QUANTIFYING THE PERCENTAGE OF SHADING ON A PV MODULE AND ITS SUBSEQUENT IMPACT ON ITS OUTPUT POWER

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Abstract

The output power of any PV module may be influenced by a number of factors, including the installation and environmental conditions. One of these conditions involve partial shading, where a section of a PV module is shaded due to an interruption in the direct-beam radiation from the sun. The purpose of this article is to quantify the percentage of partial shading of a given PV module within a controlled environment, correlating it to its output power. This correlation helps to reinforce the importance of allowing no shading to occur on a PV module or array. The percentage of partial shading is determined using images taken of a 10 W PV module that are processed using online imaging software. Results indicate that a partial shading percentage of 4,7 % caused by a vertical aluminum tube results in an output power reduction of 59 %. However, the results are limited to a specific string design of a PV module and to the position of the partially shaded cell. It is recommended to remove all causes of partial shading, as this impacts on current and future power generation from the PV module.

Keywords: surface; image software; direct-beam radiation

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1. Introduction

"Every day, people settle for less than they deserve. They are only partially living or at best living a partial life. Every human being has the potential for greatness" [1]. These words by an American businessman, Bo Bennett, well emphasize the fundamental truth that each person has the potential to contribute to the well-fare of their families, communities, and society at large. However, this is dependent on their full commitment, and not on a partial way of life. The same can be said of PV modules. They have the potential to produce an optimal amount of output power when fully illuminated by the sun under ideal atmospheric conditions. However, if partial shading should occur, then their potential for greatness would drop drastically.

Swart and Hertzog [2] reported on the results of full uniform shading of a PV module and its subsequent impact on its output power. Their study indicated a 56 % reduction in output power for a 36 % shade net which covered the entire module. This reduction increased to 82 % for a 63 % shade net. This well illustrates that full shading (as caused by dense clouds) results in a reduced output power. However, they did not report on the partial shading of a PV module and its subsequent impact.
Partial shading of a PV module causes disproportionate power loss as one shaded cell impacts on the power output of other unshaded cells connected in series [3]. Typical solutions to this problem involves the use of bypass diodes, using solar cells with low reverse breakdown voltages and placing low shunt resistance cells in shading prone areas of the module. However, what quantifiable power reduction occurs with partial shading?

Swart [4] undertook a study on the impact of pigeon droppings on the output power of a 10 W PV module. The pigeon dropping caused partial shading of the PV module which led to a 5 % reduction in output power. The size of the dropping was limited to a circular form with a diameter of 13 mm on a singular PV cell with a 22 x 78 mm dimension. No percentage value of the overall module size was stipulated as causing this 5 % reduction.

Another study conducted in 2021 found that the surface temperature of a PV module increased significantly due to the original forward current being forced through a higher resistance path within an individual cell that was partially shaded by a single pigeon dropping (~17 % higher than a non-shaded module) [5]. It was further reported that the total Wh for a day was reduced from 55.08 Wh for a module with no shading to 47.15 Wh for one with partial shading. Again, no percentage value was stipulated in causing this 8 Wh reduction.

The percentage of shading of a PV module is defined as the ratio between the area of a PV module's top surface which is shaded to that of a totally unshaded PV module. This can be determine using visual inspection, or online visual comparison software. In this article, two online websites are used, namely online image comparison and Resemble.js which analyses and compares images with HTML5 canvas and JavaScript. The amount of power reduction was determined using a customizable energy monitoring system [6].

The purpose of this article is to quantify the percentage of partial shading of a given PV module within a controlled environment, correlating it to its output power. This may help to reinforce the importance of PV module installations which must be free of partial shading conditions, such as the presence of a pole, tree or roof. An experimental setup is used where images of unshaded and partially shaded PV modules are compared using online software. The article firstly considers causes of partial shading, and then further discusses the two online websites. The experimental setup is then presented which includes the study context. The research methodology, results and conclusions follow.

Causes and Impact of Partial Shading

A study in 2016 investigated the performance effects of shading due to soiling on a PV module [7]. The effects on voltage and current output were discussed and the article differentiated between two types of shading, namely soft and hard shading. An example of soft shading was air pollution and an example of hard shading was dust which builds up on a PV module. The results showed that soft shading only affects the current of a PV module, with the voltage remaining more or less the same. Thin cloud cover, shown in Fig. 1, can also cause soft shading on a PV module.

