The Effect of Partial Shading on PV Characteristics and Maximum Power Point Tracking

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Abstract
PV arrays get shaded, completely or partially, by the passing clouds, neighboring buildings and power poles. Under partially shaded conditions PV characteristics get more complex with multiple peaks. Hence, it is necessary to understand them in order to extract maximum power. This paper presents a simulation study of the effects of partial shading on PV characteristics and the result of using conventional MPPT schemes (P&O) in tracking the MPP under partial shading conditions.
Keywords: Photovoltaic (PV), Maximum Power Point (MPP), Global Peak, Perturb and Observe (P&O)

1. INTRODUCTION
Global warming and energy policies have become an important topic in the international agenda in recent years, with countries trying to reduce their greenhouse gas emissions. In light of this, PV power generation has a key role to play as it is a green source, with the only emission occurring in the production of the components of the PV solar cell.

After its installation it generates electricity from solar radiation without emitting greenhouse gases. In its lifetime, PV solar cells produce more energy than that for their manufacturing. [1]

PV power generation is more expensive than other resources like wind power. To make them more competitive, research is focusing on reducing the cost of power generated by PV solar cells by increasing their efficiency. [2] Towards this end, focus is on improving the tracking of the maximum power point tracking (MPPT) algorithm by modifying the already existing algorithms leading to an immediate increase in PV power generation and consequently a reduction in its price.

The use of PV power is complicated by the non-linear nature of the characteristic I-V curve, which results in a unique point known as the Maximum Power Point (MPP) on the P-V curve. It is at this point that maximum power is generated. Its use is further complicated by the dependence of the MPP on the ambient temperature and solar insolation, which constantly vary during the day.

Given the high cost of PV power, it is of economic importance to operate the PV module at the MPP.

DC-DC converters are used in conjunction with PV modules to either increase or decrease the output. However, they also serve an important role in shifting the operating point of the module to the desired region (hence tracking MPP) by varying the duty cycle.

Various tracking schemes have been proposed to track the MPP. Among them are perturb and observe (P&O) [3], incremental conductance [4], short circuit current [5], open circuit voltage [6] and ripple correlation [7].

These techniques have been tested under uniform insolation, where the P-V curve of the PV module exhibits only one MPP for a given temperature and insolation. However, when the PV module does not receive uniform insolation (as in partial shading), the P-V curve displays multiple peaks (one of which is the global peak and the rest local peaks).

Miyatake et. al. [17] used a Fibonacci sequence to track the GP in the presence of multiple peaks. However, the method did not guarantee GP tracking under all conditions. Kobayashi et. al. [18] proposed a two stage technique for tracking the GP. In the first stage, the operating point moves to the point referred to as the load line and in the second stage, searches for the actual GP. However, in this method, if the GP lies on the left side of the load line, the operating point is shifted to 90% of V_{OC}, hence missing the GP.

2. EFFECT OF PARTIAL SHADING ON MPP
Using a Simulink model developed in MATLAB/SIMULINK software, a comparative study was carried out to investigate the effect of partial shading on the P-V, I-V characteristic curves of a solar module.

The curves of figure 1 and 2 were obtained when modeling was done for three series connected cells with uniform insolation of $1000W/m^2$.

