International Journal of Applied Research 2020; 6(12): 132-140

ISSN Print: 2394-7500
ISSN Online: 2394-5869
Impact Factor: 8.4
IJAR 2020; 6(12): 132-140
www.allresearchjournal.com
Received: 12-09-2020
Accepted: 23-10-2020

Pragaspathy Subramani
Electrical and Electronics Engineering, Vishnu Institute of Technology, Bhimavaram, Andhra Pradesh, India

Kalyan Sagar Kadali
Electrical and Electronics Engineering, Shri Vishnu Engineering College for Women, Bhimavaram, Andhra Pradesh, India

S Karthikkumar
Electrical and Electronics Engineering, Jai Shriram Engineering College, Tirupur, Tamil Nadu, India

Corresponding Author:
Pragaspathy Subramani
Electrical and Electronics Engineering, Vishnu Institute of Technology, Bhimavaram, Andhra Pradesh, India

Performance evaluation and circuit competence of multiple photovoltaic configurations under fractional shading state

Pragaspathy Subramani, Kalyan Sagar Kadali and S Karthikkumar

DOI: https://doi.org/10.22271/allresearch.2020.v6.i12c.8060

Abstract
Fossil fuels are the only measure to encounter the day today life activities. Slowly the depended resources are getting depleted and continuous exposure towards it is resulting in the negative effect on the environment. More to the point, energy demand of the world has increased in past few decades and therefore the society is searching for an alternate viable solution. Solar photovoltaic (SPV) energy is widely used among the renewable energy sources and the photovoltaic cell can directly convert solar energy into electricity. On the other hand, efficiency of SPV cell is negatively affected during the fractional shading state. Fractional shading conditions occur on the photovoltaic systems due to the passing clouds in the sky, nearby building shadow, moving objects, tree etc. As a result, power generated from the photovoltaic system is less than the expected value. One of the best solutions for this issue will be the multiple array configurations scheme. In this proposed article, conventional SPV array configuration such as series parallel (SP), bridged linked (BL) and honeycomb (HC) are compared under different cases with the newly proposed complete cross tied configuration to yield the possible peak power for different fractional shading states. This approach can be done with 4×4 SPV array under six different shading cases and the simulations of all shading cases are implemented using MATLAB/Simulink respectively.

Keywords: Solar photovoltaic, fractional shading state, series parallel, bridge linked, honeycomb, complete cross tied, MATLAB/SIMULINK

1. Introduction

Energy production from renewable energy sources is accelerating due to the increase in oil prices, depletion of fossil fuel reservoirs, energy security concerns, worries about climate change and public health concerns. The known renewable energy sources include hydro, wind, tidal, geothermal, bio, and solar [1]. The energy received from solar irradiation in the form of light can be directly converted to electricity through SPV process. SPV conversion does not produce any harmful by products. It is renewable and clean. Also, it does not have any moving parts, which makes it an attractive solution from the maintenance requirements and life span points of view.

SPV power systems offer a variety of applications, ranging from a few milliwatts to tens of megawatts. Non-terrestrial applications are like calculators, mobiles and satellites, while terrestrial applications are like buildings, pumps and telecommunication antennas. Terrestrial applications are divided into stand alone system which is not connected to the electrical utility grid and utility grid connected systems. Stand alone systems could be subdivided into domestic applications like households and villages and non domestic applications like telecommunications, pumps and navigational aids. Also, utility connected systems could be subdivided into residential, intermediate and central station. The residential and intermediate are treated as distributed generation and the central station is treated as a power plant [2]. The basic SPV configuration is depicted in Fig. 1.

