Modelling and Investigation of Best PV Array Configuration and Implementation of MPPT Under Partial Shading Conditions

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Abstract.

In practical, majority of the photovoltaic (PV) modules are possessing inbuilt bypass diodes for avoiding hotspot formation under partial shading conditions. However, on account of the activation of bypass diodes, multiple peaks will occur on the characteristics of PV array. The traditional maximum power point tracking (MPPT) algorithms decline to track the global peak and settles at the local peak, thereby resulting in huge power loss. Thus, this paper investigates the influence of partial shading on different PV array configurations (like , total-cross tied, series-parallel, honey-comb, series) under distinct shading patterns (such as wide and short, narrow and short, wide and long, narrow and long, and diagonal). Further, best suitable PV array configuration is identified by comparing the array losses and global peak position is discussed under various shading patterns. Apart from this, traditional P&O algorithm is implemented in MATLAB to extract the Maximum Power Point (MPP) amongst the best PV array configuration.

Keywords. PV Module, Power-Voltage Characteristics, Photovoltaic (PV) array configurations, Partial Shading patterns, MPPT, P&O algorithm.

1. INTRODUCTION

On considering recent times, there is a drastic upsurge in the global photovoltaic (PV) installations owing to the growing emphasis on reducing global warming, natural abundance of solar irradiance, easy scalability, flexibility and low maintenance costs. Apart from these encouraging aspects, PV output power mainly depends upon the environmental conditions such as irradiation, load profile, temperature and moving clouds [1]. Further, due to non-linear characteristics of PV, Power-Voltage curve exhibits a unique Maximum Power Point (MPP), at which peak power is extracted. This MPP operating will never remain constant and varies considerably with respect to environmental conditions. For extracting the peak power under varying environmental conditions, a Maximum Power Point Tracking (MPPT) scheme is commonly adopted [2], which requires power electronic interfaces such as DC/AC inverters or DC/DC converters.

Depending on the current and voltage required by the system load, series-parallel connections of individual PV modules are usually adopted. A "string" refers to a set of series-connected PV modules. Under normal operating conditions, each module in a string receives the same amount of irradiance, and the PV characteristics of the string resembles that of the single module, with the voltage increased by as many times as the number of series modules and the current being the same. In such cases, the P-V curve of that string exhibits single peak [3].

However, as the PV modules are installed in outdoor, due to the shadow originated by nearby objects such as, poles, trees, or bird droppings, clouds, buildings and dirt etc, these modules receive unequal levels of irradiance/mismatch in the irradiance values, and this phenomenon is called to be as partial shading[4]. Under partial shading systems, shaded module turns reverse biased and leads to considerable heat dissipation known as hotspot. To avert the hotspot formation, bypass diodes are connected in antiparallel with each PV module to safely bypass the shaded module. However, under partial shading conditions, due to the activation of these bypass diodes, the string P-V characteristic exhibits multiple peaks, with several Local MPPs (LMPPs) and also drastically affects the PV output power [5]. Under certain partial shading conditions, traditional MPPT algorithms fails to track the global peak and settles on a local MPP, thereby results in huge power loss. It has been proclaimed that, reduction in output power by applying improper MPPT technique might be up to 70% under partially shaded conditions. This power loss may vary from one configuration to another, shading pattern, shading intensity and number of modules having shading [6].

Patel et al [7] inspected the effect of shading on series-parallel array configuration under distinct shading patterns is enclosed. While in [8][9], presented the performance comparison among various array configurations such as Total Cross-tied, Series-parallel, Honey-comb, Series and identified TCT as the best array configuration. In another study [10], devised a MATLAB program to analyse the shading patterns effect on various array configurations. By comparing all the configurations under various shading pattern, the best configuration is then investigated and P&O algorithm is applied for the tracking of maximum power point.