Fig. 1: Soft shading of modules by thin cloud cover – experimental site

In the case of hard shading (see Fig. 2), the output voltage is reduced depending on how many cells are shaded. However, the current is also reduced which then impacts on the energy produced by the module. Partial shading can be caused by passing clouds [8] and by the remains of birds or animals [9]. Cracks that form in the glass surface of PV modules can also present partial shading-like characteristics [10]. In research that was conducted in 2014 by Ramli and Salam, the loss of energy due to partial shading was recovered by using a simple circuit [11]. The circuit comprised of power electronic switches and storage components that harvested the energy of the unshaded cells during partial shading. The idea was to take the current from non-shaded modules and divert it using a power electronics circuit and process it to become part of the output power. The inclusion of the proposed circuit enables 32% more power to be delivered compared to a normal bypass diode method.

Fig. 2: Hard shading by a solid object – experimental site

PV modules with different cell connection configurations may perform differently under partial shading conditions. In a study done by Wang and Hsu [12], five different connection configurations were used in order to investigate the influence of partial shading on the performance of a PV module. It was found that the total cross tied (TCT) connection style where the modules are first connected in parallel and then in series outperformed the other connection styles for a specific cell shading pattern that was used. An example of this style is shown in Fig. 3.

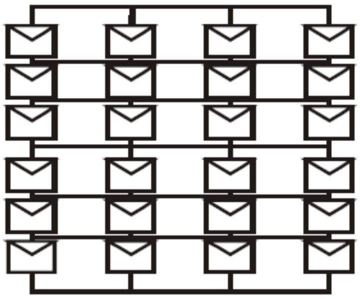

Fig. 3: TCT connection style [13]

Online Image Processing Techniques

The online image comparison tools that were used in this study can be found at the following web addresses https://online-image-comparison.com/ and https://rsmbl.github.io/Resemble.js/. Both of the websites do simple image comparisons [14] where the user inserts two images that need be compared to each other. The output from the first website (online image comparison) only provides a visual indication of the differences between the two images. The second website (Resemble.js) provides a visual presentation and a percentage difference between the two images. The images used in the comparison should be of the same size and scale to avoid inaccuracies. The images should only show the PV module, otherwise other differences in the images may be captured. Images should also be of a higher resolution and quality as this will make the comparison more accurate. For the first website, the fuzz value on the website affects the differences detected. A smaller fuzz value picks up smaller differences while a higher fuzz value picks up larger differences. A higher fuzz value is better as this will mainly show the shaded area on the PV module. The highlighted color of the differences can also be set. For the second website, the “Ignore less” option needs to be changed to “Ignore anti-aliasing”. This prevents minor differences from being considered in the analysis.

Practical setup

An aluminum frame was designed and constructed to mount a 10 W PV module at a tilt angle of 29º, equating to the latitude value of 29º for the Central University of Technology [15, 16]. The practical setup was done inside an air-conditioned room where the temperature was kept constant at 25ºC. This was to reduce the influence of other variables that impact on the performance of a PV module, which include high temperature, dust and pigeon droppings. Fig. 4 highlights the installation of the PV module where part of the aluminium frame is visible in the background.

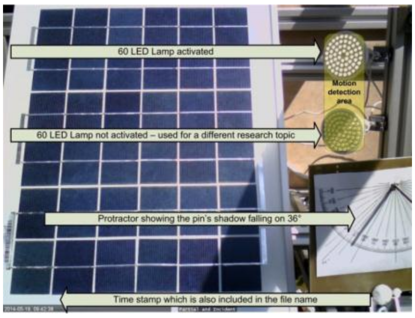

Fig. 4. PV module inside an airconditioned office at the Central University of Technology [17]

A 2 W LED lamp was used to visually observe when the output power reached 10 % of the total output power of the 10 W PV module. This value was set by using a resistor in series with a regulated LED lamp that required a higher current flow from the module in order to activate it. This required current would only start to flow when the required number of individual cells within the module where exposed to direct-beam radiation. The natural motion of the sun and a vertical aluminium tube (stationary frame support for a window) causes automatic partial shading of the module. The result is a shadow in the form of a straight line that move across the PV module from the top left-hand side to the bottom right-hand side. When 1 W of output power was attained, then the 2 W LED lamp would activate and a Webcam would capture this event. The photo taken could then be analysed in terms of the percentage of shading that results in a specific reduction of output power. Note the shading on the bottom right-hand side of the module in Fig. 4 which was caused by the vertical aluminium tube.

