ANALYSIS OF SHADING INFLUENCE ON MODELING OF STANDALONE PV ARRAY SYSTEM FOR OPTIMAL POWER OUTPUT

L Navinkumar Rao[1], S Gairola[2]

[1]*Assistant Professor, Dept. of Electrical Engg, I.T.S. Engineering College, Greater Noida, (India)*

[2]*Professor, Dept. of Electrical Engg, Noida Institute of Engineering and Technology, Greater Noida, (India)*

ABSTRACT

A photovoltaic power system exhibits non linear characteristics and the maximum power point tracking (MPPT) operation is essential for best performance. The P-V array characteristics for partial shading condition (when some panels are under shadow) show multiple maxima points and normal operation fails to locate global maximum power point. In this paper, shading effect on PV array system of low rating is investigated and its characteristics under different shading conditions are studied. A small PV system consisting of nine 50 W PV modules connected in series and parallel configurations, is investigated for different shading conditions. The analysis is carried out for PV panel connection reconfiguration to increase power output. A new model is also proposed for the PV modules during partial shading and the results are validated by simulations using Matlab/Simulink software platform.

Index Terms: Photovoltaic (PV) Module, Global Maximum Power Point (GMPP), Partial Shading, Standard Test Condition (STC), Sine Model

I. INTRODUCTION

The demand for electrical energy is globally increasing day by day and the use of renewable energy is the only alternative to meet this demand as the fossil fuel stock on earth is limited. Considering the environmental and technical constraints, the solar energy is becoming popular due to its advantages like absence of moving parts, ease of control and no air and noise-pollution. The major drawback with solar power generation is that it is available only during day time, however, there are applications like farming (water pumping, winnowing, etc), office work, certain industries which may require power only during day time. Moreover, PV generated power can also be fed to the grid and each watt of power fed helps in meeting the demand.

A PV generation system generally consists of solar panel connected to load through a DC-DC converter that may be buck, boost or buck-boost type. Such an arrangement with Boost DC-DC converter is shown in Fig. 1 to be employed in this paper. In PV generation systems, generally a large number of PV modules are connected in series and parallel combinations and obviously PV generation gets affected by shading phenomenon. This shading may be there due to change in earth's inclination with seasons and presence of tall structures close to the PV modules. If a PV panel in a array is shaded, then the panel will be damaged due to formation of hot spots and the effect is avoided by connecting bypass diodes in parallel with the PV modules which prevent reverse current flow through shaded panel. In PV generation system, the insolation is not uniform throughout the day, moreover, some panels may be under shadow during the day time because of obstruction from long trees, tall buildings, cloudy conditions, poles, etc. present near the panel layout. This shading causes a mismatch in generation of modules output in each string and affects the overall efficiency of PV generation. The loss in generation due to shading can be found to be proportional to shaded area and location of PV module in a given array. A single PV panel has low voltage and current rating and its single diode model is shown in Fig. 2 for 50W ratings. Its I-V and P-V characteristics are shown in Fig. 3 under standard test conditions (STC) that depicts its non linear behavior. The modeling and parameter identification for PV systems is described by various researchers [1-2]

J.S. Ramos et.al. [3] has shown that at well depth of 100 m the pumping of water cost about 1.07 €/m^3 where the required pump power is of 154 W and a solar array of 195 W-peak (W_p) is used. When a 720 W-p PV array is connected to a permanent magnet DC (PMDC) motor coupled with centrifugal pump at 5-8 m water head 20 to 840 lit/min can be drawn depending on the solar intensity. This means 38000 l volume of water can be pumped for the water head of 5 m with 9 hours of operation [4]. Several types of pumps and motors are available in the markets which are based on the PV pumping technology. If such PV based water pumping is used in villages or fields, the shading influence shall hamper the performance and therefore the investigation becomes important.