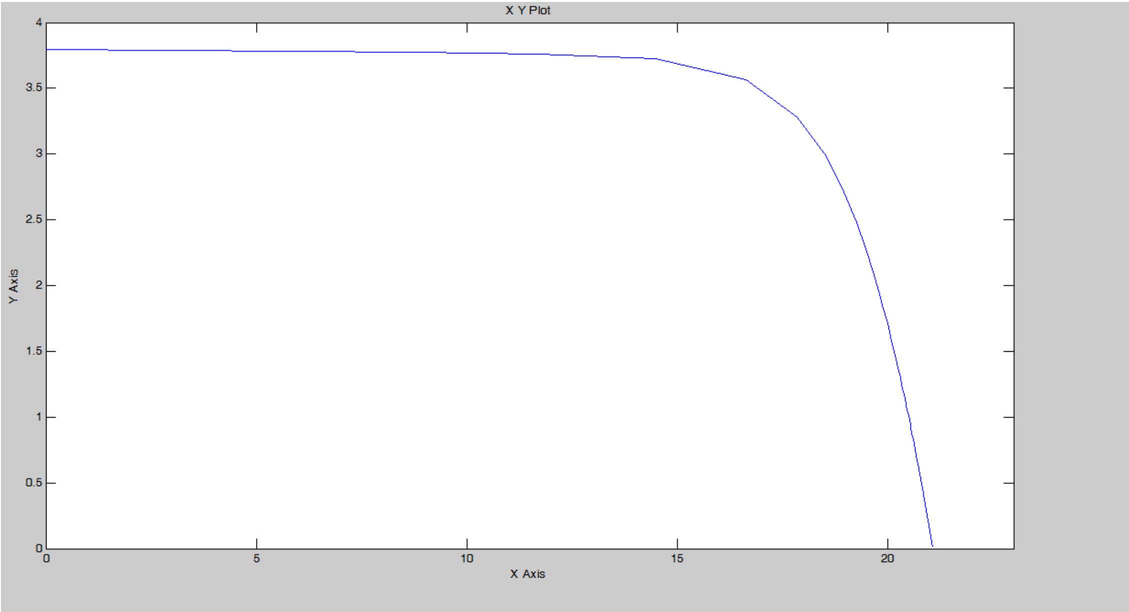

Figure 1: I-V (Current vs Voltage) Curve of Module under Uniform Insolation

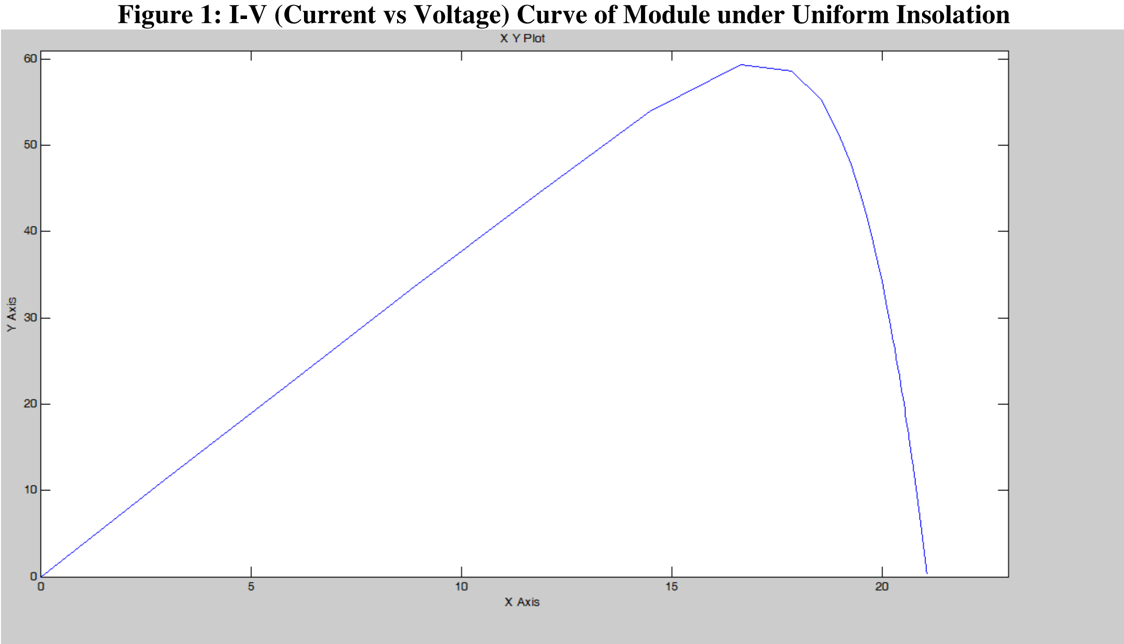

Figure 2: P-V (Power vs Voltage) Curve of Module under Uniform Insolation

The characteristic curves of figures 3 and 4 were obtained when modeling was done for three series connected cells receiving different levels of insolation at 1000W/m^2, 500W/m^2 and 250W/m^2 to simulate the effect of partial shading.

