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INFLUENCE OF BACKTRACKING AT SOLAR-TRACKING PHOTOVOLTAIC POWER PLANTS FOR GENERATION AND PROTECTION

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ABSTRACT

Photovoltaic plants appear as an option for a more environmentally friendly centralized generation. Solar-tracking is used for efficiency gain presenting better performance than fixed tilted plants. However, the system suffers generation and protection problems without the use of backtracking algorithms. Shading conditions can prejudice the energy generation and cause diode failure. This paper studies the influence of backtracking for protection and generation. For protection, it is shown that the bypass diode takes time to activate, generating hotspots. For efficiency, the production and plant size gains are highlighted.

Keywords: bypass diode, hotspot, partially shading, solar-tracking energy

1. INTRODUCTION

With the increase in energy demand and the reduction of fossil fuel, solar energy has grown worldwide in recent decades. It appears as a solution for the sustainable growth of societies. Even with the great advances, the photovoltaic (PV) modules present a low conversion efficiency.

Works study different ways to increase the efficiency of a PV system. Papers study different techniques of tracking the maximum power point [1] to ensure system operating at maximum power in systems even under shading conditions. Other works [2] analyze the different photovoltaic modules connections to form the array. Further the traditional Series-parallel, the bridge-linked [3] and the total-cross-tied [4] are highlighted. Another field studied is the PV cell technology [5] for increase conversion efficiency.

An efficient solution and widely used is the installation of PV system with trackers. Generally installed in PV plants, solar-tracking systems move the PV modules to position them at the best angle to generate more energy.

Backtracking algorithms are used to avoid efficiency losses by shading modules, moving PV modules at the opposite direction. In addition, backtracking algorithms are also important to prevent shaded PV cells from overheating by generating hotspots and permanently damaging the cell.

This paper presents in section 2 the solar-tracking PV system and the backtracking use; in section 3, the shading effects at PV cell and I-V curves are discussed; the protection issue is discussed and simulated in section 4; in section 5, the results simulation of an 1 MWp PV plant is presented and analyzed.

2. ELECTRICAL GENERATION AT SOLAR-TRACKING PHOTOVOLTAIC POWER PLANTS

Photovoltaic systems with fixed panels lose their productivity when the panels are not facing the optimum angle, which happens when the normal coincides with the direction of the solar irradiance [6]. Solar trackers provide a solution to this disadvantage, increasing the power generation by keeping the PV modules approximately perpendicular to the solar irradiance [7].

Sun tracking provides an energy gain of approximately 25% when single-axis solar trackers are used, and approximately 35% when two-axis solar trackers are used, depending on the system configuration and the installation location [6]. Also, solar tracker systems use a smaller area to produce the same amount of power as photovoltaic systems with fixed panels. However, equipment and maintenance costs also increase slightly [8].

One of the problems of the solar tracker systems is the loss by shading caused by the photovoltaic panels themselves, as shown in Fig 1. Depending on how the panels are positioned (portrait or landscape), panels with bypass diodes have a significant loss of power generation because the bypass diode will force the strings to decrease generation. Considering that this shading happens in a whole row, the losses of power generation are even greater [9]. That is why it is indicated that the panels are positioned in landscape.

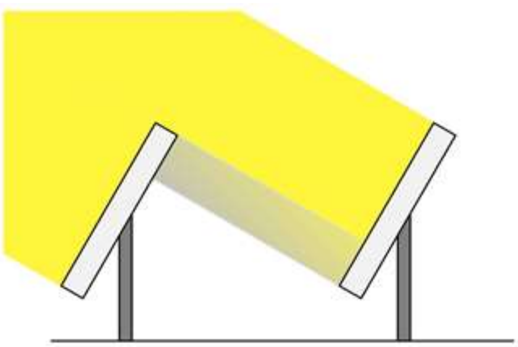

Fig 1. Solar tracker system without backtracking (adapted from [12]).

To avoid the occurrence of this problem, backtracking algorithms are used, assuming that the losses due to the increase of the angle of incidence are not as large as the losses due to shading, and this is especially true for cases of high Ground Coverage Ratio (GCR) [9]. There are several backtracking algorithms available in the literature [10]–[13].

