Investigation of solar panel characteristics and MPPT performance under partial shading conditions

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Abstract

This paper presents an investigation study of solar panel characteristics under uniform solar irradiance and partial shading conditions (PSC) and an analysis for determining the global maximum power point (GMPP) of solar panel. As known, solar panel experiences multiple maximum power points (MPPs) if PSC occurs. Therefore, MPP tracking (MPPT) becomes harder compared with the uniform irradiance condition in case of usage of classical algorithms. In this regard, analyzes for uniform and PSC are made by using perturb and observe (P&O) algorithm in this study. By performing several simulations, behavior of the GMPP under PSC is aimed to detect accurately. With the help of these simulations, range of voltage (region for GMPP) can be estimated as user defined accuracy.

1. Introduction

Meeting energy demands from clean and sustainable sources have been important issue in recent years. Continuously growing electricity demand accelerates the usage of renewable energy in electricity generation over the world. Among renewables, with its huge potential, solar energy is very promising [1,2].

Electricity generation from solar energy is realized by photovoltaic (PV) effect. In this context, solar panels are used to generate electricity in DC form by using this effect. Even though solar energy is unlimited and environment-friendly, utilization cost of PV system is rather high compared with the other power generation systems (PGSs). Furthermore, PGS that uses the solar energy has low capacity factor due to the efficiency of solar panels and nature of sun. Since electrical power generated from solar PGSs depends on environmental conditions, these systems are not reliable in terms of meeting the energy demand and quality [3].

As mentioned earlier, solar panels have low capacity factor. Under uniform solar irradiance condition, this factor depends on power conversion efficiency of solar panel, efficiency of power processing unit and sunshine duration in a day. However, solar irradiance is not uniform every time. Sometimes, PSC occurs and capacity factor is affected adversely. Therefore, maximum available power of solar panel is not extracted. In order to obtain the highest capacity factor, changes in environmental conditions should be detected properly. In this study, characteristics of solar panel under PSC are investigated. By performing several simulations, limited region for GMPP voltage is aimed to determine in order to provide high tracking efficiency. Remains of the paper are organized as follows. Section 2 describes the mathematical model of solar panel under uniform irradiance conditions. In the third section, solar panel characteristic is shown under PSC. Analyzes of P&O algorithm under two irradiance conditions are presented in the fourth section. In the last part, some important points that are reached in this study are presented.

2. Mathematical Model of Solar Panel

Solar panels are kind of semiconductor devices that consist of many solar cells connected in series and/or parallel [4]. Solar cells are similar to diodes due to the p-n junction. The main difference between solar cells and diodes is the having power generation capability under enough solar irradiance. Electrical equivalent circuit of solar cells is generally given based on the one diode model [4-6] as presented in Fig. 1.

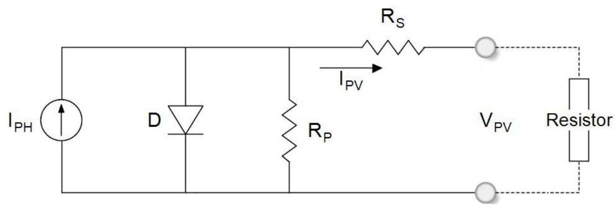

Fig. 1. Electrical equivalent circuit of solar cell

In Fig. 1, I_{PH} is the photo current which depends on amount of solar irradiance. I_{PV} is the current of solar cell as formulated below [4] in (1):

$$I_{PV} = I_{PH} - I_S\left(e^{\frac{\left[q(V_{PV} - I_{PV}R_S)\right]}{kT_JA}} - 1\right) - \frac{V_{PV} - I_{PV}R_S}{R_P} \qquad (1)$$

where I_S is the diode saturation current, R_S and R_P are the series and parallel resistances, respectively. q is the electron charge in coulomb, k is the Boltzmann constant, T_J is the junction temperature of solar cell, A is the diode ideality factor. V_{PV} and I_{PV} are the voltage and current of solar cell, respectively. Since this formulation includes exponential expression, voltage-current (V-I) and voltage-power (V-P) characteristic of solar cell (or solar panel) are highly complex as shown in Fig. 2.

