interface with PV System.

The GMPPT algorithm is executed at every fixed interval of time to generate reference voltage for PV system for peak power operation. This generated reference voltage is fed to PI controller which generates the duty ratio corresponds to reference voltage and is feed to boost converter (Fig. 1(a)) to obtain GMPP operating voltage. This boost converter will act as an interface between PV array, load and the control algorithm. Whenever there is change in environmental conditions which leads to shifting of GMPP.

The duty ratio generated by PI controller for boost converter at the n[th] interval D_n is given as

$$D_n = D_{n-1} + K_p.\left(V_{e,n} - V_{e,n-1}\right) + K_I.V_{e(n)} \qquad (12)$$

Where K_p is proportional constant, K_I is integral constant and $V_{e,n}$ is the error voltage and given by

$$V_{e,n} = V_{p\max} - V_{panel}$$

Where $V_{p\max}$ is the voltage of PV array, corresponds to maximum power, which is a reference voltage generated by GMPPT algorithm.

$$V_{ref} = V_{p\max} \qquad (13)$$

The Global tracking system will respond to disturbance as explained in section III and which generates new reference voltage which is controlled by adjusting duty cycle of pulses feed to boost converter. The boost converter continuously maintains the stable operating voltage by fine tuning of duty ratio set by PI controller.

5. Results and Discussion

The non-linear electrical characteristic of PV panel is given by Eqn. 1. The 3×3 PV array is formed by connecting nine panels in series-parallel arrangement is shown in Fig. 2. The PV system is analyzed for two different shading conditions--1) 100% shading and 2) 50 % shading. The characteristic is explained by considering five different cases as shown in Fig. 3 to Fig. 7. The multiple maxima points are observed for each case and the operating point is controlled by boost converter.

The MPPT technique fails to track GMPP for partial shading condition with Perturbation and Observation technique. The stable operation at local MPP may be present which shall affect the efficiency of PV system. The proposed sine model helps in predicting the global peak point. The coefficients of Sine model and the computed value of Root Mean Square Error (RMSE) at three insolation levels for shading Case-E in comparison are shown in Table 4. Some researchers have suggested values of PSO parameters for guaranteed convergence for different cases in literature. In our case, the best PSO parameters for determining the unknown coefficients are given in Table 5. It is worth mentioning the exact value of the coefficients in such problems is not so important (because more than one solution may exist) till the value of RMSE is small in measured data and estimated data. The value of RMSE over 65 point data is always about 4 or less. The convergence of PSO particles with the number of iterations is shown in Fig. 15.

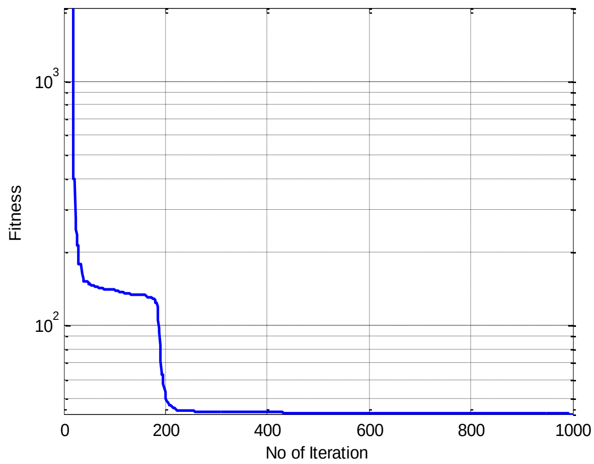

Fig. 15. Response showing the convergence of fitness function.

GMPP control algorithm continuously tracks the peak point until global peak point is tracked. It also checks the operating point after a certain interval of time by giving a small disturbance and ensures the GMPP operation. This peak power tracking is done by comparing it with value obtained on P-V curve plotted in Fig. 11. The characteristics show that the overall maximum output power under partial shading condition is low as compared to the actual capacity of the array. This is caused due to shading loss.

Fig. 14 shows the GMPP tracking response observed for Case-E when insolation level of three panels are changed (G=1, G=0.5 and G=0) and remaining panels are at normal insolation. The small disturbance is applied at each interval of time and GMPPT algorithm tracks the maximum power.

Table 5. PSO Parameters For Coefficient Determination

S. No.	Variables	Symbol	Value
1	Number of variables (ρ_1- ρ_6, ω_1- ω_6, ϕ_1- ϕ_6)	ρ_x, ω_x, ϕ_x	18
2	Population Size	N	324
3	Weight-1	W_1	0.5
4	Weight-2	W_2	0.48
5	Maximum Iteration	Itr_{max}	2000
6	Cognitive learning rate	K_1	1
7	Social learning rate	K_2	2.5
8	Hybrid learning rate	K_3	1.8
9	Objective function constant1	α	-1
10	Objective function constant2	β	10

6. Conclusion

This paper has analyzed the effect of shading on a 3×3 PV array for different shading cases. The obtained P-V characteristics data is investigated to develop Sine model. The paper has established the method for finding the coefficients of sine model given by Eqn. (3) employing PSO. A systematic approach for solving difficulty in finding the unknown coefficients for a highly non-linear system (over-determined, over-constrained problem) is proposed. It shall be most suitable for such complex curve fitting problems.

The developed Sine model for partial shading conditions is employed to analyze the GMPPT and maximum power point operation of a boost converter. This model simplifies the PV array modeling for simulations by cutting the cost of mathematical implementation for MPPT.

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