The rest of the paper is explicated as follows- section II-PV module modelling in MATLAB/simulink, PV array configurations and shading patterns (wide & short, diagonal, wide & long, narrow & short and narrow & long,), Section III- presented the P-V characteristics of distinct array configurations under distinct shading patterns and implementation of P&O algorithm on the best configuration is discussed, flowed by conclusion in Section IV. Thus, to investigate the performance of array configuration paper investigates on identifying the best PV array configuration positioning of global peak and performance

2. VARIOUS PV ARRAY CONFIGURATIONS, SHADING PATTERNS

2.1. PV Module Modelling

In a PV module, many PV cells are connected in series. A single diode model described in Fig.2.2 [12] is considered for modelling the 250 Wp PV module and its datasheet parameters are mentioned in the Table 1. For modelling the PV module, the unknown parameters such as shunt resistance, diode ideality factor, reverse saturation current, photon current and series resistance are demonstrated by using the Lambert function [11]. The PV module's I-V characteristics are illustrated by the following equation.

$$Ipv = Iph - Io * \left[e^{\left(\frac{Vpv+Ipv*Rs}{Ns*\left(\frac{Kb.\eta.t}{q}\right)} \right)} - 1 \right] - \frac{Vpv+Ipv*Rs}{Rsh} \quad (2.1)$$

The above equation is simulated in MATLAB/simulink and is mentioned in Figure 2.2. For obtaining the I-V characteristics, a capacitor is connected across the load (described in Figure 2.2.), which act as a variable load. At distinct irradiance and temperature values, P-V curves and I-V curves are plotted and is illustrated in Figure 2.1.

Table 1. Specifications for PV Module and various Array Configurations

	PV Module	**SeriesArray Configuration**	**Series-Parallel / Honey-Comb/TCT Array Configurations**
Peak Power	250 Watts	6250 Watts	6250 Watts
Voltage At Max Power (V_{mp})	30.72 Volts	768 Volts	153.6 Volts
Current At Max Power (I_{mp})	8.14 Amps	8.14 Amps	40.7 Amperes
Open Circuit Voltage (V_{oc})	37.82 Volts	945 Volts	189 Volts
Short Circuit Current (I_{sc})	8.633 Amps	8.63 Amps	43.15 Amps

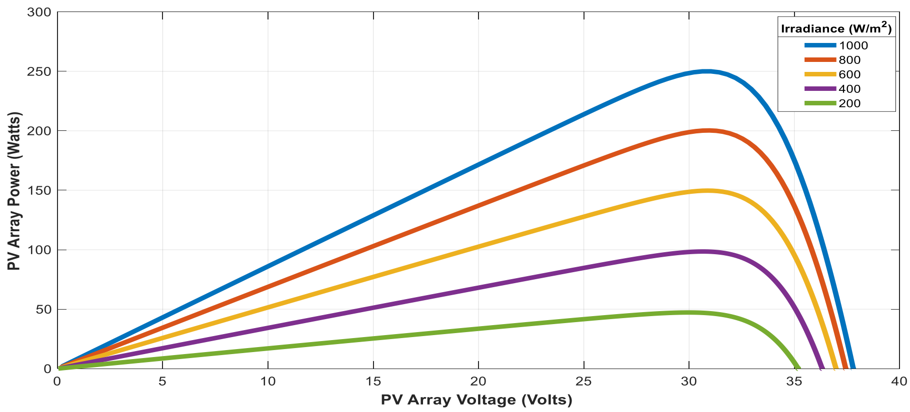


Figure 2.1 PV Module's Characteristics at 200 W/m^2, 400 W/m^2 , 600 W/m^2 800 W/m^2 and 1000 W/m^2

