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Evaluating the Role of Hour Angle in Photovoltaic Systems Amidst Various Partial Shading Conditions

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Abstract *– Partial shading presents a significant challenge to the performance and efficiency of solar photovoltaic (PV) systems, impacting their power output and overall reliability. As a result, shaded cells experience reduced current production, leading to mismatch losses, hot spots, and potential damage to the panels. This paper analyzes the performance of a 3kW photovoltaic system based on the hour angle of the sun. The effect of hour angle under partial shading contributes to a better understanding of PV system behavior under different conditions, which is important for integrating solar energy into the grid and ensuring its stability and reliability. The variation of irradiance is divaricated in three hour spans. The partial shading variations over the solar panels during the sunlight hours modifies the casted shadows from radiation obstructing structures impacting the performance of the solar panels. Maximum power point tracking (MPPT) technique has been used to enhance the power during different partial shading conditions in MATLAB/ Simulink.*

Keywords – Duty Cycle, MPPT, Partial Shading, Photovoltaic Array, Solar hour angle.

1. INTRODUCTION

Partial shading occurs due to obstructions such as buildings, trees, or cloud cover, leading to non-uniform irradiance on solar panels. PV modules are combined in series-parallel configurations to obtain the desired output voltage and current levels. During partial shading, the maximum power of a photovoltaic system can drop drastically, which significantly reduces the energy yield of the photovoltaic system.

The study in [1] examined the scenario in which a single photovoltaic plant experiences non-uniform irradiance, or partial shadowing, and it suggested a method for determining the one-diode model's five parameters utilizing only the manufacturer's supplied data.

On the output P-V characteristics, the shaded PV arrays produce a global peak as well as several local peaks. The shading pattern and array design determine how many local peaks there are. The obtained results in [2] further show that the presence of shaded modules on the same assembly can significantly minimize the global peak. Moreover, the global peak's value exceeds that of the local peaks.

The researchers have compared the performance of a partially shaded PV module with bypass diode and battery energy storage in parallel with the module. It is established in [3] that the setup complemented by battery energy storage fares better in mitigating partial shading effects on the power and voltage outputs. It is also indicated that larger the battery capacity better will be the performance of the overall setup.

The work presented in [4] indicates that there could be multiple MPPs for a given solar PV module which occur at different partial shading conditions. Mathematical equations for estimating voltage at MPP are presented which can be helpful in tracking global MPP using appropriate algorithm.

The authors suggest using a reconfigurable PV module using embedded complementary metal-oxide-semiconductor which can be reprogrammed according to the user in a partially shaded scenario. The maximum power reported for the proposed method exceeds the maximum power offered by other topologies like series-parallel and honeycomb configurations [5].

The researchers in [6] have highlighted that bypass diodes which turn on during partial shading conditions marginally help the AC converter while achieving local MPP but are not helpful in eliminating local hotspots creation in the PV panels. It has also been stated that the worst shading condition occurs at 46.5% value.

The paper [7] discusses the application of voltage gradient method for the detection of occurrence of partial shading phenomena and its withdrawal. The detection of shading on various sections of the panel can be used to activate appropriate measures to track the MPP.

The efficacy of Fuzzy Logic based controller with Perturb and Observe algorithm for tracking MPP has been suggested in [8] for faster response under dynamic environmental conditions.

The analysis based on hour angle of sun under partial condition is not considered in any article. The hour angle, which indicates the sun's position relative to solar noon, affects the amount of sunlight hitting PV panels. By considering the hour angle under partial shading

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optimizes the panel orientation and tracking systems to enhance energy capture throughout the day. Secondly, shading analysis benefits from this consideration helps to identify the impact of different shading patterns on PV panel performance. Thirdly, accurate performance prediction and modeling, incorporating hour angle and shading effects, are essential for planning and optimizing the integration of solar energy into power grids.

In this paper this research gap is filled by considering the hour angle of the sun under partial shading condition. The impact of partial shading on PV system has been studied for a full day at a particular geographic location. The solar irradiance during sunlight hours have been divided in 4 cases with different shading patterns on the 9 panels used in the array. These 4 cases are decided based on hour angle of the sun. The MPPT technique has been to extract maximum power from the PV system.