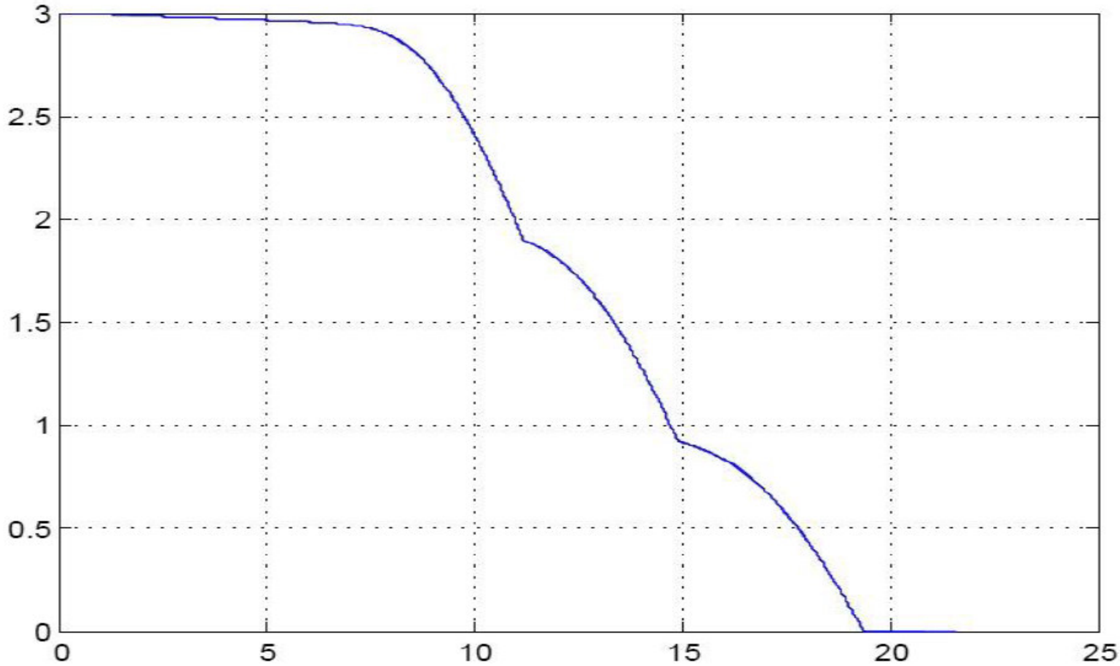

Figure 3: I-V (Current vs Voltage) Curve of Module Under Partial Shading

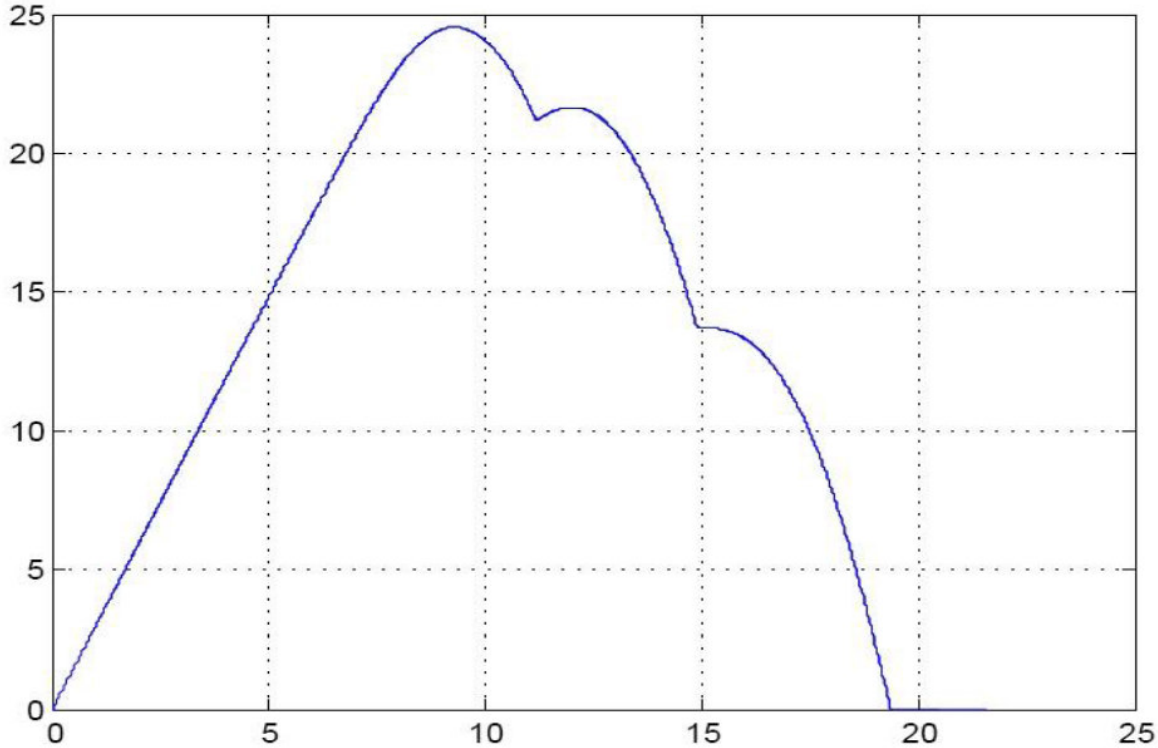

Figure 4: P-V (Power vs Voltage) Curve of Module under Partial Shading

It can be observed that the P-V curve develops multiple peaks with one peak being the global maximum and the other peaks being the local maxima. Each of these peaks has a maximum power point (MPP) with that of the global maximum being referred to as global peak and that of the local maxima referred to as local peak. The I-V curve as well develops multiple steps as compared to that obtained during uniform insolation.

The first peak occurs at 8.4V, the second peak occurs at 12.1V and the third peak occurs at 16.2V. The first peak occurs at nearly at voltage V_1=5×1.688V=8.44V, where 1.688V is 8% of the open circuit voltage (21.1V) of the module. A similar analogy can be applied to the other two peaks, which occur at nearly V_2=7×1.688V=11.816V and V_3=10×1.688V=16.88V, respectively. A significant outcome of this observation is that power peaks are displaced from each other by a multiple of 8% of the value of open circuit voltage, V_{OC}, that is, $(n \times 0.08 \times V_{OC})$.

It was observed that the magnitude of the global peak and the voltage at which it occurs is not only dependent on insolation and temperature at that particular instance but also on the shading pattern across by the solar cells.

3. MPP TRACKING USING P&O ON PARTIALLY SHADED MODULE

Using a Simulink model developed in MATLAB/SIMULINK software, a study was carried out to investigate the behavior of P&O when tracking the MPP of a solar module under both uniform insolation and partially shaded conditions. The system used two array, series connected module and a DC-DC converter modeled with its exact circuit, with a switching frequency of 10 KHz.

3.1. CASE 1: TRAPPING AT THE WRONG PEAK

The irradiance and temperature changes for this case are shown in the figure 5.

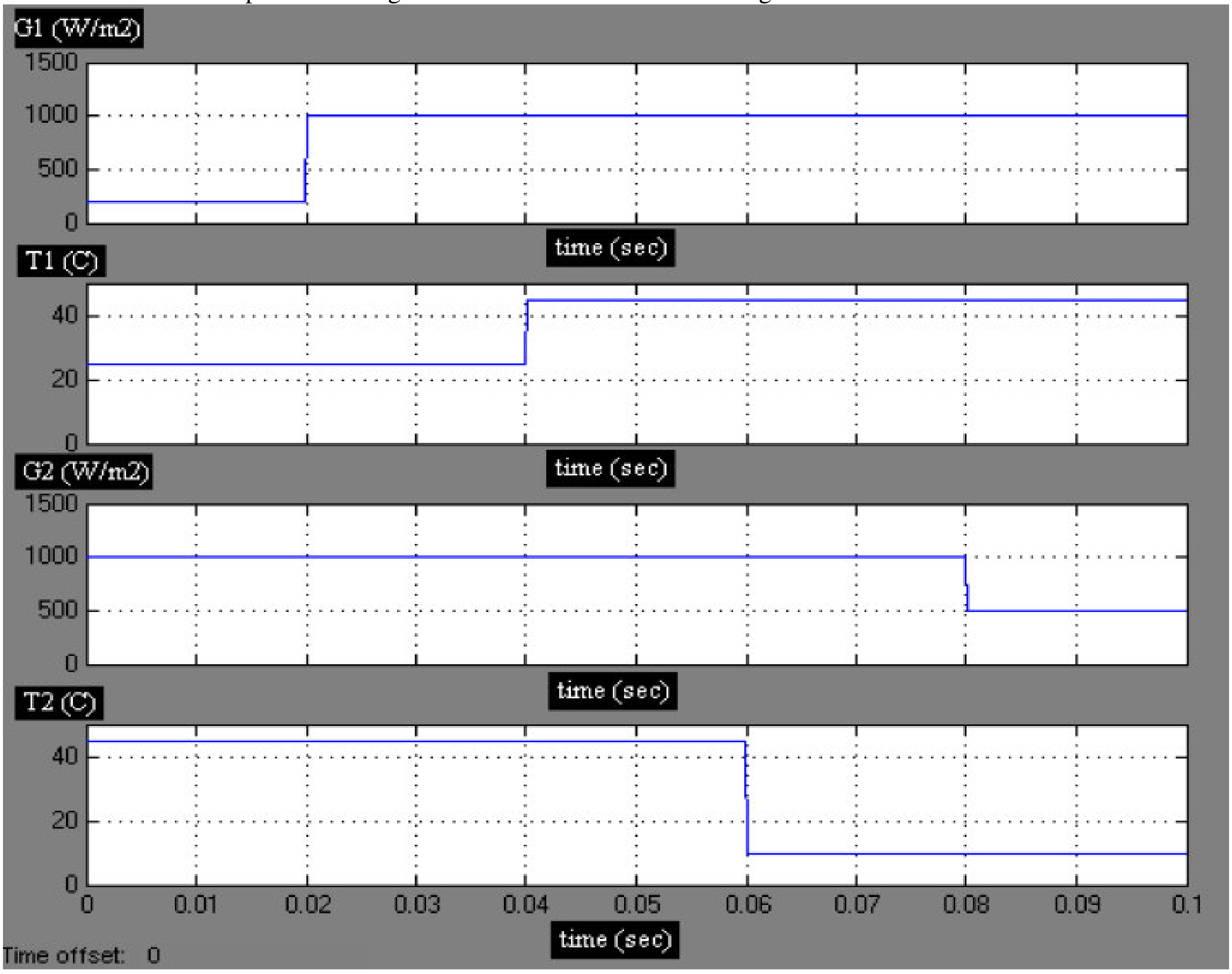

Figure 5: Temperature and Irradiance Changes for Case 1

The P-I curve of the module was generated after every 0.02 seconds, with the results being displayed as in figure 6.