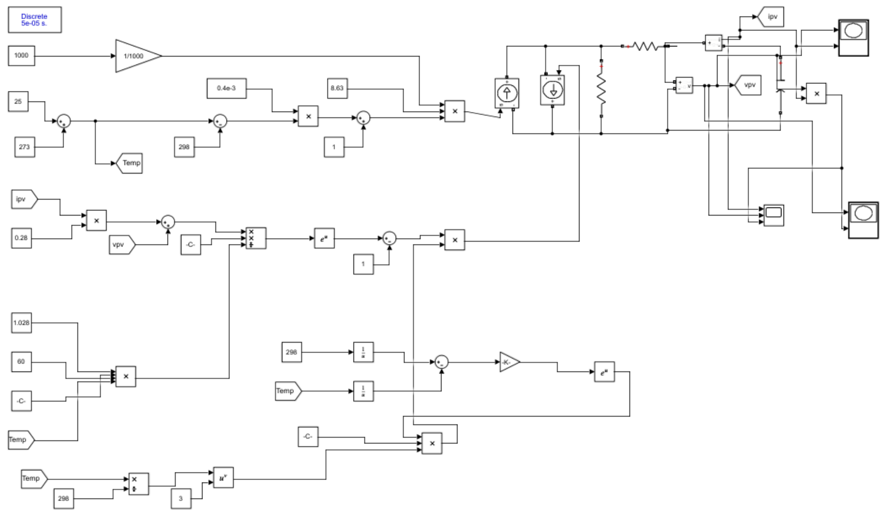
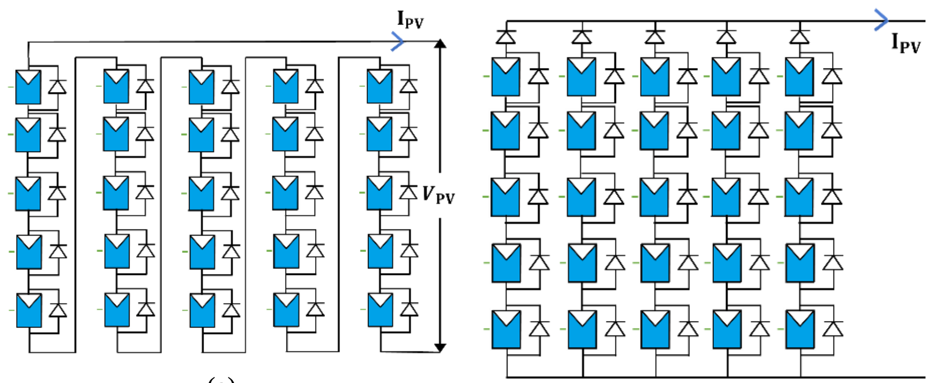


Figure. 2.2. PV Module Simulation diagram

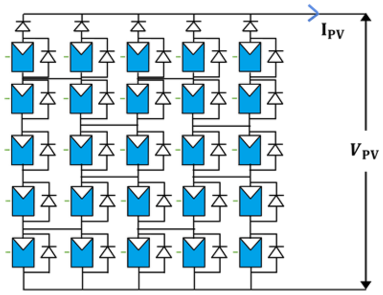
2.2. PV Array configurations

Few number of the PV Modules are connected in a particular pattern to achieve the required voltage, current and power ratings. The various array configurations considered for the investigation are - i) Series, ii) Series-parallel, iii) Honey-Comb (H-C), iv) Total Cross-tied (TCT).

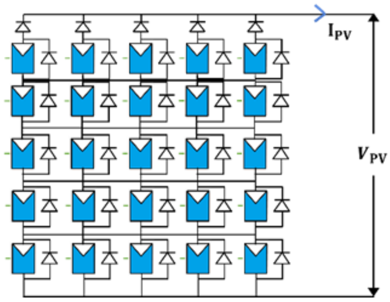
The figure 2.3(a). shows a 5x5 Series PV Array configuration. In this, Series PV Array configuration is formed by connecting all the 25 PV modules in series. In this configuration, module current is considered to be the array current, and the sum of the individual PV module voltages connected in series is considered as the array voltage. The product of the array current and voltage is calculated as the array power.



(a) (b)



(c)



(d)

Figure 2.3. Series PV Array Configurations (a) 5 x 5 Series, (b) 5 x 5 Series-Parallel, (c) 5 x 5 Honey-Comb (d) 5 x 5 TCT

The figure 2.3(b). shows 5x5 Series-parallel PV Array configuration and its specifications mentioned in Table 1. To meet the output current and voltage requirement, to form a string, photovoltaic modules are connected in series, and these are connected in parallel then after. This arrangement is that the most typically used since it's straightforward to line up and has no redundant connections.

The figure 2.3(c). shows 5 x 5 Honey-comb PV Array configuration and its ratings are tabulated in Table 1. Photovoltaic modules are connected in such a way as shown in the figure 2.3(c). to replicate the obtain the output current and voltage.

The figure 2.3(d). shows 5 x 5 TCT PV Array configuration and its specifications are mentioned in Table 1. Photovoltaic modules are cross tied to each other to secure the required output current and voltage. In this case, each row's voltage is the same, and the sum of the voltages across each row is same. The current in each column is the same.

A blocking diode to connected to each string to avoid the circulating currents among the strings under equal irradiance conditions and to resist the current flow from battery/grid to photovoltaic panel.