When the elevation angle is too low and the panels begin to shade each other, the backtracking algorithm begins to act by compensating for this angle and reducing the shading effect between the panels [12], as shown in Fig 2.

The angle of elevation of the sun is low at two periods of the day, in the early morning and late afternoon. Therefore, throughout the day, the backtracking algorithm is used in these two periods [12].

Some previous studies have evaluated the energy gain from using backtrack. Ko and Chung [10] performed experiments of solar trackers without backtrack and with backtrack simultaneously. In one month of measurement, the solar tracker with backtrack provided a power gain of 2.44% with respect to the solar tracker without backtrack.

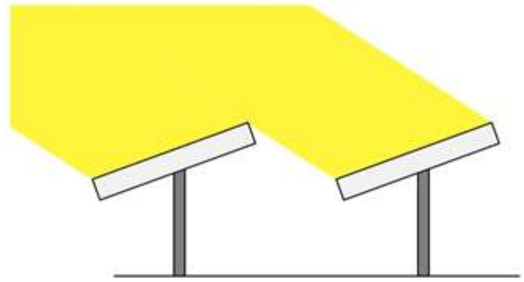

Fig 2. Solar tracker system with backtracking (adapted from [12]).

Lorenzo *et al.* [14] calculated the energy yield of grid-connected photovoltaic systems for the locality of Amareleja, Portugal, whose latitude and longitude are equal to 38.2 ° and -7.2 °, respectively, in order to analyze the backtracking energetic impact. The energy gain from backtrack use was 5.46% for horizontal single-axis tracker with North-South axis, 0.38% for vertical single axis tracker and 4.38% for two axes tracker with backtrack performed on the horizontal axis.

When a row of PV modules causes shading in the next row, the PV array is partially shaded, generating hotspots [12]. Hotspots are one of the main causes of accelerated aging and, sometimes, of irreversible damage to PV panels [15]. Also, partial shading makes it difficult to trace the maximum power point [16].

The advantage of using backtracking algorithm in large PV systems is the possibility of reducing the distance between the rows of PV panels, without worrying about the shading that the rows can cause each other, allowing the best use of the available area for the production of electricity. Therefore, backtrack allows reducing the costs with land purchase, site preparation, installation of security fences, deforestation, excavation and cabling [12]. In addition to reducing the risk of hotspots, reducing operation and maintenance costs [14].

3. EFFECTS OF SHADING

The energy generation of a photovoltaic array varies with the day. It is dependent of the irradiance incident on the photovoltaic modules and the temperature array. Despite I-V and P-V curves vary with changes in irradiance and temperature levels, the I-V curve remains at the same format and the P-V curve continues presenting one peak only. Occasionally the PV array may be partially shaded, causing the modules receive more than one level of irradiance or present different temperatures. This shading can be caused by different reasons: passing clouds, neighboring constructions, branches or objects brought by wind, dirt left by animals, and by other modules.

For a solar-tracking system without backtracking using, it is common that at dawn and dusk, one shed causes a partial shading over the other. The time shading depends of the distance between sheds. The closer, more time under PSC.

PV cell shading pattern that occurs in a solar-tracking system is predictable. The shading grows gradually at the shaded cell, causing a slow variation of the shaded area, additionally, causing a slow variation of current capacity at the PV cell.

The current capacity at the PV cell depends of its short-circuit current. With the PV cell conducts a current level higher than its short-circuit current, this can cause damage [15].

Taking into account the I-V curve of a PV cell, it is known that the short-circuit current is directly proportional to the level of irradiance incident on it. However, for PV cells that have two levels of irradiance, i.e., that are partially shaded, the logic must to be different. When a PV cell receives different levels of irradiance, must be done the weighted average of the irradiances considering the affected area [17]. The weighted average formula for a PV cell receiving two different levels of irradiance is written in Equation 1.

$$G_{\text{weighted}} = \frac{A_1}{A_{total}} G_1 + \frac{A_2}{A_{total}} G_2 \qquad (1)$$

Where G_{weighted} is the weighted average irradiance for the PV cell. A_1 and A_2 are the areas of the cells in which G_1 and G_2 the different irradiance, respectively. A_{total} is the total area of the cell.