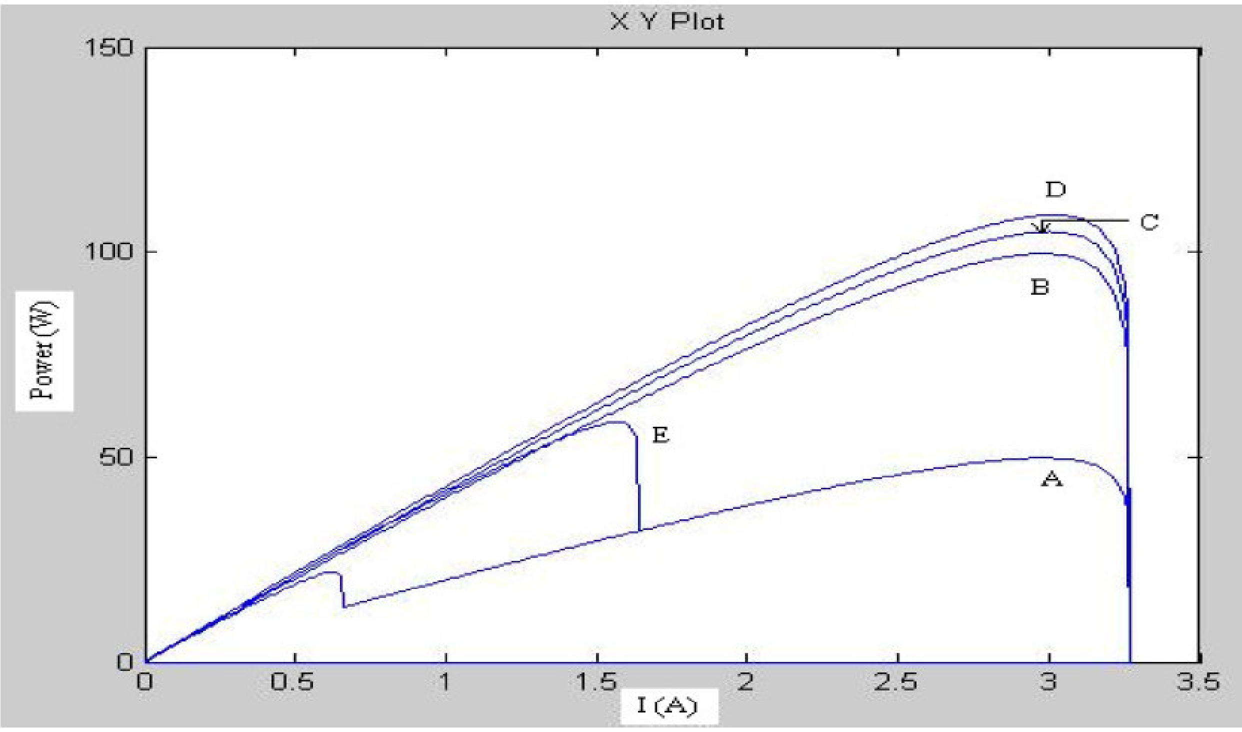

Figure 6: P-I Curve of the Module for Case 1

There are five curves (A, B, C, D and E), with each curve generated after 20ms such that curve A is generated within the first 20ms of simulation, curve B is generated in the subsequent 20ms of simulation and so on till curve E is generated. Curves A and E have multiple peaks (meaning the solar module is experiencing partial shading during the period of generation of these curves), while curves B, C and D having just one peak (meaning the solar module is experiencing uniform insolation during the period of generation of these curves).

Table 1 shows the theoretical values of Power, Voltage and Current at MPP and the actual value of Power tracked by the P&O during the entire period of simulation.

Table 1: Table of Theoretical Values of Power, Current, Voltage and Tracked Power

Time	Curve	P_{MPP} (W)	I_{MPP} (A)	V_{MPP} (V)	Tracked Power (W)
t<0.02	A	49.78	2.98	16.7	≈ 18
0.02< t <0.04	B	105	3	34.99	≈ 105
0.04< t <0.06	C	99.55	2.98	33.41	≈ 100
0.06< t <0.08	D	109	3.01	36.22	≈ 109
0.08< t < 1	E	58.5	1.58	37.03	≈ 58

Figure 7 shows the graph of PV module power against time for the entire duration of simulation.

