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New Improved Maximum Power Point Tracking Algorithm for Partially Shaded PV Systems

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Abstract

The paper presents new MPPT algorithm for partial shading of series connected PV cells/modules. In the shaded condition, there is a problem of decrease in the total output power of the PV system. The proposed algorithm aims to reduce this problem by active bypassing of the shaded cells. The algorithm senses the irradiance of each cell and performs calculation in order to decide if to actively bypass the shaded cell or not. Extensive simulation results proved that algorithm works and increases the output power under partial shading conditions. Furthermore, the algorithm becomes more efficient when the number of cells is increased.

Keywords

MPPT, Algorithm, Partial Shading, Simulation

1. Introduction

There is a constant increase in worldwide electrical power consumption and the conventional energy resources are limited. As a result, the need for renewable energy sources is constantly increasing. The photovoltaic (PV) systems draw special attention as one of the most promising renewable energy sources due to the fact that solar energy is clean, inexhaustible, without pollution and can be easily harvested. The PV panels convert solar energy into electrical energy.

The PV panels can be used as standalone electric power sources or integrated to the main grid as additional power source. The total cost of the PV system depends on the cost of PV array and the area it catches.

The solar cell, in terms of an electrical source, acts as a current source. The light hits the solar cell surface and as a result the solar cell produces current [1]. The PV systems have drawbacks of electric parameters and power generation varia-

tion with irradiation level and temperature changes. These variations influence short-circuit current, the open-circuit voltage, the Fill Factor (FF), the efficiency etc. [2]. Another important disadvantage is low conversion efficiency of the PV panels.

Often, PV modules are shaded fully or partially due to few reasons like movement of clouds, adjacent high buildings, trees and the movement of the sun itself [3]-[9]. This shading leads significant reduction in the output power and internal devastating effects.

During partial shading, the PV curve of the array has multiple maximum points—several local peaks and one global peak. This can lead to the situation where the local peak is mistakenly recognized by the MPPT algorithm as a maximum point instead of true global peak in this case the system will operate at this local peak and significant power losses will be present [10] [11]. Therefore, the PV system has been operated at the real global maximum power point in all conditions, including during partial shading.

The standard MPPT methods can't identify the real global peak during the partial shading because they are not sophisticated enough to differentiate between the local and global points. The standard MPPT methods can be divided into two categories: direct and indirect tracking. The direct tracking methods have the advantage of being independent from prior knowledge of PV characteristics. Thus, the operation point is independent of isolation, temperature or degradation levels. The most common direct tracking methods are Incremental Conduction (IC) [12], Perturb and Observe (PO) [13] [14], as well as neural network and fuzzy logic techniques [15] [16] [17]. The indirect tracking methods use databases of parameters that include empirical data of typical P-V curves for different irradiances and temperatures, or use mathematical functions obtained from the empirical data to estimate the MPP [18] [19]. The direct tracking methods include the techniques of look-up table, open circuit PV voltage and short circuit PV current and more. The MPPT methods are implemented by insertion of DC-DC converter between the PV panel and the load [20] [21]. The switching of DC-DC converter is controlled by MPPT algorithms by Pulse Width Modulation (PWM).

The simplest solution is using by-pass diodes and inverters, which track the maximum power point, thus keeping the cells safe and utilize them. However, this solution has a limited effectiveness due to the fact that one inverter can draw just one current from all the modules. If one of them is shaded it can't be utilized in full potential. On the other hand, the use of inverter for each module increases costs.

Additional methods were reported in the literature [22] [23] [24] [25] [26]. They have some drawbacks such as limited application (not appropriate for all limited conditions), slow response and computationally complicated.

2. The Benefits of the Bypassing PV Modules during Partial Shading

In order to understand the processes that happen during partial shading of dif-

ferent PV cells, two PV arrays each consisted of ten series connected cells. Each module has parallel diode for bypassing. The load of the PV system is implemented by the voltage source. The simulated model is shown in **Figure 1**. Different cases of irradiation combinations were simulated and the total output power of the PV system was calculated. The simulation results are concentrated in **Table 1**. **Table 2** shows simulated output power of the PV system consisted of only one PV module.

