Correlating the switch-on time of two identical PV modules using a simplified measuring approach

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***Abstract*—The installation of different renewable energy systems is gaining momentum globally, as governments and industry seek to reduce carbon emissions and fossil fuel usage. PV systems have become more common place, as evidenced by the number of PV array roof-installations visible in many communities today. However, it is assumed that the modules in these arrays are identical, as it is important to have similar currents flow through each branch of an array. Partial shading or unmatched PV modules may lead to power mismatches, hot spots and ultimately a lower overall output power than what is desired. The purpose of this paper is to present a simplified measuring approach to validate the operating performance of two identical PV modules by determining their switch-on time. Any significant differences in switch-on time between identical PV modules could lead to possible power mismatches in a PV array. Results confirm that both PV modules are very similar in switch-on time, with an average on-time difference of 2 minutes and 27 seconds.. This indicates that both PV modules start operating at roughly the same time of the day, thereby providing similar current flows which contribute to the optimum performance of a PV array.**

***Keywords*—shading, mismatch, Webcam, motion-detection**

I. INTRODUCTION

"Extracting power "from thin air" has a quality of science fiction about it, yet in the near future technology trends make it likely that small computers in urban areas will use ambient RF signals for both power and communication"[1]. The idea of extracting power from thin air was commented on by Nickola Tesla over a century ago. Little did those early inventors realize that large amounts of electrical power would eventually be extracted "through thin air" by exposing semiconductor material to direct sunlight! This phenomenon, referred to as the photovoltaic (PV) effect, has seen the proliferation of PV modules and arrays as humanity seeks to harness the tremendous amount of power available from the sun.

Multiple PV cells are usually interconnected to increase the current flow and output voltage of a singular module. In turn, multiple PV modules are interconnected to increase the overall output power from a PV array. Figure 1 highlights the installation of two different PV arrays in Brighton, UK where 10 modules have been interconnected to form an array. These PV array roof-installations have proliferated over the past few years as man seeks to reduce carbon emissions and dependence on fossil fuels.

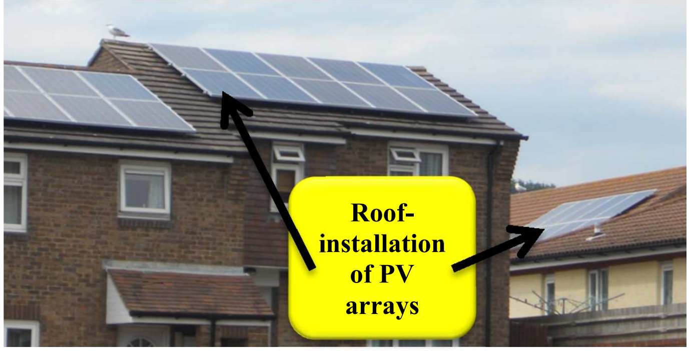

Fig. 1. PV arrays comprise a number of PV modules, as evident in this photo taken in Brighton, UK, during July 2015 by the researcher

A key requirement for PV modules, or arrays, is that all PV cells, or modules, need to be roughly identical [2]. Mismatch power losses arise when cells or modules with different current–voltage characteristics are interconnected [3]. Fewer degrees of freedom are left for biasing the devices, so that the overall output is less than the sum of the power that the individual cells could deliver. Differences come from the unavoidable fabrication spread or from non-uniform irradiance or working temperature within an array [4]. This fabrication spread occurs in the manufacturing process, which produces cells with relatively large tolerances in their power output capability. While industry has been able to lower these tolerances to around 3% by using specific techniques [5], notable differences still exist in the electrical characteristics of nominally identical PV modules [3].

The performance and characteristics of individual PV modules in an array should be fairly similar under uniform irradiation patterns [6]. However, when subjected to partial

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shading conditions, these modules tend to generate different branch or string currents [7]. Hot spots occur when a large number of series connected cells are dissipating power in a shaded cell. This results in the individual PV cells (or modules in the case of an array) being forced to operate at a power level other than their own, which leads to losses in overall output power [8]. These hot spots are a common problem in PV systems that accelerate cell degradation and reduce system performance [9]. These hot spots occur mainly during the day when ambient temperatures are above the STC level and the MP current is being drawn. However, power mismatches between modules may even occur early in the morning, before the PV array starts to work at its maximum output power. Although these power mismatches may be negligible, when added together, they have the ability to impact negatively on the overall output power generated for a given day. These power mismatches may be discerned by the switch-on times of different PV modules.

