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original Article

Design and Study a Solar PWM Inverter Under Partial Shading Effect on PV Strings

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Abstract *- These days, with the great development of electrical engineering sciences, the world is moving towards clean energy sources. Especially solar energy, there are many studies and research on PV panels, developing their productivity, increasing efficiency, and reducing losses. Remains a partial shadow problem for researchers, developers, and producing companies. In this research, a PWM solar inverter was designed to be powered through four PV panels. These four panels are connected in two ways: first, all panels are connected in series. The second way was these four panels splatted into two strings, each string contains two PV panels in series, and the two strings are connected in parallel to each other. After confirming the design of the inverter, the partial shadow effect has been tested with many scenarios. The voltage and current of each panel and the overall voltage, current, and power of the inverter have been measured in each one of the scenarios, and characteristic curves were drawn for each case. It will be explained in detail in these search paragraphs.*

Keywords *- Solar energy, Partial shadow, PWM solar inverter, Solar cells.*

1. Introduction

The SPWM inverter is a device used in solar power systems to transform the current produced by PV from DC form into AC, which is suitable for use in domestic and other electrical applications [1, 2]. It is a major important device in solar power systems, playing a crucial role in power conversion, the benefits of solar energy, and providing clean electrical power [3]. A device that converts solar energy into electrical power is called a PV panel and is based on an electronic semiconductor. Crystalline silicon is the base of the solar system, containing two types: mono-crystalline and multi-crystalline panels. In this paper, an in-depth study of the solar power inverter was initially conducted. Subsequently, the electrical circuit for it was designed using MATLAB software. The primary components of the circuit included a source of DC voltage from the solar panels, as well as components like the MOSFET and control circuit, along with display elements. The control circuit consists of two reference waves, a sinusoidal and a triangular wave, to regulate the operation of the four MOSFETs and thereby control the entire circuit. This contributes to producing voltage with high efficiency and minimal losses. Partial shading is the most common problem that occurs in a PV system. It may be caused by any nearby object that blocks sunlight from reaching the cell, such as nearby buildings, trees, birds dropping, etc., or it is formed due to natural phenomena such as clouds, dust, snow, etc. Partial shading creates a barrier that prevents light from reaching the PV cell, which reduces the efficiency of the solar panel and reduces its power production if the partial shading is on all the matrices, which usually occurs as a result of natural phenomena, so its effect stops at this point.

However, the biggest problem is whether the effect is on some panels or on some cells in the same panel. In this case, the shaded parts behave like a resistance, through which a direct current passes, which leads to an increase in their temperature due to current passage. These point are called hot spots, which cause many problems such as reducing panel efficiency or damaging it, fires, and others. There is a lot of research in this field, some of which was obtained in the following.

In research titled "Investigation of the Partial Shading Effect of Photovoltaic Panels and Optimization of Their Performance Based on High-Efficiency FLC Algorithm," published in Energies journal 2023, the researchers studied the effect of partial shading on the PV systems' performance, focusing on improving performance using fuzzy logic to track the maximum power point [4].

In another study entitled "Irregular SuDoKu Modelling of Solar Photovoltaic Arrays for Partial Shading Optimization" published in the Arabian Journal for Partial Shading Optimization in 2023, the researchers suggested an innovative model that depends on SuDoKu distribution to improve the arrangements of panel arrays in order to reduce the power losses caused by partial shading [5].

Another research titled “Mitigating the Impact of Partial Shading Conditions on Photovoltaic Arrays Through Modified Bridge-Linked Configuration” published in the Sustainability journal 2025, studied the effect of partial shading on the PV string matrices and suggested a new configuration known as (modified bridge-linked configuration) to reduce effects on the shading regions [6].

Most researchers studied the partial shading effect in a one method or scenario, while in this research, different operating conditions of the inverter were simulated to understand the impact of changing working conditions on its performance. In order to depth studying the effect of partial shading, four PV panels used with two methods of connections (i.e. Series (SC) and Series Parallel (SPC) connection), in each connection method many scenarios of partial shading was studied such as the effect of it on one PV panel, two neighbour panels, two panels in same string, and two panels in different string. In each scenario, the irradiation was reduced to simulate the partial shading on panels, the voltages, currents, and power at each irradiation value were registered and tabulated, and then curves were drawn for each connection method and scenario.

2. Photovoltaic (PV) System

A PV system is an electrical system that converts energy from sunlight by PV panels into a DC current, firstly, then into an AC current [7, 8]. Two types of PV systems existed: on-grid-connected and off-grid systems. The most common system used is the first one, which is combined with conservative residential and industrial electricity systems [9, 10].

2.1. PV Panels

PV boards harness the sun’s energy and transform it into electrical power through a semiconductor (silicon) material. When the sunlight exposes the silicon cells, the semiconductor material engages an energy-specific value, removing electrons, which are negatively charged particles crucial to electricity [11]. The process that produces an electrical voltage or current from a PV cell from sunlight is called the photovoltaic effect. These cells are made up of two different semiconductor (P and N) types connected together to form a p-n junction [12].

This connection of semiconductors creates an electrical field in the intersection space, causing electrons to transfer in the direction of the positive p-side and holes to move in the direction of the negative n-side. Therefore, this field prompts negatively charged particles to move in one direction and positively charged particles [13]. Figure 1 shows an electrical power building process in a PV cell.

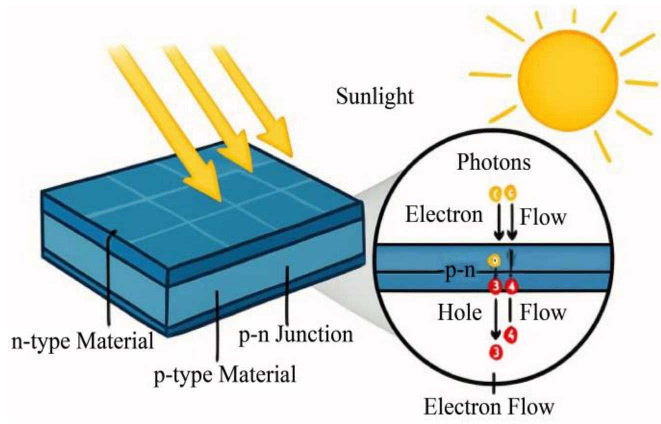

Fig. 1 Electrical power process of PV cell [16]

This process can be characterized by an electrical circuit consisting of a generator, a diode, and a shunt resistor, all of them connected in parallel, in addition to a resistance connected in series, as shown in Figure 2.

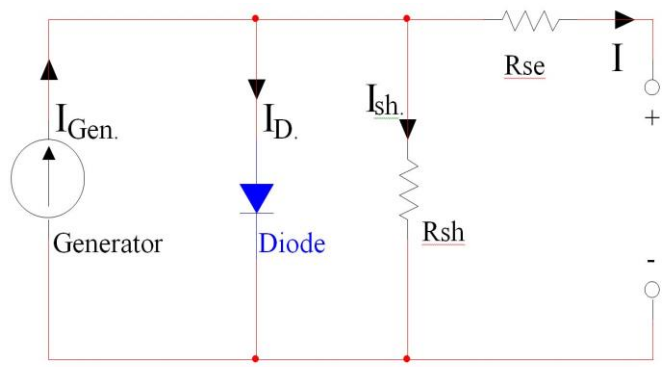

Fig. 2 Equivalent circuit of PV cell [14]

From the previous circuit, a description equation can be extracted depending on the current flows in the circuit components. The load current expression is [15]:

$$I = I_{\mathrm{Gen}} - I_{\mathrm{Diode}} - I_{\mathrm{sh}} \quad (1)$$

The ideal diode equation ID is [16]:

$$I_D = I_0 \left\{ e^{\frac{\mathrm{qV}}{\mathrm{nkT}}} - 1 \right\} \quad (2)$$

Io: reverse saturation current, n: ideality factor, q: charge constant, k: Boltzmann constant, T: temperature.

Substituting the diode equation in the load current equations yields

$$I = I_{Gen} - I_0 \left\{ e^{\frac{qV}{nkT}} - 1 \right\} - I_{sh} \quad (3)$$

This equation gives us the characteristic current-voltage graph shape as seen for solar cells in Figure 3.

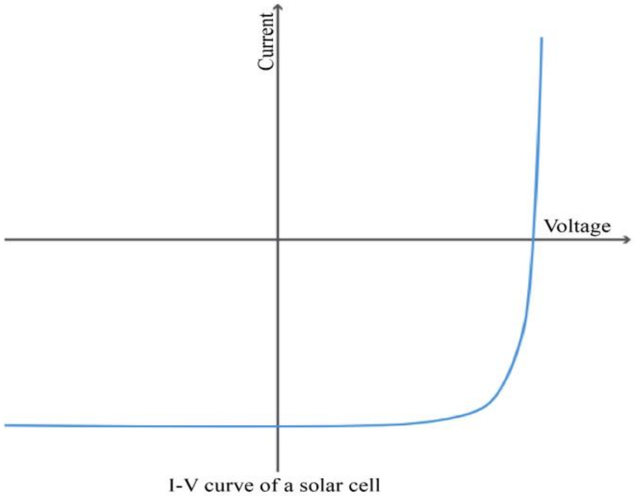

Fig. 3 PV cell VI characteristic curve [17]

2.2. PWM Inverter

The Pulse Width Modulation (PWM) inverter is the most famous and commonly used in a solar power system. It converts DC power into AC power by varying the width of pulses according to the desired AC output voltage. The technique of PWM produces a smooth sinusoidal signal easily, which closely resembles the ideal waveform of utility power. Furthermore, PWM inverters top in power efficiency due to their ability to control the amplitude and frequency of the output AC waveform. The basic design of a PWM inverter, called a full-bridge inverter, consists of four MOSFETs controlled by two signals: a sinusoidal signal, also called the reference signal. and a triangle signal. The circuit diagram for the full-bridge inverter is depicted in Figure 4.

