Energy and Power Engineering, 2024, 16, 121-129
https://www.scirp.org/journal/epe
ISSN Online: 1947-3818
ISSN Print: 1949-243X

Inter-Row Spacing of PV Power Plant

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How to cite this paper: Khan, L.A. (2024) Inter-Row Spacing of PV Power Plant. *Energy and Power Engineering*, **16**, 121-129.
https://doi.org/10.4236/epe.2024.163006

Received: February 11, 2024
Accepted: March 23, 2024
Published: March 26, 2024

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Abstract

When designing a solar power plant, it is much more important to avoid the shadow on the PV Panels. As the shadow falls on the PV Panels; it significantly reduces the generation of required power as planned and designed. This research paper and case study will help a lot to avoid shadow, especially when selecting inter-row spacing between the strings of solar power plants.

Keywords

Inter Row Spacing, Shadow Effect on PV Plant, Hot Spot Heating

1. Introduction

Solar energy from the sun can be utilized directly in the form of heat or first converted to electricity and then utilized. Based on this classification, solar energy is either solar thermal or solar PV. Solar thermal concentrated mirrors inside the greenhouse concentrate the solar power on stationary boilers which convert the water in boilers to high pressure steam, the steam can be utilized for many purposes. Steam is used to rotate the generator and generate electricity [1]. Another example of this steam is injected into oil wells where the steam reduces the viscosity of oil, and more oil can be recovered from a well. This is called EOR (Enhanced Oil Recovery) technology [2]. On the other hand, PV panels convert solar energy into DC electricity which can widely be utilized in many applications.

The DC energy achieved from the solar PV Panels can directly be utilized for DC loads or this energy can first be converted to AC (Alternate current) electricity and then utilized. For example, an ac submersible pump is used to suck water from a well and utilize it for agricultural usage. The solar energy is converted to AC with the help of inverters and then after passing through the pure sine wave filters it is given to power up the submersible pumps [3]. Similarly, energy from the solar PV plants is achieved for home usage and the extra energy is fed back to the grid with the help of Net metering or fed in the tariff process. Factories, Agricultural forms, industries, offices, homes etc. are all converting the power source to solar to get free energy from the sun based on initial investments only and a very rare cost of operation and maintenance.

To get the maximum solar power from the PV panels, the PV panels are connected in series and parallel connections to construct a complete solar plant. The configuration of series and parallel panels are based on the requirement of load under STC standard test conditions. In some cases, the design is perfect based on requirements but still required power could not be received from the solar plant due to many factors. Some of the factors that degrade the overall performance of the solar plants are listed below.

The type of PV panel is either Mono Crystalline which has the highest efficiency or poly crystalline and thin film which has the lowest efficiency. The location where the PV power plant is located, the insolation at that point under normal conditions, the weather conditions, the time of the day and the day of the year conditions [4] but most important is the shadow on the PV panels which degrades the PV plant significantly. The shadow may be due to an object on PV panels, due to the birds' shit, due to dust particles, due to a tree or even the shadow of one string on another [5]. This research paper deals with the shadow calculation of the inter-row spacing which a designer needs to understand before designing a PV power plant.

2. Solar Cell Structure

The importance of Solar energy is nowadays in a wide range of daily usage. But need to know how to get the maximum power from the solar power plant for which first it is a must to see the internal arrangement of the cells. In a PV panel, the cells are arranged in series. In a series connection, the current remains constant throughout the circuit. All these cells are made of doped P-N junction. The depletion region in a solar cell is much wider than the normal PN junction. In solar cells when the photon enters the depletion region, energy is transferred to the valence electrons of doped semi-conductor material (Silicon or Germanium) and this energized electron leaves the valence band and jumps into the conduction band, leaving a hole behind. This process is called the generation of electron hole pair. When there is no light on a cell or a low intensity light falls on a cell, enough energy is not transferred to the valence electrons which is required for a valence electron to jump into conduction band and the electron-hole pair is not generated [6]. Whenever there is a small shadow, the light intensity reduces, and generation of electron hole pairs decreases dramatically. In a PV Panel, all these cells are connected in series, and in series connection the current remains the same. But what if all these cells have different currents, only that current will be selected which is the lowest one to flow through the circuit to load. So, when a shadow falls on any one cell, the cell current will significantly be reduced, and this reduced current will flow in the whole PV panel towards the load. What will happen to the maximum current which is generated in case of no shadow cells. Let's make an equation.