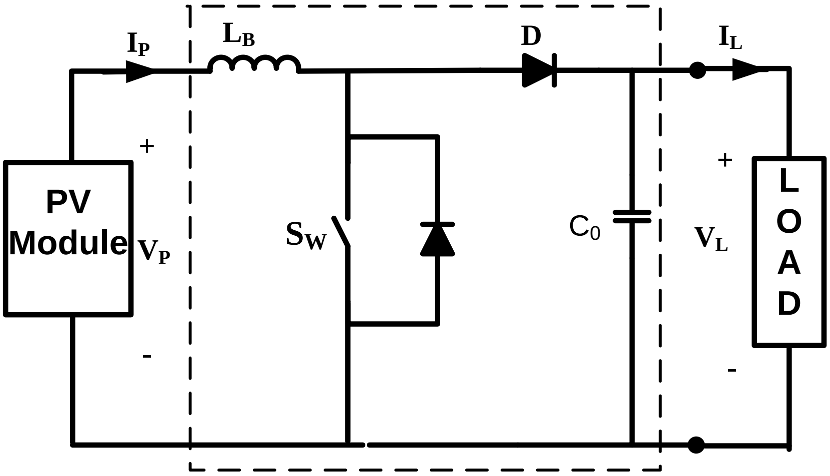

Fig.1 Circuit Diagram of Boost Converter for Effective Load Matching

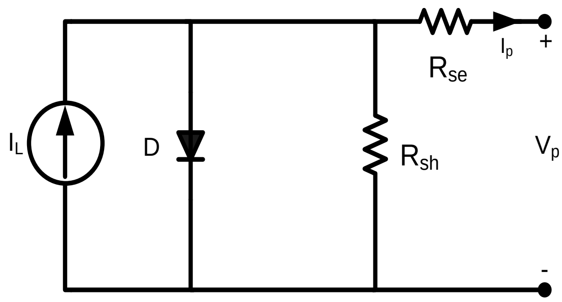

Fig.2 Single Diode Equivalent Circuit of PV Panel Representing Model Parameters

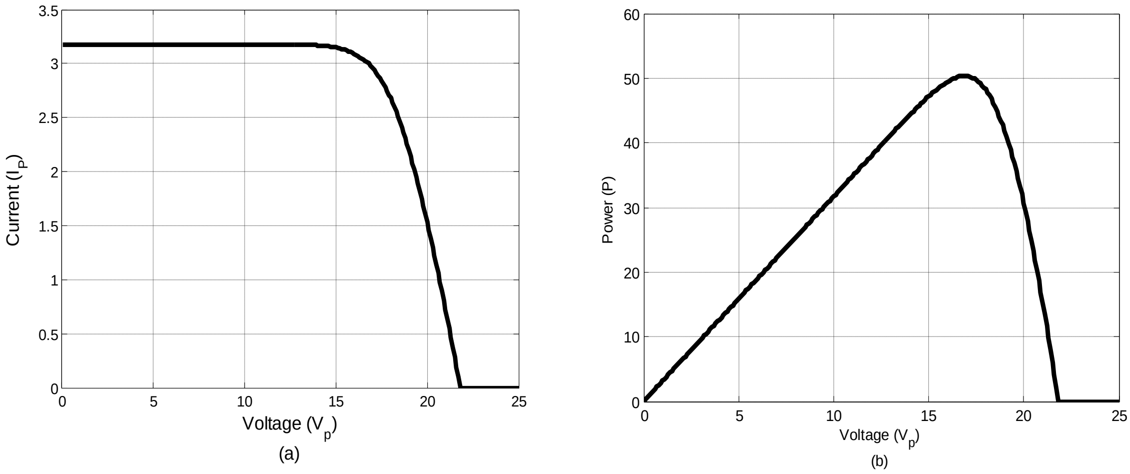

Fig. 3 I-V and P-V Characteristics of a 50W Solar Panel at Insolation of 1000W/m^2 at 25^{0}C

During Standard test conditions (STC), normally all the panels in PV array are subjected to same temperature and insolation and P-V characteristics has only one peak as shown in Fig. 3 (b). However, it is reported in literature [5-8] that the PV system shows multiple peaks in PV characteristics under partial shading conditions. The presence of multiple maxima points makes it difficult to operate PV system at Global Maximum Power Point (GMPP). The controller should be accordingly designed otherwise operating point may work stably on local maximum power point rather than GMPP. Some techniques and algorithms for tracking global maxima have been given by [6] and [7], however, in the presence of shading influence the controllers also need improvement. Patel. H et.al. [9]-[10] has given the various shading pattern for non uniform insolation and proposes the method for tracking the global peak under partial shaded conditions. It is observed that none of researchers have given representation of these PV characteristics that shall facilitate the investigation of such system under shading. This paper investigates the shading effect in a small PV system comprising of nine PV modules connected in an 3×3 array as shown in Fig. 4. The detailed characteristics, analysis and representation are presented here in a novel way that shall be highly beneficial for flexible controller development including shading conditions.

Table I. BP-PV Panel Specifications

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

II. SYSTEM MODELLING

2.1 Model of PV Cell

A PV array consists of number of PV panel connected in series and parallel. The 50 W PV panel BP350, also described in [1], is used for PV array and analysis purpose. A PV panel is modeled as a current source connected in parallel with diode with shunt and series resistance and the current equation that governs panel voltage and current [1-2] is given by

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

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

I_L is light generated current,

D is diode

q is electron charge 1.6×10^{-19} C

K is Boltzmann's constant. 1.38×10^{-23} J/K

γ is the photovoltaic single cell ideal factor (value for which varies within 1-2).

N_S is the number of cells in series

T is the PV panel temperature in K.

I_0 is diode reverse saturation current

R_{se} and R_{sh} are the resistance shown in Fig. 2

The electrical power output delivered by a photovoltaic panel depends upon solar insolation, cell temperature, sun's incidence angle and load resistance. The PV module manufacturer typically provides operational data for photovoltaic panels at STC. The data provided is the open circuit voltage (Voc), the short circuit current (I_{sc}), the maximum power point voltage (V_{mpp}) and maximum power point current (I_{mpp}), the temperature drift coefficients at open circuit voltage and short circuit current. The specification for the 50 W PV panel employed is given in Table I [1]. It is worth mentioning here that Eqn. (1) is a mixed equation that is difficult to solve moreover, it is for STC and not for partial shading. It can be solved only with iterative methods by making certain assumptions.

2.2 Series and Parallel Configuration of PV array

A 3×3 PV array (450 W) is formed by connecting PV panels in series and parallel arrangement for investigation, as shown in Fig 4 (CASE-1). In this arrangement, three strings are connected in parallel and each string consists of three PV panels connected in series. Each panel has characteristics as given in Fig. 3. The 3x3 array of these panels has P-V characteristics given in Fig. 4(b) for STC. However during partial shading condition, multiple peak points are formed in P-V characteristics as shown in Fig. 5(a)-5(e) for some cases (CASE 2-6). Therefore, for best utilization of PV system, it is necessary to operate PV generator at global maximum power point and whole of generated power may be fed to the power grid or loads where varying power can be supplied. This matching of load to PV source is possible by employing the intermediate DC-DC converter, which continuously controls the voltage and current levels thereby moving the operating point as described by some researchers [6-8].