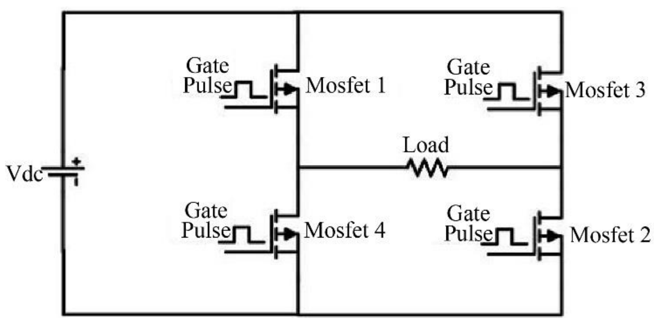

Fig. 4 PWM inverter circuit diagram

MOSFET1 and MOSFET2 pulsating from the same pulses, as well as MOSFET3 and MOSFET4, have the same pulses. i.e., both MOSFET1 and MOSFET2 operating at the same time; this principle applies to the other two transistors.

2.3. PWM Controller

Since the input to the inverter is DC power, a controller was required to convert it to AC. This controller directly controls the AC voltage according to a sine signal by comparing the amplitude of the triangle signal with a reference (sine wave) signal using a comparator, which generates the pulses depending on signal amplitude. If the triangle signal is less than the sine signal, then the comparator will give a pulse; otherwise, the output of the comparator will be zero. Figure 5 shows the PWM switching technique.

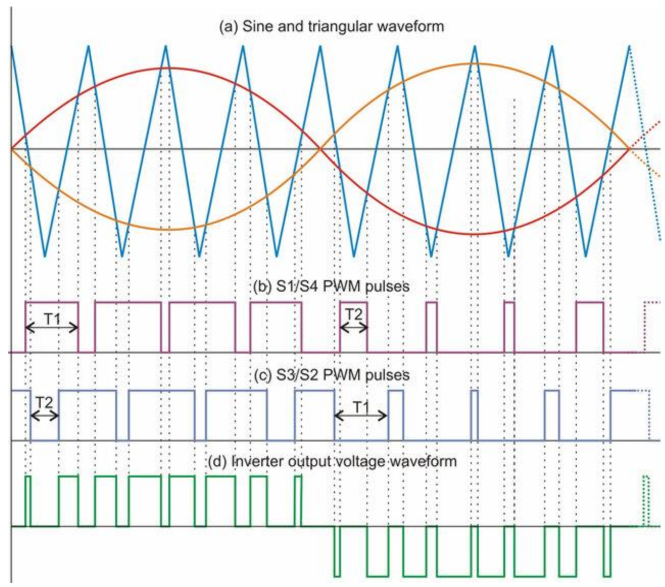

Fig. 5 PWM switching technique

3. Simulation and Results

A single-phase solar system will be designed, comprising 4 solar panels and an inverter operating with PWM technology, controlled by two waves, one being sinusoidal and the other triangular. The inverter will be utilized to produce a square wave, which will then pass through a smoothing circuit to obtain a pure sinusoidal waveform.

3.1. Controller Simulink

The controller circuit was designed based on generation triggers to trigger the four MOSFETS in the PWM inverter. The reference signal was a sinusoidal signal with an amplitude of 7V. This signal entered an absolute block to make it a unipolar signal in order to match the pulsating signal. The second signal is a triangle signal with amplitude of 8 V since it the nearest value to the reference value, both reference and triangle signals to a comparator logic gate to compare between them simultaneously to build a trigger signals, after that the first half period of reference signal multiplying by the unshifted unit step signal, while the second half period multiplied with the shifted unit step signal, these multiplications done by using two AND gate logical operator. The result from the previous operations is a trigger signal that switches the MOSFETs in the PWM inverter. The controller Simulink is shown in Figure 6. MATLAB software was utilized in the design due to its high reliability and extensive options.The Simulink design consists of 4 MOSFETs and a control circuit composed of two waves, one sinusoidal and the other triangular. Additionally, there are 4 solar panels connected in two cases: series and series-parallel.

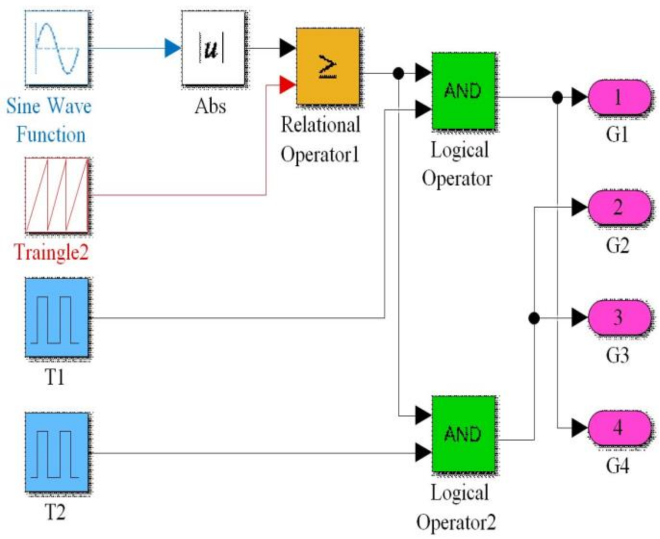

Fig. 6 Controller circuit Simulink

Firstly, the signals of the switching controller should be shown in order to check that the inverter is working correctly. Figure 7 shows these signal waveforms.

The first and second signals are the reference and triangle signal. The triangle wave amplitude is 10 volts, and the reference sine wave frequency is 1000 Hz, while the third is the pulses that will trigger MOSFET1&2 and the fourth is the pulses that will trigger MOSFET3&4.

After confirming the controller is working correctly, the inverter will be operated and fed from 4 PV panels, and the effect of partial shadow on it will be studied. The solar panel specifications were practically taken from a PV panel 570 watts, as tabulated in Table 1:

Table 1. PV specifications

Specification	Value
Maximum Power (W)	570
Open circuit voltage Voc (V)	51.7
Voltage at maximum power point Vmp (V)	43
Temperature coefficient of Voc (%/°C)	-0.36099
Cells per module (Ncell)	72
Short-circuit current Isc (A)	13.95
Current at maximum power point Imp (A)	13.26
Temperature coefficient of Isc (%/°C)	0.102

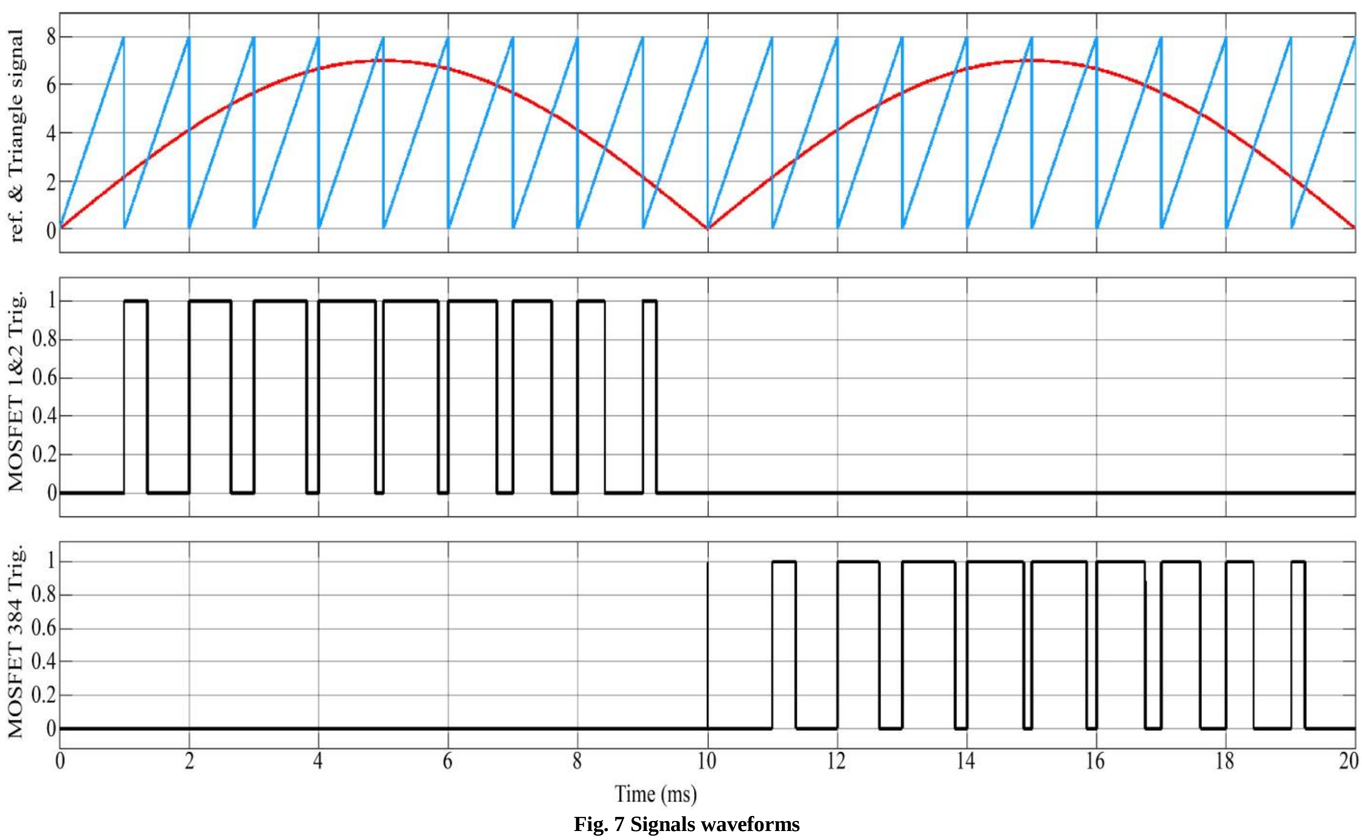

Fig. 7 Signals waveforms

3.2. Case 1: Series Connection (SC) with Partial Shading on PV4

In this case, all four PV panels are connected in series as shown in Figure 8.