2. SINGLE DIODE MATHEMATICAL MODEL OF SOLAR CELL

Many mathematical models have been suggested in literature, out of which single diode, shunt and series resistance model, shown in Figure 1, is near to actual and fairly easy to simulate.

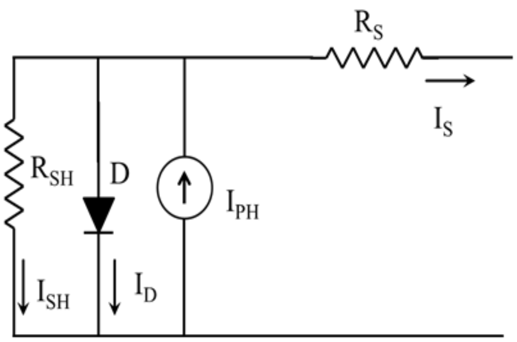

Fig. 1. Single diode-two resistance model of solar cell.

The photon induced current of solar cell is represented by current source I_{PH}. R_{SH} and R_S represent shunt and series resistances. As seen in Figure 1, I_{SH} and I_D currents are bypassed and by applying Kirchhoff's current law, we get the current supplied by solar cell (I_S) using equation (1).

$$I_S = I_{PH} - I_D - I_{SH} \quad (1)$$

$$I_S = I_{PH} + I_0 \left[e^{\frac{V + I_S R_S}{a}} - 1 \right] - \frac{V + I_S R_S}{R_{SH}} \quad (2)$$

Substituting the values of I_D and I_{SH} in equation (1) we get the final expression for current of solar cell as shown in equation (2).

Here V is the terminal voltage of cell and a= nV_T, n=Ideality Factor, V_T =Thermal Voltage = kT_{cell}/q.

Where k represents Boltzmann's constant =1.38E-23 Joule/Kelvin, T_{cell} is working temperature of cell and q is electronic charge= 1.6E-19.

The current provided by the solar cell depends on the irradiance and cell temperature as given in equation (3).

$$I_{PH} = \left(I_{PH,n} + K_1 (T - T_n) \right) \frac{G}{G_n} \quad (3)$$

Where $I_{PH,n}$ is the reference short-circuit current of cell, T is solar cell temperature, T_n is cell reference temperature, K_1 is short-circuit current temperature coefficient, G is solar insolation in W/m^2 and G_n is reference solar insolation in W/m^2.

The power (P) available from the solar panel can be expressed as given in equation (4).

$$P = VI_S - VI_0 e^{\frac{V}{V_T}} \quad (4)$$

3. SYSTEM CONFIGURATION AND CHARACTERISTIC GRAPH

The system includes a 3*3 PV system in which 1 array consists of 72 cells i.e. 12x6 cells, MPPT controller, boost converter, filters, a control system and load. SunPower SPR-X20-250-BLK model is used to simulate the model. The model parameters are given in Table 1.

Table 1. Parameters of simulated module.

Parameter	Value
Maximum Power (W)	249.952
Voltage at MPP (V)	42.8
Current at MPP (A)	5.84
Open circuit voltage(V)	50.93
Short circuit current (A)	6.2
Cells per module	72
Light generated current (A)	6.2119
Diode saturation current	1.3593E-11
Diode ideality factor	1.0262
Shunt resistance (ohms)	420.5449
Series resistance (ohms)	0.37748
Temperature coefficient of open circuit voltage (%/ºC)	-0.291

The panel power is calculated by multiplying its current and voltage. The standard test condition to assess the efficiency of the PV energy system is used. The change in irradiance and temperature affects the voltage and current output PV solar panel. Each panel is generating an open circuit voltage of 132 V and short circuit current of 6 A.

4. PV ARRAY MODULE CONFIGURATION

The irradiance is calculated in real time from sunrise to sunset tabulated in Table 2. The time zone is divided into four slots from 06:00 am to 6:00 pm.

The DC load is connected for the analysis purpose. The solar power and load power, solar voltage and load voltage, and solar current and load current are analyzed. The MPPT is used to obtain the maximum power under different shading condition.

Table 2. Irradiance distribution on the panels in W/m².