3. Effect of Shadow and Hot Spot Heating

Let's suppose (*Ia*) is the current of the cell where there is shadow and (*Ib*) is the current of the cell where there is no shadow. So, $Ia < Ib$ but only current equal to *Ia* will flow throughout the PV panel to the load. The amount of current let's says *Ic*:

$$Ic = Ib - Ia \tag{1}$$

This current in Equation (1) will dissipate inside the panel in terms of heat and it will crack the PV Panel, and this is called hot-spot heating.

Hot-spot heating occurs when there is one low current solar cell in a string of at least several high short-circuit current solar cells, as shown in Figure 1 below.

One shaded cell in a string reduces the current through the good cells, causing the good cells to produce higher voltages that can often reverse bias the bad cell.

If the operating current of the overall series string approaches the short-circuit current of the "bad" cell, the overall current becomes limited by the bad cell. The extra current produced by the good cells then forward biases the good solar cells. If the series string is short circuited, then the forward bias across all these cells reverses biases the shaded cell. Hot-spot heating occurs when many series connected cells cause a large reverse bias across the shaded cell, leading to large dissipation of power in the poor cell. Essentially the entire generating capacity of all the good cells is dissipated in the poor cell. The enormous power dissipation occurring in a small area result in local overheating, or "hot spots", which in turn leads to destructive effects, such as cell or glass cracking, melting of solder or degradation of the solar cell as shown below in Figure 2 [7].

From the above discussion, it is concluded that the shadow on any single cell can degrade the system to the maximum extent. The main content is when a designer designs a Solar Power plant, it needs to avoid the shadow to get the maximum possible power from the plant when solar power is available. To avoid the shadow from the Solar power plant first designer needs to select an appropriate location where there is no shadow on the PV panels. Then during the operation and maintenance the PV panels should be kept clean from the birds' shit and dust particles to avoid the shadow on individual cells. But normally design

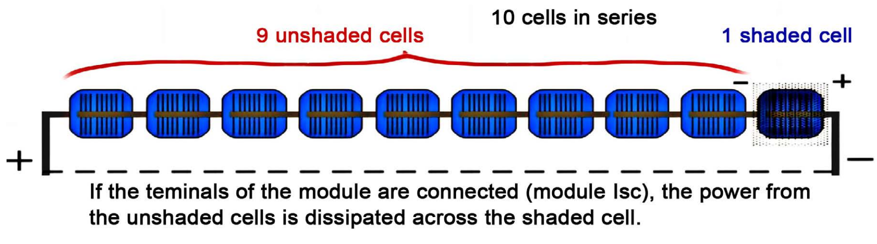

Figure 1. String of many PV cells with one shaded cell.

Figure 2. The PV module is cracked due to hot spot heating.

should be in such a way that the shadow of one string should not fall on the other string for which normally designers use the following trigonometry to get the maximum distance between two solar strings.

4. Calculations and Trigonometry

In **Figure 3** $d1$ is the horizontal distance of the PV Panel, w is the Length of the Panel, Angle ($\angle\beta$) is the tilt angle of the PV panel which is normally considered to be equal to the tilt angle of the site. Angle $\angle\gamma$) is the shadow angle of the sun ray with the horizontal surface. Let's find the distance ($d2$) which is the actual distance between two strings.