The investigation for analysis of partial shading influence on PV system is carried out under non-uniform insolation (at 1000 W/m^2 and 500 W/m^2) and standard operating temperature (25^{0}C) and kept under following six cases:

CASE 1: All nine panels are working under normal insolation condition, without any shading as shown in Fig. 4(a). The P-V characteristics obtained for this case is also shown at 100 % insolation level (1000 W/m^2)

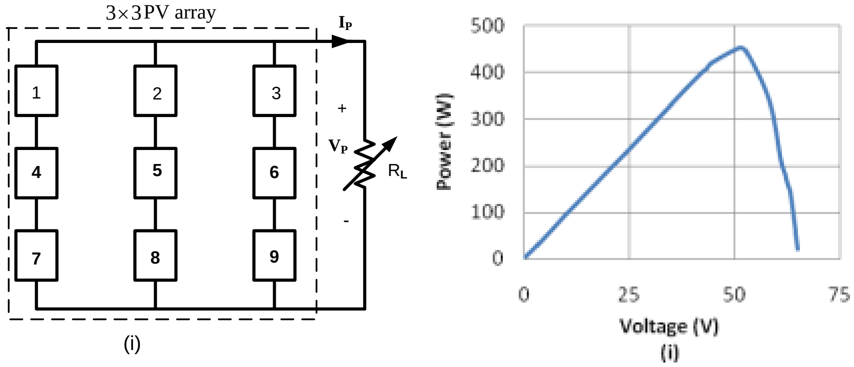

Fig. 4 3×3 PV Array Configuration Having Nine Panels Connected in Series-Parallel Arrangement. (CASE 1 All Panels are Receiving Insolation of 1000 W/m^2 at 25° C)

CASE 2: A single panel (No. 7) in the corner of 3×3 PV array is shaded due to obstruction while other 8 panels are working under normal insolation condition. The P-V characteristics obtained is as shown in Fig. 5(a). The characteristic shows two peak power points.

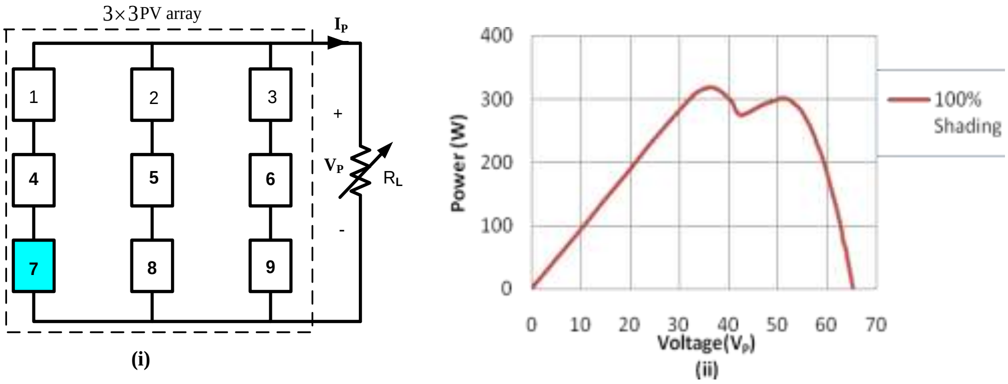

Fig. 5 (A) A 3×3 PV Array Configuration Having Nine Panels Connected In Series-Parallel Arrangement With One Panel Shaded (CASE 2). PV Characteristic Is Shown For 100% Shading On Panel 7.

CASE 3: When two panels (No. 7 and 8) in a corner of the 3×3 array are shaded while other seven panels are working under normal insolation condition as shown in Fig. 5(b). The characteristic shows two peak power points.

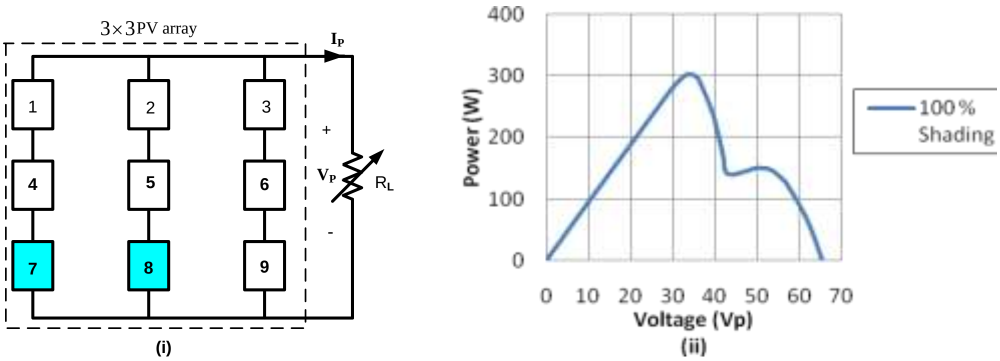

Fig. 5 (B) A 3×3 PV Array Configuration Having Nine Panels Connected in Series-Parallel with Two Panels Shaded (CASE 3). PV Characteristic is Shown for 100%, Shading on Panel 7 & 8.