Due to the nonlinear characteristic, solar panel has one unique point that maximum power is extracted under certain environmental condition. By changing solar irradiance and/or temperature, MPP also changes. Since solar panel has low power conversion efficiency, MPPT is very important. Under uniform solar irradiance condition, as presented in Fig. 2, there is one MPP on the V-I curve of solar panel. In this condition, classical MPPT algorithms perform well [5,6].

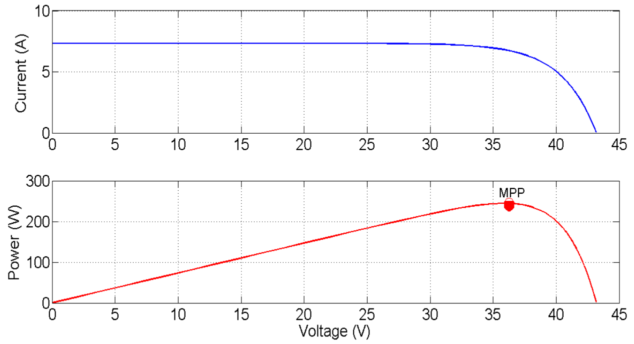

Fig. 2. V-I and V-P curves under uniform irradiance conditions

3. Partial Shading

Solar panels or solar array may experience partial shading due to the lots of things such as shadow of building, tree, leaves etc. in a certain time. When technically considered, partial shading occurs if solar panel is exposed to different level of solar irradiance. As illustrated in Fig. 3, large part of the solar panel is exposed to 500W/m^2. It is assumed that solar cells in this panel are connected in series. In this condition, due to the connection type, all solar cells generate the current correspond to the lowest irradiation (500W/m^2) exposed to the solar panel. Therefore, available efficiency is not obtained under PSC.

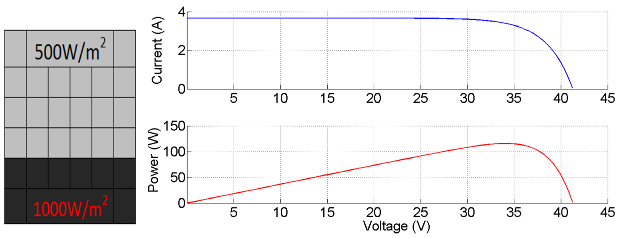

Fig. 3. Example for partial shading

In order to obtain the highest efficiency in solar panels, bypass diodes are equipped with per determined series connected cells in solar panels. Thus, shadowed part of solar panel is bypassed and maximum utilization is acquired. Unlike, as shown in Fig. 3, maximum power increases thanks to the bypass diodes as presented in Fig. 4. Solar panel presented in Fig. 4 has three bypass diodes which are connected as reverse parallel per twelve solar cells. Since solar panel is exposed to two different solar irradiances, there are two MPPs on the V-P curve.

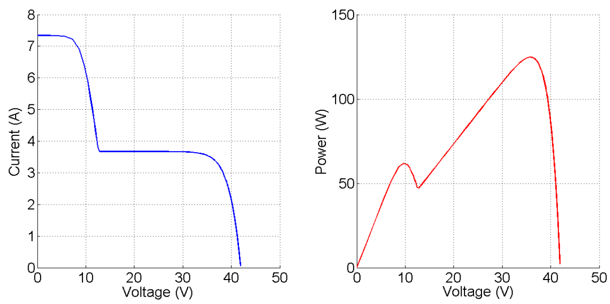

Fig. 4. Partial shading with bypass diodes

With the help of the bypass diodes, negative impact on the output power of the solar panel in Fig. 3 is eliminated and new V-P curve is shown in Fig. 4. It is clear that by adding bypass diodes, V-P curve of solar panel becomes more complex than the V-P curve without bypass diodes. It is indicated that classical MPPT algorithms fail under PSC since they track the local MPPs [7-10].