3.2.1. Series Connection 1st Scenario (SC-FS): Series Case with Partial Shading on One Panel

The first scenario was studying the partial shadow on the fourth PV panel by varying the radiation value submitted on it, the radiation value decreased from 1000 (which is the highest value) to zero (which is the lowest value -dark-). Noticed that the highest effect was on PV-4, where its voltage decreased from 52 V (when the radiation was 1000) to 0 V (when the radiation value was 0). With the current decrease from 13.92 A to 0.

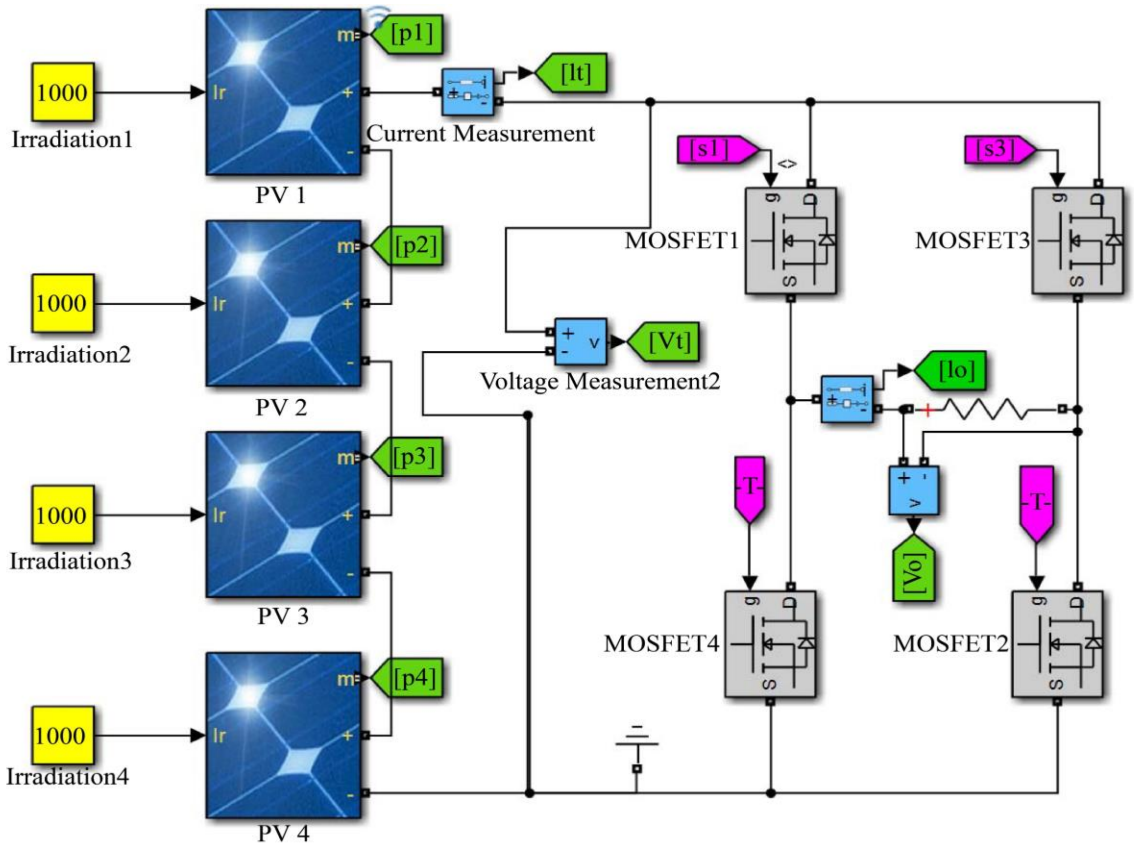

Fig. 8 Series connection diagram

Table 2 shows the extent of variation when changing solar radiation on PV4 from 1000 to 0 :

Table 2. Voltages and Currents VS Radiation Reduction on PV4 (SC-FS)

Rad4	PV1		PV2		PV3		PV4	
	V	I	V	I	V	I	V	I
1000	51.7	13.92	51.7	13.92	51.7	13.92	51.7	13.92
900	51.7	13.92	51.7	13.92	51.7	13.92	51.47	12.53
800	51.7	13.92	51.7	13.92	51.7	13.92	51.21	11.14
700	51.7	13.92	51.7	13.92	51.7	13.92	50.93	9.748
600	51.7	13.92	51.7	13.92	51.7	13.92	50.59	8.356
500	51.7	13.92	51.7	13.92	51.7	13.92	50.2	6.964
400	51.7	13.92	51.7	13.92	51.7	13.92	49.72	5.571
300	51.7	13.92	51.7	13.92	51.7	13.92	49.1	4.178
200	51.7	13.92	51.7	13.92	51.7	13.92	48.23	2.786
100	51.7	13.92	51.7	13.92	51.7	13.92	46.73	1.392
90	51.7	13.92	51.7	13.92	51.5	13.92	46.51	1.25
80	51.7	13.92	51.7	13.92	51.7	13.92	46.25	1.11
70	51.7	13.92	51.7	13.92	51.7	13.92	45.97	0.97
60	51.7	13.92	51.7	13.92	51.7	13.92	45.63	0.83
50	51.7	13.92	51.7	13.92	51.7	13.92	45.24	0.69
40	51.7	13.92	51.7	13.92	51.7	13.92	44.76	0.55
30	51.7	13.92	51.7	13.92	51.7	13.92	44.13	0.41

20	51.7	13.92	51.7	13.92	51.7	13.92	43.26	0.277
10	51.7	13.92	51.7	13.92	51.7	13.92	41.75	0.13
0	51.7	13.92	51.7	13.92	51.7	13.92	0	0

From the previous table, it is clear that all PV voltages and currents were not affected by partial shading except PV-4, which is greatly affected by shading, so Figure 9 shows the relation between the irradiation and the voltages.

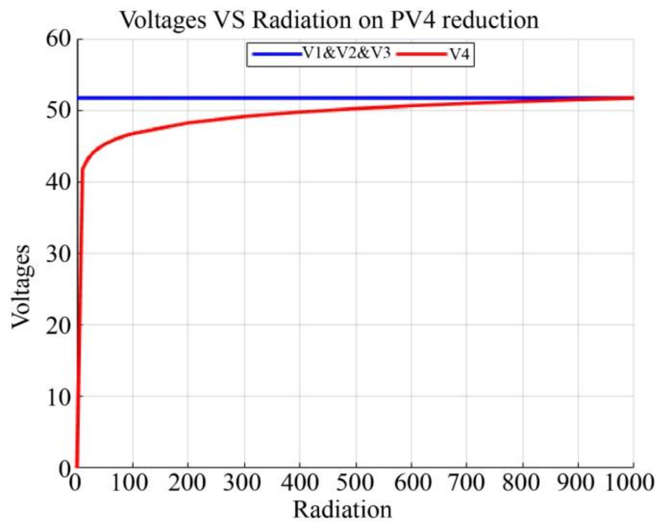

Fig. 9 Voltages of four PVs with radiation on PV4 reduction (SC-FS)

The voltage across PV1, PV2, and PV3 is constant and do not vary with radiation reduction, while the voltage across PV4 will reduce synchronously with radiation. The voltage profile for Series Connection (SC-FS) with partial shading on PV4 is shown in Figure 10.

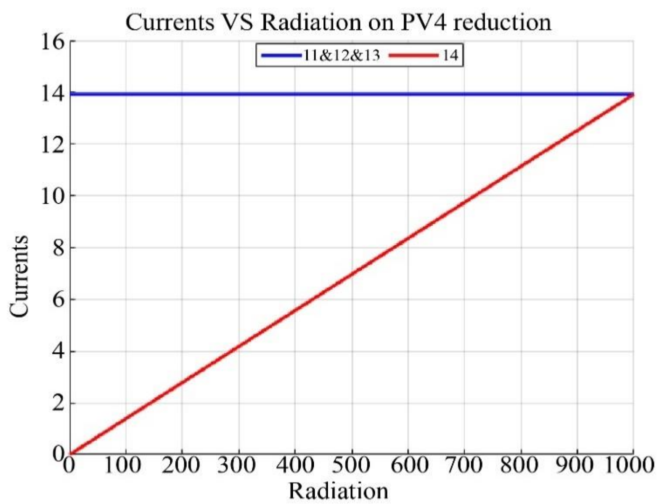

Fig. 10 Voltage profile for Series Connection (SC-FS)

The irradiation data selected are from 100 down to 0 since the maximum difference on these data occur, so its clear that the voltages at panels that not exposed to partial shading did not effect, but the voltage of PV4 was decreased from maximum value (i.e. open circuit voltage) when the irradiation value is 1000 W/m2 down to zero when the irradiation value is 0. The relation between radiation and currents is shown in Figure 11. The relation is linear, so the current through PV4 reduces linearly with the radiation, while I1, I2, and I3 are not affected by the irradiation reduction in PV4 since all panels are connected in series. The current profile of this scenario is shown in Figure 12. It is clear that the most effect of irradiation reduction is on the fourth panel current since it reduces linearly with irradiation reduction, so the current is affected by the radiation reduction more than the voltage in the same panel.