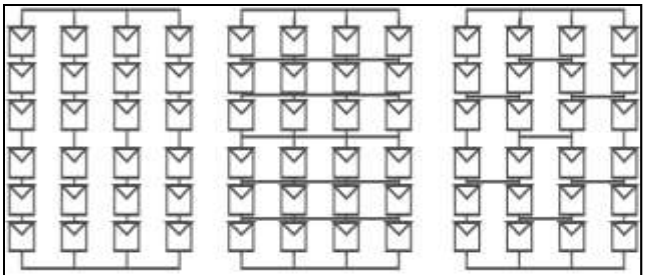

Fig 1: Basic SPV Configurations

The main research about this article is to model, study and analyse the performance of different SPV array configurations under various fractional shading conditions (FSC). By using the conventional SPV array configurations, giving less power in FSC and losses are increased due to mismatch losses. The aim is to improve the efficiency of SPV systems in general by reducing mismatch losses and to select the most appropriate array configuration which provides the best performance i.e. the highest maximum power and hence the lowest relative power losses under FSC. For this purpose, a comprehensive study which considers all the available array configurations such as SP, BL and HC is carried out under all possible scenarios of shading. To overcome the FSC proposed a new configuration total cross tied. The performance and output characteristics of these array configurations are analysed and compared by using 4 × 4 SPV array size under various possible shading scenarios. The bishop model of a photovoltaic module which describes best the solar cell behaviour at negative voltages is considered in this paper for modelling the SPV arrays and it is implemented by using the SIMULINK MATLAB 2018b software. On the whole, the obtained results proves the superiority of the TCT SPV configuration which provides the best performances under most cases of FSC, Uneven or random distribution of fractional shading. However, for some cases of FSC, this is not the case because the performance depends strongly on the patterns of shade. This paper certainly enrich and complement previous studies in this area through a detailed analysis and comprehensive study of the different SPV array configurations under all possible shading scenarios which may occur in reality, the thing that has not been carried out previously. This will allow the estimation and prediction of maximum power and consequently will help to select the most suitable SPV array configuration [3, 4].

Whenever shading occurs on one panel the effective production of current can be reduced and it affects the entire string efficiency. The main focus of the paper is to develop the new designs of SPV array to overcome the problem of fractional shading. The paper is organized as follows. Section 1 describes about the SPV array fields, array control, solar cell materials, electrical storage subsystem and power conditioning subsystem. Effect on partial shading on SPV configurations is structured in Section 2. Simulation study of conventional and proposed configuration is shown in the last section followed by the concluding remarks.

2. Solar Photovoltaic Systems

SPV systems convert sunlight directly into electricity. This is different to the solar thermal collectors for solar water heaters. A SPV system can help reduce carbon emissions and your electricity bill by producing sustainable electricity from the sun instead of burning fossil fuels. Apricus offers a range of solar SPV products to help you harness the power of the sun for commercial, industrial and residential electricity applications of all sizes. A SPV system has the following subsystems SPV array, power conditioning, system monitoring and control, SPV system utility interface; energy storage and thermal management are shown. SPV system utility interface and the thermal subsystems are not present in all SPV systems [5, 6].

Table 1: Terrestrial cell and module efficiencies measured

Solar Cell Material	Cell Efficiency (Laboratory) (%)	Cell Efficiency (Production) (%)	Module Efficiency (Production) (%)
Crystalline	25	25	17
Polycrystalline	21	28	15
Ribbon	20	18	14
Crystalline Thin- Film Silicon	20	9	8
Amorphous	14	11	9
Micromorphous	11	11	11
Cis	19	15	10
Cadmium Telluride	17	12	10

SPV system utility interface is not found in standalone applications and the thermal subsystem is not found in small size applications. Each of these subsystems has its own components like DC cables, junction box, DC main switch, inverter, AC cables and meters [7]. The SPV system may have some external subsystems that can be connected to the SPV system like DC loads, auxiliary power sources and AC loads. Terrestrial cell and module efficiencies measured are depicted in Table 1.

3. Effect of Fractional Shading Conditions

FSC generally occurs on SPV systems due to passing cloud, neighboring building, tree, etc. As a result of partial shading, produced power from SPV system is less than the expected power value. FSC may make solar cells reverse biased and act as an external load consuming the power produced by other solar cells. It will then reduce the output power of SPV modules, and more seriously, bring about hotspot phenomena, which can permanently damage SPV modules. Solar panels help in maximum utilization of solar energy during the day [8, 9]. However, shading can have a huge impact on the performance of solar photovoltaic panels. A common misconception is that fractional shading does not affect the output of solar panels. In fact, the solar photovoltaic panels consist of a number of cells which are wired together into a series circuit. Because of this, the performance of the solar panel is significantly reduced even if a smallest section of the panel is in shade. Intuition suggests that power output of the panel will be reduced proportionally to the area that is shaded. However, this is not the case. The Fig. 2 shows the fractional shading due to chimney and neighbor buildings. It causes to reduce the power. It can be avoided by using best configuration and get maximum power [10, 11].

Fig 2: Partial Shading on Phovoltaic Panels

The panels are shaded right most two panels. The shaded panels produce less current as compared to unshaded panels. To conceptualize why shading results in such severe losses, it is helpful to use the analogy of through a cell string is constant for a given irradiance level. Shading a solar cell is similar to introducing a clog in a pipe of water. The clog in the pipe restricts the flow of water through the entire pipe. Similarly, when a solar cell is shaded, the current through the entire string is reduced. This is significant because every cell in the cell string has to operate at the current set by the shaded cell. This prevents the unshaded cells from operating at maximum power. Therefore, only a small amount of shading can have a dramatic effect on the power output of a solar panel. Similar principles apply to SPV modules connected together. The current flowing through an entire string of modules can be heavily reduced if even just a single module is shaded, leading to potentially significant loss of power output. When the panels are not shaded the current flows without any disturbance. It does not offer any series resistance in panels [12-14].

3.1 Measures to Overcome fractional Shading Conditions

Fortunately, there are a number of different approaches that can be applied in SPV system design to reduce shading losses. The following with respect to control the shading issues are listed out here respectively [15, 16].