3.1. Analyzes of MPPs under PSC

Up to now, V-I curve of solar panel is investigated under uniform and partially shaded irradiance conditions [10-15]. In order to determine the general behavior of solar panel under PSC, many different PSC scenarios have been performed by simulation in MATLAB/Simulink environment. Series connected three and four solar panels are used in the simulations. Increment level of solar irradiance is chosen as 200W/m^2 and range of solar irradiance was set to 200W/m^2 - 1000W/m^2. In the first case, series connected three solar panels are used in simulations. For the first case, there are two main conditions. These are conditions which have two MPPs and three MPPs. Number of possible scenarios are defined as a novel aspect as formulated below.

$$x = n\frac{n!}{(m-1)!t!} \tag{2}$$

where x is the number of scenarios; n is the number of solar panels, m is the level of irradiance (in Fig. 3, m=2 (Q_1=500W/m^2, Q_2=1000W/m^2)) and t! is the probability of occurrence of the same irradiance level.

According to the (2), simulation scenarios are listed in Table 1 and Table 2. In the first result presented in Fig. 5 is the case that irradiance level is two. It is clear that there are two MPPs and while MPP located at the right side of V-P curve does not change remarkably, MPP on the left side of this curve has decreasing characteristic. When it comes to the case that irradiance level is three, as expected, there are three MPPs. Unlike the first case, right, left and the middle MPPs change in a very small range. It is worth noting that even if PSC occurs, MPPs are located in a limited region on the V-P curve.

Table 1. Scenarios for two level irradiances (3xPV)

		Irradiance for two solar panels				
		1	0.8	0.6	0.4	0.2
Irradiance for a solar panel	0.2	1	2	3	4	-
	0.4	5	6	7	-	8
	0.6	9	10	-	11	12
	0.8	13	-	14	15	16
	1	-	17	18	19	20

Table 2. Scenarios for three level irradiances (3xPV)

P12, P3, P4 (kW/m^2), N.=Number of case.							
N	P1	P2	P3	N	P1	P2	P3
1	1	0.8	0.2	6	1	0.4	0.2
2	1	0.8	0.4	7	0.8	0.6	0.2
3	1	0.8	0.6	8	0.8	0.6	0.4
4	1	0.6	0.2	9	0.8	0.4	0.2
5	1	0.6	0.4	10	0.6	0.4	0.2

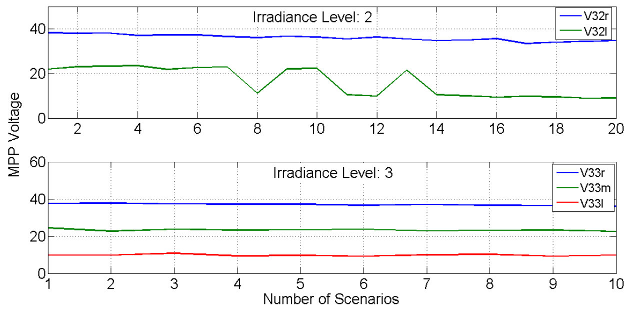

Fig. 5. Voltage at MPP for all irradiance conditions (3xPV)

Likewise, scenarios for two and three irradiance levels are listed in Table 3 and Table 4, respectively for four series connected solar panels. If number of solar panel increases, voltage of MPPs becomes more complex as shown in Fig. 6. Both in two MPPs and in three MPPs condition, MPP voltages change in a large range which increases the difficulties of tracking the global MPP.

Table 3. Scenarios for two level irradiances (4xPV)

		Irradiance for three solar panels (W/m^2)				
		1000	800	600	400	200
Irradiance for a solar panel	200	1	2	3	4	-
	400	5	6	7	-	8
	600	9	10	-	11	12
	800	13	-	14	15	16
	1000	-	17	18	19	20

Table 4. Scenarios for three level irradiances (4xPV)

