Studying the Shading Effect of PV System on Energy Performances in Restricted Spaces

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Abstract. Shading has a considerable influence on solar cells’ characteristics, temperature, and irradiation. Shading can be represented as partial or total shading over a few cells, panels, or even a set of modules. This study investigates the effect of shading rate on the PV panel's performance when used with modifies SEPIC converter. A mathematical model is performed and simulated on the MATLAB/Simulink platform. The investigation is conducted to study the effect of barrier height, tilt angle, and altitude angle changes for one day, one month, and the whole year. The results showed that the shadow factor depends on a set of parameters and varies from one system to another. Furthermore, the most affected months are the winter months, where the shadowing exceeds 28%, while in the summer months it falls to 10% at the highest barrier. The annual loss of energy is studied with and without obstacles, where results indicate that the loss of energy varies between 30% and 1% as the spacing from the closest PV row increases from 0.5m to 10m. This fact motivates designers to allow a certain rate of shadowing, especially in restricted and narrow spaces, keeping in mind that lost energy is negligible. Also, the energy gained is far greater than that when shading is completely eliminated by keeping enough spaces.

Key words: Modified SEPIC Converter, Photovoltaic Source, PWM, MPPT, and Inverters.

1. Introduction

Renewable energy (RE) resources are being progressively integrated into power systems to support a continuous increase in power generation due to the limitations of fossil fuel supply and to reduce negative environmental impacts [1]. Among the RE resources, the energy from the solar photovoltaic (PV) effect can be considered the most necessary and sustainable resource due to its ubiquity, large quantity, and sustainability [2]. This PV system consists of solar panels, a DC chopper, a smoothing unit, and a power management unit for operating the PV panels at maximum extracted power, called the Maximum Power Point Tracker (MPPT) [3, 4]. Usually, photovoltaic systems operate at a point near the point of maximum power, known as MPP, in order to obtain maximum system efficiency and extracted power. Therefore, in order to extract maximum energy with reduced chopper switching losses and minimal total system losses at high efficiency, an MPPT system is a necessary step in the energy conversion process. The proper selection of the cell's materials, a clear and stable maximum achievable solar irradiation, stable temperature within an acceptable safe limit, tilt angle, and shade can all help to maximize the PV characteristics. To determine the loss of the PV outputs, the shading impact will be modelled [5, 6].

Recently, there have been great investments in building PV systems in urban and residential environments. Urban environments often include obstacles that could cast shadows on a PV system, badly affecting energy production [7]. In Germany, studies have shown that shading is one of the main causes of a lower energy yield [8]. Results from the German 1000 Roofs Program in 1990 revealed shading losses of up to 10% in more than half of their PV systems [9]. More recently, an analysis of more than residential PV systems in the United States showed that annual shading losses exceeded 20% [10]. Bayrak et al. [11] conducted an experiment where they applied different shading ratios to a single module. They analyzed three shading configurations: namely, shading of a single cell, horizontal shading of a row of cells, and vertical shading of a column of cells. This paper provides a detailed investigation into the shading effect in three aspects:

- Studying the shading effect causes partial shadowing over a portion of the PV panel.
- Studying the shading effect causes complete shadowing over the complete surface of the PV panel for a predetermined time interval during the day, but with different shadowing rates from 0% to 90%.
• For a given shadowing rate and the same time interval, the investigations described the 21st of the month of all 12 months of the year in order to find which month is the most affected.

Figure 1: Modified SEPIC Converter

In this paper, a simulation model is built to detect the effect of various shadowing scenarios on the panels’ main parameters. Taking into account the approach of [13], a direct detection of the maximum power at any value of solar irradiation and temperature during the daytime is realized.

Various DC-DC converters are applied, such as the single and modified single-ended primary-inductance converters SEPIC and MSEPIC, respectively. Figure 1 illustrates the principle electrical circuit for MSEPIC, while figure 2 presents the control circuit with a partial shading condition. The proposed model is analyzed and simulated in MATLAB/ Simulink, and m-file code.