Practical Case Example:

For example, in one of the below examples, which is operated at Jouf KSA 340 kW project, the PV modules that are used are Jinko JKM550M-72HL4-V, and the length of each PV panel is 2278 mm. The tilt angle which is the latitude of this location is 24˚. The structure for the installation of the PV panels is designed at the angle of 24˚. Refer to above **Figure 3**:

L.H.S ⊿:

$$\sin(\beta) = h/w \tag{2}$$

Rearranging Equation (2) we get.

$$h = w \times \sin(\beta) \tag{3}$$

In this combination, each array has two strings as shown in **Figure 4** so, length will double:

$$W = 2 \times 2278\ \text{mm} = 4.556\ \text{m}$$

Putting the values of w and β in Equation (3)

Equation (3) ⟹

$$h = 4.556 \times \sin(24^\circ)$$

$$h = 1.853\ \text{m} \tag{4}$$

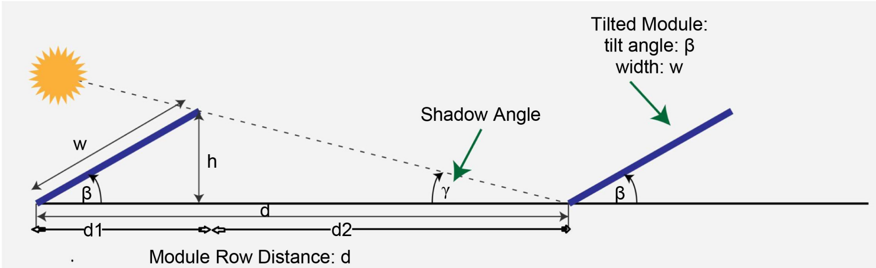

Figure 3. The structure of PV panel makes a right-angle triangle.

Figure 4. Each array contains two strings and panels.

While the height of the foundation to be used is 1.002 m

As shown in Figure 5.

So total height H of the PV panel from the ground surface

Is $H = h + 1.002$ m

Put the value of h from Equation (4)

$$H = 1.853 + 1.002 = 2.855 \text{ m} \tag{5}$$

Now to find out the distance between two strings ($d2$) in **Figure 3**

First, need to find out the shadow angle.

Please note that the maximum shadow is on 21st December when the sun is at the minimum height in the sky. If you plot the sun's daily location on a star chart or celestial globe, you'll find that it gradually traces out a great circle as shown in Figure 6. This circle is called the ecliptic [8]. So, the ecliptic is an imaginary circle around the celestial sphere, centered on us, that marks all the possible locations of the sun with respect to the constellations. Each day, as the sun takes four minutes longer than the constellations to spin around us, it creeps approximately one degree eastward along the ecliptic. It completes the circle in exactly one full year (365.24 days).

The ecliptic intersects the celestial equator at two opposite points, the sun's locations at the equinoxes. But the ecliptic is tipped at a 23.5˚ angle with respect to the celestial equator, so half of it is in the celestial sphere's northern hemisphere and half is in the south. The sun reaches the ecliptic's northernmost point at the June solstice and reaches its southernmost point at the December solstice.

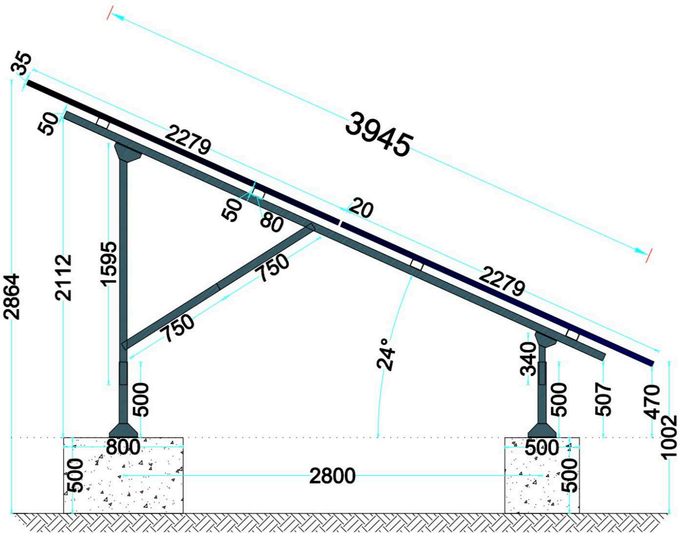

Figure 5. Design and parameters of PV panel and structure.