3.2 By-pass Diodes

Bypass diodes are used to reduce the power loss solar panels experience due to shading. Because current flows from high to low voltage, when a solar panel has cells that are fractionally shaded, the current is then forced through the low voltage shaded cells. This causes the solar panel to heat up, and have severe power loss. Those shaded solar cells become consumers of electricity instead of producers. Bypass diodes inside the junction box of a solar panel provide a low resistance path for the current to go around a series of solar cells that have been shaded. The diode is wired in parallel with the cells. Because electricity takes the path of least resistance, it is easier for the current to go through the diode than through the shaded cell, so it does. This minimizes the heat gain, and reduces current loss. Most solar panels have bypass diodes built in these days, so you typically won't have to worry about that anymore. However, if you have multiple solar panels wired together in series, and you consistently have shading on one or more of the solar panels, wiring a bypass diode in parallel across the shaded panel can prevent the current from being forced back through the shaded panel and cause it to heat and lose power. So, it acts the same as the internal bypass diodes, but bypasses the entire panel instead of the individual cells.

3.3 Series connected solar cells

SPV panels are made from interconnected crystalline silicon cells and are therefore sensitive to shading. In a standard SPV panel, these solar cells are connected together in series result in high voltage but the same value of current flows through all the connected cells. So as long as the sunlight hitting the surface of the SPV panel is uniform, each photovoltaic cell within the same panel will produce the same amount of electrical voltage, approximately 0.5 volts.

3.4 String arrangements

Modules connected in series form strings, and strings can be connected in parallel to an inverter. The current through all the modules of a string has to be the same, and the voltage of parallel strings has to be the same. As we saw in the last section, a shaded module in a string can bring down the power output of the string significantly. However, a shaded module in one string does not reduce the power output of a parallel string. Therefore, by grouping shaded modules into separate strings, the overall power output of the array can be maximized. For example, in a commercial system with parapet walls, it can be beneficial to group modules that receive shade from the parapets into strings, and keep modules that do not receive shade from the parapets in separate, parallel strings. This way the unshaded strings can maintain a higher current and power output.

3.5 Module level power electronics

Module-level power electronics are devices that can be incorporated into a solar SPV system to improve its performance in certain and to achieve a number of other solar design benefits. MLPE include micro-inverters and DC power optimizers. They perform some of the same functions as a string inverter or central inverter, but are typically coupled to just one a solar modules rather than many, and offer additional features. There are a number of reasons why incorporating MLPE into your solar designs can be a good option. One of the primary reasons is to improve the energy production of the system. MLPE can help mitigate production losses from a variety of different factors such as shading, module mismatch losses, and orientation mismatch losses.

4. Conventional Solar Photovoltaic Array Configurations

Mismatch losses in SPV arrays can be caused by internal sources such as manufacturing tolerance and aging, or by external sources such as fractional shading. Partial shading can be caused by easy to predict sources such as nearby trees and arrays, and difficult to predicted sources such as snow, dust and clouds. Mismatch losses could be reduced by either passive or active techniques [17]. Passive techniques use passive elements such as bypass diodes while active techniques use active elements such as solid state switches.

The most common passive technique uses bypass diodes across SPV modules to reduce fractional shading losses. These diodes protect the modules from local heating and increase the overall power generation from the array under FSC. However, these diodes do not allow the array to produce the maximum possible power under fractional shading. Another passive technique is based on changing SPV array interconnections. SPV arrays can be connected in SP, BL, HC configurations in order to get the required current and voltage ratings. In SP interconnection, modules are connected in series forming strings then, these strings are connected in parallel [18, 19].

4.1 Series-Parallel Configuration

Series wiring is when the voltage of a solar array is increased by wiring the positive of one solar module to the negative of another solar module as shown in Fig. 3. This is similar to installing batteries in a flashlight. As you slide the batteries into the flashlight tube the voltage increases.