The purpose of this paper is to present a simplified measuring approach to validate the operating performance of two identical PV modules by determining their individual switch-on time early in the morning. The switch-one time difference should be around 3%, which is the accepted output power tolerance of PV modules. The target area of this research is located in the heart of South Africa (Bloemfontein, Free State) in the Southern Hemisphere which is classified as a semi-arid region with temperatures reaching well beyond 40°C in December. The effect of shade and power mismatches of PV modules will firstly be given. The practical setup and methodology will then be substantiated. Descriptive results, in the form of sketches and tables, will be presented, along with succinct conclusions.

II. EFFECT OF SHADE AND POWER MISMATCHES

Shaded PV cells exert a strong negative influence on the overall output power of a specific string within a PV module. This same principle applies to a string of PV modules within an array. This impact is illustrated in Figure 2 (b) which indicates that a major problem exists. When shade falls on the middle PV cell, it changes its electrical characteristic from a forward biased device to a reversed biased device [10]. This means that its internal resistance increases significantly, thereby inhibiting the flow of current, and becoming more like an open circuit. However, to counteract this increased resistance, the surrounding cells attempt to drive more current through the shaded cell in an attempt to maintain the original current flow prior to shading. This, in turn, results in significant heat being dissipated in the cell leading to hotspots and cell burn out. The shaded PV cell now becomes a power consumer instead of a power producer.

To negate this ill effect, to a certain degree, requires the use of a bypass diode, as shown in Figure 2 (a). As the middle PV cell becomes reversed biased due to the shading condition, the bypass diode's voltage state changes to that of being forward biased [11] with its internal resistance now being lower than the resistance of the PV cell. This means that current will rather flow through it, than through the shaded PV cell. Surrounding PV cells do NOT need to drive more current through the shaded cell by moving from their MP current for a specified load to their short circuit current. This suggests that the MP voltage is maintained, although the output power is reduced to 66% of the total possible available power. However, the shaded PV cell is spared destruction as no high currents are driven through it with any subsequent heat dissipations.

The ideal condition is highlighted in Figure 2 (c), where no shading occurs. This results in MP current flow and MP voltage for a specified load, resulting in 100% total power being produced. Shaded PV cells therefore result in power losses, which may also be caused by power mismatches, as shown in Figure 3.

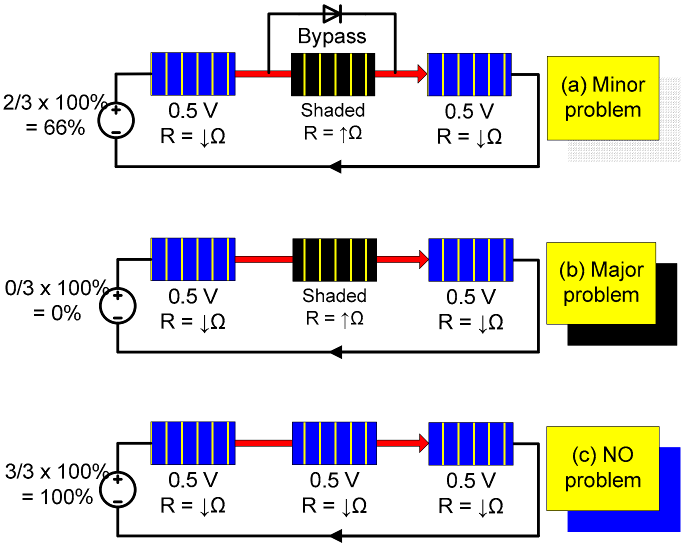

Fig. 2: Shaded PV cells result in a power mismatch

In Figure 3, the total voltage produced by String A equals 75 V (this becomes x1). However, that produced by String B (x2) is only 72 V, as the last module is not yet working at its MP due to a difference in its electrical characteristics. This means that the overall system voltage mismatch is equal to 4% (or 0.04 as a ratio), being calculated with the following equation:

$$MisMatch = \left(1 - \frac{x2}{x1}\right) \times 100\% \qquad (1)$$

This same equation may be used to calculate the overall system current mismatch by using the current in Sting A (x1 now becomes 500 mA) and that in String B (x2 now becomes 300 mA). This equates to 40% (or 0.4 as a ratio). The overall power mismatch may now be calculated using the following equation using the calculated mismatch ratios:

$$PowerMM = [1 - (1 - V\ MisMatch) \times (1 - I\ MisMatch)] \times 100\% \qquad (2)$$