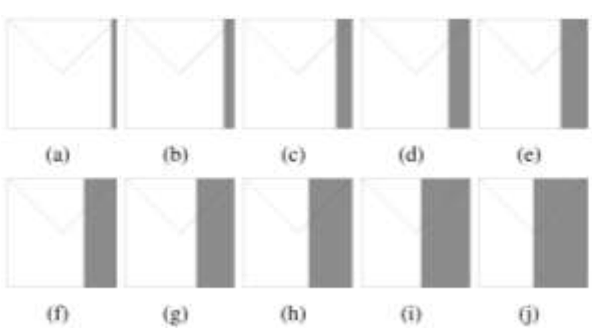

Fig 3. Evolution of a PV cell shading pattern caused by the next shed. Percentage shading varies from 5% to 50%.

PV cell shading pattern is a rectangle that grows slowly as the sun position is behind the next shed. When a percentage of area is shaded, the incident irradiance at this area is 17% of the ambient irradiance. Due to direct irradiance blocking, only 17% is detected by a shaded area. This percentage represents horizon brightening, sky diffuse and ground reflected irradiance. Fig. 3 presents the evolution of the PV cell shading pattern.

By the appliance of Equation 1 at Figure 3 examples, it is possible to find the weighted average irradiance of the PV cell, and consequently the short-circuit current. Table 1 presents the calculated percentage values.

Table 1. Shading area and its effects of irradiance and short-circuit current.

Figure	Shading Area	$G_w/G = I_{SC}'/I_{SC}$	Figure	Shading Area	$G_w/G = I_{SC}'/I_{SC}$
3(a)	5%	95,85%	**3(f)**	30%	75,10%
3(b)	10%	91,70%	**3(g)**	35%	70,95%
3(c)	15%	87,55%	**3(h)**	40%	66,80%
3(d)	20%	83,40%	**3(i)**	45%	62,65%
3(e)	25%	79,25%	**3(j)**	50%	58,50%

It is worth note that for each 5% of more shaded area, it is 4.15% less short-circuit current. Therefore, the difference between the short-circuit current between two PV cells at the same PV module can presents different values until 83%.

4. PROTECTION

When a partial shading occurs, it is necessary that the bypass diode goes into forward biased mode, creating a new path for the current flow of the PV module, protecting against damages by hotspots. However, the speed of this forward biased depends on the installation location, the irradiance, the ambient temperature and the shading profile [18].

Nowadays, the most PV modules are manufactured with 72 PV cells, which are connected in series, nevertheless, only three bypass diodes are used to protect all the module cells against the hotspots. Thus, each bypass diode protects 24 PV cells separately [19]. As shown in Fig. 4.

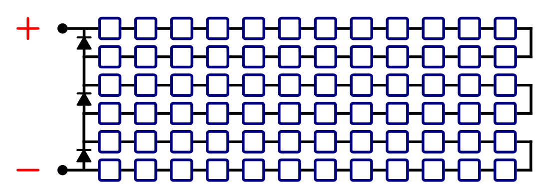

Fig. 4. 72-cell photovoltaic module with three bypass diodes.

The tracker system usage increases the performance of a PV plant, nonetheless, without the use of backtracking technology, at dawn and dusk a partial shading will occur, initially affecting the lower part of the module, which is put in the horizontal orientation, i.e., in the first row of 12 cells and, then, increase the shaded area on the module.

When the first cell row begins to be shaded, the second row remains illuminated normally. In this way, the current flow does not change, but it will change the voltage level of the shaded cells, according to the shaded percentage [20].

In the Fig. 5, a cell is shown without shading and receiving an irradiance equivalent to the period of dawn, that is, 100 W/m², resulting in a current of 0.811 A and a voltage of 0.506 V. In addition, another three curves are shown with 17%, 33% and 44% of shaded area, respectively: 0.000 V, -0.506 V and -0.540 V.