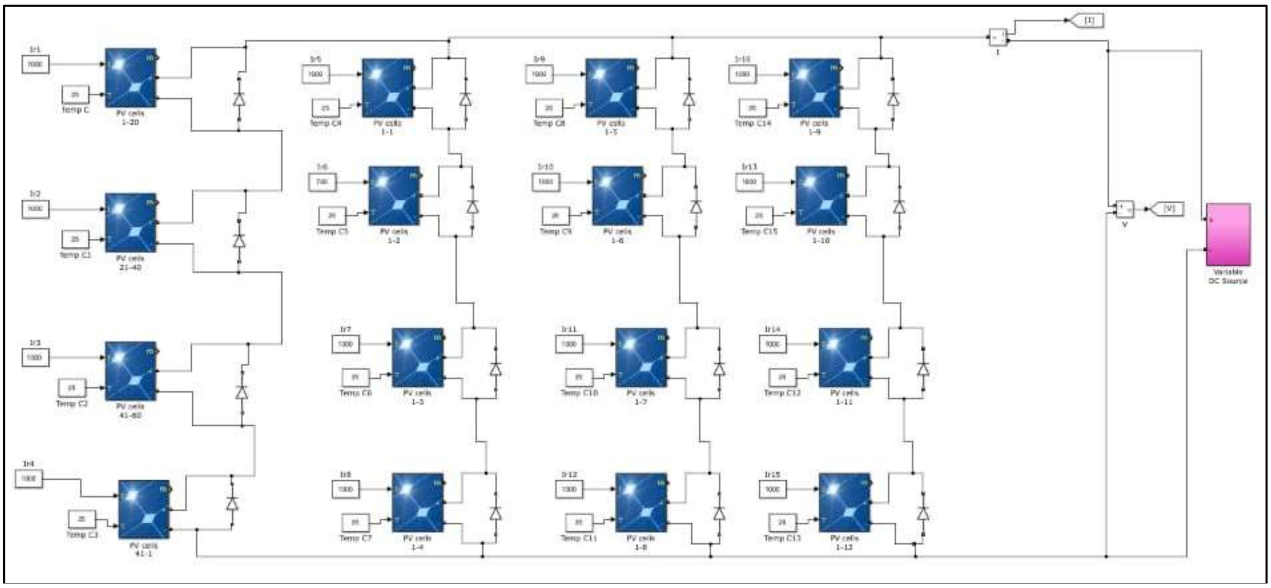

Fig 3: Series parallel configuration of SPV array

Parallel wiring increases the current output of a solar array while keeping the voltage same. In parallel wiring positives of multiple modules are connected together and all the negatives for the same modules are connected together. Here is an example of what is found in most large solar systems, a series and parallel wiring combination. Traditional array configurations SPV arrays connected in SP, are the most common configurations and have discussed their performance in detail. In this topology, a few series strings of SPV modules are connected in parallel to obtain the required voltage level and current level as shown in Fig. 4.

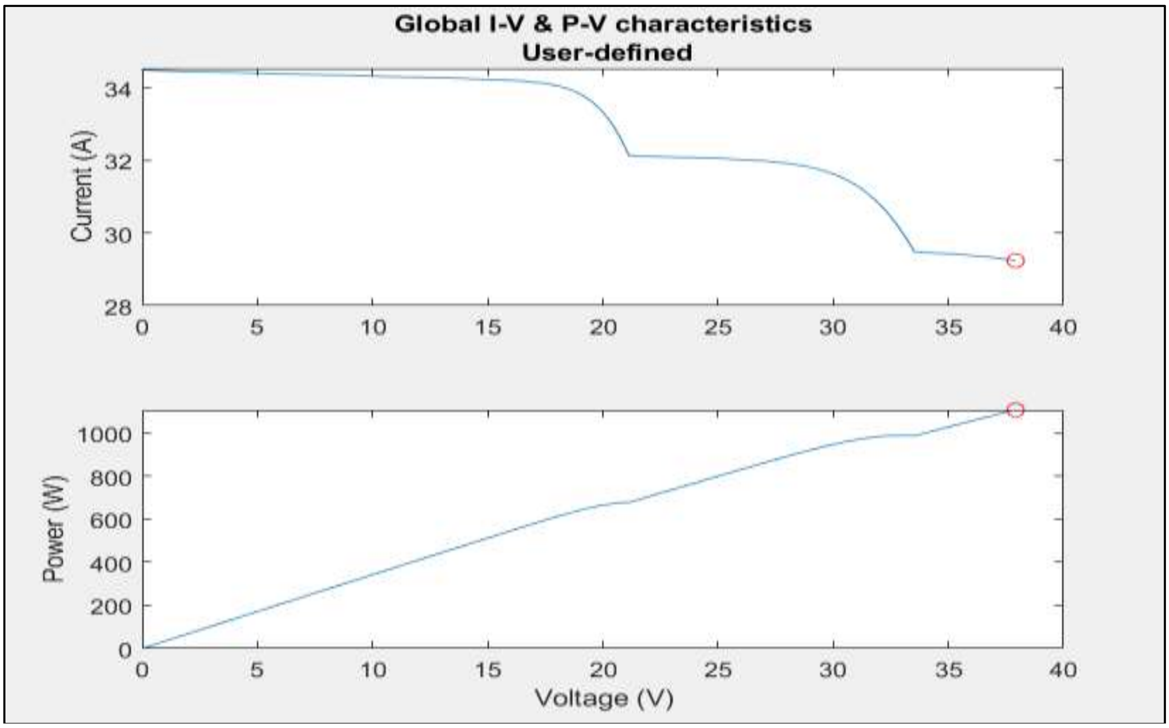

Fig 4: Characteristic waveforms under series-parallel configuration

4.2 Bridge-Link Configuration

The modules are connected in a form reminiscent of a bridge rectifier circuit where every four neighboring modules are grouped together as shown in Fig. 5. Between two groups of these modules, a cross tie link is inserted to connect two adjacent series strings so that all the links resemble a brickwork pattern based on the stretcher bonding method. Clearly this configuration shows fewer tie cross links, but has more alternative current paths than the SP scheme so the ML is lower than that of SP under fractional shading. Considering the figure it can be seen that the number of these links in BL is more than SP, so increase wiring cost and installation time. Whenever fractional shading occurs on a solar panel the current flows to near link path without turning on the bypass diode. The work in showed that the BL form can achieve the highest maximum output power point compared to and SP arrays. Results are showed that out wave forms of BL under most FSC.