2.3. Shading Patterns

For investigating the PV array performance and positioning of global peak, five shading patterns are considered namely; under wide & short, diagonal, wide & long, narrow & short and narrow & long.

	S1	S2	S3	S4	S5
R1	300	300	1000	1000	1000
R2	500	500	1000	1000	1000
R3	700	700	1000	1000	1000
R4	1000	1000	1000	1000	1000
R5	1000	1000	1000	1000	1000

(i)

	S1	S2	S3	S4	S5
R1	300	300	500	500	1000
R2	300	300	500	500	1000
R3	700	700	700	700	1000
R4	1000	1000	1000	1000	1000
R5	1000	1000	1000	1000	1000

(ii)

	S1	S2	S3	S4	S5
R1	300	300	1000	1000	1000
R2	500	500	1000	1000	1000
R3	500	500	1000	1000	1000
R4	500	700	1000	1000	1000
R5	700	700	1000	1000	1000

(iii)

	S1	S2	S3	S4	S5
R1	300	300	500	500	1000
R2	300	300	500	500	1000
R3	300	300	500	500	1000
R4	700	700	900	900	1000
R5	700	700	900	900	1000

(iv)

	S1	S2	S3	S4	S5
R1	300	1000	1000	1000	1000
R2	1000	400	1000	1000	1000
R3	1000	1000	500	1000	1000
R4	1000	1000	1000	700	1000
R5	1000	1000	1000	1000	900

(v)

Figure 2.4. Pictorial illustration of module level irradiance in a PV array under Various shading pattern, (i) Narrow & Short, (ii) Wide & Short, (iii) Narrow & Long, (iv) Wide & Long, (v) Diagonal

2.3.1. Narrow & Short Shading Pattern

In narrow and short shading condition, out of five strings (narrow by comparing alongside the width of the PV array), only two strings are shaded and the three modules are shaded per string (short by comparing alongside the string's length), thus this shading type is considered to as narrow and short shading condition as illustrated in the Figure 2.4(i).

2.3.2.Wide and Short Shading Pattern

In such pattern of shading, out of five strings four are shaded (wide by comparing alongside the PV array's width) and there are three number of shaded modules per string is described in Figure 2.4(ii).

2.3.3. Narrow & Long Shading Pattern

In this shading pattern, shading is confines to only two strings (narrow, say) and in these strings, each and every modules in that string are shaded to different irradiance values (long, say), illustrated in Figure 2.4(iii).

2.3.4.Wide & Long Shading Pattern

Out of five strings, the four strings of the photovoltaic array are shaded and each and every module of these strings are to be shaded, and noted to as wide and long shading condition.

2.3.5. Diagonal Shading Pattern

In a Photovoltaic array, the five diagonally placed PV modules are subjected to different solar irradiance levels. The different levels of solar irradiance on diagonally positioned PV modules are set to be as 900 Watts/m^2, 700 Watts/m^2, 500 Watts/m^2, 400 Watts/m^2 and 300 Watts/m^2 respectively and is depicted in Figure. 2.4(v).

Under shading condition, irradiance at some of the modules are changed according to the type of pattern and the remaining are left at an irradiance of 1000 Watts/m^2.

3. SIMULATION RESULTS AND DISCUSSION

In this chapter, each array configuration (i.e., TCT, Honey-Comb, Series-Parallel and Series) is simulated under various partial shading pattern (i.e., Diagonal, Narrow & Short, Wide and Long, Wide & Short, Narrow and Long,) and their respective P-V curves are plotted. These P-V curves are compared and the best configuration is determined based on the computation of mismatch losses and global peak position.

3.1. Performance Analysis of Photovoltaic Array Configurations under various Partial Shading Conditions (PSCs).

In this section, it describes about the performance of TCT, Honey-Comb, Series-Parallel and Series photovoltaic array configurations under normal and PSC's is to be selected as the best photovoltaic array configuration that which furnishes the better performance overall. The performance of photovoltaic array configuration is examined with respect to maximum power and the mismatching losses.