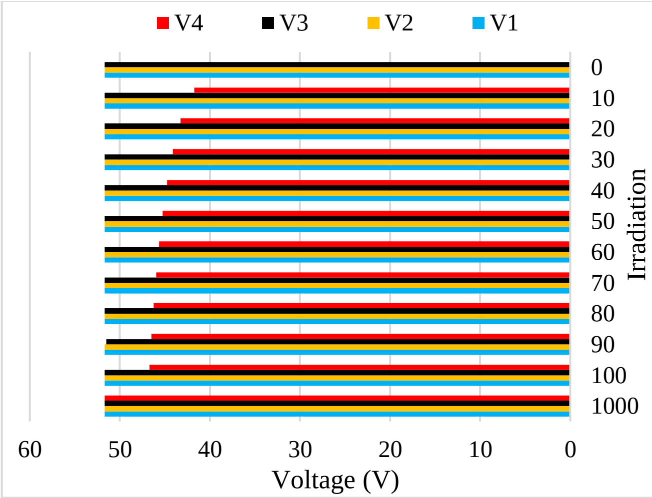

Fig. 11 Currents of four panels with radiation on PV4 reduction (SC-FS)

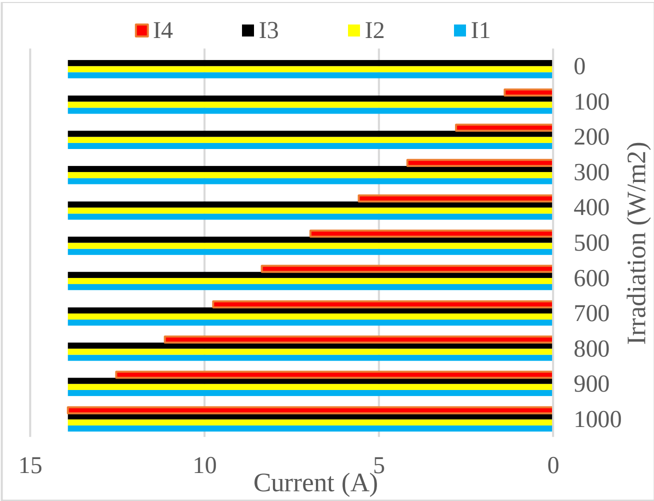

Fig. 12 Current profile (SC-FS)

The V-I curve of PV4 can be drawn as shown in Figure 13.

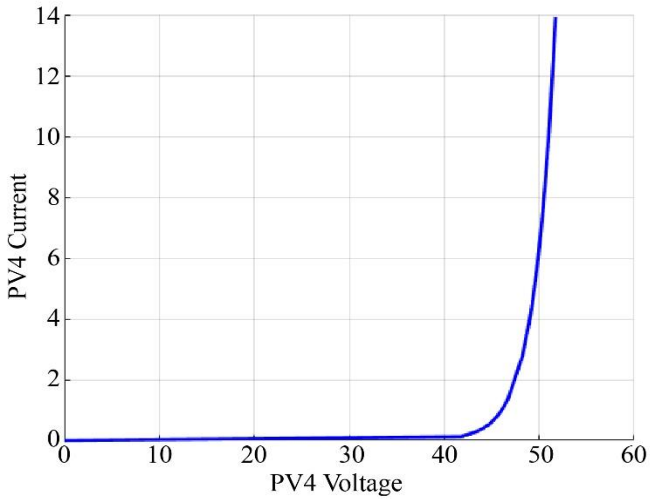

Fig. 13 V-I curve of PV4 (SC-FS)

The VI profile of all panels is shown in Figure 14.

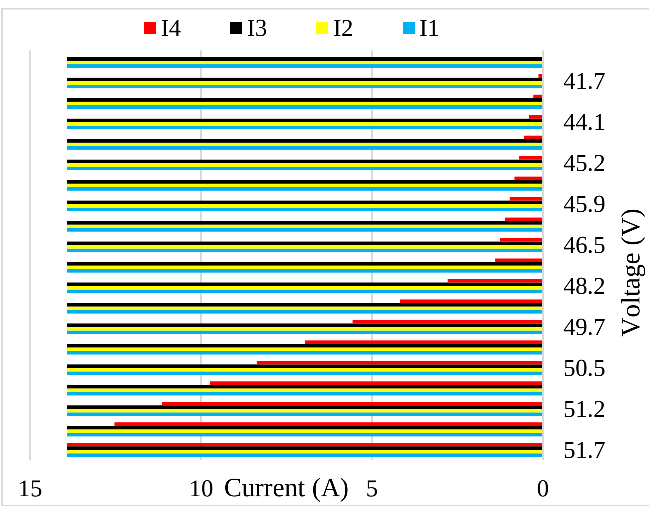

Fig. 14 VI profile of (SC-FS)

The current reduces instantaneously with the voltage reduction till it breaks down, approximately when the voltage equals 46 V. At this point, the current becomes less than 1A. Inverter Output power against irradiation reduction is shown in Figure 15 Output power increased in a parabolic curve with irradiation on PV4 increasing, so the relation between the output power and irradiation is a direct relationship, since the output power increased as irradiation increased.

3.2.2. Series Connection 2nd Scenario (SC-SS): PV3 has a Half Shadow (i.e. irradiation on it = 500 W/m2) and Reducing Irradiation on PV4

In This case, half shading on one panel (PV3) is chosen to apply 500 W/m2 irradiation on it, then applying variable partial shading on the fourth panel by reducing irradiation from 1000 to W/m2. For each voltage and for each value of irradiation, the results were tabulated in Table 3.

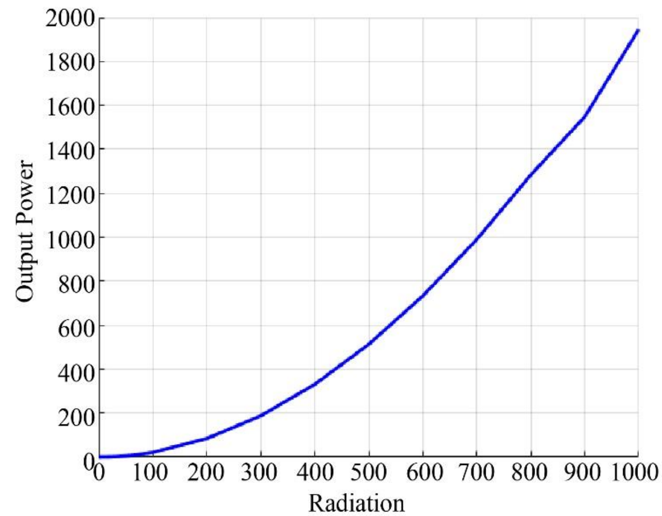

Fig. 15 output power curve (SC-FS)

Table 3. Voltages vs Radiation reduction on PV4 (SC-SS)

Rad4	V1	V2	V3	V4
1000	51.7	51.7	50.2	51.7
900	51.7	51.7	50.2	51.47
800	51.7	51.7	50.2	51.21
700	51.7	51.7	50.2	50.93
600	51.7	51.7	50.2	50.59
500	51.7	51.7	50.2	50.2
400	51.7	51.7	50.2	49.72
300	51.7	51.7	50.2	49.1
200	51.7	51.7	50.2	48.23
100	51.7	51.7	50.2	46.73
90	51.7	51.7	50.2	46.51
80	51.7	51.7	50.2	46.25
70	51.7	51.7	50.2	45.97
60	51.7	51.7	50.2	45.63
50	51.7	51.7	50.2	45.24
40	51.7	51.7	50.2	44.76
30	51.7	51.7	50.2	44.14
20	51.7	51.7	50.2	43.26
10	51.7	51.7	50.2	41.75
0	51.7	51.7	50.2	0

The voltage across PV4 through it will reduce sensuously with irradiation reduction. Figure 16 shows the voltages of all panels versus the irradiation. The voltages across PV1 and PV2 are constant and are not affected by radiation reduction. The voltage across PV3 is also constant, but its amplitude is less than the previous two voltages because the irradiation on PV3 is 500 W/m2. The voltage of PV1 and PV2 is constant, equal to 51.7 V, independent of shading on another panels, while the voltage on PV3 is less than the previous two panels, where the voltage is equal to 50.2 V since its irradiation is 500 W/m2. The voltage profile of this scenario can be drawn depending on the data collected from studying the effect of half shading of this case, as shown in Figure 17.

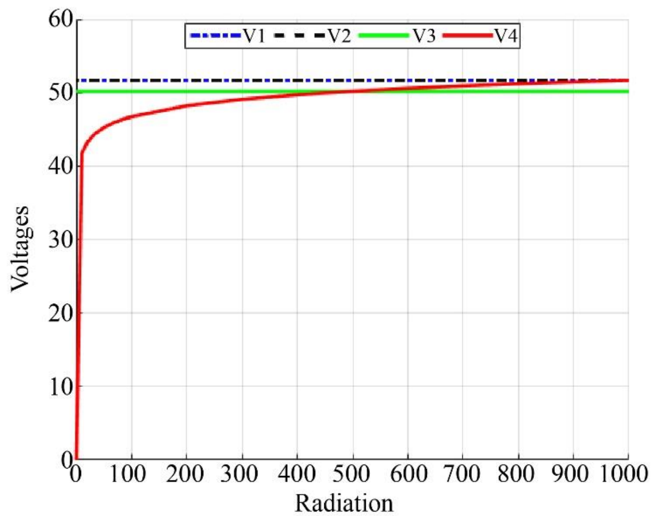

Fig. 16 Voltages drop with irradiation reduction (SC-SS)

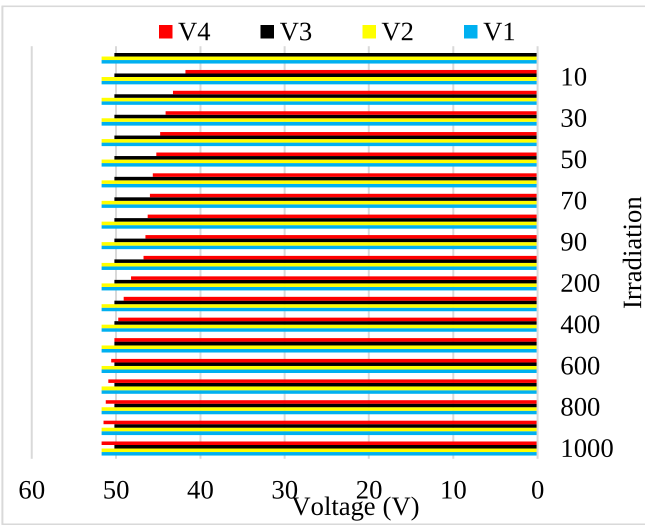

Fig. 17 Voltage profile (SC-SS)

The voltage of PVs 1,2, and 3 was constant and not affected by irradiation reduction on PV4, while the voltage of PV4 decreased simultaneously with irradiation reduction. The currents of this scenario can be tabulated in Table 4.