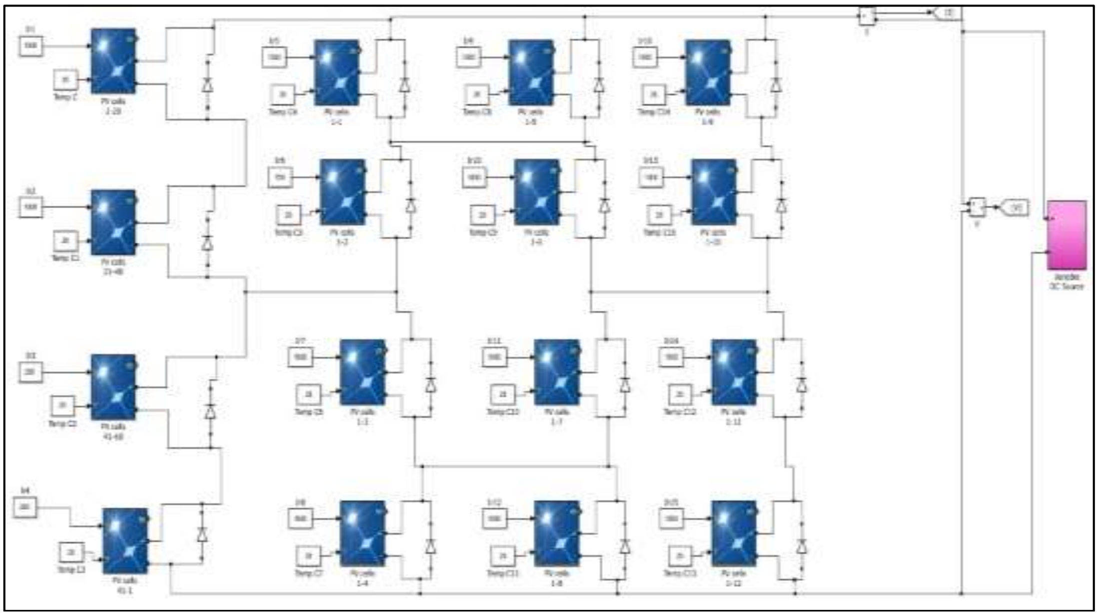

Fig 5: Bridge link configuration of SPV array

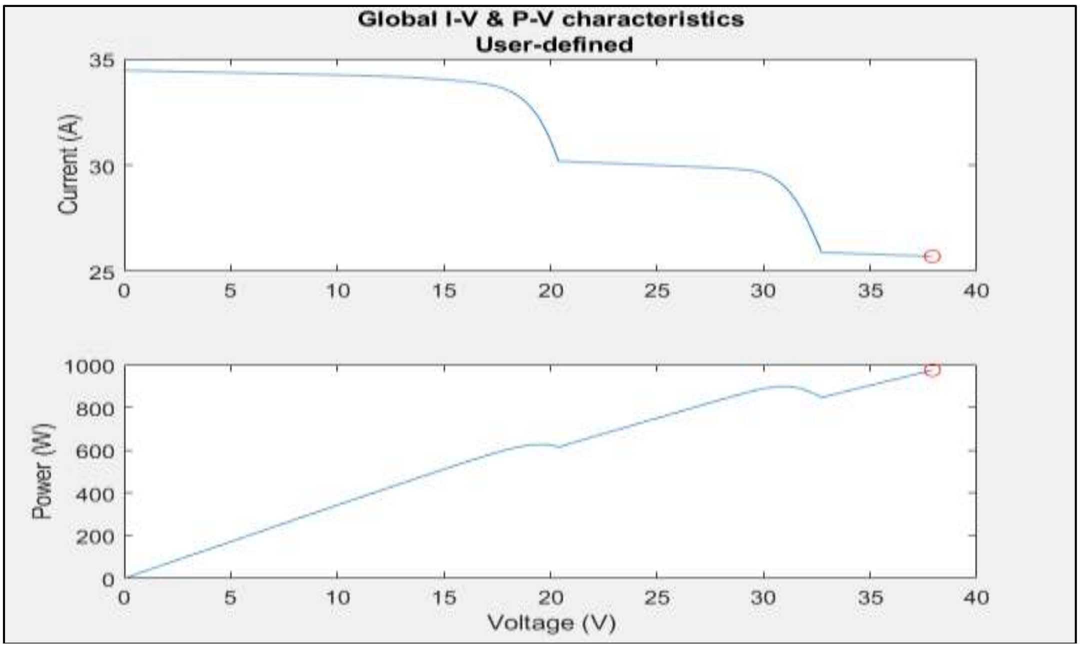

Fig 6: Characteristic waveforms under bridge-link configuration

The Fig. 6 represents the current, power and voltage waveforms of bridge link. In this case the panels are shaded in a diagonal way. In this case the current of all string are affected.