CASE 4: When two panels (No. 4 and 7) in a corner of the 3×3 array are shaded while other seven panels are working under normal insolation condition as shown in Fig. 5(c). The characteristic shows multiple peak points.

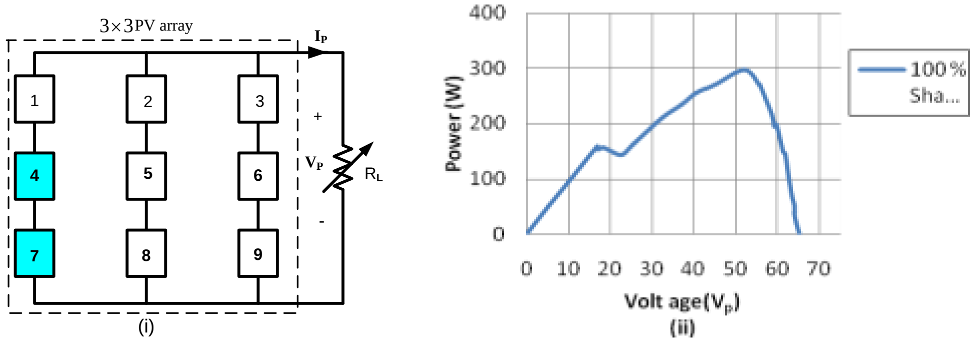

Fig. 5 (C) A 3×3 PV Array Showing Configurations Having Nine Panels Connected In Series-Parallel Arrangement with Two Panels in Series are Shaded (CASE-4). PV Characteristic is Shown for 100% Shading On Panel 4 & 7.

CASE 5: The three panels (No. 4, 7 and 8) in a corner of the 3×3 array are shaded (two from first string and one from second string) due to obstruction, while other 6 panels are working under normal insolations as shown in Fig. 5(d). The characteristic shows three peak points.

CASE 6: The three panels numbered as 4, 7 and 8 of an 3×3 array are shaded due to obstruction are reconfigured (one from each string) and other 6 panels are working under normal insolations condition as shown in Fig. 5(e). A four pole double throw (FPDT) switch is employed (Fig 5(e)) for reconfiguration of PV panels. The characteristics shows single peak point and output power is more than that obtained from case 5 when insolation on shaded PV panels is zero. The characteristics obtained for case 2 to 6 cannot be represented simply by exponential equation like Eqn. (1) and needs the mathematical expression for analysis and control. The representation is detailed in following section.

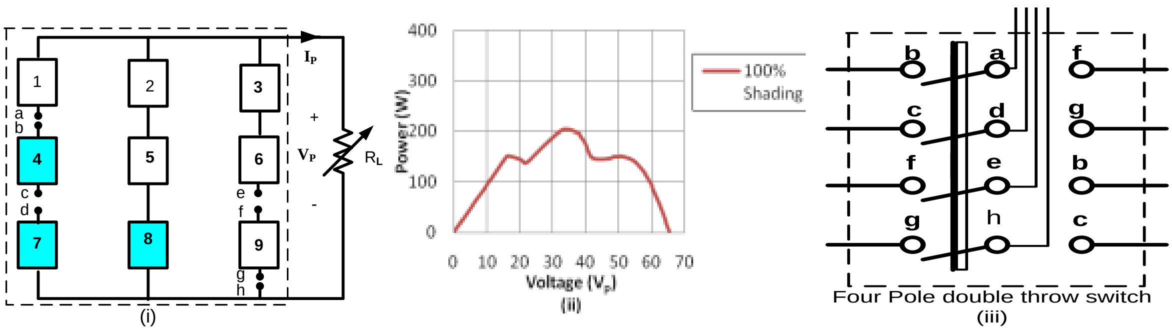

Fig. 5 (D) 3×3 PV Array Showing Configuration Having Nine Panels Connected in Series-Parallel Arrangement with Three Panels (Panel 4, 7 & 8) Shaded (CASE 5). the PV Characteristic is Shown for 100% Shading on Panel 4, 7 & 8.

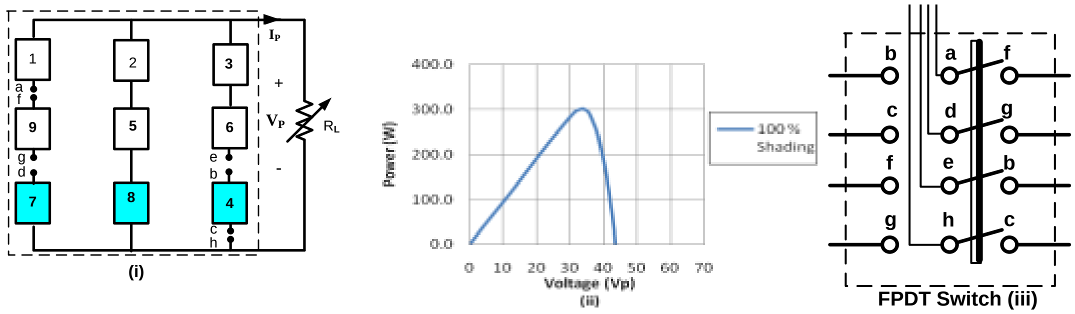

Fig. 5 (E) 3×3 PV Array Showing Configuration Having Nine Panels Connected in Series-Parallel Arrangement with Three Panels (Panel 7, 8 & 4) Shaded (Reconfigured) (CASE 6). The PV Characteristic is Shown for This Case For 100%, Shading on Three Panels.