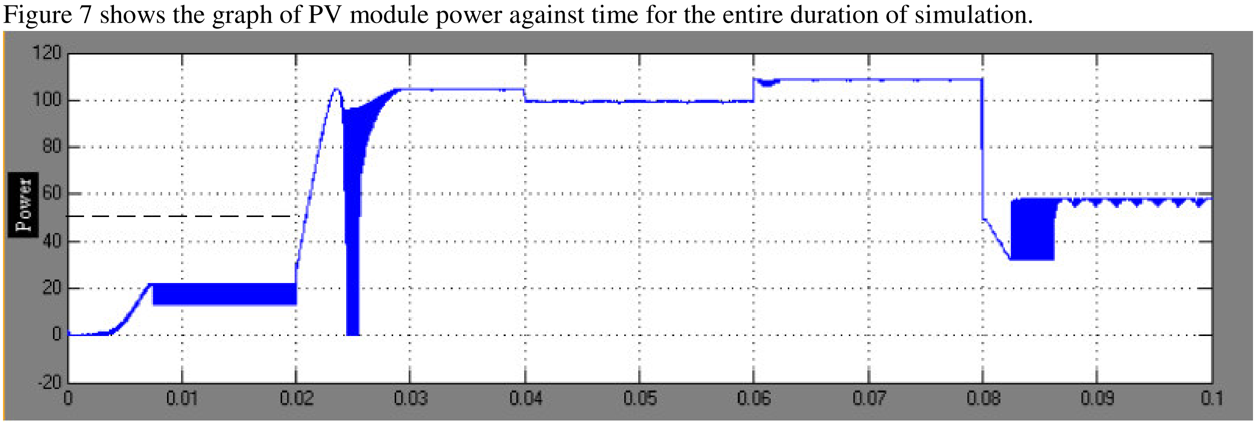

Figure 7: PV Module Power vs Time

In curve A, the P&O was trapped because it climbs the P-I curve as long as the power is increasing, so when it reaches the first peak, it cannot go beyond it since the power starts actually decreasing. The theoretical value of the power at MPP (49.78W) is shown as a dotted line in Figure 7. Thus for the curve A, the P&O fails in tracking the global MPP, which is expected since the curve has two peaks, the local one and the global one; and in this case, the P&O tracks the local peak.

The P&O continued to find the actual global MPP for curves B, C, and D since only one peak was present. When the curve changed from D to E, which also has multiple peaks, it was expected that the P&O would not track the global MPP as was the case in curve A. However, the P&O was able to track the theoretical value of the PMPP (58 W), contrary to what would be expected.

For this case, the P&O was trapped at the wrong peak for a while when tracking the MPP in the presence of multiple peaks and then reached the global MPP by sheer coincidence when tracking the MPP of curve E. A significant outcome is that even though this run does not show a complete failure of the P&O under partial shading conditions, it shows that the P&O could be trapped at the wrong peak.

3.2. CASE 2: EFFECT OF ARRANGEMENT OF PEAKS

The irradiance and temperature changes for this case are shown in the figure 8.

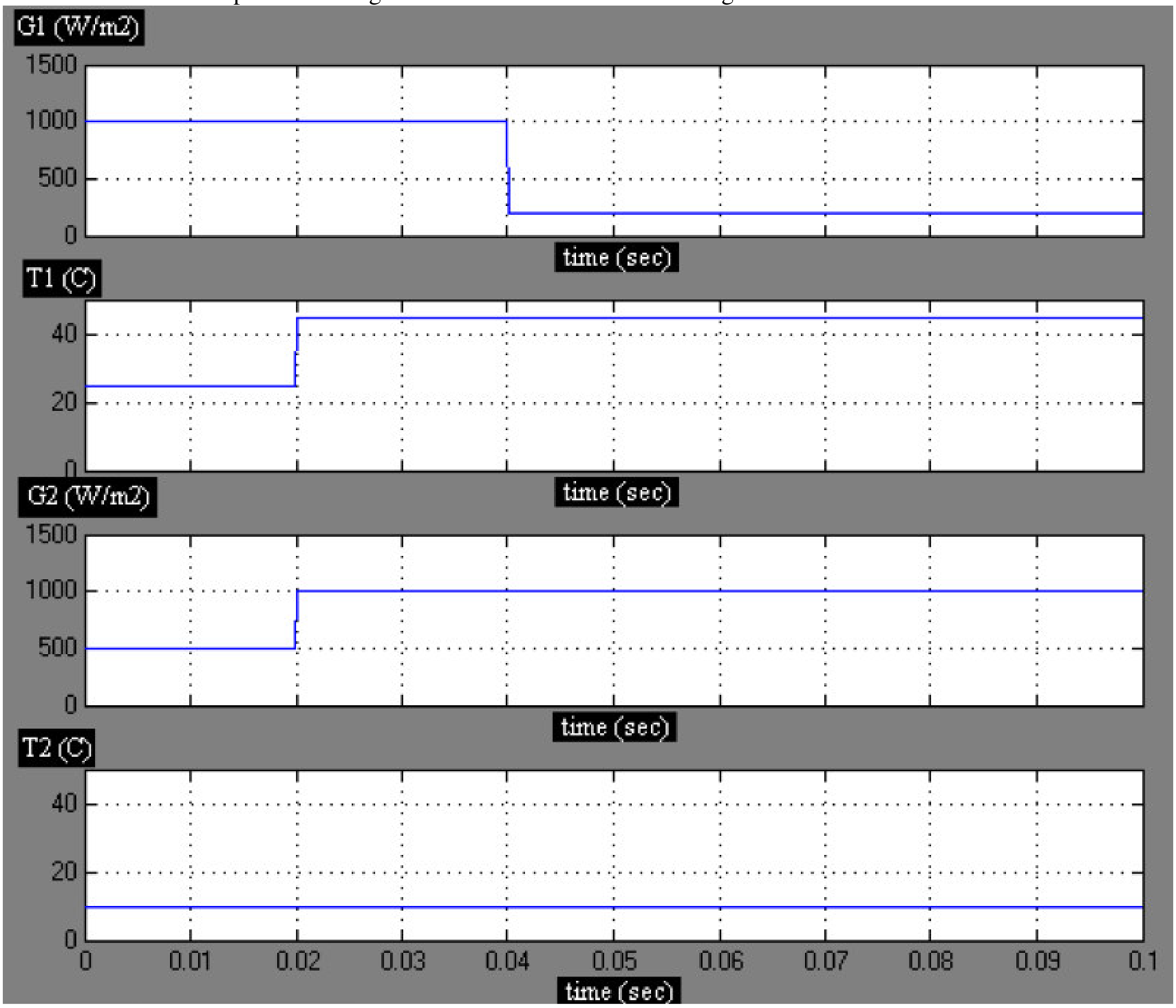

Figure 8: Temperature and Irradiance Changes for Case 2

The P-I curve of the module is generated after every 0.02 seconds, with the results being displayed as in figure 9.