	Panel 1	Panel 2	Panel 3	Panel 4
6-9am	435.8	235	235	370
9-12n	652.5	600	600	652.5
12-3pm	843.67	843.67	843.67	843.67
3-6pm	678.67	600	678.67	500

	Panel5	Panel6	Panel7	Panel8	Panel 9
6-9am	335	435.8	400	435.8	435.8
9-12n	652.5	652.5	652.5	652.5	652.5
12-3pm	843.67	843.67	800	843.67	800
3-6pm	650	500	450	678.67	450

5. RESULTS AND DISCUSSION

PV array characteristic under different partial condition is described in this section. Power, voltage and current of source and load with respect to time are represented in the graph. The effect of shading pattern is important under different irradiance and possible conditions. The time zone is divided into different slots and according to that slot irradiance is calculated. The effect of irradiance under different slots are analyzed.

Figure 2 exhibits the maximum power condition for Cases 0, 1, 2, 3 & 4 as discussed in Table 2. For Case 0 the maximum power is 2248.2 W at 128.49 V.

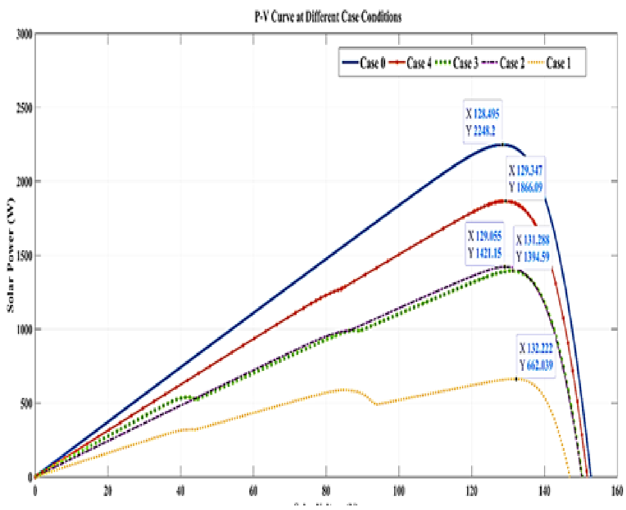

Fig. 2. PV curve at different shading case condition.

Maximum power is 662.04 W at 132.22 V for Case 1. Maximum power is 1421.15 W at 129.06 V for Case 2. Maximum power is 1394.59 W at 131.29 V for Case 3. Maximum power is 1866.09 W at 129.35 V for Case 4.

5.1 *CASE 0: No Shading Condition*

The output power of solar PV and load are calculated using the Simulink model keeping irradiance value 1000 W/m². The solar output is obtained 2.2 KW under no shading condition. The load is getting same power with the help of MPPT technique. The MPPT is enabled at 0.3 sec of the simulation run time.

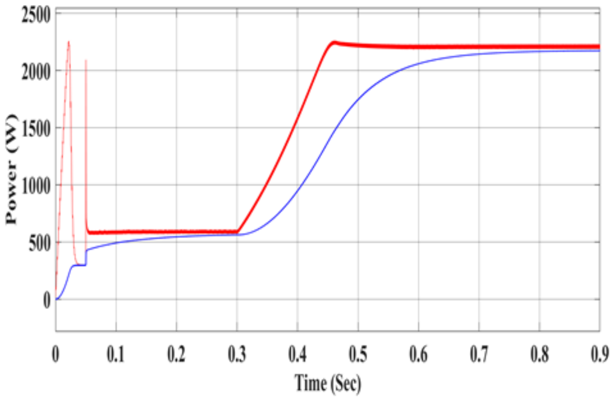

Fig. 3. Solar power and load power in no shading conditions.

The first cycle shows the maximum power that can be obtain from solar array system. When the load is connected to the system the power is 560 watt which is shown before 0.3 sec. The solar power, voltage and current are shown with the solid line where as load power, voltage and current are shown with dotted line. It is observed that solar power and load power is stated to increase when the MPPT is ON state. The solar and load power reaches to its maximum value by the use of MPPT which was desirable as shown in Figure 3.

The solar voltage and load voltage at the beginning was 45 V and 200 V respectively. The voltage profile improves due to the use of MPPT. The voltage of solar increase to the 140 V and load increases to 402 V after MPPT get switch ON as shown in Figure 4.

The solar current and load current at the beginning was 18.25 A and 2.9 A respectively. The current reduces due to the use of MPPT to maintain the power constant.