4.3 Honeycomb Configuration

Another alternative configuration to BL topology is HC structure shown in Fig. 7. Similarly to the BL array, the cross tie links connecting the adjacent series strings form a pattern like brickwork based on the combined stretcher and header bonding method. All the SPV modules are interconnected similar to the hexagon shape of the honey comb architecture. The HC SPV array configuration is having more number of electrical connections between the SPV modules compared to SP SPV array configuration and having less number of series connections compare SP array configurations.

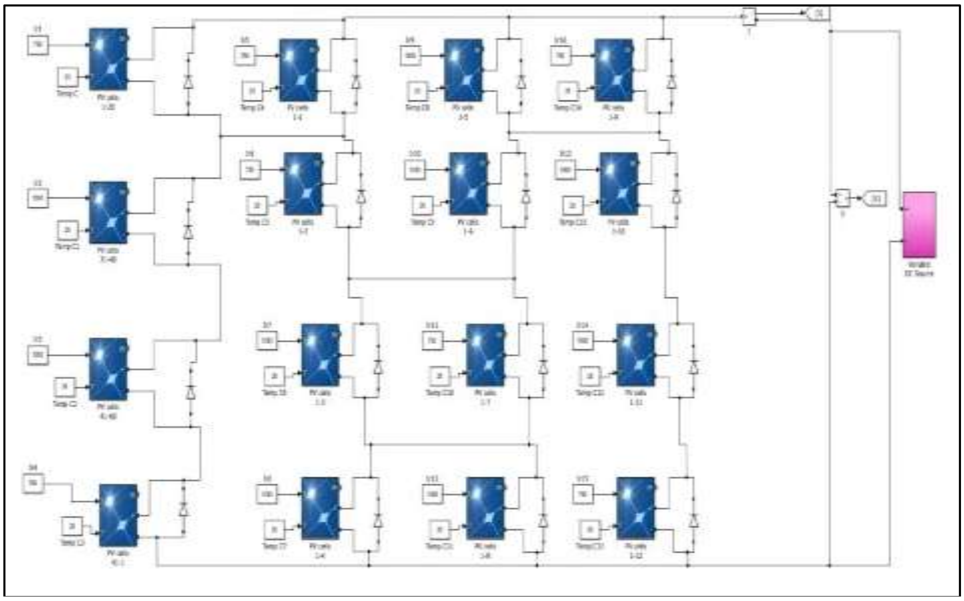

Fig 7: Honeycomb configuration of SPV array

Therefore, the mismatch power losses of HC SPV array configurations are less than SP SPV array configurations. The output characteristics of HC array configuration under different FSCs are shown in the below Fig. 8.

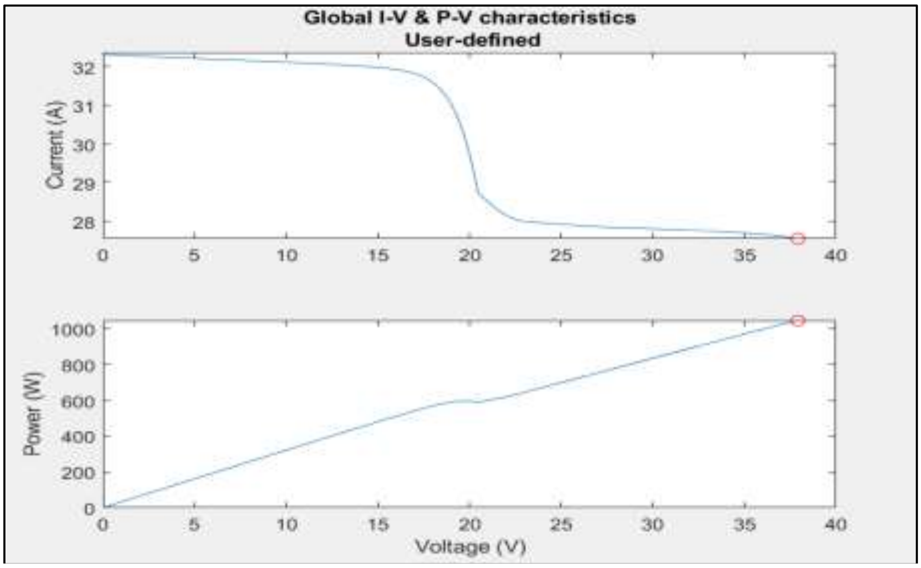

Fig 8: Characteristic waveforms under honeycomb configuration

This configuration was claimed in to combine advantages of both BL and SP. However in the work in HC still generally shows the better output power performance than SP and BL under most shading conditions because of the structure still offers the maximum number paths for the current flow. It takes to more time to installation and more cost for wire.