Figure 2: Block diagram of closed loop MSEPIC converter with partial shading.

2. Mathematical Modeling

2.1: The concept of shadow factor

Depending on the sun’s position, the position of the PV panel, and surrounding objects, partial or complete shading can occur. The shading effect is defined as a change in the current-voltage characteristics (I-V) of the system, which in turn leads to a light or sharp reduction in the power output. Figure 2 illustrates the sun’s location with respect to the solar panel and related angles.

The sun position is defined as a function of the daytime, latitude, and longitude in order to determine the shaded area of the PV panel. The altitude of the sun as a function of latitude $\phi$, solar declination $\delta$, and angle $\omega$ subtended by the sun at a particular hour is given by [12] as follows:

$$\sin \alpha = \sin \phi \sin \delta + \cos \phi \cos \delta \cos \omega$$  \hspace{1cm} (1)

The direction of the irradiation beam striking the panel surface can be expressed as follows:

$$\cos \theta = \cos \phi \cos \delta + \sin \phi \sin \delta \cos \omega$$

$$+ \cos \phi \cos \beta \cos \omega$$

$$+ \sin \phi \sin \beta \cos \delta$$

$$- \cos \phi \sin \beta \cos \delta$$

$$+ \sin \gamma \sin \beta \cos \delta$$

$$+ \sin \gamma \sin \delta$$

$$\cos \omega$$  \hspace{1cm} (2)

where $\beta$ is the tilt angle, and $\gamma$ is the angle measured from the direct south facing to the location of the sun with respect to the south.

The angle $\omega$ is the hour angle that presents the difference between noon and the desired time of day in terms of a 360° rotation in 24 hours. In other words,

$$\omega = \frac{12-T}{24} \times 360^\circ = 15(12-T)^\circ$$  \hspace{1cm} (3)

where $T$ is the time of day expressed in hours with respect to solar midnight on a 24-hour clock. By relating $\omega$ to the other angles, the sunrise and sunset angles can be expressed according to [14] as follows:

$$\omega_{\text{sun}} = \cos^{-1}(-\tan \phi \times \tan \delta)$$

$$\omega_{\text{set}} = -\omega_{\text{sun}}$$  \hspace{1cm} (4)

and $\omega_{\text{set}}$ is the sunset angle.

For complete south-facing panels where $\gamma=0^\circ$, eq. (2) becomes:

$$\cos \theta = \sin \phi \sin \delta \cos \omega + \cos \phi \cos \delta \cos \omega$$  \hspace{1cm} (5)

This energy reduction can be calculated by using so-called shading factor. To do that, let’s look out from the sun path and related angles as shown in figure 3 and the effect of shadowing for winter and summer time. Three rows of panels are presented with shading effects of 0%, 30%, and 60% due to hard-shaded objects or fixed barriers or obstacles such as building chimneys, water tanks for containers, trees, etc. Taking into account the panel dimensions of SPR-315E [15] with $L_p=1.56m$ and $W_p=1.05m$ and the optimized tilt angle of $\beta=27^\circ$ with ground cover ratio GCR=51% [12], the distance between panels’ rows can be obtained as follows:

$$d = \frac{L_p}{2} - \frac{GCR \cos \beta}{GCR} = 1.67m$$  \hspace{1cm} (6)

Where $L_p$ is the panel length and $d$ is the safe distance to avoid panel’s shading. According to eq. (6), the shadow effect due to adjacent PV rows is overcome while the shading due to above-mentioned obstacles cannot be crossed, but their effect can be reduced by keeping sufficient distance between the PV panel and the obstacle, and/or suggesting a movable mechanism that slides up or down according to the shadow rate that changes from point A to point B, according to figure 3 having in mind that the panel length faces the barrier width.