Table II Design Parameters of Boost Converter

S. No.	Input voltage	V_i	10-70 V
1	Output voltage	V_o	10-150 [V]
2	Switching frequency	f_S	10 [kHz]
3	Main inductor	L_B	10 [m H]
4	Output capacitor	C_0	470 [µ F]
5	Input capacitor	C_i	50 [µ F]
6	Power	P	450 W

III. PROPOSED MODEL

For panels with or without partial shading of photovoltaic system as shown in CASES 1-6, the relationship between P and V is proposed have as follows:

$$P=\left\{\begin{array}{l} a_1\sin(b_1V+c_1)+a_2\sin(b_2V+c_2)+a_3\sin(b_3V+c_3) \\ +a_4\sin(b_4V+c_4)+a_5\sin(b_5V+c_5)+a_6\sin(b_6V+c_6)\end{array}\right\}\{u(V)-u(V-V_{max})\} \quad (3)$$

Where

V is the panel output voltage of 3x3 PV array;

P is the power output of 3x3 PV array;

V_{max} is the maximum possible voltage generated by PV system.

a_1, a_2, a_3, a_4, a_5 and a_6 are constants having dimensions of power.

b_1, b_2, b_3, b_4, b_5 and b_6 are constants having dimensions of radians/volt

c_1, c_2, c_3, c_4, c_5 and c_6 are constants having dimensions of radian.

This representation is called sine model for PV array in this paper and it is suitable for PV system with or without shading provided the coefficients a_x, b_x and c_x are correctly known. The power P, the voltage V and current I are directly related, therefore a similar equation between I and V can also be written and may represent its model. This form of equation has advantage over Eqn. 1 which is mixed equation and difficult to solve. The sine model shall also reduce the solving time for iterative control algorithms such as PSO technique used by some researchers [8].

IV. SIMULATION OF A PV ARRAY

Using MATLAB/Simulink software the PV array system is simulated. Fig. 6 shows the schematic diagram of complete system, while Fig. 7(a) represents the simulation of complete PV system along with boost converter connected to load. Fig 7(b) shows the schematic diagram of subsystem for simulation of BP-350 photovoltaic panel which employs parameters like series resistance, shunt resistance and reverse saturation current obtained from [1]. Fig.7 (c) shows the schematic diagram of subsystem for simulation of boost converter which employs parameters obtained from Table II. DC-DC boost converter act as interface between PV generating system and load.

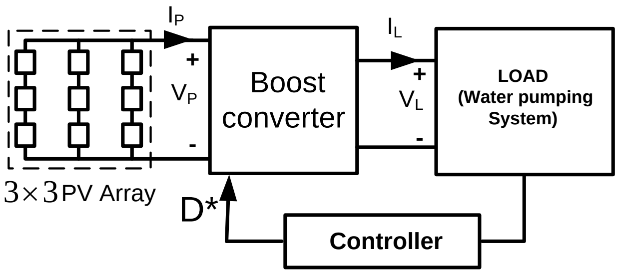

Fig. 6 Block Diagram Showing PV Array Connected to Load Through Boost Converter

The operating point of PV array at different load conditions is controlled by DC-DC converter. By varying the duty ratio of the converter, the load matching is obtained. Fig. 3 shows the circuit of boost converter used for changing operating point on P-V characteristics. TABLE II shows the design specifications of boost converter and parameters which are employed for simulation. The output voltage of boost converter is function of duty ratio of switching signal. The output voltage of boost converter is given by equation

$$V_{op} = \frac{1}{1-D} V_{ip} \tag{4}$$

Where

D is duty ratio.

V_{ip} is input voltage for converter

V_{op} is output voltage for converter

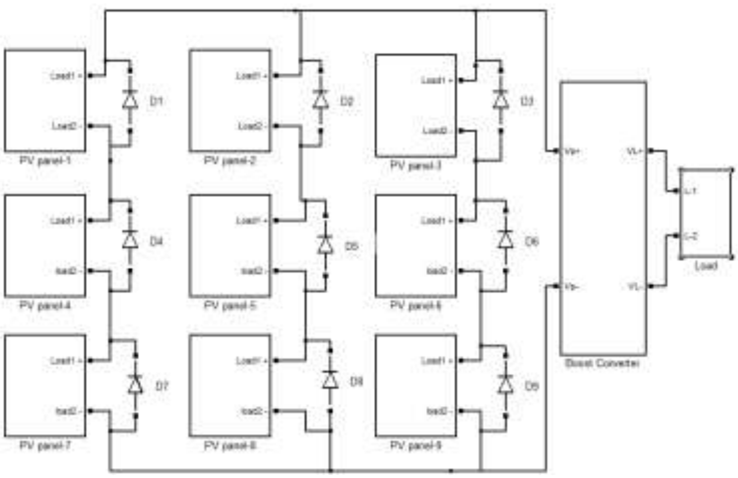

Fig. 7(A) Simulation Model of 3×3 PV Array Connected in Series Parallel Arrangement and Connected to Load Through Boost Converter