2. Methodology

An experimental research design was used were data was collected during the winter months (June through August). This period was chosen due to the lesser chance of rain that could hamper the collection of data through full shading caused by dense cloud movements. Voltage and current measurements were made using a simple interface circuit that was connected to a PicoLog 2016 device. These measurements helped to determine at which time point the output power increased beyond 10 % of the total output power of the 10 W PV module. A Webcam would automatically capture an image of the PV module at this exact same time point, enabling a correlation between the amount of shade on the PV module to its output power. This procedure has been detailed in a previous publication [17]. The images obtained from the webcam were then submitted to two online image comparison websites, namely online-image-comparison.com and Resemble.js. Results from the Web sites where used to calculate the percentage of shading on the images that were correlated to the percentage of power reduction.

3. Results and Discussions

Fig. 5 highlights the difference between the shaded and unshaded PV module that was obtained through the use of the first online website, namely online image comparison. The two images used to produce the result were the image of the unshaded PV module (see Fig. 6) and the image of the shaded PV module shown in Fig. 7. The two images were each loaded onto the website, where a fuzz value of 12 was used to compare them. A value of 12 was used since these two images differ slightly in size, thereby allowing for some variance. In other words, some of the smaller differences will not be shown in the final result. Finally, the result was generated by selecting the “Compare” button on the website. The result produced using this website only serves to highlight the visual differences between the shaded and unshaded PV module snapshots. In order to get an estimate of how much of the PV module was shaded, another website was required which provided this functionality.

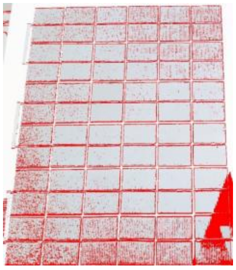

Fig. 5: Result produced by the first website, online image comparison

Fig. 6: Example of a snapshot taken on the 19 May 2015

Fig. 7: Example of a snapshot taken on the 19 May 2015

Resemble.js was then used to gain a rough estimate of the shading coverage on the PV module. This website works in a similar manner as the first, requiring two similar images to complete the comparison. Fig. 6 and Fig. 7 were again used for the comparison, producing the result shown in Fig. 8. In addition to the visual result, this second website also provided a value difference of approximately 2,17 % in shade coverage between the shaded and unshaded PV module snapshots. This shade coverage is the approximate pixel difference between the two images. However one can consider it the shading difference as the website only picks up larger changes between colours in the two snapshots, i.e. the difference between light and dark pixels.

Fig. 8: Result produced by the second website, Resemble.js

Upon visual inspection of the result obtained from the first website, it appears that 2 blocks or 1 cell of the PV module is shaded (Fig. 5). In total there are 36 cells on the PV module. The following calculation is used to calculate the percentage of shading present on the PV module: (1 / 36) x 100 = 2,78 %. Fig. 9 provides the result from the PicoLog 2016 showing the difference in output power between the shaded and unshaded PV module for 19 May 2015. The Blue line (PV 1 Power) shows a sharp rise in output power after 08:30 am in the morning. This is when the vertical aluminium tube is no longer causing a shadow on this module. However, the shadow from this tube is still present on PV 2, as the sun has not moved sufficiently from east to west across the sky. This indicates that the shaded module lags behind the unshaded module in terms of providing sufficient output power to activate the 2 W LED lamp (the load resistor). Then, just before 12:30, PV 1 is fully shaded to highlight the comparison between a fully-shaded and unshaded module.