Table 4. Currents VS Radiation reduction on PV4 (SC-SS)

Rad4	I1	I2	I3	I4
1000	13.92	13.92	6.964	13.92
900	13.92	13.92	6.964	12.53
800	13.92	13.92	6.964	11.14
700	13.92	13.92	6.964	9.748
600	13.92	13.92	6.964	8.356
500	13.92	13.92	6.964	6.964
400	13.92	13.92	6.964	5.571
300	13.92	13.92	6.964	4.178
200	13.92	13.92	6.964	2.786
100	13.92	13.92	6.964	1.392
90	13.92	13.92	6.964	1.253
80	13.92	13.92	6.964	1.114
70	13.92	13.92	6.964	0.974
60	13.92	13.92	6.964	0.834
50	13.92	13.92	6.964	0.695
40	13.92	13.92	6.964	0.556
30	13.92	13.92	6.964	0.416
20	13.92	13.92	6.964	0.277
10	13.92	13.92	6.964	0.137
0	13.92	13.92	6.964	0

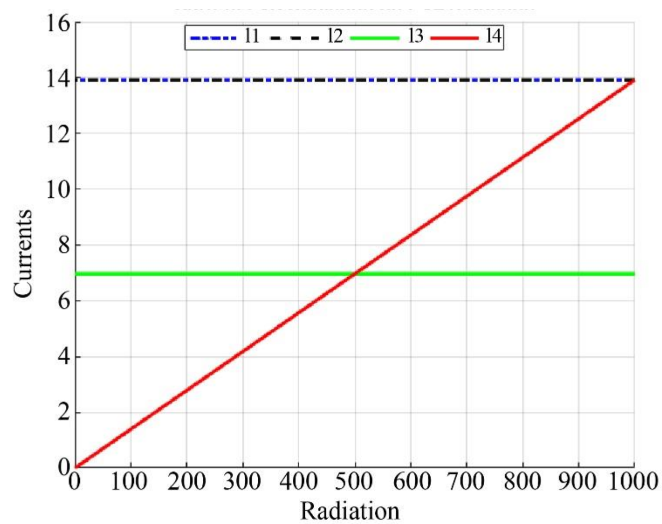

Fig. 18 currents with irradiation reduction (SC-SS)

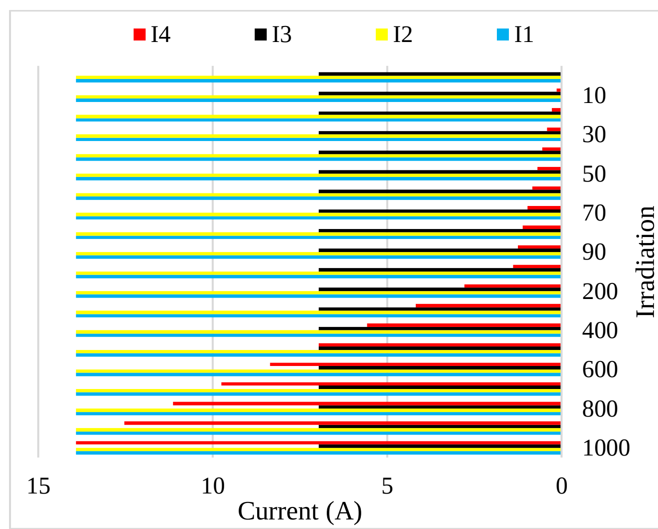

Fig. 19 Current profile (SC-SS)

The current curves of each panel are shown in Figure 18, and the current profile is shown in Figure 19. The currents of PV1 and PV2 are constant, equaling 13.92 A since their irradiations are 1000 W/m2. Current of PV3 is also constant, but its value is 6.964 A since its irradiation value is half the maximum value. In comparison, the current of PV4 was decreased with irradiation reduction. Notice that when the irradiation becomes 500 W/m2, the current is equal to the current of PV3 since the irradiations of both panels are equal. The current profile of this scenario was collected from the irradiation reduction effect on PV4, shown in Figure 19.

In this case, the VI characteristic curve, the effect of radiation reduction did not appear elsewhere in the PV that was reduced. The reduction in the inverter output power will be minimal when the radiation is more than 500 W/m2. When the radiation turns to less than this point, the output power will collapse quickly, as shown in Figure 20. After analyzing characteristic curves of voltages, currents, and power in the first case with two scenarios, the connection method will change to a parallel connection.

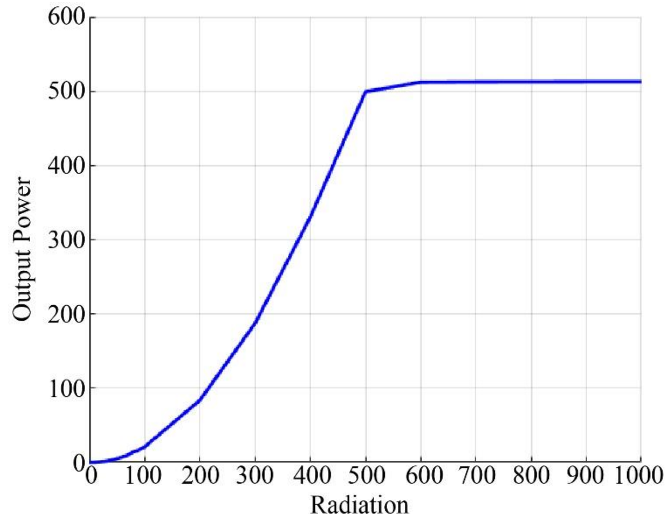

Fig. 20 Output power with irradiation (SC-SS)

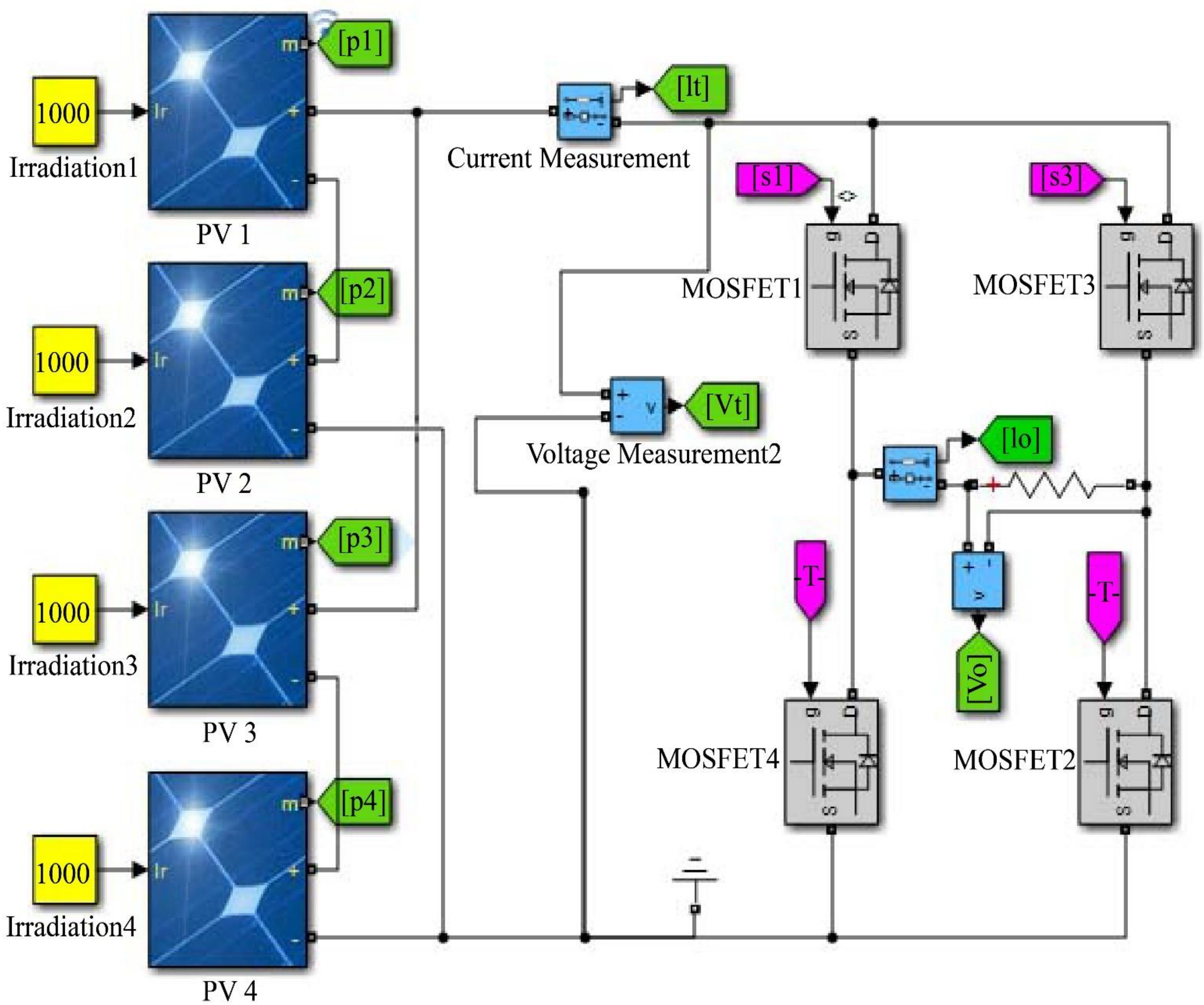

Fig. 21 Series-Parallel Connection (SPC)

3.3. Case 2: Series-Parallel Connection (SPC)

In this case, each two PV panels are connected in series in a group, and each group is connected in parallel, as shown in Figure 21.