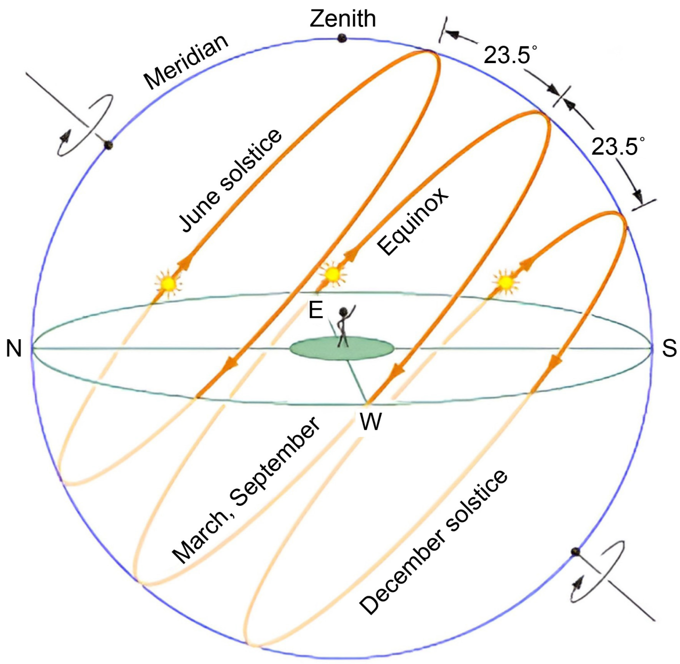

Figure 6. Sun ecliptic circle.

Refer to **Figure 3**:

The shadow angle which is achieved on 21st of December, is.

$$\angle\gamma = 90^\circ - \text{Tilt angle} - 23.45^\circ = 90^\circ - 24^\circ - 23.45^\circ = 42.55^\circ \quad (6)$$

Figure 3: Middle ⊿:

$$\tan(\gamma) = H/d2 \quad (7)$$

$$d2 = H/\tan(\gamma) \quad (8)$$

$$d2 = 2.855\text{ m}/\tan(42.55^\circ)$$

$$d2 = 3.110 \text{ m} \tag{9}$$

Due to the azimuth angle some of the designers suggest keeping a safe factor of 1.2 because of the azimuth angle, different times of day, different days of the year etc., even if keep the safe factor of 1.2 then the distance between two rows will become:

$$d2 = 3.110 \times 1.2 = 3.72 \text{ m} \tag{10}$$

In this project the distance between each two strings is kept 5 m but unfortunately, the same shadow issue again as shown below in Figure 7.