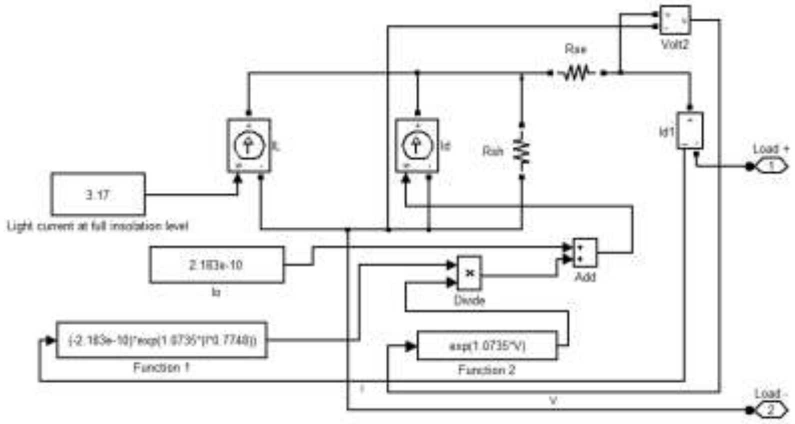

Fig. 7(B) Simulation Model of One PV Panel Fed From Constant Insolation

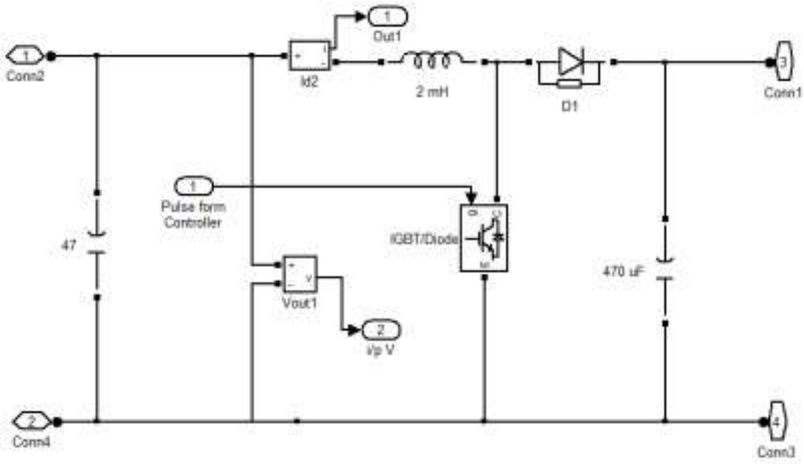

Fig. 7(C) Simulation Model of Boost Converter Employed in The PV Based System

4.1 Simulation of Proposed Model

From the values of constants shown in Table V, Eqn. 3 is employed as proposed sine model for the shading condition of CASE V. This model of 3×3 PV array connected in series parallel arrangement during shaded condition is connected to load through boost converter. Fig. 8(a) shows the schematic diagram for simulation of proposed model of 3×3 PV array connected in series parallel arrangement when three panels are shaded (CASE V). Fig. 8(b) shows the schematic diagram of subsystem for simulation of Eqn. 3 employing parameter from Table V (a). The proposed model is simulated and P-V curve is plotted as shown in Fig. 9 and compared with PV curve obtained from actual model.

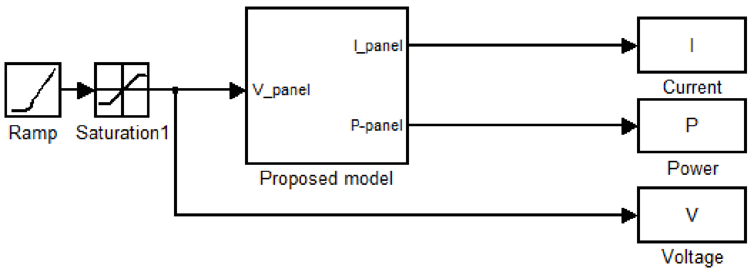

Fig. 8(A) Simulation of Proposed Model of 3×3 PV Array Connected in Series Parallel Arrangement When Three Panels are Shaded

V. RESULTS AND DISCUSSION

Fig. 3 has shown the I-V and P-V characteristics of 50 W single PV panel given by manufacturer for constant temperature 25^{0}C and constant insolation 1000 W/m^2 operation. The electrical characteristics is non linear as given by Eqn. 1. Fig. 4 shows the 3×3 PV panel array connected in series-parallel arrangement. The PV array is subjected to 100% shading condition and its characteristics is explained by considering different cases as shown in Fig 5(a) to Fig. 5(e). The P-V curves shows that the multiple peak points are formed for different shading cases and it becomes more complex to control the operating point. The MPPT techniques fail to track GMPP with normal perturbation and observation method. The operating point may become stable at local MPP which shall reduce the overall efficiency of PV system. To resolve the said problem, the sine model is proposed as shown in Eqn. 3, for predicting the GMPP. The parameters of proposed model and the observed root mean square error (RMSE) for each shading case in comparison with detailed simulation are shown in Table IV (a) and IV (b).