5. Result and Discussion

TCT connection which alleviates the issues of SP is derived through fully cross tying the rows of junctions as in Fig. 9. Thus, the total array voltage is determined by summing the voltage across the individual rows, and the overall current is the sum of the currents flowing in all the strings in the array. The cross ties within the TCT configuration reduce the possibility of turning on bypass diodes and can increase the lifetime of the SPV array to nearly double that in SP form. When one module is less illuminated, the higher current of the other more illuminated modules can flow in the other series strings through the cross ties without the need to activate the bypass diodes of the shaded module. The ability of the current to flow from one series string to another also implies that one module can be open circuited. For example, shows that since one short circuited module does not disable an entire string, the TCT scheme allows one module to be taken out for maintenance while others modules are in normal operation. It has been proven in that the TCT topology offers a better output performance than the SP scheme. This article is pointed out that the TCT topology offers a better output performance than the SP scheme under any kind of shading condition while those in highlighted that, foremost cases, there is only a single power peak in the power voltage characteristic of TCT arrays, especially when they experience column wise shading.

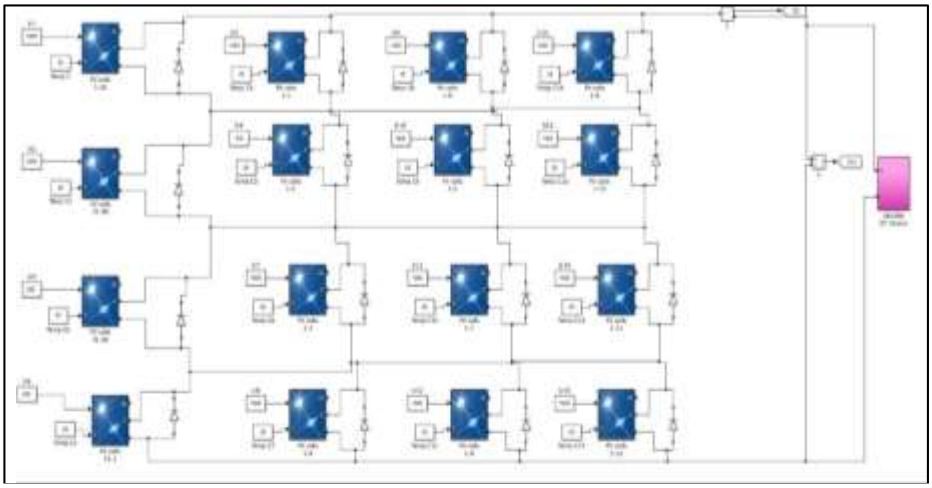

Fig 9: Characteristic waveforms under TCT configuration

However, there are many redundant links in TCT arrays and if all the SPV modules are experiencing uniform illumination, there will be little or no current flowing through these links. The many links of TCT may incur some more cost and takes more installation time.

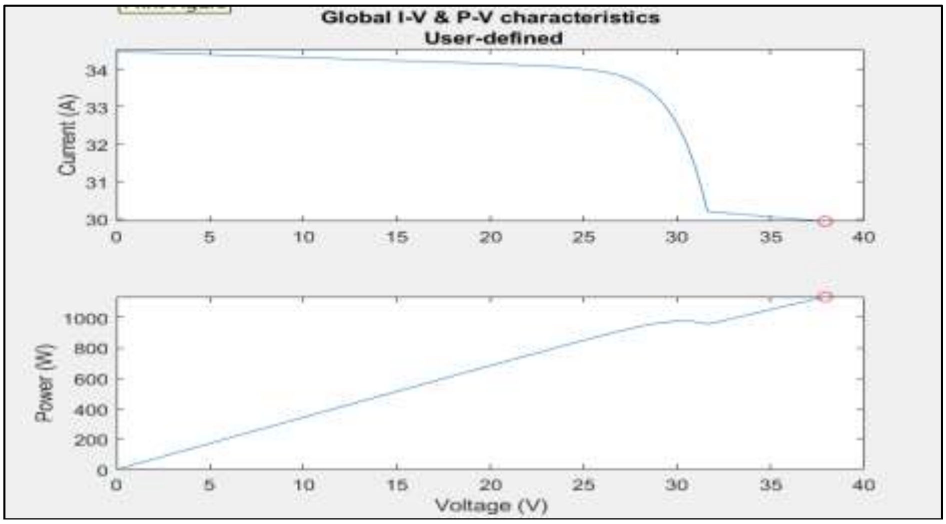

Fig 10: Characteristic waveforms under TCT configurations

The Fig. 10 represents the current, power and voltage waveforms of TCT. In this lowermost rows of two panels are shaded. The current of shaded panels is reduced and does not affect the entire string current. Comparisons of existing and proposed configurations are given in Fig. 11-12 and Table 2.