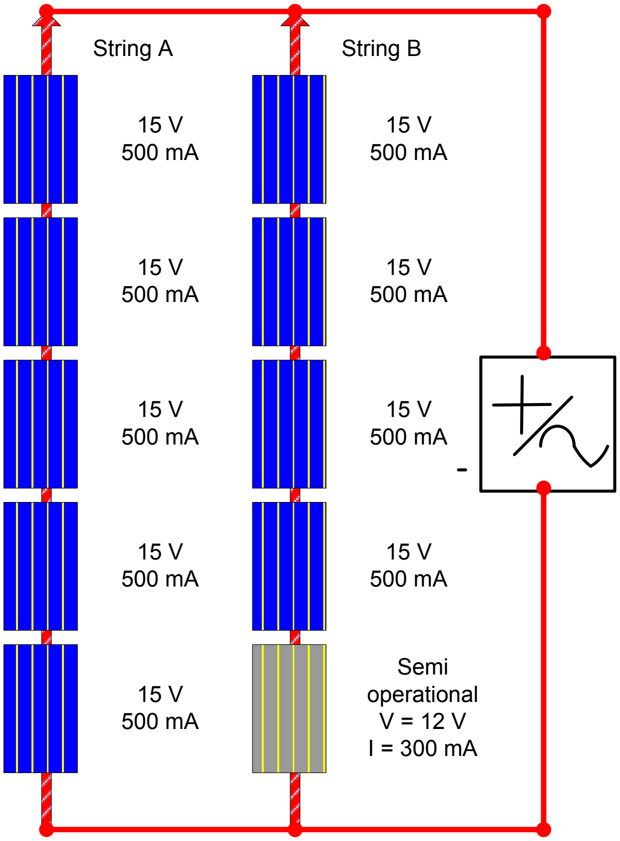

Fig. 3: Different PV modules in an array result in a power mismatch

This equates to an overall power mismatch of 42.4%, resulting in power losses within the system. Although the conditions mentioned in Figure 2 have been specific for a shaded cell or module in an array, they may further apply to a cell or module which has not yet started operating as shown in Figure 3. Due to shading, construction tolerances, or different orientations, some of the PV modules in an array could experience different operating conditions, generating the mismatching phenomenon [12, 13] which has been calculated earlier. In other words, the first module in a string may be producing its MP current early in the day, while the last module may only reach that point a few minutes later. This is primarily due to the 3% tolerance in output power between identical PV modules from the same manufacturing batch [5]. This tolerance may be discerned by determining the switch-on time of two identical PV modules used in the practical setup of this study.

III. PRACTICAL SETUP OF THE SIMPLIFIED APPROACH

The simplified measuring approach consists of two identical PV systems comprising a 10 W polycrystalline PV module, a 60 LED Lamp (MR16, rated 3 W at 12 V), a protractor, a Webcam (Prestigio), an aluminum frame, a notebook and a software package for motion detection (Yawcam). The 60 LED Lamp was chosen as its threshold operating voltage may be adjusted by using a series resistor, thereby ensuring that a higher output power would be required from the PV module to activate it. This series resistor also ensures that the voltage over the 60 LED Lamp never exceeds 13 V, as the MP voltage from the PV module is 16.5 V. A 22 Ω resistor was therefore used based on previous research [14], which requires an output voltage from the PV module that is at least 50% of its MP voltage. The current at this point would have to be at least 33% of the PV module's MP current. This would ensure that the PV module would be operating at an output power of more than 1.5 W (being 15% of its peak output power which equates to the efficiency of this PV module under STC). It must be noted that 3 W is the maximum power rating of the LED, which does activate at lower power values.

An aluminum frame (see Figure 4) was constructed to securely mount the 10 W PV module at a tilt angle of 29º, equating to the latitude value of 29º for CUT [15, 16]. CUT is located in the semi-arid part of South Africa that enjoys 55% of its annual rainfall between January and April [17], with very little rainfall during the winter months of May through August. The practical setup was done inside an air-conditioned room where the temperature was kept constant at 25^{0}C. This was in order to prevent excess temperature degradation which has a significant impact on the output voltage of a PV module [18]. The protractor was primarily used in another research study, but was also used to verify the direction of the sun with regard to the switch-on time of the PV modules.

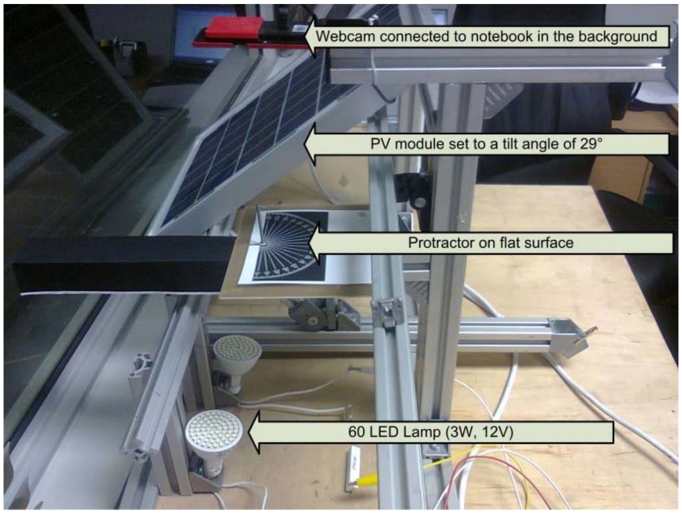

Fig. 4: Practical setup showing the webcam, one PV module, two 60 LED lamps and the aluminium frame

The Webcam was focused on the two 60 LED Lamps, in order to take a snapshot when signaled by the motion detection option available in the software package when the LED is activated. The sensitivity of the motion detection was set to 75% with a tolerance value of 15%. A higher tolerance value implies that a significant amount of motion needs to occur for the Webcam to be signaled. Multiple snapshots were taken over a 3 month period where the timestamp value was visually observed and recorded in an Excel sheet (part of the methodology).