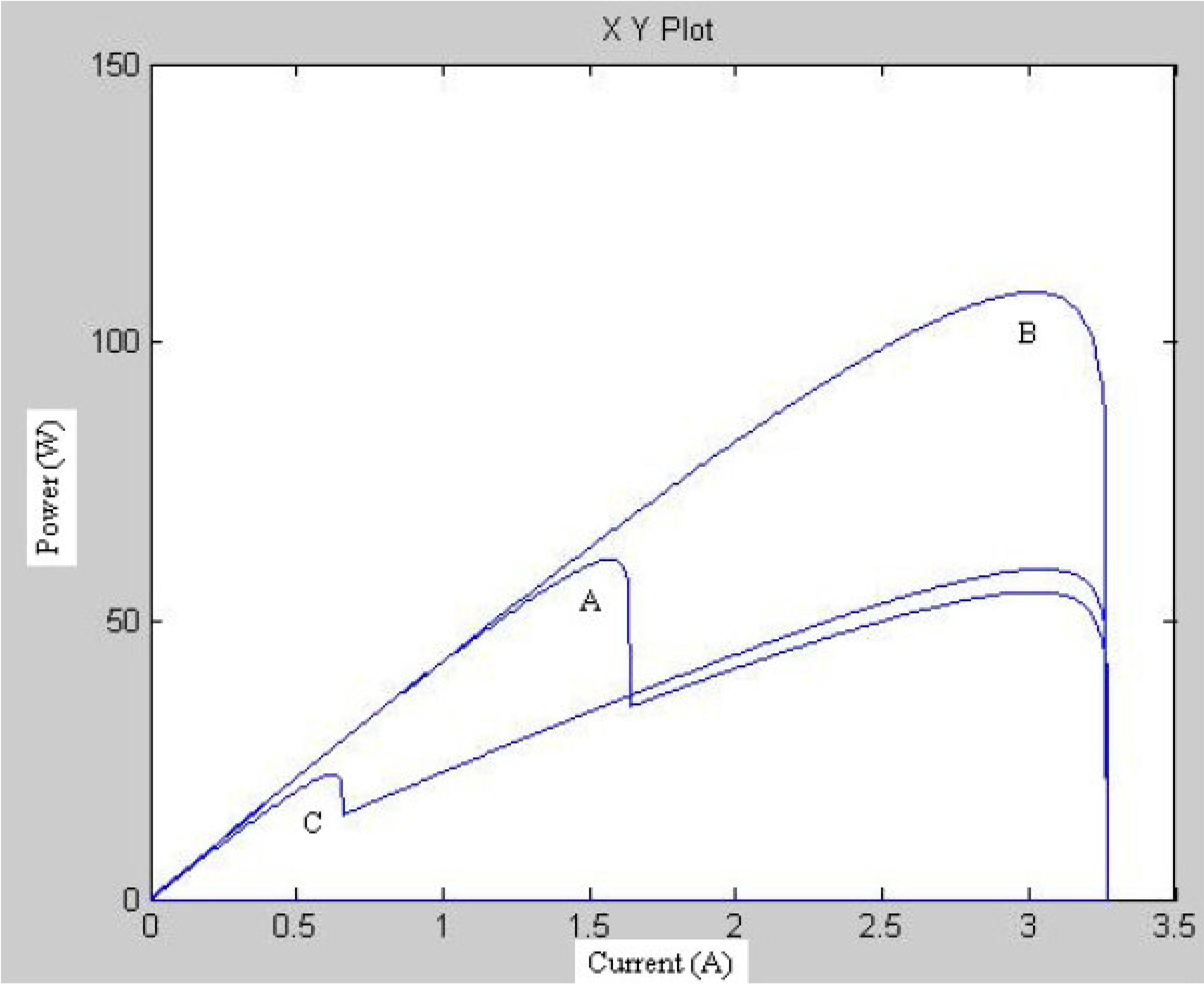

Figure 9: P-I Curve of the Module for Case 2

There are three curves (A, B and C), with each curve generated after 20ms such that curve A is generated within the first 20ms of simulation, curve B is generated in the subsequent 20ms of simulation and so on till curve C is generated. Curves A and C have multiple peaks (meaning the solar module is experiencing partial shading during the duration of generation of these curves) while curve B has just one peak (meaning during the duration of generation of curve B, the solar module is experiencing uniform insolation). The first peak of curve A is the global peak while the second is the local peak.

Table 2 shows the theoretical values of Power, Voltage and Current at MPP and the actual value of Power tracked by the P&O during the entire period of simulation.

Table 2: Table of Theoretical Values of Power, Current, Voltage and Tracked Power

Time	Curve	P_{MPP} (W)	I_{MPP} (A)	V_{MPP} (V)	Tracked Power (W)
t<0.02	A	61.06	1.58	38.64	≈ 58
0.02< t <0.04	B	109	3.01	36.22	≈ 100
0.04< t <0.1	C	59.32	3.04	19.51	≈ 54

Figure 10 shows the graph of PV module power against time for the entire duration of simulation.