3.1.1. Series PV Array Configuration

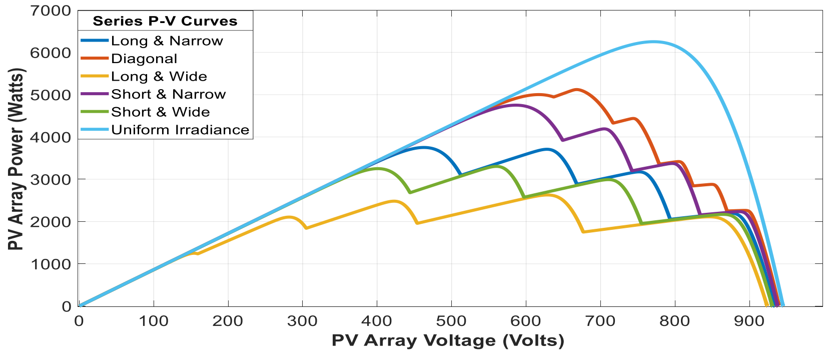


Figure 3.1. P-V Curves of Series PV Array Configuration under uniform and PSCs

The simulation is carried out for Series photovoltaic array configuration under uniform irradiance and partial shading conditions like wide & short, diagonal, wide & long, narrow & short and narrow & long, and the respective P-V curves are plotted in figure 3.1. The Series photovoltaic array configuration gives maximum power of 6250.48 Watts at uniform irradiance. Under partial shading condition, series PV array configuration generates a peak power of 5120.8 Watts under diagonal shading pattern, 4742.8 Watts – under narrow and short, 3708.55 Watts- narrow and long, 3295.81 Watts- Wide and short and 2627.16 Watts -wide and long patterns as referred to the Figure 3.2.

3.1.2. Series - Parallel PV Array Configuration

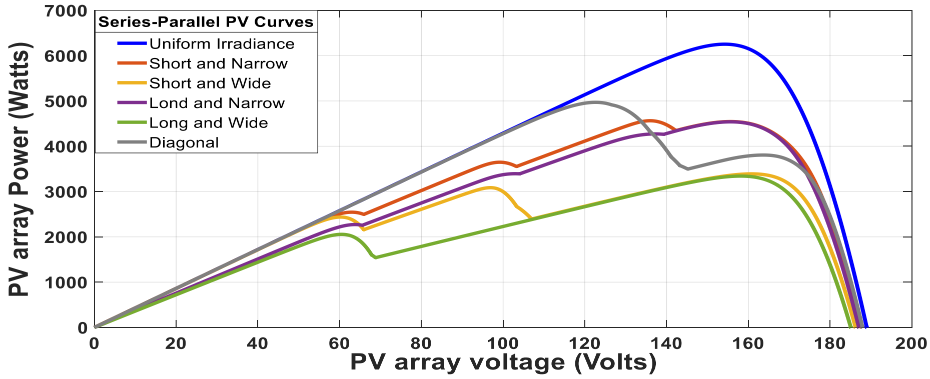


Figure 3.2. P-V Curves of Series-Parallel photovoltaic Array Configuration under uniform and PSCs

The simulation is carried out for Series-Parallel photovoltaic array configuration under uniform irradiance and PSC's like wide & short, diagonal, wide & long, narrow & short and narrow & long. The P-V curves of each condition are plotted as depicted in the figure 3.2. The Series - Parallel photovoltaic array configuration gives maximum power of 6249.4 Watts at uniform irradiance. At diagonal shading condition, the Series - Parallel photovoltaic array gives the maximum power of 4996.95 Watts followed narrow and short (4683.7 Watts), narrow and long (3973.12 Watts), wide and short (3325.56 Watts) and then by wide and long (3092.7 Watts) as referred to the Figure 3.2.

3.1.3. HONEY-COMB PV Array Configuration

The simulation is carried out for Honey-Comb PV array configuration under uniform irradiance and PSC's like wide & short, diagonal, wide & long, narrow & short and narrow & long. The P-V curves of each condition are plotted as shown in figure 3.3. The HC photovoltaic array configuration gives maximum power of 6248.9 Watts at uniform irradiance. At diagonal shading condition Series PV array gives the maximum power of 4855.9 Watts followed by narrow and short (4825.22 Watts), narrow and long (4637.28 Watts), wide and long (3462.38 Watts) and wide and short (3336.91 Watts) as referred to the Figure 3.3.