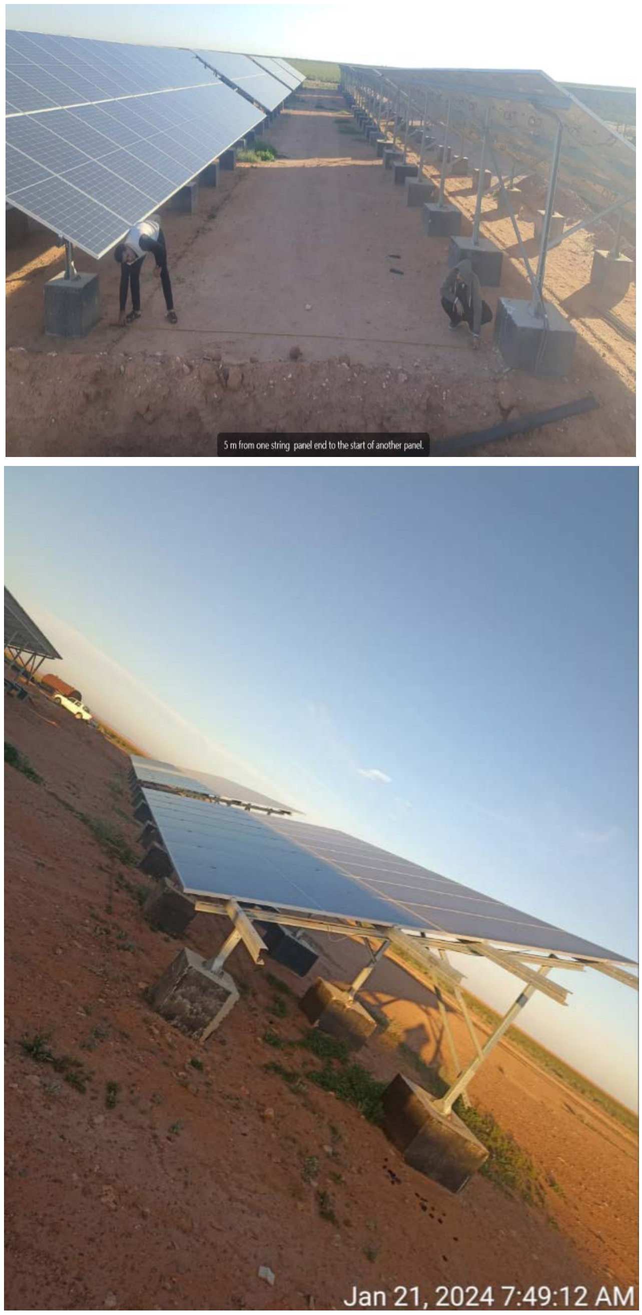

Figure 7. Sun ecliptic circle.

The length of the shadow on 21st of January at 7:49 early morning is 5 m between the strings plus it covers the length equal to length of the PV Penal, so the total shadow length is equal to

$$5 + 2.278 = 7.278\ \text{m} \tag{11}$$

Which is a clear deviation from the above trigonometry and the same formula cannot be used to design a PV Power plant.

5. Correction Factor

In case of avoiding such issues in huge projects where the dismantling of the PV strings and keep up the more distance is not so easy and it costs a lot, this paper will be able to resolve the issue.

If the shadow angle is decreased further with the amount of tilt angle, then it will give the maximum possible shadow on 21st of December as the sun first ray hit the PV Panel irrespective of including the safe factor. The result will be the actual maximum shadow length on 21st of December.

Equation (8) ⟹

$$d2 = H / \tan(\gamma)$$

Here $\angle\gamma$ is further reduced with the amount of tilt angle which in this case is 24˚.

$$\gamma = 42.55^\circ - 24^\circ = 18.55^\circ \tag{12}$$

Put the value of Equation (12) in Equation (8) to get the value of $d2$

$$d2 = 2.855 / \tan(18.55^\circ)$$

$$d2 = 8.5\ \text{m} \tag{13}$$

This is the maximum shadow distance which will get on 21st December as the sun rays appear in sky. In the above project case, the shadow distance is 7.27 m at 7:49 am on 21st of January, so if the shadow distance at 7:00 am on 21st of December, its value for the above configuration must be 8.5 m.

Thus, the correction factor which must be included is:

$$\angle\gamma = 90^\circ - 2 \times (\text{tilt angle}) - 23.45^\circ \tag{14}$$

6. Comparison Table

Let's compare the result for the practical example of the Jouf Project explained above based on Equation (14) and Equation (6) before and after the correction in the formula for shadow angle in terms of the table below:

7. Conclusion

Based on the comparison in Table 1 it is clear that to get zero shadow at any time of the day, of the month, and of the year while designing a solar power plant, it is advisable to use the shadow angle with the below correction: Equation (14) ⟹

Table 1. Comparison of shadow angle formula with and without correction.

$\angle\gamma = 90^\circ - \text{Tilt angle} - 23.45^\circ$	$\angle\gamma = 90^\circ - 2 \times (\text{Tilt angle}) - 23.45^\circ$
Distance to keep between each two strings: 3.110 m with tilt angle 24˚	Distance to keep between each two strings: 8.5 m with tilt angle 24˚
Shadow length is 7.278 m on 21st January.	The proposed distance covers the shadow length on 21st January.
Deviation from the formula	No deviation from the formula

$$\text{Shadow Angle } \angle\gamma = 90^\circ - 2\times(\text{tilt angle}) - 23.45^\circ$$

8. Dedication

The paper is dedicated to my beloved mother.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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