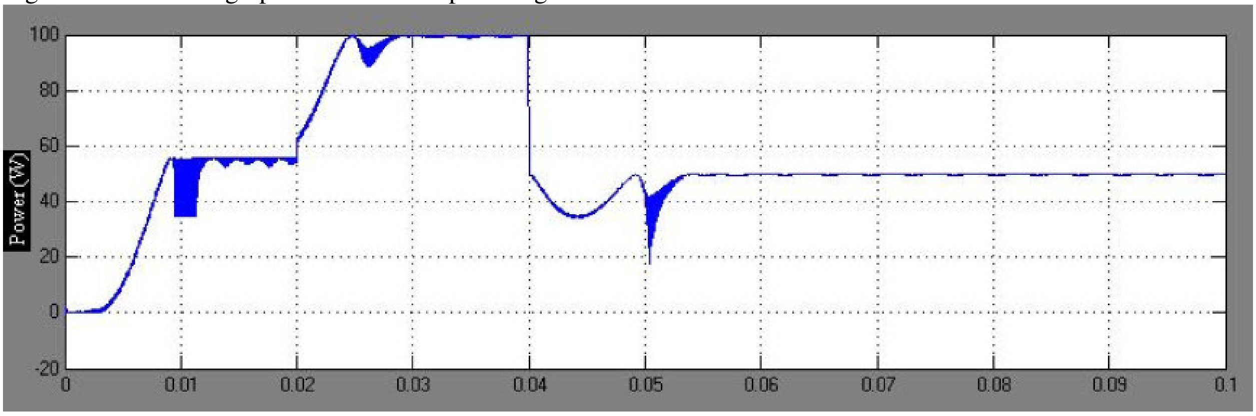

Figure 10: PV Module Power vs Time

The P&O algorithm has successfully tracked the global MPP in all the three curves. This is not expected as two of the curves have multiple peaks, bearing a local and global one. However, this may be attributed to the arrangement of the curves. As it tracks the MPP of curve A, it reaches the first peak and gets stuck. However, this peak happens to be the global MPP and as such, tracks the MPP by coincidence. In curve B, there is only one peak and as such, the algorithm is expected to naturally converge around the real MPP. As the system shifts to curve C, the operating point is already closer to the real MPP and since the first peak is in a far region, then the system also happens to converge to the real MPP.

A significant outcome of this case is that the P&O could find the global MPP by chance, because of the arrangement of peaks on the curves, as is the case where the first peak encountered by the P&O is the global MPP.

3.3. CASE 3: EFFECT OF SUSTAINED PARTIAL SHADING

The irradiance and temperature changes for this case are shown in the figure 11.

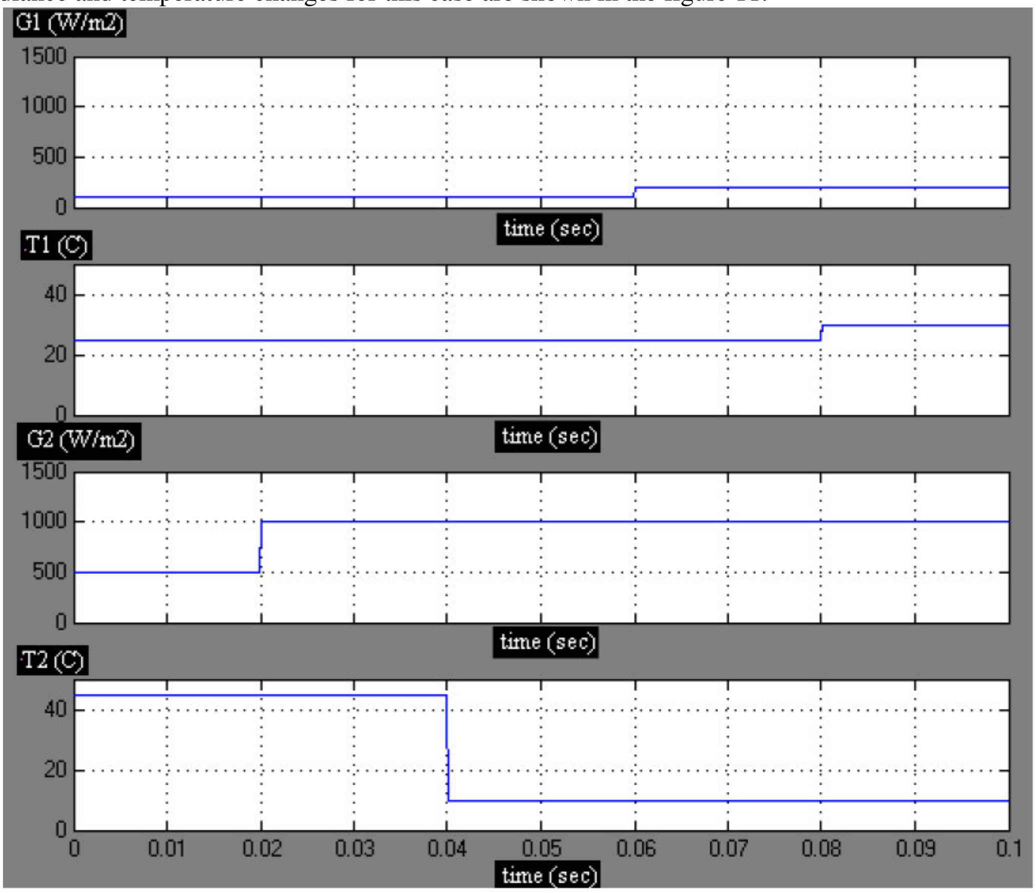

Figure 11: Temperature and Irradiance Changes for Case 3

The P-I curve of the module is generated after every 0.02 seconds, with the results being displayed as in figure

12.