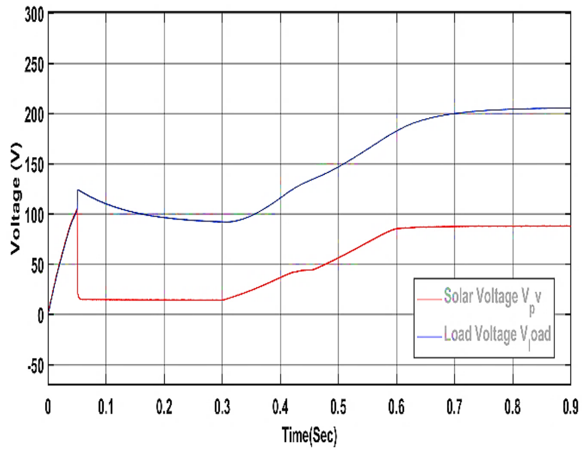

Fig. 4. Solar voltage and load voltage in no shading condition.

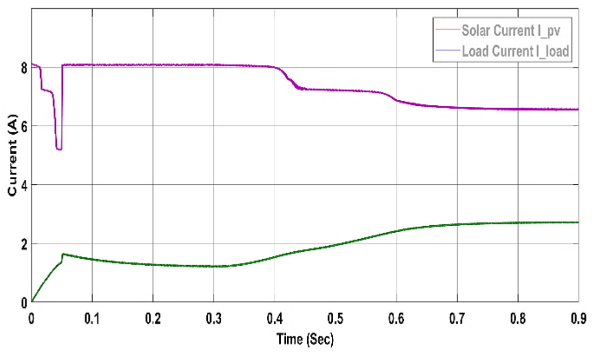

Fig. 5. Solar current and load current in no shading condition.

The current of solar increase to the 17 A and load increases to 5.89 A after MPPT get switch ON. The result obtain was quite satisfactory as the current did not drop to much and maintain its magnitude constant throughout the analysis as shown in Figure 5.

5.2 Case 1: Partial shading condition for first time zone

In Case 1, the time zone is selected as 06:00 am to 09:00 am. The real time irradiance data is taken from the Table 2. The PV array cell experience different irradiance values due to shadow of pillar. The irradiance value for case 1 is given in Table 2. The maximum solar power that can be extract from this irradiance is 590W which is shown in Figure 6.

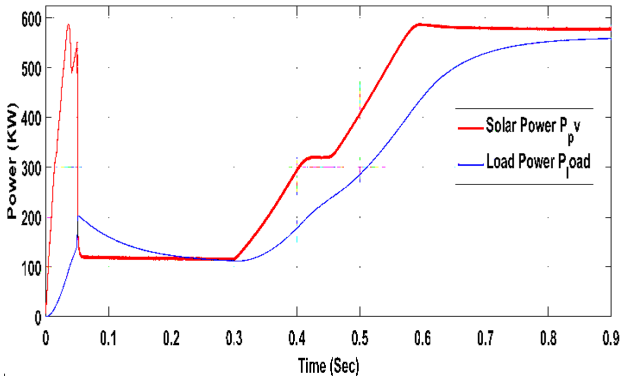

Fig. 6. Solar power and load power due to partial shading conditions in case 1.

When the load connected, the power due to solar is 120 W and constant. The solar and load power started to increase when the MPPT on after 0.3 sec. The solar power reaches to maximum value in 0.2 sec. The load power is also reaches to maximum value but it is not equal to solar power due to losses in the system.

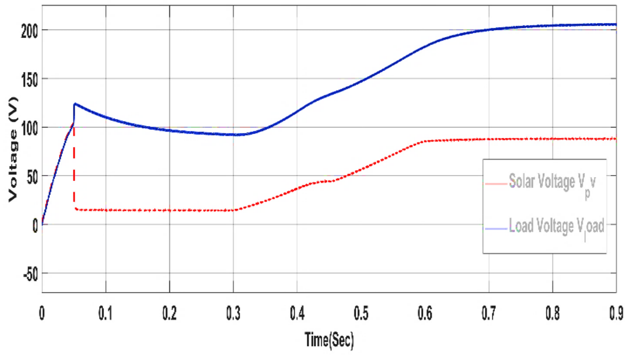

Fig. 7. Solar voltage and load voltage due to partial shading condition in case 1.

The solar voltage before the MPPT is 20 V and load voltage is 100V. the voltage increses once the MPPT is on and reaches to 85 V and 210 V respectively as shown in Figure 7.