In this case, three scenarios will be explained. Firstly, reducing irradiation on PV4 without any change in other panels. Secondly, half shadow on PV3 and reducing irradiation on PV4 (i.e., partial shading on two panels in the same string), finally, half shadow on PV2 and reducing irradiation on PV4 (i.e., partial shading on two panels in different strings)

3.3.1. Series-Parallel Connection 1st Scenario (SPC-FS): Partial Shading on PV4

In this scenario, the partial shading will appear on PV4 only, i.e., reducing the irradiation from 1000 to 0 W/m^2 without any shadow on other panels, i.e., the irradiation on other panels is equal to 1000 W/m^2. Voltage values of each step of radiation reduction are measured and tabulated in Table 5.

Table 5. Voltages VS Radiation reduction on PV4 (SPC-FS)

Rad.4	V1	V2	V3	V4
1000	51.7	51.7	51.7	51.7
900	51.64	51.64	51.75	51.53
800	51.58	51.58	51.82	51.34
700	51.51	51.51	51.88	51.14
600	51.44	51.44	51.96	50.92
500	51.35	51.35	52.04	50.67
400	51.26	51.26	52.13	50.4
300	51.16	51.16	52.23	50
200	51.03	51.03	52.35	49.71
100	50.89	50.89	52.49	49.29
90	50.87	50.87	52.5	49.24
80	50.85	50.85	52.52	49.19
70	50.84	50.84	52.53	49.14
60	50.82	50.82	52.55	49.09
50	50.8	50.8	52.57	49.04
40	50.79	50.79	52.58	48.9
30	50.77	50.77	52.6	48.94
20	50.75	50.75	52.62	48.89
10	50.73	50.73	52.63	48.83
0	29.36	29.36	56.35	2.36

Voltage curves of panels versus irradiation reduction are shown in Figure 22.

The voltage profile of all panels with the irradiation reduction from 1000 to 0 W/m^2 on panel 4 can be drawn in Figure 23.

Voltages across panels 1 and 2 are minimal, varying while voltage across panel 4 varies till collapse, depending on irradiation value, where it collapses at the moment when irradiation value reduces to zero.

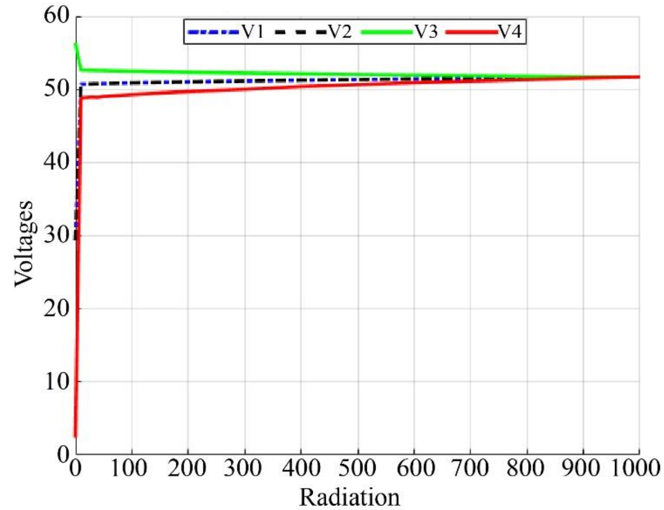

Fig. 22 Voltage curves (SPC-FS)

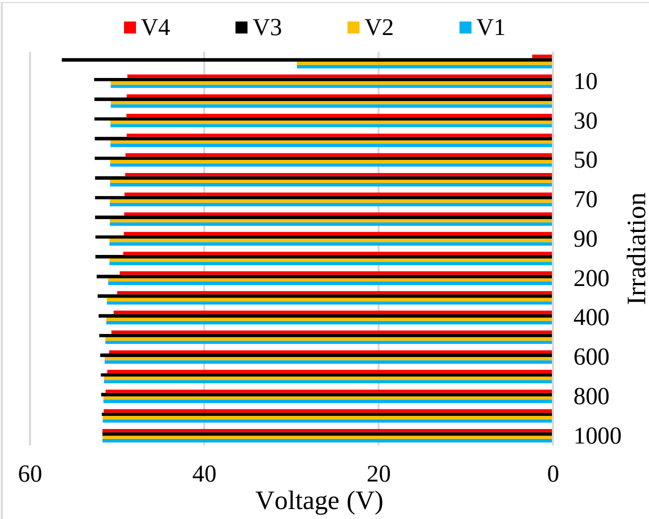

Fig. 23 Voltage profile (SPC-FS)

Currents through each panel are calculated and tabulated in Table 6.

Table 6. Currens VS Radiation reduction on PV4 (SPC-FS)

Rad.4	I1	I2	I3	I4
1000	13.92	13.92	13.92	13.92
900	13.75	13.75	14.1	12.71
800	13.57	13.57	14.28	11.5
700	13.37	13.37	14.48	10.31
600	13.15	13.15	14.71	9.138
500	12.9	12.9	14.94	7.993
400	12.62	12.62	15.23	6.876
300	12.31	12.31	15.54	5.795
200	11.96	11.96	15.89	4.755
100	11.55	11.55	16.31	3.774
90	11.5	11.5	16.35	3.68
80	11.45	11.45	16.4	3.55
70	11.41	11.41	16.45	3.49

60	11.36	11.36	16.49	3.4
50	11.31	11.31	16.54	3.31
40	11.26	11.26	16.59	3.22
30	11.21	11.21	16.64	3.1
20	11.16	11.16	16.69	3.04
10	11.11	11.11	16.74	2.95
0	0	0	20.9	0

From the above table, the Currents through each panel are shown in Figure 24. I1 and I2 reduced slowly while I4 quickly reduced with radiation reduction; at the same time, I3 increased in an attempt to cover the shortage in I4.

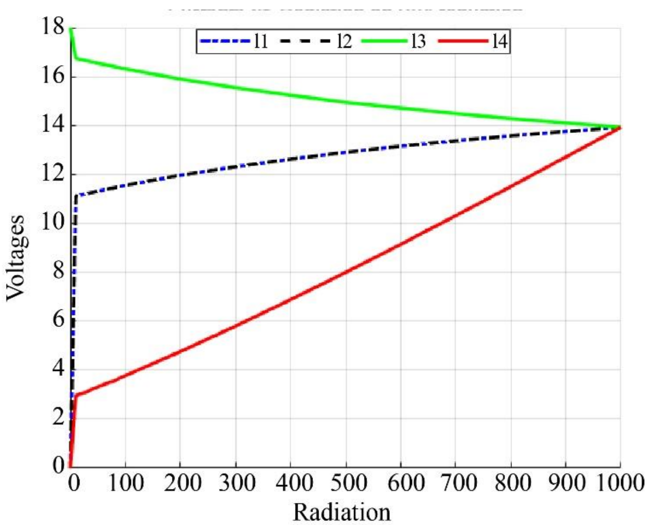

Fig. 24 Current curves (SPC-FS)

As shown in the current curves, the current profile of each panel can be drawn in Figure 25, depending on the data in Table 6.

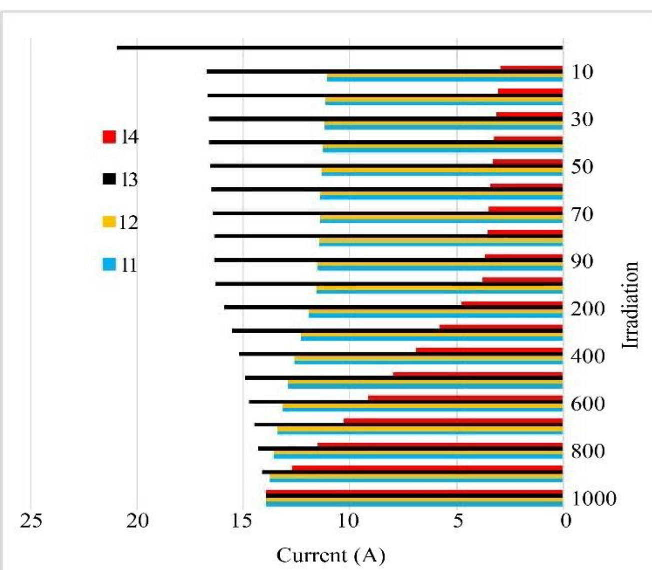

Fig. 25 Currents profile (SPC-FS)

The VI curve of the fourth panel is shown in Figure 26. Current begins to grow slowly with voltage increasing till voltage reaches 48.94 V, then the current will grow rapidly till it reaches its maximum value. The Inverter output power against irradiation reduction on PV4 is shown in Figure 26.