During the shading the irradiance on each module is different and this causes the output power reduction of the whole PV system. For some irradiance conditions, the output power of the whole system will be smaller than the output power of one cell. This conclusion is seen from comparison between the values in **Table 1** and **Table 2**. In these cases, it is preferable to bypass cell in order to increase the output power. These cases are colored in red in the **Table 1**. For example, when the irradiance of two modules is 1000/2 and 450/2 the obtained output power is 16.31 W (see **Table 1**) and if the module with 450/2 is by-passed, the output power will rise to 16.8 W (see **Table 2**). This effect will become even more complicated when the number of the PV cells connected in series is increased.

3. The Proposed Method

The paper proposes method that performs active bypassing of the modules by switches (**Figure 2**). In **Figure 2**, each PV cell has parallel bypass switch that can be closed in order to bypass the cell in the case of cell shading.

The typical P-V curve for PV system with three cells is shown in **Figure 3**.

During the partial shading, the most shaded module will has the lowest current that will limit the current of the whole string due to the series connection of the modules. The proposed algorithm checks if it is more efficient to bypass the most shaded module or not. The flowchart of the algorithm is shown in **Figure 4**.
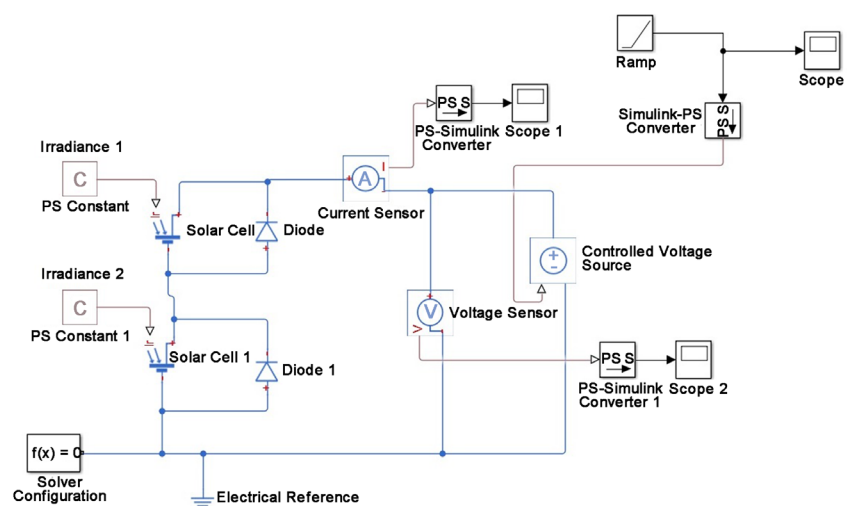

Figure 1. The simulated PV system for output power calculation for different cases of irradiation and shading.

Table 1. The simulated output power of the PV system for different irradiance conditions, two PV modules.