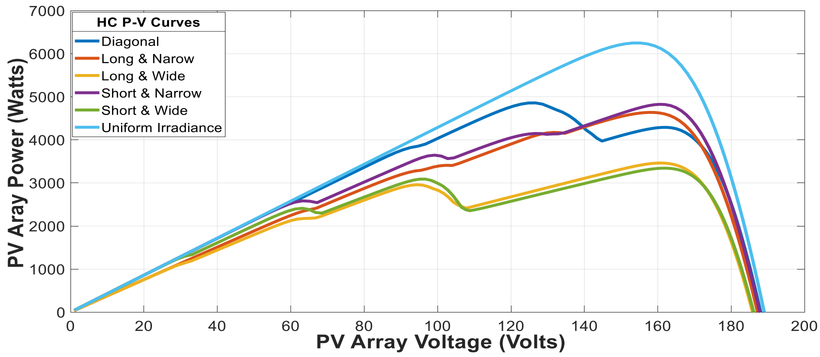


Figure 3.3. P-V Curves of HC PV Array Configuration under uniform and PSCs

3.1.4. TCT PV Array Configuration

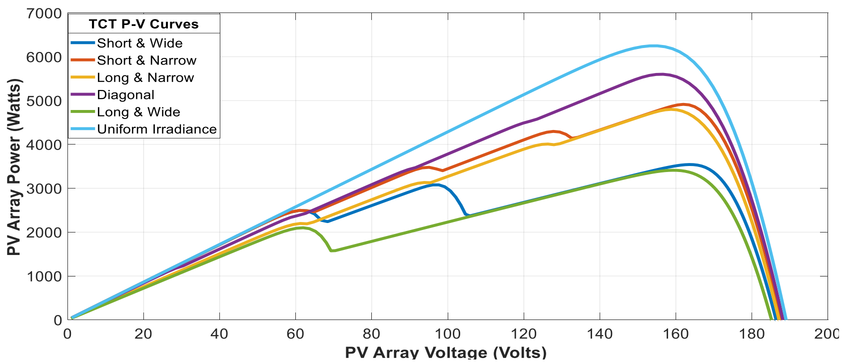


Figure 3.4. P-V Curves of TCT PV Array Configuration under uniform and PSCs

The simulation is carried out for TCT photovoltaic array configuration under uniform irradiance and PSC's like wide & short, diagonal, wide & long, narrow & short and narrow & long. The P-V curves of each condition are plotted as depicted in Figure.3.4. The maximum power in each shading condition is noted and compared with each other as shown in the fig.3.4 . The Series photovoltaic array configuration gives maximum power of 6248.9 Watts at uniform irradiance. At diagonal shading condition Series photovoltaic array gives the maximum power of 5596.82 Watts followed by short and narrow (4914.31 Watts), long and narrow (4790.31 Watts), Short and Wide (3538.12 Watts) and long and wide (3408.35 Watts).

3.2. Comparison of photovoltaic Array Configurations under various PSC's.

After plotting all the P-V characteristics, the maximum powers are compared for each and every array configuration under each shading pattern. By referring the data from Figure 3.5., it can be observed that under wide & short, diagonal, wide & long, narrow & short and narrow & long, TCT gives the maximum power and low losses as taken from the Table 2, and chosen as the best configuration for all the shading patterns except Long & Wide (L&W) as Honey-Comb provides the max power and lowest losses than TCT, although the difference between the losses between TCT and Honey-Comb for Wide & Long is neglected. By overall consideration from the Figure 3.5. and Table 2, TCT is spotted as the best configuration.

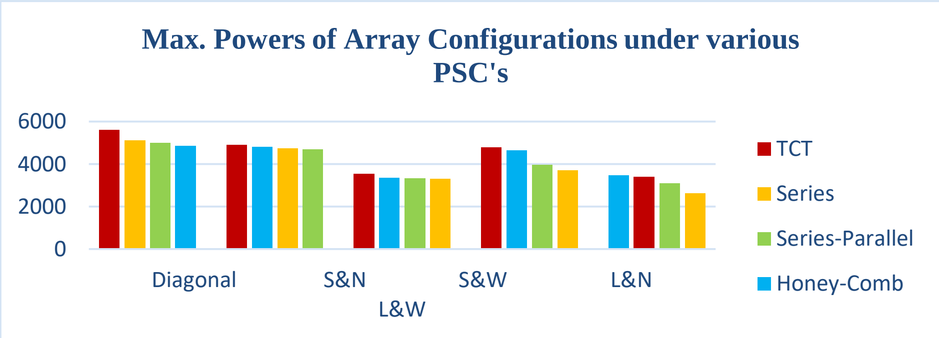


Figure 3.5. Max. Powers chart of distinct PV Array Configuration under various PSCs