Furthermore, the shadow distances $d_{s1}$ and $d_{s2}$ for the first two PV rows also must be determined; $d_{1}$ and $d_{2}$ can be determined based on the panel length and the tilt angle; $h$ and $h_s$ are the heights of the PV panel and the obstacles, respectively. For more details, let us describe figure 4, which illustrates the sun path and the resulting
shadow with the angles mentioned and their relations as follows:

At given angle $\alpha_2$, the shadow occupies a portion of the panel surface with projection of $d_{s1}$, therefore this angle is:

$$\alpha_2 = \tan^{-1} \frac{h_s}{d_{s1}} \quad \text{(7)}$$

Taking the trigonometrically ratio $\frac{h_s}{h} = \frac{d_{s1}}{d_{s2}}$, the length of the occupied panel’s portion $L_{s1}$ is:

$$L_{s1} = \sqrt{h_s^2 + d_{s1}^2} = h_s \sqrt{1 + \left(\frac{d_{s1}}{h_s}\right)^2} \quad \text{(8)}$$

Since $h_s$ and $\alpha_2$ are unknown, a good starting point is to determine the angle $\alpha_3$. The variations of the shadow range from 0% shadow to 100% shadow. The end limits of this angle are as follows:

The angle $\alpha_4$ is known as the lower limit of the shadow range when the light strikes point B.
The angle \( \alpha_A \) is known as the upper limit of the shadow range when the light strikes point A.

\[
\alpha_A = \tan^{-1} \left( \frac{h_A - h}{d_1 + d_2} \right) \quad 0 \leq \alpha_A \leq \frac{\pi}{2} - \alpha_0 .
\]

(10)

And the change in the striking angle \( \alpha_S \) is:

\[
\alpha_S = \alpha_A - \alpha_0 .
\]

(11)

The range of the strike angle change is

\[
\alpha_{SK} = \frac{\pi}{2} - (\alpha_X + \alpha_0) \quad \text{where} \quad \alpha_X \leq \alpha_{SK} \leq \alpha_0 , \quad \text{and} \quad 0 \leq \alpha_{SK} \leq \alpha_0
\]

Therefore, the shadow area depends on

\[
\alpha_1 = \max \{ L_A \} + L_P \quad \text{and} \quad A_{sk} = L_{sk} \times W_{p}
\]

(12)

Since \( \alpha_{SK} \) depends on the sun’s location, the shading area varies according to this angle. The following are concrete relations to \( \text{Ash=f}(\alpha_{SK}) \) by using MATLAB platform [16] as follows:

1- When \( 0 \leq \alpha_{SK} \leq \left( \frac{\pi}{2} - \alpha_0 \right) = \alpha_A \):

\[
A_{sk} = L_P \times W_P = \text{complete shadow} ;
\]

(13)

2- When \( (\frac{\pi}{2} - \alpha_0) \leq \alpha_{SK} \leq (\frac{\pi}{2} - \alpha_1) \):

\[
d_{sk} = \tan \alpha_{SK} - d_1 = \tan \alpha_{SK} + \tan \beta \quad \text{and} \quad L_{sk} = \frac{h_0}{\tan \alpha_{SK}} \times A_{sk} = L_{sk} \times W_{p}
\]

(14)

3- When \( (\frac{\pi}{2} - \alpha_1) \leq \alpha_{SK} \leq \pi/2 \):

\[
L_{sk} = 0 \quad \text{and} \quad A_{sk} = 0
\]

(15)

4- The shaded factor according to [29,30] is

\[
K_{sh} = \frac{A_{sk}}{A_{tot} \times (1 - K_{sh})}
\]

(16)

5- The actual direct irradiation for PV1 is:

\[
G_{actual} (PV1) = G_{Ls} \times \left( 1 - K_{sh} \right)
\]

(17)

2.2 The effect of shadowing over set of panels

Refer to figure 3, where a set of ordered panels in adjacent south-facing rows are exposed to shadowing due to an existing hard barrier. The rate of shading differs from one panel to another and can be determined as follow:

- The overall distance is

\[
d_{st} = h_1 / \tan \alpha_{SK}
\]

(18)

- The number of rows, or rows in column panels is:

\[
N_{st} = \frac{d_{st} - d_0}{d_0} + 1
\]

(19)

- The obtained number is correlated to an integer number in both directions:

\[
N_{st} = \text{Truncate} \left( N_{st} \right) + 1 ; \quad \text{and} \quad N_{p-} = \text{Truncate} \left( N_{p-} \right) ;
\]

(20)

where \( N_{st} > 1 \).