11Irr	1000	950	900	850	800	750	700	650	600	550	500	450	400	350	300	250	200	150	100	50
1000	33.61	32.58	31.31	29.87	28.34	26.73	25.07	23.37	21.64	19.88	18.1	16.31	14.49	12.68	12.36	12.17	11.98	11.79	11.6	11.44
950	32.58	31.86	30.82	29.54	28.09	26.54	24.92	23.25	21.54	19.79	18.04	16.25	14.46	12.64	11.86	11.68	11.5	11.3	11.14	10.96
900	31.31	30.82	30.1	29.06	27.76	26.3	24.74	23.1	21.42	19.71	17.96	16.19	14.41	12.6	11.35	11.18	11.01	10.84	10.67	10.5
850	29.87	29.53	29.06	28.35	27.3	25.99	24.51	22.94	21.29	19.6	17.88	16.12	14.35	12.56	10.82	10.66	10.5	10.34	10.18	10.01
800	28.34	28.09	27.76	27.3	26.6	25.54	24.21	22.73	21.13	19.48	17.78	16.05	14.29	12.52	10.72	10.13	9.98	9.83	9.67	9.52
750	26.73	26.53	26.3	25.99	25.54	24.85	23.79	22.44	20.94	19.33	17.67	15.96	14.22	12.46	10.68	9.59	9.44	9.3	9.16	9.01
700	25.07	24.92	24.74	24.51	24.21	23.79	23.11	22.04	20.68	19.15	17.53	15.86	14.14	12.4	10.63	9.02	8.89	8.75	8.62	8.48
650	23.37	23.24	23.1	22.93	22.73	22.44	22.04	21.37	20.29	18.9	17.37	15.74	14.05	12.34	10.58	8.82	8.33	8.2	8.07	7.95
600	21.64	21.54	21.43	21.29	21.13	20.94	20.68	20.29	19.64	18.54	17.14	15.58	13.95	12.25	10.52	8.77	7.74	7.63	7.51	7.4
550	19.88	19.8	19.71	19.6	19.48	19.33	19.15	18.9	18.54	17.91	16.8	15.06	13.81	12.16	10.46	8.72	7.15	7.04	6.94	6.83
500	18.1	18.04	17.96	17.88	17.78	17.67	17.53	17.37	17.14	16.8	16.19	14.47	13.62	12.04	10.37	8.67	6.91	6.44	6.34	6.25
450	16.31	16.25	16.19	16.13	16.05	15.96	15.86	15.74	15.58	15.38	15.06	14.17	13.34	11.88	10.28	8.59	6.88	5.83	5.74	5.66
400	14.5	14.45	14.4	14.35	14.29	14.23	14.05	14.05	13.95	13.81	13.62	13.34	12.76	11.61	10.12	8.51	6.83	5.21	5.13	5.05
350	12.68	12.65	12.61	12.56	12.52	12.46	12.4	12.33	12.26	12.16	12.04	11.87	11.61	11.07	9.89	8.38	6.75	5.07	4.5	4.43
300	12.36	11.86	11.35	10.82	10.72	10.68	10.64	10.58	10.52	10.47	10.37	10.27	10.12	9.89	9.38	8.18	6.66	5.01	3.86	3.8
250	12.17	11.68	11.18	10.66	10.13	9.59	9.02	8.82	8.77	8.72	8.67	8.59	8.51	8.38	8.19	7.72	6.49	4.93	3.29	3.16
200	11.98	11.5	11.01	10.5	9.98	9.44	8.89	8.33	7.74	7.15	6.93	6.88	6.83	6.75	6.65	6.49	6.07	4.81	3.24	2.51
150	11.79	11.32	10.84	10.34	9.83	9.3	8.75	8.2	7.63	7.04	6.44	5.83	5.21	5.07	5.01	4.94	4.081	4.55	3.16	1.86
100	11.6	11.14	10.57	10.18	9.57	9.16	8.62	8.07	7.51	6.94	6.34	5.74	5.13	4.5	3.86	3.29	3.24	3.16	2.87	1.53
50	11.41	10.96	10.5	10.01	9.52	9.01	8,48	7.95	7.4	6.83	6.25	5.66	5.05	4.43	3.8	3.16	2.51	1.86	1.53	1.35

Table 2. The simulated output power of the PV system for different irradiance conditions, one PV module.

1000	950	900	850	800	750	700	650	600	550	500	450	400	350	300	250	200	150	100	50
16.8	15.93	15.05	14.17	13.29	12.42	11.55	10.69	9.82	8.95	8.07	7.23	6.38	5.53	4.69	3.84	3.03	2.23	1.42	57γ0

The main principle of the proposed method relies on the measurement of the irradiance of each PV module. By knowing the irradiance and the I-V curves, the possible output current of each cell is calculated. The cell with the lowest possible current is the most shaded cell. The algorithm locates this cell. Afterwards, the total output power of the PV system (P_{out}) is calculated by:

$$P_{out} = I_{out} * n * V_{cell} \tag{1}$$

where n is the number of series connected cells, V_{cell} is the output voltage of each cell and I_{out} is the current of the PV module. The next step is to calculate the new output power of the PV system (P_{out_new}) if the most shaded cell is by-passed.