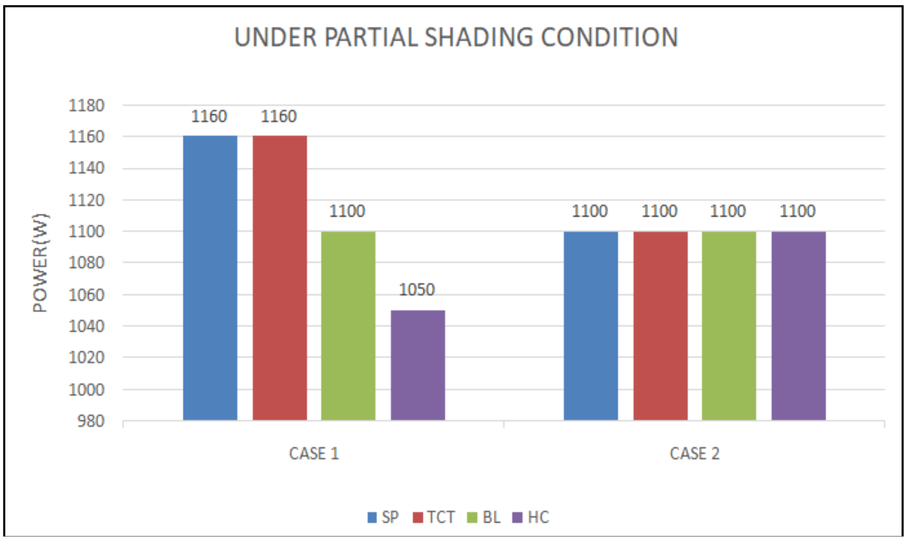

Fig 11: Output power comparisons under fractional shading condition (Case 1)

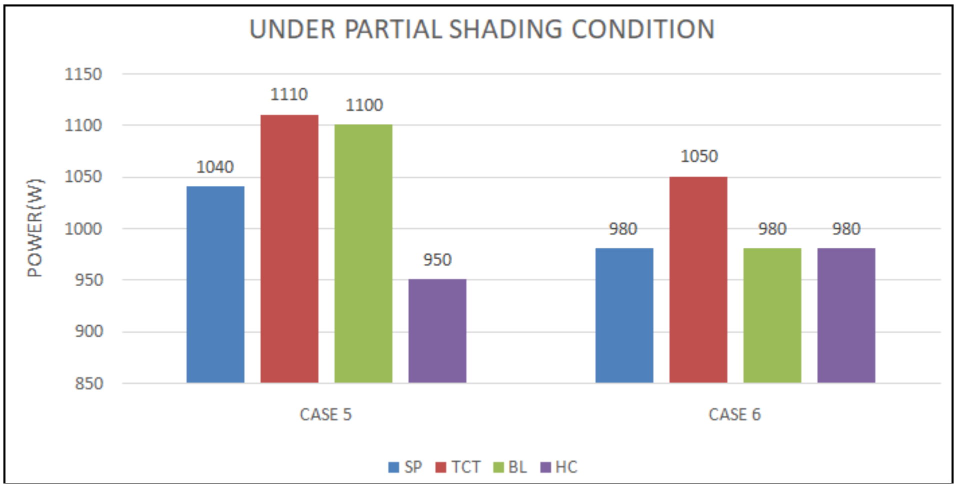

Fig 12: Output power comparisons under fractional shading condition (Case 2)

Table 2: Comparison of all SPV array configurations under different shadings

	SP	BL	HC	TCT
Case1	1160	1110	1050	1160
Case 2	1100	1100	1100	1100
Case 3	1200	1200	1230	1300
Case 4	980	980	980	980
Case 5	1040	1100	950	1100
Case 6	980	1050	980	980

By observing Table 2 the TCT configuration giving maximum power foremost cases. When shading occur in uniform manner the conventional configurations giving the maximum power. But, the shadows are not constant, changes with respective of time. In that case TCT giving maximum power.

6. Conclusions

In conventional methods the power output of SPV array configuration under different FSC is very low and power is wasted in the form mismatch losses due to one panel is shaded in the string it reduces the total current of the string. Proposed a 4 × 4 TCT SPV configuration, it has interconnections between the solar panels when one solar panel is less illuminated, the higher current of the other more illuminated solar panel current can flow in the other series strings through the cross ties or interconnections without the need to activate the bypass diodes of the shaded module. The shadows are changes the every instant of time the conventional methods give maximum output in uniform irradiance but in non-uniform irradiance condition TCT gives maximum power. The simulations results are compared with conventional methods. The results shows TCT array configuration giving maximum power in different maximum fractional shading conditions

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