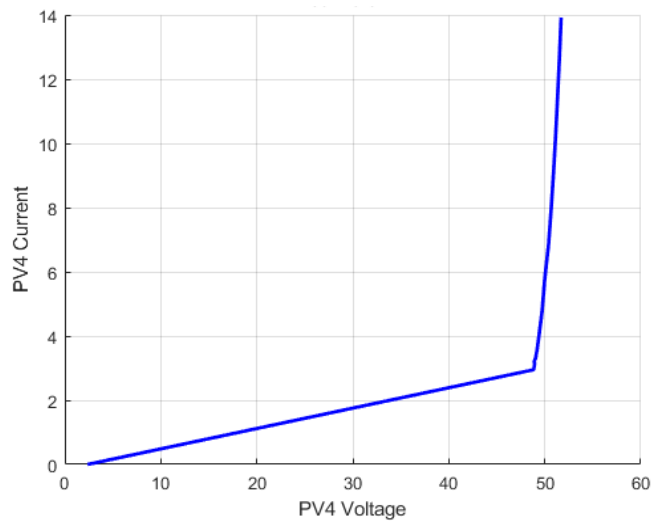

Fig. 26 VI curve of PV4

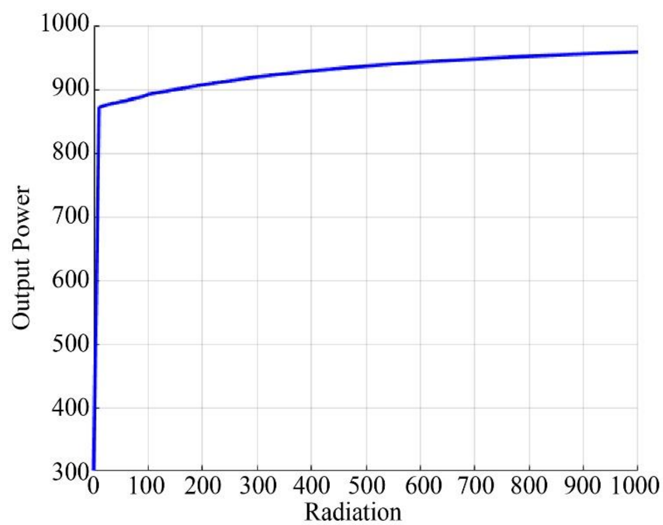

Fig. 27 Inverter output power (SPC-FS)

The output power mostly keeps its value (minimally reduced) along irradiation reduction till reaching 0 W/m2 at this point, the power will collapse to zero.The other curves are likely curves in the first case, 1st scenario, since in this scenario, the same procedure was followed.

3.3.2. Series-Parallel connection 2nd scenario (SPC-SS):): PV3 has a half shadow (i.e. irradiation on it = 500 W/m2) and reducing irradiation on PV4

In this scenario, partial shading on two panels on the same string was studied, where irradiation was applied on the third panel at 500 W/m2, and the irradiation on the fourth panel was varied from 1000 to 0 W/m2. Voltages of all panels were measured for each irradiation value and tabulated in Table 7.

Table 7. Voltages VS Radiation reduction on PV4 (SPC-SS)

Rad.4	V1	V2	V3	V4
1000	51.35	51.35	50.67	52.04
900	51.3	51.3	50.74	51.86
800	51.25	51.25	50.81	51.69
700	51.19	51.19	50.88	51.5
600	51.12	51.12	50.97	51.28
500	51.05	51.05	51.05	51.05
400	50.97	50.97	51.14	50.79
300	50.87	50.87	51.25	50.49
200	50.77	50.77	51.37	50.16
100	50.64	50.64	51.51	49.92
90	50.62	50.62	51.52	49.72
80	50.61	50.61	51.54	49.68
70	50.59	50.59	51.55	49.64
60	50.58	50.58	51.57	49.59
50	50.56	50.56	51.58	49.54
40	50.55	50.55	51.6	49.5
30	50.53	50.53	51.61	49.45
20	50.52	50.52	51.63	49.4
10	50.5	50.5	51.65	49.35
0	28.79	28.79	55.21	2.362

Voltage curves of this scenario are shown in Figure 28.

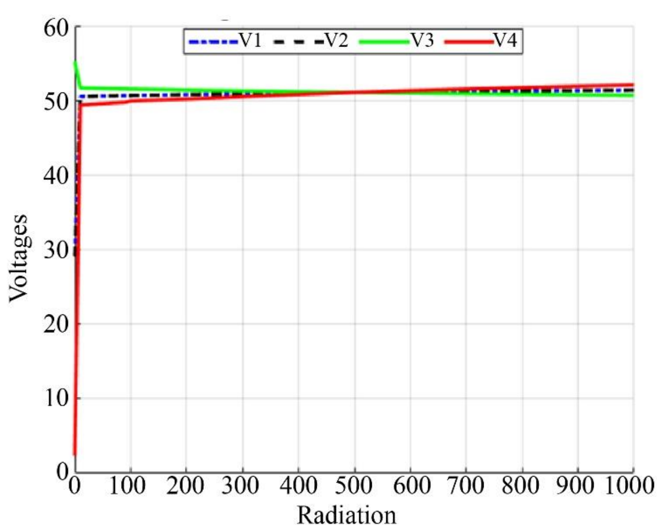

Fig. 28 Voltage curves (SPC-SS)

Voltages V1, V2, and V4 begin high when irradiation is 1000 W/m2 and decrease depending on irradiation reduction.

At the same time, V3 begins low and increases synchronously with V4 reduction till it reaches a high value.

This case caused an overheating in the PV panel. Also, the voltage profile is shown in Figure 29.

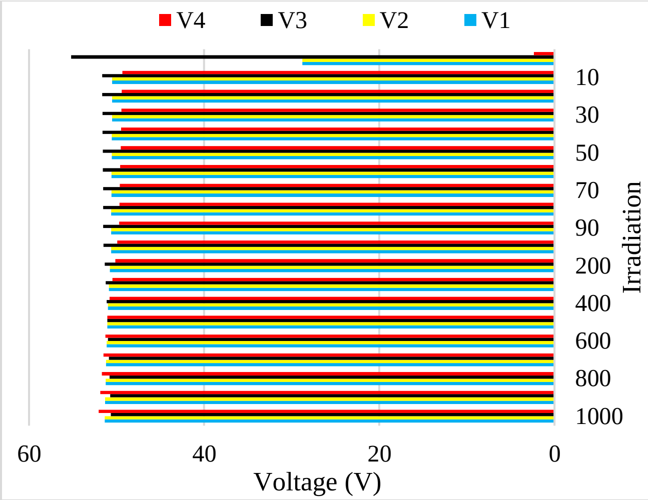

Fig. 29 Voltages profile (SPC-SS)

Currents of all panels were measured for each irradiation value and tabulated in Table 8.

Table 8. Currents VS Radiation Reduction on PV4 (SPC-SS)

Rad. 4	I1	I2	I3	I4
1000	12.9	12.9	7.993	14.95
900	12.74	12.74	8.152	13.72
800	12.58	12.58	8.31	12.49
700	12.34	12.34	8.486	11.27
600	12.22	12.22	8.675	10.07
500	12.01	12.01	8.885	8.885
400	11.77	11.77	9.118	7.725
300	11.51	11.51	9.385	6.6
200	11.2	11.2	9.688	5.51
100	10.85	10.85	10.04	4.471
90	10.81	10.81	10.08	4.37
80	10.77	10.77	10.12	4.268
70	10.74	10.74	10.16	4.168
60	10.69	10.69	10.2	4.069
50	10.56	10.65	10.24	3.971
40	10.61	10.61	10.28	3.87
30	10.57	10.57	10.32	3.77
20	10.53	10.53	10.36	3.67
10	10.48	10.48	10.41	3.58
0	10.47	10.47	15.95	0

Dependent on the previous table, the Current curves are shown in Figure 30. The relation between I4 and irradiation is linear till it collapses, while the same relations with I1, I2, and I3 are non-linear. The third panel current starts at a low level when radiation on PV4 is 1000 W/m2, then increases till it reaches its maximum value when irradiation on PV4 is 0 W/m2. Since irradiation on PV3 is constant and equal to 500 W/m2, the cross section between I3 and I4 should be at the point where irradiation on PV4 is 500 W/m2. i.e., these two panels provide the same current at the same radiation. The current profile of this scenario is shown in Figure 31.

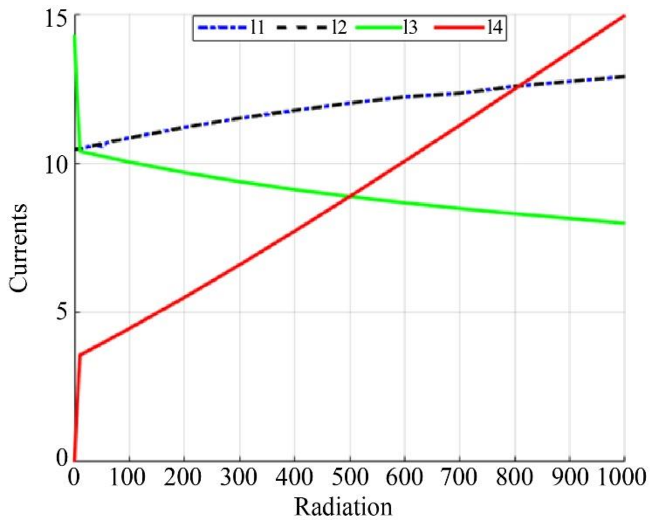

Fig. 30 Current curves (SPC-SS)

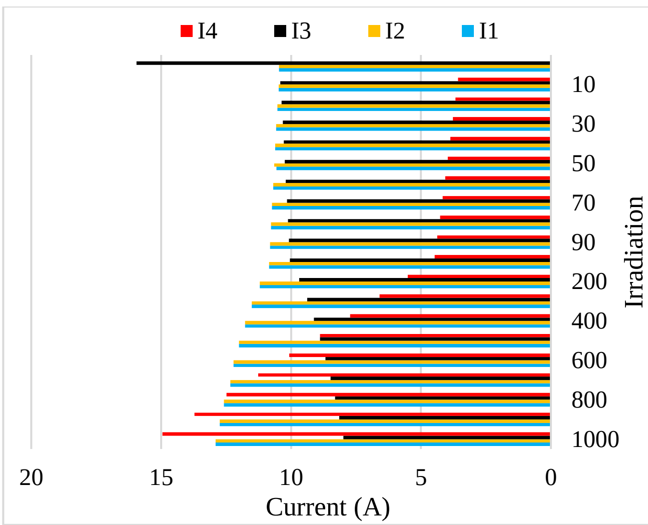

Fig. 31 Current profile (SPC-SS)

The other curves are the same as the first scenario.