In this case there will be (n-1) cells:

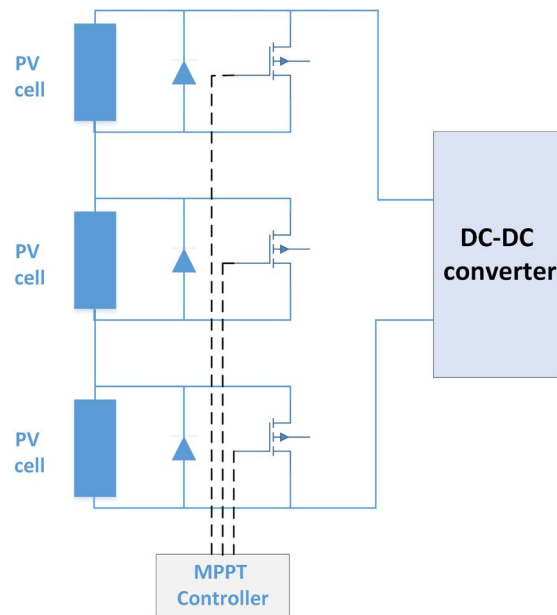$$P_{out\_new} = I_{out\_new} * (n-1) * V_{cell} \tag{2}$$
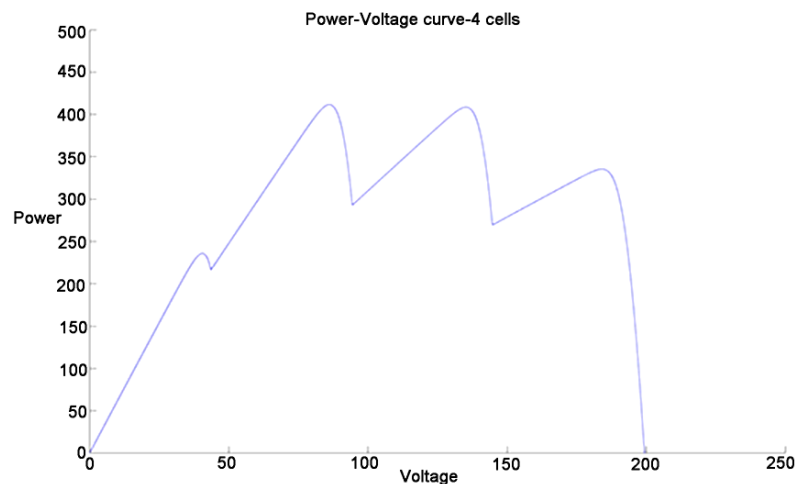
Figure 2. Active bypassing.

Figure 3. Typical I-V curve during partial shading [27], three PV modules are present in the system.

where I_{out_new} is the new obtained P module current due to the bypassing the shaded cell.

Then, the algorithms checks if the new output power with bypass is higher than the original output power including the switching losses of the switch P_{loss}:

$$P_{out\_new} > P_{out} + P_{loss} \tag{3}$$

If true, then the most shaded cell is bypassed by parallel switch. At the end of cycle the algorithm returns to the beginning.

4. Simulation Results

The proposed algorithm is tested on two series connected PV cells with parallel bypass switches (see **Figure 5**). The load was chosen as variable voltage source
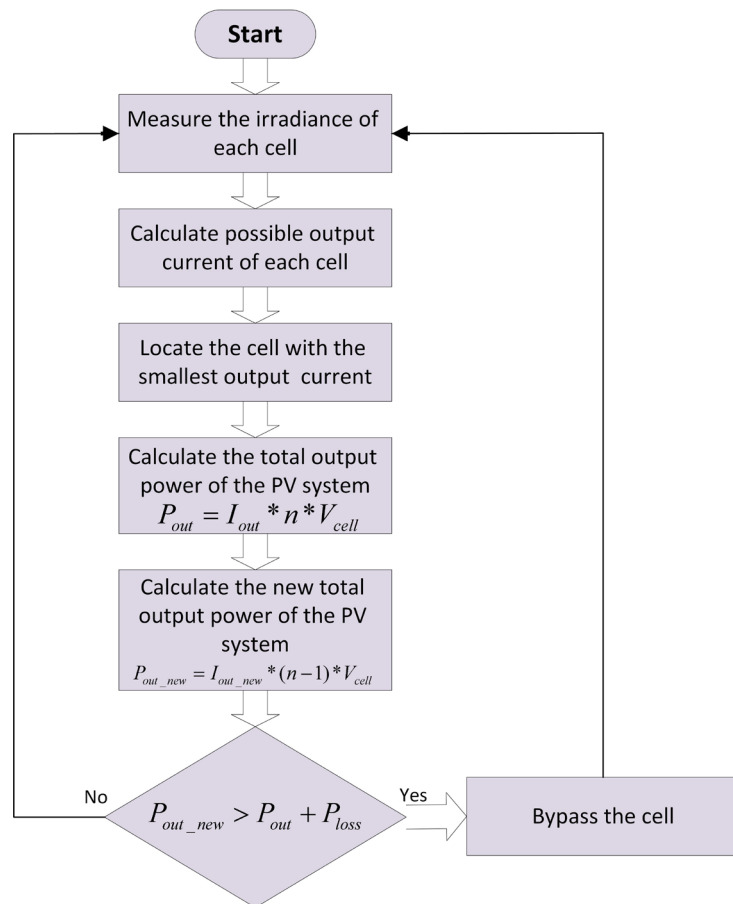
Figure 4. The flowchart of the proposed algorithm.