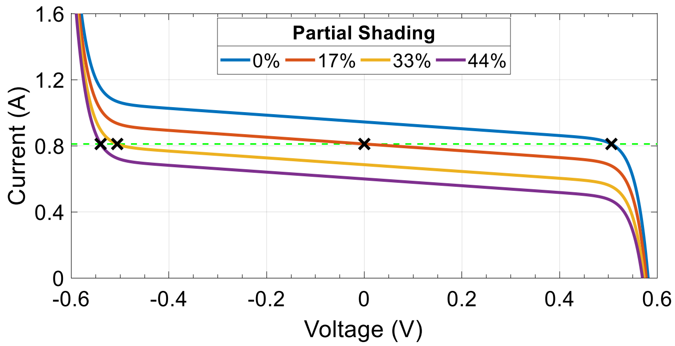

Fig. 5. Voltage drop level for the first cell row.

Due to the shaded percentage, a voltage drop occurs in the shaded cells, even with a negative voltage level, because the current flow does not change.

In the 17% shaded area does the polarity change occur. With 33%, the same voltage level is obtained with the negative polarity, however, this value is not yet able to forward biased the bypass diode (considering Schottky diode with 0.4 V of voltage drop). It is only possible with 44%, because it exceeds the diode forward voltage drop.

To achieve 44% shaded area, it takes 120 seconds, during which time the cell behaves as a resistive load, dissipating thermal energy and generating the hotspots. Therefore, a single cell, during that time period, generates 384 J, if consider all the cells of the same row would have 4.6 kJ. As shown in Fig. 6.

The bypass diode protects the cells, but at dawn or dusk and without the use of backtracking, it is not as efficient, being relatively slow to switch to forward biased mode. This is mainly due to the low level of irradiance, around 100 W/m², and that is the main reason for the importance of use that technology for protection of PV module against hot-spot by partial shading.

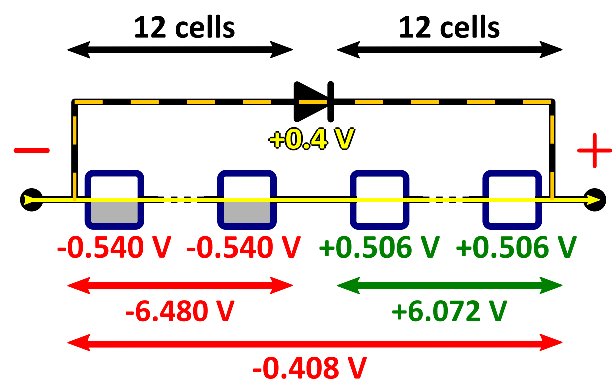

Fig. 6. When bypass diode changes to forward biased mode.

5. SIMULATIONS

To evaluate the energy gain with the use of backtrack, simulations of a solar tracker system with backtrack and without backtrack were performed. In this section, the simulations will be presented.

5.1 Methodology

Simulations of an 1 MWp PV plant were performed in five cities of the world, which are listed below with their respective geographical coordinates (latitude, longitude): Calexico - United States (32.73°, -115.50°), Bathinda - India (30.29°, 74.93°) , Guimarania-Brazil (-18.63°, -46.80°), Aswan-Egypt (24.09°, 32.90°) and Pitea - Sweden (65.32°, 21.48°). The cities were chosen in order to contemplate localities where PV systems with solar trackers are being implanted, as well as, different regions of the solarimetric map.

The solar tracker used in the simulations was the horizontal single-axis tracker with North-South axis. Since, according to the results presented by Lorenzo *et al.* [14], this provides a higher energy gain when compared to the others.

The software used to perform the simulations was the PVSyst® version 6.79, the solarimetric database used was the Meteonorm 7.2, and the model of transposition used was the model of Perez [21].

In all cities, the plant was simulated in four scenarios. In all scenarios, horizontal-tilted solar trackers are used, with optimal slope calculated by the software for each location. The scenarios are described below:

- 1st scenario: with backtrack and pitch of 6 m;
- 2nd scenario: without backtrack and pitch of 6 m;
- 3rd scenario: with backtrack and pitch of 5 m;
- 4th scenario: without backtrack and pitch of 5 m;

The specifications of the equipment used are given in Table 2.

Table 2. Specifications of the equipment used in simulations.

Equipment	Brand	Model	Power	Amount
Photovoltaic panel	Canadian Solar®	CS6K-310M S-AG	310 Wp	21x154
Inverter	Fronius International®	AGILO 00.0-3 Outdoor	100 kW	9

5.2 Results

The mean annual global and diffuse irradiances of each city, according to the Meteonorm 7.2 database, are shown in Fig. 7. The energy injected in the grid with and without backtrack for a pitch of 5 m is shown in Fig. 8. From these figures, it is possible to observe that the generation of energy is proportional to the global irradiance indexes of each locality.