P12, P3, P4 (kW/m^2), N.=Number of case.							
N.	P12	P3	P4	N.	P12	P3	P4
1	1	0.8	0.6	16	0.6	0.8	0.4
2	1	0.8	0.4	17	0.6	0.8	0.2
3	1	0.8	0.2	18	0.6	0.4	0.2
4	1	0.6	0.4	19	0.4	1	0.8
5	1	0.6	0.2	20	0.4	1	0.6
6	1	0.4	0.2	21	0.4	1	0.2
7	0.8	1	0.6	22	0.4	0.8	0.6
8	0.8	1	0.4	23	0.4	0.8	0.2
9	0.8	1	0.2	24	0.4	0.6	0.2
10	0.8	0.6	0.4	25	0.2	1	0.8
11	0.8	0.6	0.2	26	0.2	1	0.6
12	0.8	0.4	0.2	27	0.2	1	0.4
13	0.6	1	0.8	28	0.2	0.8	0.6
14	0.6	1	0.4	29	0.2	0.8	0.4
15	0.6	1	0.2	30	0.2	0.6	0.4

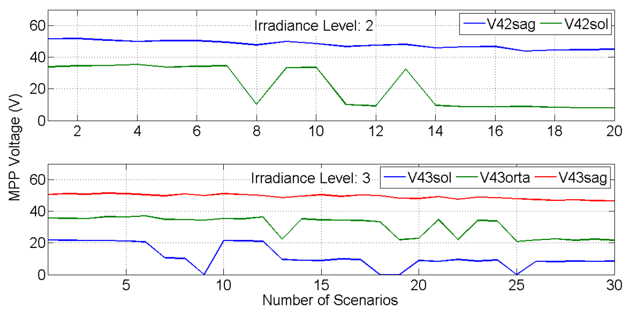

Fig. 6. Voltage at MPP for two and three irradiances (4xPV)

If irradiance level is four, some of leftmost MPPs are not formed. For the other MPPs, voltages change in limited region like the other cases as presented in Fig. 7.

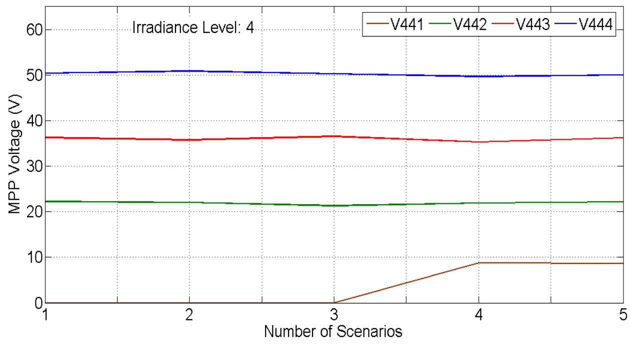

Fig. 7. Voltage at MPP for four irradiance conditions (4xPV)

4. Analysis of P&O Algorithm under Uniform Irradiance and PSC

As mentioned earlier, V-P curve of solar panel has nonlinear characteristic. When PSC occurs, this nonlinearity increases and MPPT becomes harder compared with case under uniform solar irradiance conditions. In this section, by using operation principle of P&O algorithm, MPPT is analyzed under uniform condition and PSC. First of all, a truth table is prepared for P&O algorithm instead of its flowchart. This table is presented in Table 5. In this table, eight different scenarios are considered. Four scenarios are listed for constant irradiance condition ($\Delta Q<\Delta Q_{th} \rightarrow$ Logical 0) and another four scenarios are taken into account for rapidly changing irradiance conditions. It is assumed that if changes in voltage or power are positive, it means to "logical 1". On the other hand, if changes in these parameters are negative, it means to "logical 0". On the other hand, rapidly changing solar irradiance is evaluated independently. If a change of this parameter is higher than predetermined threshold value, Q_{th}, it means to "logical 1". Under constant irradiance conditions, this parameter takes as "logical 0".

Table 5. Truth table of P&O algorithm

Movement	ΔP_{PV}	ΔV_{PV}	$p=\Delta Q>\Delta Q_{th}$	P&O V_{ref}	Right V_{ref}
B→A	0	0	0	1	1
D→H	0	0	1	1	1
E→F	0	1	0	0	0
C→I	0	1	1	0	0
F→E	1	0	0	0	0
I→C	1	0	1	**0**	**1**
A→B	1	1	0	1	1
H→D	1	1	1	**1**	**0**

As listed in Table 5, P&O algorithm decides the right direction for reference voltage under constant irradiance conditions. On the other hand, this algorithm fails if solar irradiance increases rapidly while operation point changes from H or I to anywhere on the V-P curve of the case for 500W/m^2. For this condition, P&O does not differentiate the environmental changes.