The flowchart contains the following steps:

- **Start**
- Measure the irradiance of each cell
- Calculate possible output current of each cell
- Locate the cell with the smallest output current
- Calculate the total output power of the PV system
  $$P_{out} = I_{out} * n * V_{cell}$$
- Calculate the new total output power of the PV system
  $$P_{out\_new} = I_{out\_new} * (n-1) * V_{cell}$$
- Decision: $P_{out\_new} > P_{out} + P_{loss}$
  - Yes → Bypass the cell
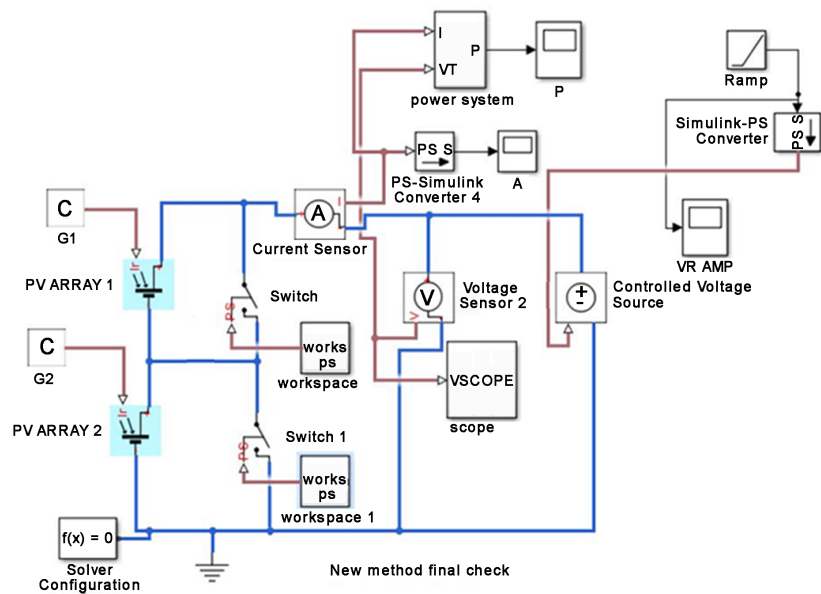 - No → (return to measure irradiance)

Figure 5. The simulated PV system for testing the proposed algorithm.

due to the convenience of this load for Simulink simulations. The simulated ambient temperature is 25 degrees Celsius. The simulated output power of the PV

Table 3. The simulated output power of the PV system for different irradiance conditions operated by the proposed algorithm.