- Comparing the actual distance of the light vector \( h_0 \) with respect to the horizon line at related panel height, then comparing both parameters and deciding whether it is fully shaded or partially shaded:

\[
h_0 \left( N_{p+} - i \right) \quad \text{where} \quad \text{if} \quad h_0 \left( N_{p+} - i \right) \quad \text{then} \quad k_i = \begin{cases} 
1 : \text{shade} \\
0 : \text{unshade} 
\end{cases}
\]

(21)

- Having the distance of \( 4^{th} \) panel which is around 1m, thus all panels located at the left of it will be completely shaded, therefore the fully shaded panels are \( N_{st} \) as shown on figure 3.

- The completely unshaded (active) panels are:

\[
N_{at} = N_{st} - N_{p-} - 1
\]

(23)

- Calculating the shading factor in terms of the active PV unshaded area:

\[
K_{sh} = \frac{A_{at}}{A_{tot} \times (1 - K_{sh})}
\]

(24)

where \( A_{ac}, A_{tot} \) are the active and total panels’ area, respectively.

- The total shading factor of the whole PV system

\[
K_{sh} = \frac{A_{sh}}{A_{tot} \times A_{tot}}
\]

(25)

To find the average daily shadow factor, it’s necessary to calculate this factor various intervals of time every 10 minutes from sunrise until noon time i.e. \( \alpha_{SK} \).

- After that, the average value per day is determined by using the following arithmetical equation.

\[
K_{sh} = \frac{1}{N_{smax}} \sum_{i=1}^{N_{smax}} K_{si}
\]

(26)

where \( N_{smax} \) is the maximum number of calculated shadow factor for various latitude angle \( \alpha_{SL} \) at given day.
Meanwhile, this procedure is repeated for 365 days, and the average annual shading factor can be expressed as follows:

\[ K_{\text{annual}} = \frac{\sum_{i=1}^{365} K_{i}}{365} \]  

(27)

The annual energy without and with the shadow factor is:

\[ E_{\text{an}, \text{no-sh}} = G \cdot P_{\text{tot}} \cdot 365 \cdot 8760 \]

\[ E_{\text{an}, \text{sh}} = E_{\text{an}, \text{no-sh}} \cdot K_{\text{annual}} \]  

(28)

Where \( G \) is the average annual irradiation, \( P_{\text{tot}} \) is the total generated PV power, and \( K_{\text{annual}} \) is the coefficient of conversion with an average value of 75%.

3. Analysis and results discussion

In order to analyze the obtained results, concrete data is used as mentioned in Table 1, where the panel data, number of rows, barrier height, location, tilt angle, and spacing from the first row are changed.

3.1 Variation of shadow factor during single day

Let us describe the performance on March 21st, where the day number is 81 of the year, with sunrise at 5:47 and sunset at 17:47. The barrier height is 5m and 2m away from the first panel, and a tilt angle of 27°.

The obtained results are illustrated in figure 5, where the altitude angle varies between 25° to 67° and the shadow factor decreases from 25% to 0% at noon for March 21st, while for December 21st it varies between 75% to 0%.

Figure 6 shows the variation of the shadow factor for various barrier heights (2m, 4m, and 8m), where the highest rate of this factor occurs for the highest barrier, which is correct.

3.2 The variation of shadow factor for one year

Figure 7 displays the variation of the shadow factor for one year, where it’s shown that for all cases of barrier height, the shadow rate is high during winter, while it goes down to its minimum value during the summer.

This indicator gives us the possibility to install the solar panel very close to the barrier, regardless of the amount of radiation loss. Of course, radiation in the winter is relatively weak, and thus we save more area and produce more energy, especially during the spring and summer, when the radiation loss is small due to shading.