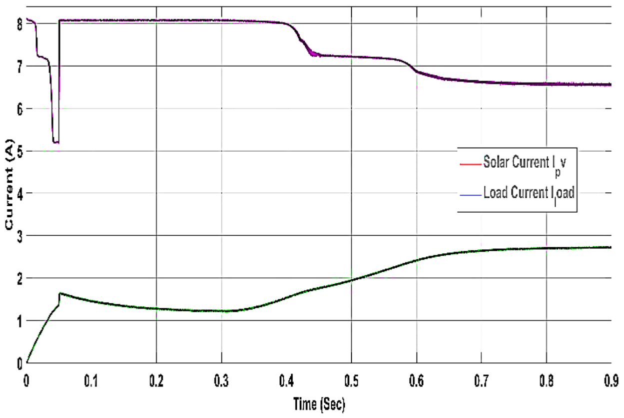

Fig. 8. Solar current and load current due to partial shading condition in case 1.

The solar current is 8A initially and reduce to 6.5 A after the MPPT get ON. The load current is 1.2 A and increase to 2.8 A and become constant as shown in Figure 8.

5.3 Case 2: Partial shading condition for second time zone

In case 2, the time zone is selected as 09:00 am to 12:00 pm. The irradiance value for the case 2 is selected from the Table 2. The solar power generated in this case is 1400W and load power is 1390 W as shown in Figure 9.

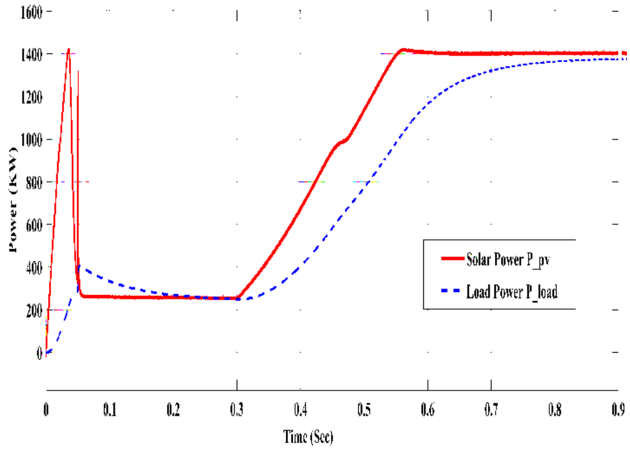

Fig. 9. Solar power and load power due to partial shading conditions in case 2.

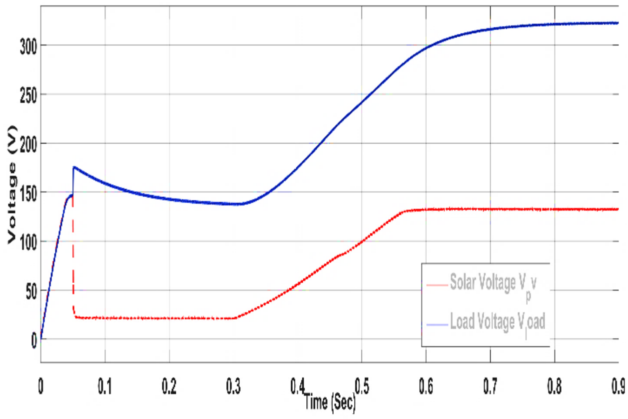

Fig. 10. Solar voltage and load voltage due to partial shading condition in case 2.

The voltage of solar PV array and load is 25V and 150 before the MPPT. The solar and load voltage increase to 135V and 325 V after the MPPT switch ON as shown in Figure 10.

The current variation under the effect of partial shading is shown in Figure 11. The initial value of the current of solar and load is 12A and 2 A. The final value of the solar and load current is 10.5A and 4.2 A respectively.

5.4 Case 3: Partial shading condition for third time zone

In case 3, the time zone is selected as 12:00 pm to 03:00 pm. The irradiance value for the case 3 is selected from the Table 2.