11Irr	1000	950	900	850	800	750	700	650	600	550	500	450	400	350	300	250	200	150	100	50
1000	33.61	32.58	31.31	29.87	28.34	26.73	25.07	23.37	21.64	19.88	18.1	16.8	16.8	16.8	16.8	16.8	16.8	16.8	16.8	16.8
950	32.58	31.86	30.82	29.54	28.09	26.54	24.92	23.25	21.54	19.79	18.04	16.25	15.93	15.93	15.93	15.93	15.93	15.93	15.93	15.93
900	31.31	30.82	30.1	29.06	27.76	26.3	24.74	23.1	21.42	19.71	17.96	16.19	15.05	15.05	15.05	15.05	15.05	15.05	15.05	15.05
850	29.87	29.53	29.06	28.35	27.3	25.99	24.51	22.94	21.29	19.6	17.88	16.12	14.35	14.17	14.17	14.17	14.17	14.17	14.17	14.17
800	28.34	28.09	27.76	27.3	26.6	25.54	24.21	22.73	21.13	19.48	17.78	16.05	14.29	13.29	13.29	13.29	13.29	13.29	13.29	13.29
750	26.73	26.53	26.3	25.99	25.54	24.85	23.79	22.44	20.94	19.33	17.67	15.96	14.22	12.46	12.42	12.42	12.42	12.42	12.42	12.42
700	25.07	24.92	24.74	24.51	24.21	23.79	23.11	22.04	20.68	19.15	17.53	15.86	14.14	12.4	11.55	11.55	11.55	11.55	11.55	11.55
650	23.37	23.24	23.1	22.93	22.73	22.44	22.04	21.37	20.29	18.9	17.37	15.74	14.05	12.34	10.69	10.69	10.69	10.69	10.69	10.69
600	21.64	21.54	21.43	21.29	21.13	20.94	20.68	20.29	19.64	18.54	17.14	15.58	13.95	12.25	10.52	9.82	9.82	9.82	9.82	9.82
550	19.88	19.8	19.71	19.6	19.48	19.33	19.15	18.9	18.54	17.91	16.8	15.06	13.81	12.16	10.46	8.95	8.95	8.95	8.95	8.95
500	18.1	18.04	17.96	17.88	17.78	17.67	17.53	17.37	17.14	16.8	16.19	14.47	13.62	12.04	10.37	8.67	8.07	8.07	8.07	8.07
450	16.8	16.25	16.19	16.13	16.05	15.96	15.86	15.74	15.58	15.38	15.06	14.17	13.34	11.88	10.28	8.59	7.23	7.23	7.23	7.23
400	16.8	15.93	15.05	14.35	14.29	14.23	14.05	14.05	13.95	13.81	13.62	13.34	12.76	11.61	10.12	8.51	6.83	6.38	6.38	6.38
350	16.8	15.93	15.05	14.17	13.29	12.46	12.4	12.33	12.26	12.16	12.04	11.87	11.61	11.07	9.89	8.38	6.75	5.53	5.53	5.53
300	16.8	15.93	15.05	14.17	13.29	12.42	11.55	10.69	10.52	10.47	10.37	10.27	10.12	9.89	9.38	8.18	6.66	5.01	4.69	4.69
250	16.8	15.93	15.05	14.17	13.29	12.42	11.55	10.69	9.82	8.95	8.67	8.59	8.51	8.38	8.19	7.72	6.49	4.93	3.84	3.84
200	16.8	15.93	15.05	14.17	13.29	12.42	11.55	10.69	9.82	8.95	8.07	7.23	6.83	6.75	6.65	6.49	6.07	4.81	3.24	3.03
150	16.8	15.93	15.05	14.17	13.29	12.42	11.55	10.69	9.82	8.95	8.07	7.23	6.38	5.53	5.01	4.94	4.081	4.55	3.16	2.23
100	16.8	15.93	15.05	14.17	13.29	12.42	11.55	10.69	9.82	8.95	8.07	7.23	6.38	5.53	4.69	3.84	3.24	3.16	2.87	1.53
50	16.8	15.93	15.05	14.17	13.29	12.42	11.55	10.69	9.82	8.95	8.07	7.23	6.38	5.53	4.69	3.84	3.03	2.23	1.53	1.35

system for different irradiance conditions is shown in Table 3. It can be seen from Table 3 that the algorithm actually works and improves the efficiency of the PV system. The algorithm becomes more efficient when the number of series connected cells/modules is increased.

5. Conclusions

The paper presents new MPPT algorithm for partial shading of series connected PV cells/modules. The algorithm performs active bypassing of the shaded cells that decrease the total output power of the PV system.

By performing extensive simulation of different shading conditions, the algorithm was tested for two series connected cells. It was shown that algorithm works and increases the output power under partial shading conditions. Furthermore, the algorithm becomes more efficient when the number of cells is increased. Therefore, it should be used in large PV installations.

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