Table 2. Losses in PV Array Configuration under various PSC's

	Diagonal	**Short & Narrow**	**Short & Wide**	**Long & Narrow**	**Long & Wide**
TCT	**652.08**	**4914.31**	**2710.78**	**1458.59**	**2830.55**
Honey - Comb	**1392.97**	**1423.68**	**2911.99**	**1611.62**	**2786.52**
Series & Parallel	**1252.45**	**1565.7**	**2923.84**	**2276.28**	**3156.7**
Series	**1129.68**	**1507.68**	**2954.67**	**2541.93**	**3623.32**

3.3. Implementation P&O algorithm for TCT by changing irradiance.

To track the maximum power point in a photovoltaic system, P&O algorithm is most generally used MPPT algorithm as it is easy and due to its flexibility. As TCT PV array configuration is found as the best configuration, P&O algorithm is applied to it and can be observed that from 6 to 8 seconds, the irradiance is uniform and is 1000 Watts/m^2. Accordingly, the power is also uniform and is about 6250 Watts. As there is a slant decrease and increase in irradiance from 8 to 10 seconds, the power also declined and then inclined respectively along with irradiance. A sudden change in irradiance from 1000 Watts/m^2 to 500 Watts/m^2 at 12th second resulting in power to sudden decrease from 6250 watts to 3125 watts is also tracked by the P&O algorithm as demonstrated in the Figure 3.5.

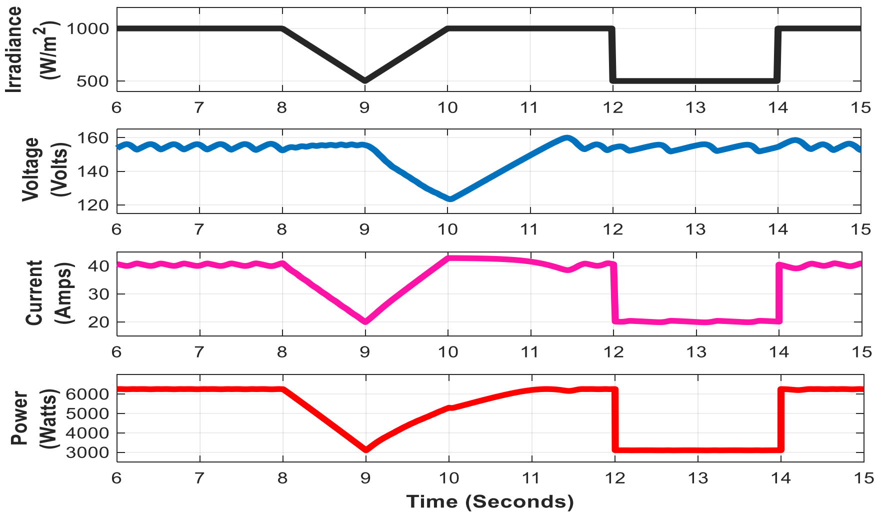


Figure 3.5. PV Voltage, Current, Power waveforms of TCT array configuration under constant irradiance, sudden and slow changing irradiance conditions.

4. Conclusion

By simulating various photovoltaic array configurations under distinct partial shading patterns, the best suitable configuration (i.e., Series, Series-Parallel, Honey-Comb, TCT) is identified as TCT based on the array losses. Furthermore, in the TCT PV array characteristics, the global peak is always located near to open circuit voltage, irrespective of the shading pattern. Hence, global maximum power point trackers are not required for tracking the global peak positions for TCT configuration and is required for other configurations, since global peak position may or may not be located near to the open circuit voltage for particular shading pattern (i.e., wide & short, diagonal, wide & long, narrow & short and narrow & long). As investigated on the whole, it is found that TCT is the best of all configurations considering various shading patterns. Furthermore P&O algorithm is implemented for the best confirmation (TCT) to track the maximum power point (MPP) by changing various irradiance which replicates the shading.

5. References

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