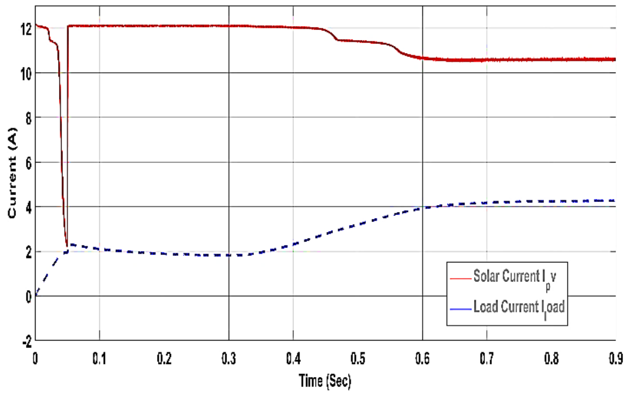

Fig. 11. Solar current and load current due to partial shading condition in case 2.

The solar power generated in this case is 1750W and load power is 1700 W as shown in Figure 12. Initial when the MPPT was not ON the solar and load power was 450W. At the time 0.3 sec the MPPT switch get ON and the power is increase to its maximum value just in 0.2 sec.

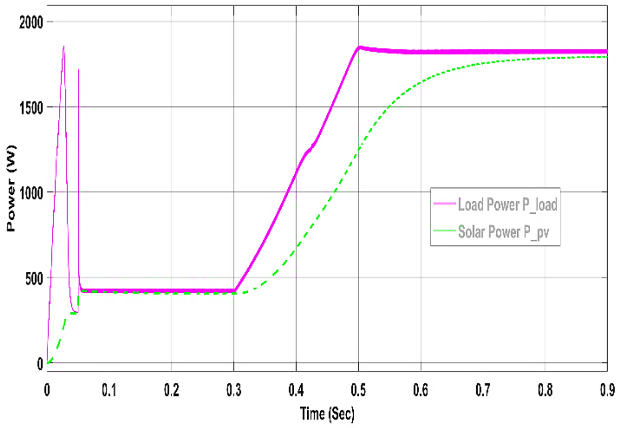

Fig. 12. Solar power and load power due to partial shading conditions in case 3.

The solar and load voltage in case 3 is obtain 45V and 175V respectively. The voltage profile get improves once the MPPT get ON after 0.3 sec. The solar and load voltage increase to 135V and 365V respectively as shown in Figure 13.

The effect of partial shading on the current variation with time is shown in Figure 14. The solar current 2.1 A and 15.8A is obtain without MPPT.

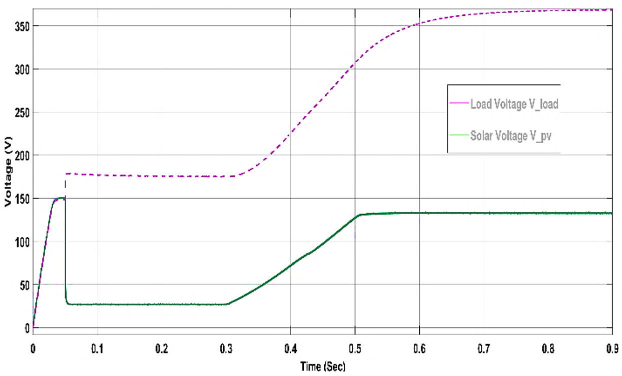

Fig. 13. Solar voltage and load voltage due to partial shading condition in case 3.

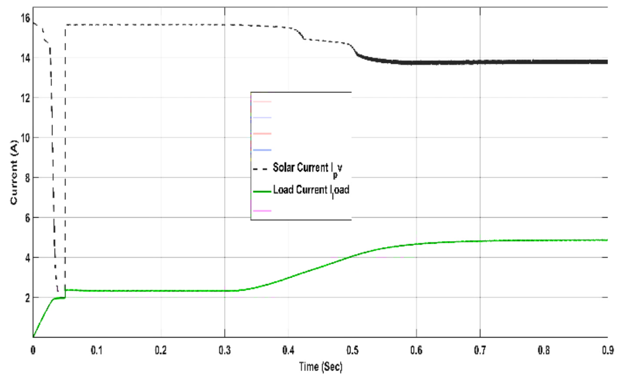

Fig. 14. Solar current and load current due to partial shading condition in case 3.

After 0.3 sec the values of current changes to maintain the maximum power on the system. The solar current value reduces a little bit i.e. 13.9 A but the load current increase to 5.5 A.