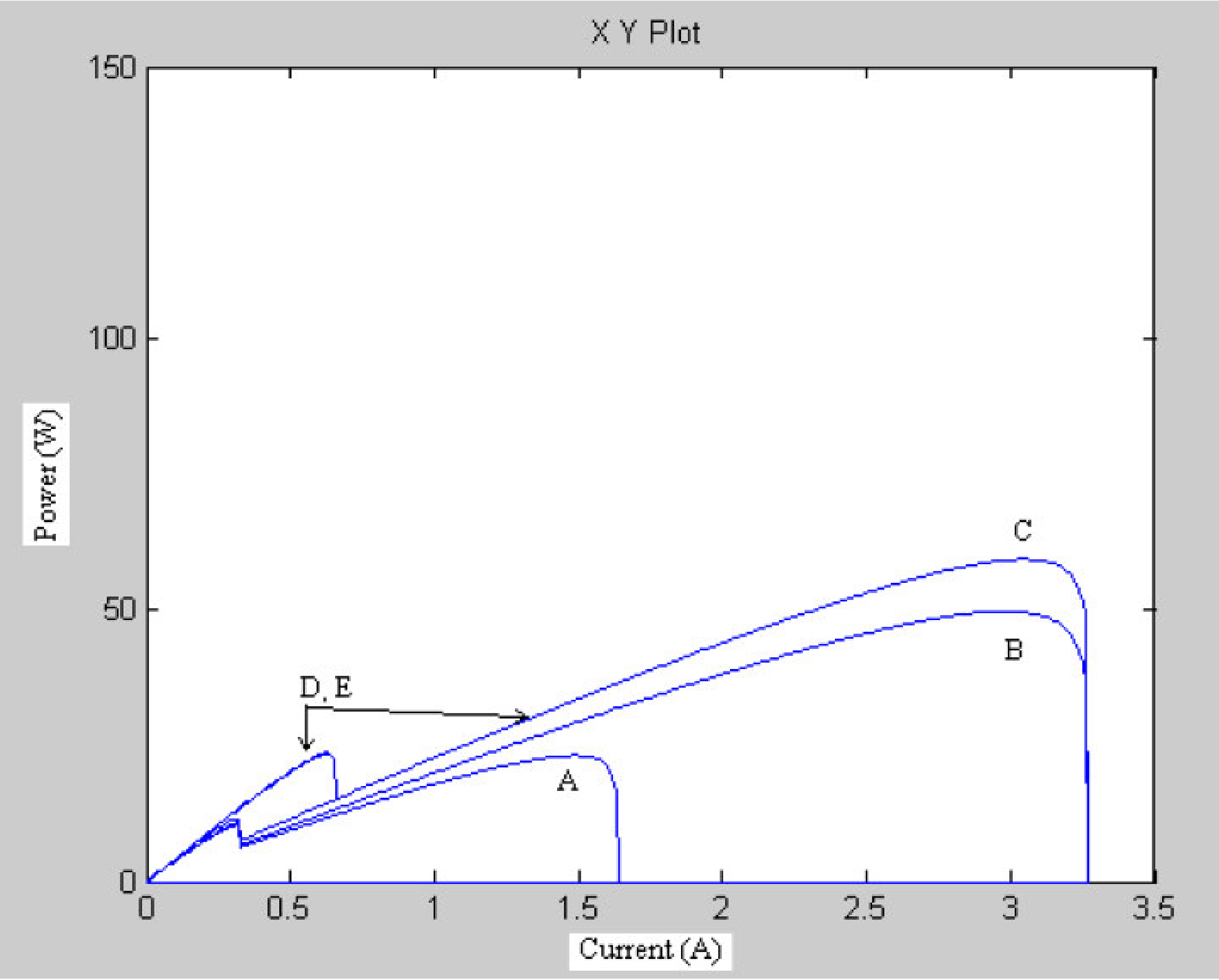

Figure 12: P-I Curves of The Module for Case 3

All curves have multiple peaks, meaning the solar module is fully under partial shading for the entire duration of this simulation. Further, in each of the curves, the first peak is the local peak, and the second peak is the global peak, with the operating points of both peaks being far from each other.

Table 3 shows the theoretical values of Power, Voltage and Current at MPP and the actual value of Power tracked by the P&O during the entire period of simulation.

Table 3: Table of Theoretical Values of Power, Current, Voltage and Tracked Power

Time	Curve	P_{MPP} (W)	I_{MPP} (A)	V_{MPP} (V)	Tracked Power (W)
t<0.02	A	23.21	1.48	15.69	≈ 9
0.02< t <0.04	B	49.78	2.98	16.7	≈ 9
0.04< t <0.06	C	59.32	3.04	19.51	≈ 9
0.06< t <0.08	D	59.32	3.04	19.51	≈ 24
0.08< t <0.1	E	59.32	3.04	19.51	≈ 24

Figure 13 shows the graph of PV module power against time for the entire duration of simulation.

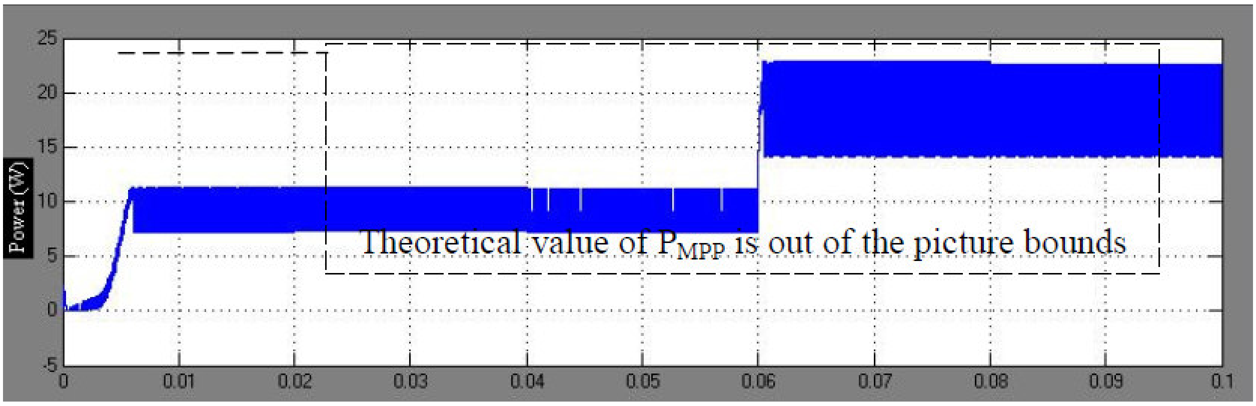

Figure 13: PV Module Power vs Time

In this run, the P&O algorithm completely failed to track the global MPP for the entire period of simulation, with the P&O algorithm being trapped in the first peak which is not the global MPP in none of the five curves.

A significant outcome of this run is that Thus, when the P&O algorithm is faced with a solar module entirely under partial shading, where the first peak happens to be the local peak, it completely fails to track the global MPP.

4. CONCLUSION

The effect of partial shading on the P-V, I-V characteristics has been investigated. The magnitude of the global peak is dependent on the shading pattern besides the commonly known factors of insolation and temperature. The power peaks were also observed to be displaced from each other by a multiple of the value of open circuit voltage.

The behavior of P&O when tracking partially shaded modules was investigated. It was noted that the algorithm could be trapped at the wrong peak for a while, but still continue to find the global peak. The P&O could also find the global MPP by chance, because of the arrangement of peaks on the curves, as is the case where the first peak encountered by the P&O is the global MPP. However, when all the curves have multiple peaks, meaning the solar module is entirely under partial shading and further, the first peak is the local peak, and the second peak is the global peak, with the operating points of both peaks being far from each other; then the P&O showed a complete failure in tracking the global MPP.

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