The results of energy injected into the grid annually for each locality and all scenarios are shown in Table 3.

Table 3. Energy injected into the grid for each locality.

Locality	Pitch	With backtracking (MWh/yr)	Without backtracking (MWh/yr)	Back track gain
US	6	2232	2196	1.6%
US	5	2196	2098	4.7%
India	6	1787	1761	1.5%
India	5	1745	1720	1.5%
Brazil	6	1711	1690	1.2%
Brazil	5	1668	1620	3.0%
Egypt	6	2374	2369	0.2%
Egypt	5	2309	2267	1.9%
Sweden	6	1195	1161	2.9%
Sweden	5	1152	1110	3.8%

From Table 3, it is possible to notice that, in all scenarios, the use of backtrack allowed a gain of power generation. However, this gain was low. In this simulation, the highest gain was 4.7% and the lowest gain was 0.2%. These gains are close to those verified for Lorenzo et al. [14] and Ko and Chung [10].

It was also noted that the power generation gains are greater in the pitch of 5 m, because in smaller pitches, the shading between sheds is higher, and that is precisely what the backtrack prevents from happening. India's results are an exception to this claim, where energy gains with pitch of 5 and 6 m are 1.5%.

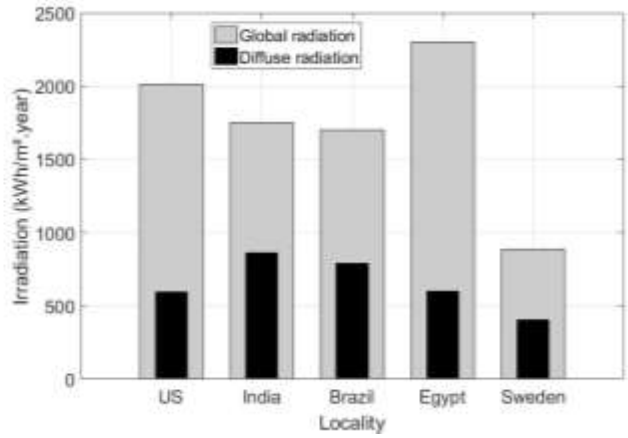

Fig 7. Global and diffuse irradiation in each locality.

Note that with the use of backtrack with pitch equal to 5 m it is possible to generate an amount of energy close to that without backtrack with pitch equal to 6 m. In Calexico, in the United States, this amount is exactly the same. Therefore, the use of backtrack allows to decrease the distance between sheds.

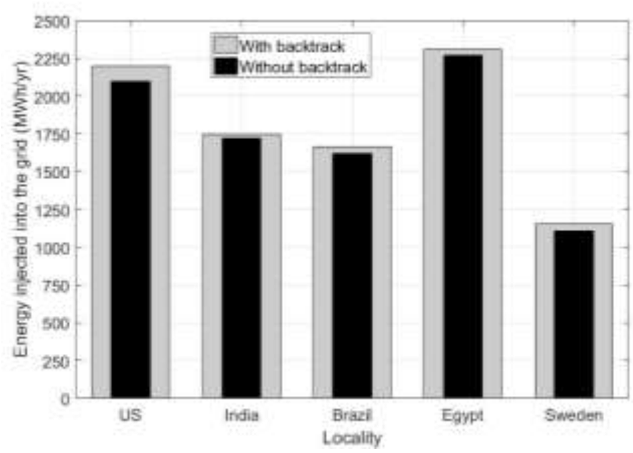

Fig 8. Energy injected into the grid with and without backtrack, for pitch of 5 m.

6. CONCLUSIONS

This paper has discussed the importance of backtracking algorithms using at solar-tracking PV systems. Both for protection and efficiency. How the PV shading process occurs and when the bypass diode is activated. For the example shown, it tooks 120 seconds to forward biased the bypass diode. For efficiency gain, it was simulated an 1 MWp PV plant for five locations and the percentage gain was calculated. In addition, it is worth note the advantage at space gain by the backtracking use.

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