5.5 Case 4: Partial shading condition for forth time zone

In case 4, the time zone is selected as 03:00 pm to 06:00 pm. The irradiance value for the case 4 is selected from the Table 2. The solar power generated in this case is 650W and load power is 625 W as shown in Figure 15. Initially when the MPPT was not ON the solar and load power was 150W. At the time 0.3 sec the MPPT switch get ON and the power is increase to its maximum value just in 0.2 sec.

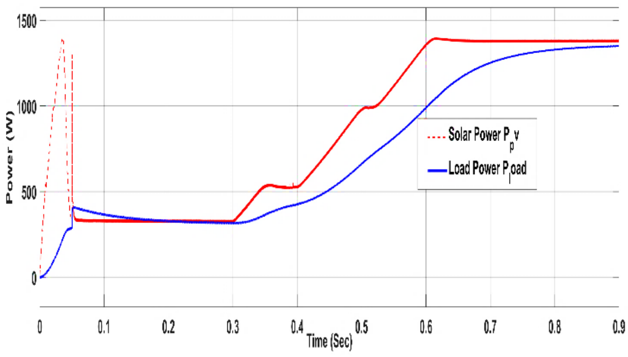

Fig. 15. Solar power and load power due to partial shading conditions in case 4.

The voltage variation of PV array and load with respect to time under partial condition is shown in Figure 16. The solar and load voltage is 15V and 105V when MPPT is OFF condition. After the 0.3 sec the voltage started to increase and settled down to 85V and 225V respectively as shown in Figure 16.

The current variation under partial shading condition is shown in Figure 17. The solar current is 9A and load current is 2.5 A respectively. Once the MPPT is ON the solar current decrease to 7.5 A and load current increase to 2.9 A to obtain the maximum power.

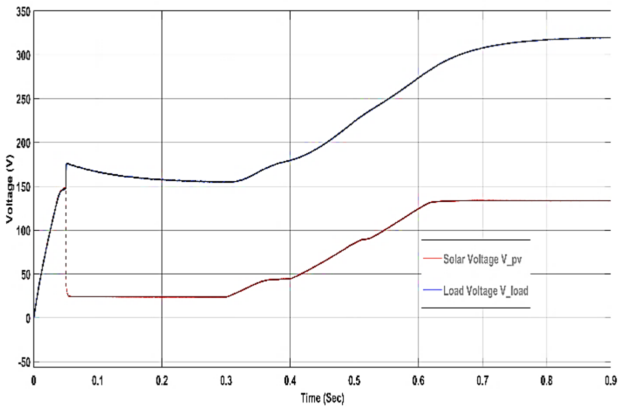

Fig. 16. Solar voltage and load voltage due to partial shading condition in case 4.

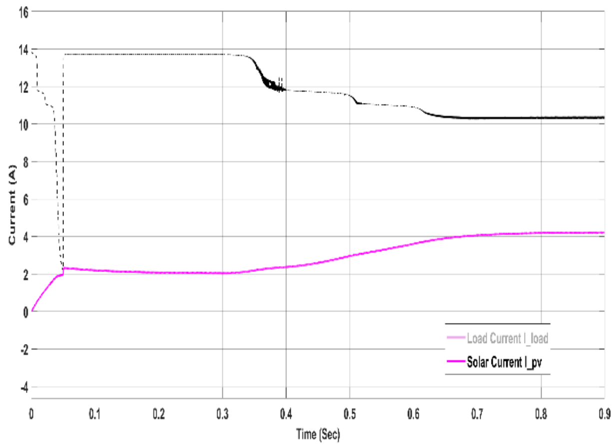

Fig. 17. Solar current and load current due to partial shading condition in case 4.

6. CONCLUSION AND FUTURE SCOPE

It is evident that partial shading decreases overall output of solar panels; however, MPPT technique compensates the decreased power output to a remarkable extent thereby allowing the connected load to function properly. The hour angle of the sun under partial shading is a significant factor in solar energy research, influencing PV system design, efficiency, economic viability, and grid integration. In this paper the analysis is perform on 3*3 PV array installed on the roof top as well as simulated on the MATLAB environments. The shading effect based on the sun's hour angle has been considered to compare hardware and simulate results. Although shading has an impact on the roof top PV array strength but the MPPT controller maintains it to the desired value. Power and voltage comparisons between the simulated results and hardware readings are consistent with minor variations. The results obtained show that once the MPPT module is enabled, the system performance enhance up to the desired level.

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