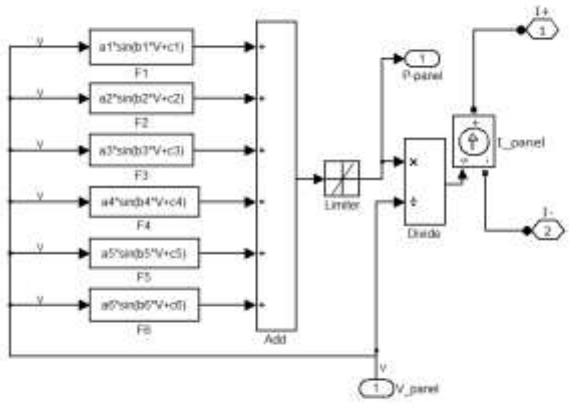

Fig. 8 (B) Simulation of Proposed Model of 3×3 PV Array (CASE 5) Employing Eqn. 3 and Constant Parameters From Table V (A)

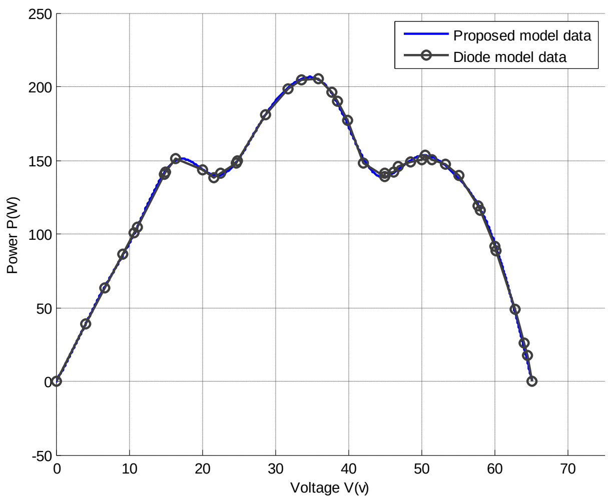

Fig. 9 The P-V Characteristic Obtained From Single Diode Model and Proposed Model for The Case When Three Panels are Shaded as Shown in Fig. 5(D)

Table III. Table Showing Values Of Voltage, Current And Power At Different Load Conditions for PV Array with Different-Panels 100% Shaded.

No Shading (CASE 1)			1-Panel Shaded (CASE 2)			2-Panels Shaded (CASE 3)			2-Panels Shaded (CASE 4)			3-Panels Shaded (CASE 5)			3-Panels Shaded(CASE-6)		
V_P	I_P	P	V_P	I_P	P	V_P	I_P	P	V_P	I_P	P	V_P	I_P	P	V_P	I_P	P
0	9.51	0	0	9.506	0	0	9.51	0	0	9.5	0	0	9.51	0	0	9.51	0
3	9.51	28.53	5	9.506	47.53	10	9.51	95.1	5.23	9.51	49.737	4.009	9.62	38.55	4	9.51	38
7	9.51	66.57	10	9.506	95.06	15	9.51	142.65	10	9.45	94.5	6.683	9.51	63.55	7	9.51	66.6
9.51	9.51	90.44	15	9.506	142.59	20	9.51	190.2	16.82	9.45	158.94	9.161	9.424	86.33	10	9.51	95.1
19.02	9.51	180.88	20	9.506	190.12	29.64	9.435	279.65	17.01	9.007	153.2	10.68	9.401	100.4	13.76	9.51	130.9
23.75	9.501	225.64	24.52	9.506	233.08	31.78	9.29	295.23	18.2	8.572	156.01	14.85	9.453	140.37	17.13	9.51	162.9
28.52	9.507	271.13	32.89	9.312	306.27	33.2	9.087	301.68	19.93	7.582	151.1	16.34	9.263	151.35	17.16	9.499	163
33.28	9.508	316.42	35.75	8.894	317.96	34.78	8.663	301.29	22.73	6.35	144.33	20.07	7.167	143.84	23.84	9.507	226.6
38.02	9.502	361.26	37.75	8.36	315.59	36	8.17	294.12	25.42	6.4	162.68	21.6	6.386	137.93	29.35	9.447	277.3
38.84	9.474	367.97	40.5	7.341	297.31	39.24	6.19	242.89	32.44	6.492	210.6	22.48	6.28	141.17	31.8	9.284	295.2
42.5	9.444	401.37	42.44	6.48	275.01	40.31	5.348	215.57	37.19	6.323	235.15	28.66	6.319	181.1	32.11	9.247	296.9
43.26	9.408	406.99	46.85	6.215	291.17	41.07	4.712	193.52	40.56	6.34	257.15	33.63	6.072	204.2	34.05	8.846	301.2
44.45	9.432	419.25	50.76	5.935	301.26	41.82	4.049	169.32	45	6	270	37.73	5.199	196.15	35.41	8.322	294.7
50.86	8.878	451.53	53.11	5.549	294.7	42.52	3.411	145.03	52.04	5.715	297.4	39.85	4.44	176.93	36.39	7.782	283.2
52.72	8.426	444.21	54.68	5.163	282.31	44.91	3.142	141.1	55.67	4.842	269.55	42	3.519	147.79	37.17	7.252	269.6
58.23	5.823	339.07	56.74	4.486	254.53	49.25	3.046	150.01	58.7	3.669	215.37	48.43	3.079	149.11	38.54	6.092	234.8
60.83	3.464	210.71	58.1	3.936	228.68	50.87	2.963	150.72	59.3	3.302	195.8	50.07	3.011	150.76	40.53	3.981	161.3
62.02	2.928	181.59	59.17	3.455	204.43	52.32	2.853	149.26	59.6	3.33	198.46	51.44	2.927	150.56	41.12	3.27	134.5
62.14	2.767	171.94	61.24	2.417	148.01	53.78	2.695	144.93	61.74	2.366	146.07	55.06	2.532	139.41	41.88	2.31	96.7
62.58	2.519	157.63	62.2	1.892	117.68	56.25	2.331	131.11	62.72	1.662	104.24	57.74	2.058	118.82	42.14	1.979	83.4
63.07	2.273	143.35	62.82	1.541	96.8	57.08	2.177	124.26	63.3	1.1	69.63	58.01	1.994	115.67	42.34	1.714	72.6
64.4	0.918	59.11	63.38	1.214	76.94	60.84	1.315	80	64.03	0.8373	53.61	60.21	1.476	88.86	43.11	0.67	28.94
64.46	0.8595	55.4	63.81	0.9621	61.39	63.11	0.6864	43.31	64.08	0.6	38.44	62.79	0.7791	48.91	43.19	0.55	23.97
65.04	0.3252	21.15	64.54	0.5247	33.86	65.3	0.035	2.28	64.5	0.3	19.35	64.081	0.4026	25.79	43.55	0.05	2.3
65.32	0.06532	4.26	65.4	0	0	65.35	0	0	65.2	0	0	64.51	0.2757	17.78	43.56	0	0