3.3 The variation of shadow factor with tilt angle

As previously mentioned, the shadow factor directly depends on barrier height, sun location, and daytime, while the light depends on the tilt angle variation as well shown in Figure 8 at a barrier height of 4m, where there is no significant decrease in shadow rate when moving from 14° to 42°, which is quite a height for the installation of a PV panel with \( h = 1.16 \) m. This high is suitable for regions with a longer winter period.

3.4 The annual energy change at various parameters

According to eq. (26), the simulation results of the gained annual energy for various design cases with respect to

<table>
<thead>
<tr>
<th>Parameters</th>
<th>March 21st</th>
<th>December 21st</th>
</tr>
</thead>
<tbody>
<tr>
<td>Altitude angle, ( \beta )</td>
<td>25° to 67°</td>
<td>14° to 42°</td>
</tr>
<tr>
<td>Shadow factor, ( K_{\text{annual}} )</td>
<td>25% to 0% at noon</td>
<td>75% to 0%</td>
</tr>
</tbody>
</table>

### Table 1: Panels data and site coordination

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Latitude</td>
<td>31.52°</td>
</tr>
<tr>
<td>Longitude</td>
<td>35.14°</td>
</tr>
<tr>
<td>Azimuth angle, ( \Phi )</td>
<td>0° to 180°</td>
</tr>
<tr>
<td>Number of Rows</td>
<td>10</td>
</tr>
<tr>
<td>Panel length, ( Lp )</td>
<td>1.56 m</td>
</tr>
<tr>
<td>Panel width, ( Wp )</td>
<td>1.04 m</td>
</tr>
<tr>
<td>Panel power, ( Pmp )</td>
<td>315</td>
</tr>
<tr>
<td>Average irradiation, ( Gav )</td>
<td>5.2</td>
</tr>
<tr>
<td>Spacing ( d1 )</td>
<td>1...10 m</td>
</tr>
<tr>
<td>Tilt angle, ( \beta )</td>
<td>0° to 65°</td>
</tr>
<tr>
<td>Barrier height ( h1 )</td>
<td>0...8 m</td>
</tr>
</tbody>
</table>
barrier height, tilt angle, and distance to the first panel’s row are displayed as follows: The effect of spacing between the barrier and first panel is shown in Figure 9, where the produced energy increases as the distance $d_1$ increases.

Figure 10 shows the percentage decrease while distance $d_1$ increases from 1m to 10m causing energy reduction in the range of 30% to 1% respectively. From this figure, $E_{ao}$ presents the energy produced when there is no shading either in the absence of a barrier or when a large number of rows are arranged. For example, at spacing of $d_1=5m$ from the barrier with a height of 5m, the energy decreases by 7.5% according to Figure 10. Let’s say there are 3 panels per row and the barrier blocks the light for whole panels in that row. So, whether to decide to remove 1 row with produced energy of 1345 kWh/yr in order to realize zero shading or keeping this row existed and losing no more than 100 kWh/yr. The acceptable solution is to allow shading with negligible energy loss rather than removing 3 panels and losing all the 1345 kWh/yr.

4. Conclusion

This research proposes a mathematical model to simply calculate the effect of shadow over a set of panels south-facing and arranged in rows with specific data and spacing distances. As a result, the shadow factor depends on the solar data, barrier height, the number of rows facing the barrier, and the distance of the first row to the barrier. It decreases as the daytime increases presented in terms of solar altitude angle for any day of the year. For example, on March 21st, it falls from 25% to about 0%. This factor is changed at different altitude angles, and depends on the years’ months. With respect to shadow rate, the significant effect is observed during winter time at the highest barrier, while during the summer time, this effect is negligible. Due to this fact, installing the solar panels close to the barrier will not cause a significant energy decrease. When studying the lost annual energy due to shading, it’s worth mentioning to estimate the shadow factor, then to decide whether to make enough spacing between the barrier and the PV system or to allow such shading. In the present study for the concrete PV system and site information with 5m spacing, 4m barrier height, and 10 rows arrangement the system just loosing 7.5% of its annual energy.

References