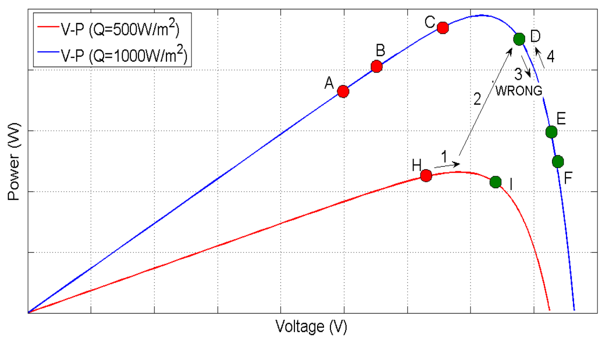

Fig. 8. An example of V-P curve for truth table

When partial shading occurs, V-P curve experiences more MPPs which deteriorate the performance of P&O algorithm. Similar to uniform irradiance condition, same illustrative is presented in Fig. 9. PSC given in this figure causes to be created three MPPs on the V-P curve. When P&O algorithm is applied to this V-P curve and it is assumed that reference voltage is started from zero volts, algorithm climbs over the first MPP. However, operation point turns back from point 2 to point 1. Therefore, global MPP is not tracked.

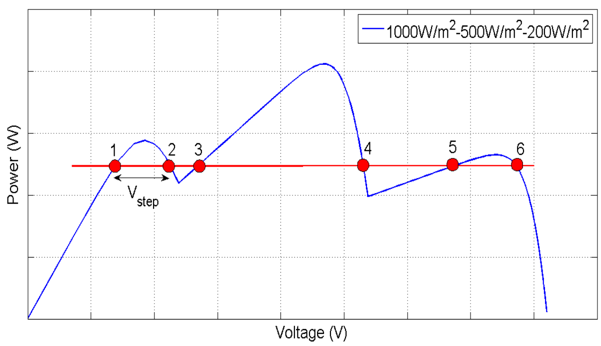

Fig. 9. Illustration of PSC

For the purpose of dealing with this problem, many approaches are proposed [10-18]. In such these conditions, it is important to detect whether partial shading or rapidly changing irradiance conditions are occurred. When solar panels are exposed to different irradiation levels, their voltages are different. For example, a solar array which consists of four solar panels is considered. Every solar panel has one bypass diodes and is exposed to different solar irradiation. As presented in Fig. 10, since this solar panel is connected in series, their currents must be equal. However, they are differently irradiated. It is clear from this figure that the current generated from the highest irradiated solar panel is only active when operation current equals to short circuit current. Meanwhile, the other solar panels generate negative voltages through their bypass diodes and they consume power undesirably. When the current of highest irradiated solar panel equals to the current of second highest irradiated solar panel, the second panel starts to generate power. This procedure continues until the lowest irradiated solar panel generates energy.

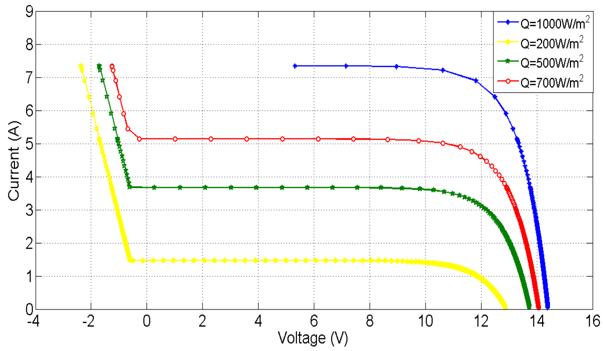

Fig. 10. V-I curves under PSC

5. Conclusions

In this paper, V-P characteristic of solar panel under uniform solar irradiance and PSC are investigated and MPPT behaviors of solar panel under these two conditions are presented by using P&O algorithm. Analyzes of PSCs are performed by the predetermined scenarios and number of scenarios are calculated by proposing a novel equation. This novel approach is based on the user defined increment range for solar irradiance. Therefore, voltage of MPPs can be estimated with based on the user defined accuracy.

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