Table IV (A) Sine Model Parameters for P-V Characteristics for Different Cases (1-6)

Sine model parameters	CASES					
	CASE 1	CASE 2	CASE 3	CASE 4	CASE 5	CASE 6
a_1	442.5	316.8	254.1	257.5	360.7	340
b_1	0.057	0.045	0.0501	0.046	0.064	0.094
c_1	-0.408	-0.152	-0.079	-0.157	0.011	-0.515
a_2	529.6	43.46	37.38	74.23	448.9	1027
b_2	0.142	0.219	0.195	0.179	0.096	0.192
c_2	-2.058	4.786	2.093	-2.779	2.891	1.338
a_3	3.393	-1295	24.47	54.53	277.9	886
b_3	0.427	0.305	0.305	0.294	0.115	0.199
c_3	-1.85	-0.564	-2.701	-3.023	5.751	-1.918
a_4	669.9	1252	14.57	35.44	29.78	1.704
b_4	0.132	0.305	0.49	0.306	0.201	0.888
c_4	1.3	5.7	-3.731	-0.392	0.683	-5.85
a_5	0	105.4	7.619	1.995	15.53	0
b_5	0	0.251	0.722	0.454	0.343	0
c_5	0	0.742	-1.169	-0.435	8.717	0
a_6	0	3.172	5.379	111	3.946	0
b_6	0	0.664	0.993	0.145	0.586	0
c_6	0	-0.123	-6.845	1.012	-0.196	0
RMSE	8.007	17.3	3.163	10.53	4.03	1.293

Table IV (B) Sine Model Parameters for I-V Characteristics for Different Cases

Sine model parameters	CASES					
	CASE 1	CASE 2	CASE 3	CASE 4	CASE 5	CASE 6
a_1	16	11.79	7.418	8.996	9.752	15.67
b_1	0.0482	0.04209	0.029	0.027	0.032	0.071
c_1	0.411	0.6053	0.787	1.26	1.284	0.457
a_2	0.433	2.46	3.351	1.051	2.051	0.535
b_2	0.183	0.089	0.061	0.137	0.084	0.262
c_2	3.424	2.296	0.919	7.088	2.459	3.701
a_3	6.887	0.278	1.0593	0.521	0.875	0.0822
b_3	0.0845	0.343	0.216	0.081	0.287	0.545
c_3	2.676	-4.034	1.164	2.851	-3.361	1.956
a_4	0.542	0.137	0.478	0.341	0.627	0.0615
b_4	0.394	0.501	0.35	0.478	0.304	0.607
c_4	1.074	-4.291	-4.374	0.219	4.703	4.053
a_5	0.5143	0.669	0.201	34.43	0.192	6.667
b_5	0.405	0.209	0.498	0.734	0.539	0.128
c_5	3.92	1.676	-4.074	1.775	-0.858	2.7
a_6	0	0.074	0	0.476	0.093	0.0021
b_6	0	0.709	0	0.293	0.626	1.329
c_6	0	5.472	0	-2.526	-2.262	7.303
RMSE	0.1396	0.03754	0.1549	0.1699	0.08378	0.01165

It is observed from the obtained characteristics that the total maximum power output with shading is less than the actual power capacity of PV array. This difference of power is because of shading loss. This shading loss is also proportional to the position of shaded panel in an array. Fig. 5(e) shows that by changing switch position of FPDT switch from *b-f-c-g* to *f-g-b-c*, the position of shaded PV panels is changed and the PV characteristics shows only single peak. This reconfiguration of panels makes it suitable for MPPT with P &O method.

VI. CONCLUSIONS

This paper has discussed the performance of a 3×3 PV array at different shading conditions. It has considered the six different cases (I to VI) of shading of a 3×3 PV array and the P-V characteristics are plotted at for these shading conditions. The shading loss due to shading effect can be easily determined. Considering the case V (shown in Fig 5(d)), it is revealed that the power output of PV array can be improved by reconfiguration of PV panels connection, as shown in Fig 5(e). The paper has also proposed the model given by Eqn. 3. When different panels are shaded the characteristic is compared from model and detailed simulation of PV array system. The simulation result is shown in Fig. 9 which indicates that the proposed model PV characteristic is matching with the diode model based PV array for shading condition in case 5. The same is also validated for all cases and RMSE is obtained. Hence proposed model can be used to predict the position of local and global peak power points for maximum power point operation thereby simplifying the control algorithm in real time.

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