3.3.3. Series-Parallel Connection 3rd Scenario (SPC-TS): PV2 has a Half Shadow and Reducing Irradiation on PV4

In this scenario, partial shading on two panels in a different string was studied, where irradiation applied on the second panel was 500 W/m2, and irradiation on the fourth panel was reduced from 1000 to 0 W/m2. Voltages of all panels were measured for each irradiation value and tabulated in Table 9.

Table 9. Voltages VS Radiation reduction on PV4 (SPC-TS)

Rad.4	**V1**	**V2**	**V3**	**V4**
1000	52.04	50.67	51.35	51.35
900	51.98	50.6	51.41	51.17
800	51.92	50.52	51.47	50.96
700	51.85	50.42	51.54	50.72
600	51.78	50.32	51.61	50.49
500	51.7	50.2	51.7	50.2
400	51.6	50.07	51.79	49.88
300	51.49	49.9	51.9	49.5
200	51.37	49.71	52.03	49
100	51.22	49.46	52.17	48.5
90	51.2	49.43	52.19	48.44
80	51.18	49.41	52.21	48.38
70	51.17	49.38	52.23	48.32
60	51.15	49.35	52.24	48.25
50	51.13	49.32	52.26	48.19
40	51.11	49.28	52.28	48.12
30	51.07	49.25	52.3	48
20	51	49.22	52.32	47.97
10	51	49.18	52.33	47.9
0	48.99	6.23	54.04	1.18

Voltage curves are shown in Figure 32.

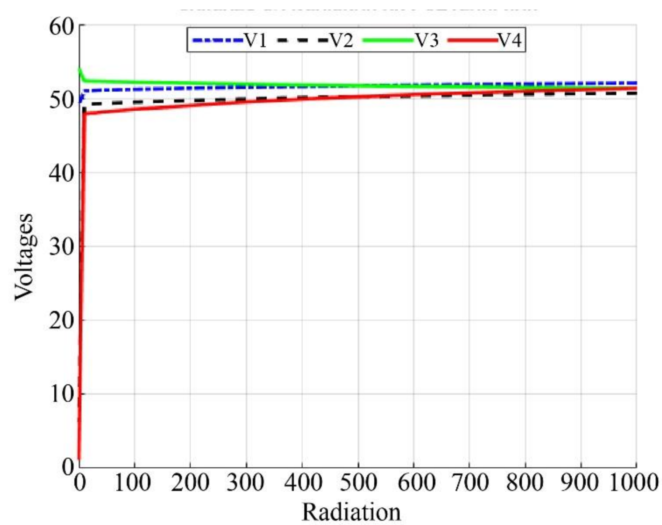

Fig. 32 Voltage curves (SPC-TS)

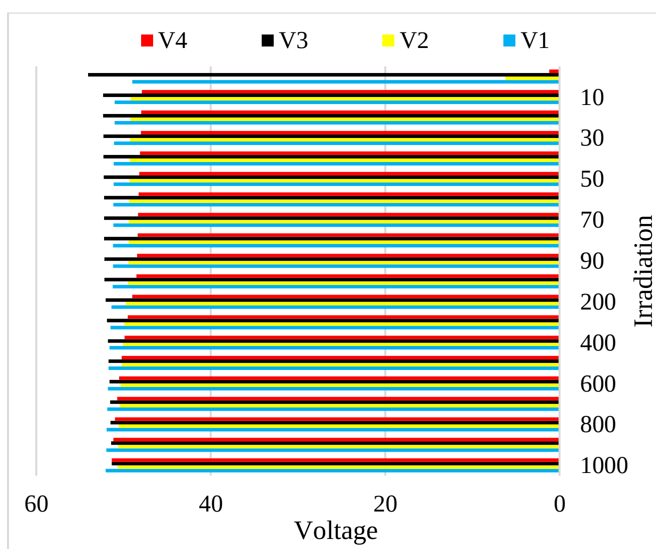

Fig. 33 Voltage profile (SPC-TS)

V1 and V2 decreased slowly with irradiation reduction, and V4 also decreased slowly, but it collapsed at 0 W/m2. V3 increased at the same time in the trial to compensate for the voltage drop in PV4. The voltage profile is shown in Figure 33. Currents of all panels were measured for each irradiation value and tabulated in Table 10.

Table 10. Currents VS Radiation reduction on PV4 (SPC-TS)

Rad.4	I1	I2	I3	I4
1000	14.95	7.99	12.9	12.9
900	14.78	7.823	13.07	11.68
800	14.6	7.633	13.25	10.47
700	14.4	7.438	13.45	9.277
600	14.18	7.215	13.68	8.108
500	13.93	6.96	13.93	6.96
400	13.64	6.68	14.21	5.857
300	13.32	6.359	14.53	4.787
200	12.94	5.98	14.91	3.775
100	12.49	5.529	15.36	2.83
90	12.44	5.479	15.41	2.74
80	12.39	5.428	15.46	2.65
70	12.34	5.37	15.51	2.565
60	12.28	5.323	15.57	2.47
50	12.23	5.27	15.62	2.39
40	12.18	5.21	15.67	2.3
30	12.12	5.16	15.73	2.22
20	12.07	5.1	15.79	2.13
10	12	5	15.84	2
0	9.89	0	15.8	0

Depending on the previous Table 10, the Current curves are shown in Figure 34. I1 begins from 14.95 A, reducing to 9.89 A. I2 begins from 7.99 A since its irradiation is equal to (500 W/m2), reducing to 0 A. I4 reduces linearly with irradiation reduction, while I3 increases at the same time to cover the current reduction in PV4

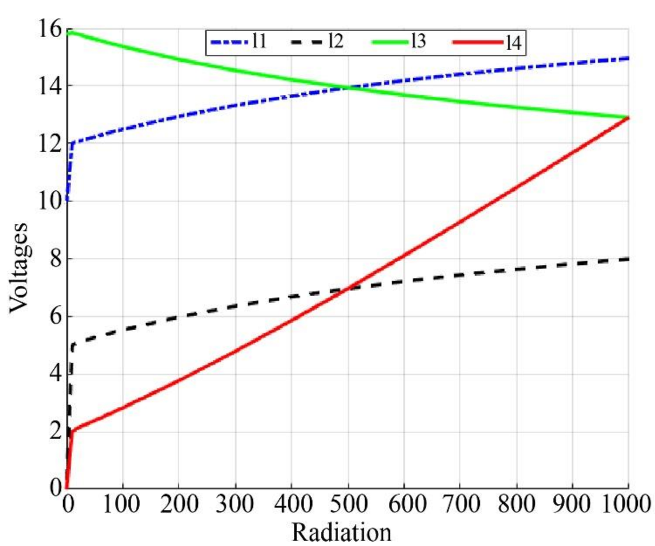

Fig. 34 Current curves (SPC-TS)

The current profile is shown in Figure 35.

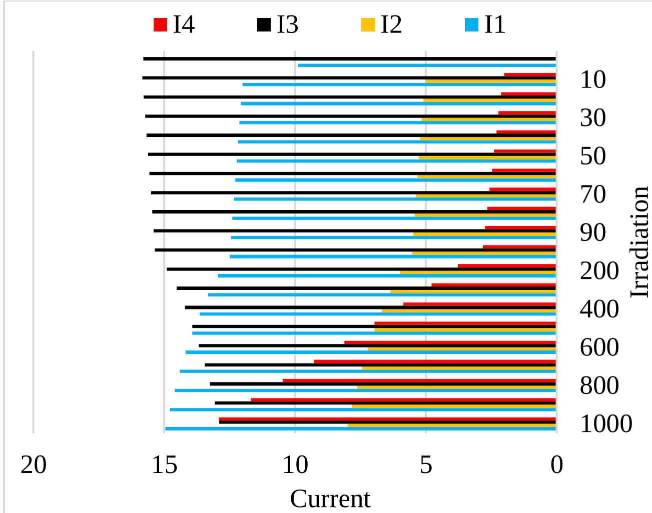

Fig. 35 Current profile (SPC-TS)

The inverter output power curve is shown in Figure 36.

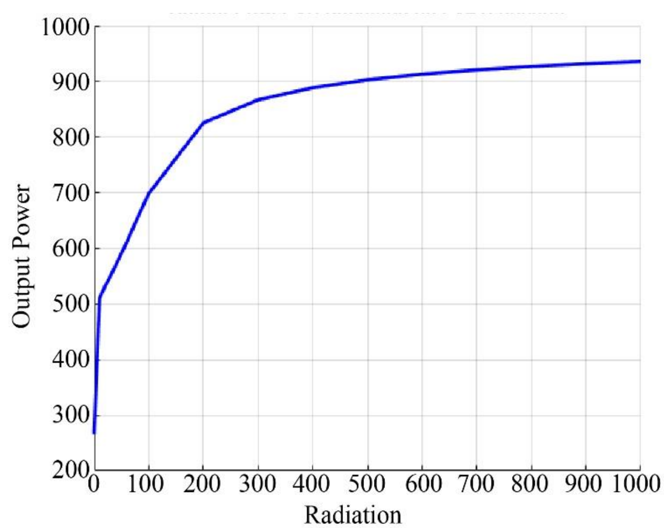

Fig. 36 Inverter output power (SPC-TS)

Output power breakdown faster than the first and second scenarios because the partial shading was in two panels from different strings.

4. Conclusion

After extensively studying the project and fully understanding the operation mechanism of the inverter, designing the project using MATLAB software, and analyzing its performance under different operating conditions, it became possible to present the reached conclusions, which are as follows:

1. Equalizing the solar radiation across all solar panels assists the inverter in producing a stable voltage.

2. Differences in solar radiation incident on one or more solar panels cause significant losses in the produced energy.
3. The lowest effect of partial shading is in one panel only. The highest effect of partial shading occurs in two panels in the same string.

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