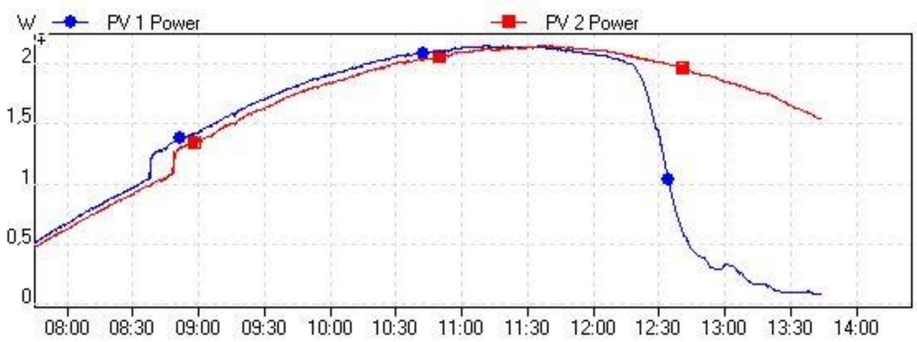

Fig. 9: Result obtained from the energy monitoring system for 19 May 2015

Fig. 10 shows the results obtained from another energy monitoring system which verifies the exact power reduction caused by the shaded module. In this case, the module was shaded with black insulation tape to replicate the shadow caused by the vertical aluminium tube. The unshaded module is represented by the RED (top) curve and the shaded module by the BLACK (bottom) curve. At 12 noon, the unshaded module produced 10.47 W of output power, while the shaded module produced 4.24 W of output power. This equates to a power reduction of 59 % for a 2,78 % shading of the 10 W PV module.

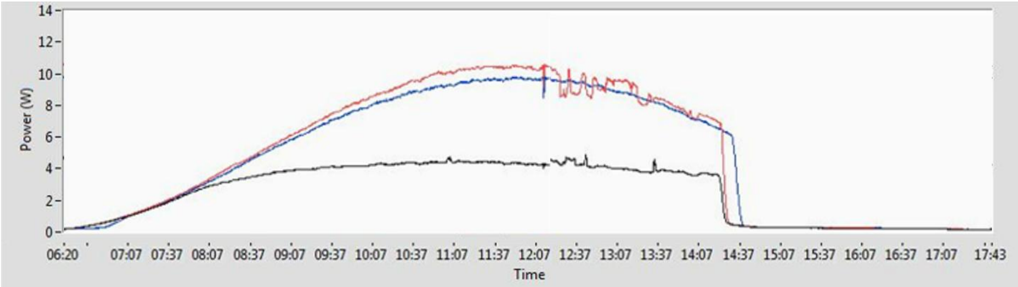

Fig. 10: Result obtained from the energy monitoring system for 6 December 2022 to verify the power reduction for midday

Table 1 presents multiple results obtained from the Resemble.js website for 4 photographs that were taken with the stationary webcam. These results indicate a measure of reliability, which validates the practical setup and the methodological process. An average shading percentage of 4,7 % is calculated for a 59 % reduction in output power of the 10 W PV module. A summary of the key findings from previous literature is noted in Table 2, where the key finding of this study is included.

Table 1: Shading results from Resemble.js

Snapshot Date (yyyy/mm/dd)	Snapshot Time (hh:mm:ss)	Snapshot Shading Percentage
2014/07/03	10:09:13	2,17 %
2014/07/06	09:55:22	7,28 %
	Average	4,7 %

Table 2: Key results pertaining to the partial shading of a 10 W PV module

Reference	Result
Swart, 2021	Pigeon dropping causes an instantaneous 5 % output power reduction
Swart and Hertzog, 2021	17 % rise in surface temperature for a partially shaded module Daily 8 Wh reduction in output power for a partially shaded module
This study	4,7 % shading of a module caused by a vertical aluminum tube results in a 59 % reduction in output power

This points to a quantitative reference level which is completely objective in nature. It indicates that partial shading of a PV module does result in an output power reduction of between 5 % and 85 %, depending on the size of the shading (pigeon dropping versus 4,7 % shading). It also indicates that the surface temperature of a shaded PV module can increase by 17 %, while producing an 8 Wh reduction in output power per day.

4. Conclusions

The purpose of this article was to quantify the percentage of partial shading of a given PV module within a controlled environment, correlating it to its output power. This correlation may help to reinforce the importance of allowing no shading to occur on a PV module or array. Two online image comparison tools were used. Results from the first website (online image comparison) only indicated visual differences between the shaded and unshaded PV module snapshots. The second website (Resemble.js) was used to compare shaded and unshaded pictures of a 10 W PV module. The study found that if 4.7 % of the PV module is shaded by hard shading, it results in a 59 % reduction in output power for the module. The study only investigated the influence of shading caused by a vertical aluminum tube. It also only considered a specific cell in a series string, which forms part of the limitations of the study. However, the results clearly indicate that even a small percentage of shading on a PV module can have a significant influence on the modules generation capacity. Indeed, partial shading of a PV module has led to a drastic fall in the potential greatness of the module to produce an optimum amount of electrical energy.

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