IV. METHODOLOGY

An experimental research design is used to gather quantitative data from snapshots taken from a Webcam (data collection instrument). The timestamp was set in the software to be included on the top of the photo (see Figure 5). Each snapshot (photo) was viewed in the Microsoft Explorer window to visually observe at which time each 60 LED Lamp had switched-on each morning. The switch-on time for each Lamp was then recorded in an Excel sheet, along with the specific date. Data was recorded from the 04 October 2015 to the 17 April 2016 which corresponds to the summer months for the installation site. This would be the period when maximum solar irradiation would be expected, leading to a relevant early switch-on time for both PV modules (being around 07:00 am).

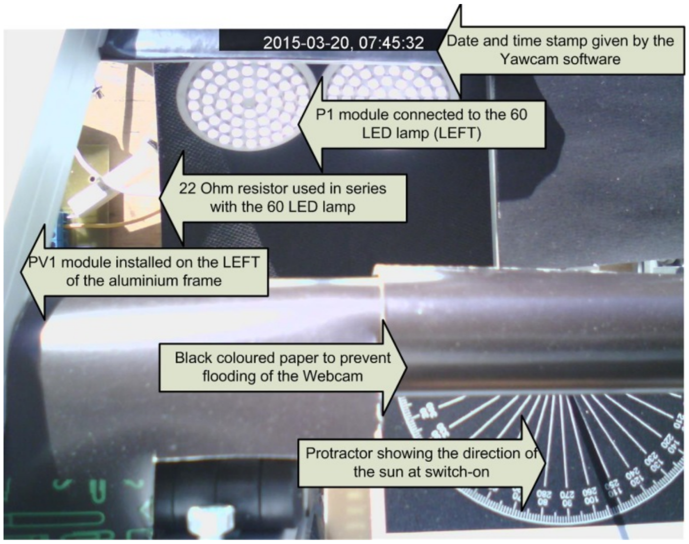

Fig. 5: Example of a snapshot taken on the 20 March 2015

PV1 was connected to the left hand LED (see Figure 5) and PV2 to the right hand LED for the first 3 months of the specified time period. The modules were then swopped around on the 22 January 2016, so that PV1 was connected to the right hand LED and PV2 to the left hand LED. This was to ensure that the PV modules were being analyzed, and not the LED lamp in series with the 22 Ω resistor. The PV modules were swopped again on the 20 March 2015, resulting in to two months of verifiable data (data used to verify that the different switch-on times were caused by the PV module itself). The protractor in Figure 5 further highlights that the sun is 18° of due east at this specific date and time.

The setup was installed in an office with an east facing window to ensure that the ambient temperature never exceeded 25ºC. Motion detection was limited to a specific area defined in the software package in order to avoid numerous snapshots of unrelated or erroneous events. This area was defined to include only the 60 LED Lamp, and not the rest of the practical setup. Sufficient black colored paper was wrapped around different parts of the aluminum frame, so as to prevent direct sunlight from reflecting off these surfaces into the Webcam. This excessive light floods the Webcam, resulting in a white snapshot been taken with very little discernable information. The analyzed results from the Excel sheet are presented next in a series of graphs and tables.

V. RESULTS

Figure 6 shows the results of the different switch-on times of PV1 and PV2. Both follow the same pattern in terms of decreasing time from the 4 October 2014 to the 11 December 2014, when the trend reverses and the switch-on time increases to 08:42 on the 10 April 2015. This forms an inverted relationship with the typical annual solar irradiation curve which peaks in summer (December) and falls to a minimum in winter (June). The peak in summer would suggest an earlier switch-on time, as the sun has reached a higher point in the sky resulting in its direct beam radiation falling within the acceptance zone of the PV module. The higher solar radiation would also cause the PV module to start operating at an earlier time in the morning. Noteworthy, however, is the fact that both PV1 (Grey area) and PV2 (Black area) seem to switch-on at the same time. However, a more detailed picture is painted with Figure 7, which illustrates the difference in minutes between the switch-on times of PV1 and PV2. This figure indicates a maximum time difference of 14 minutes between the two identical modules for the 7 April 2015. This occurred only once as Figure 8 shows.

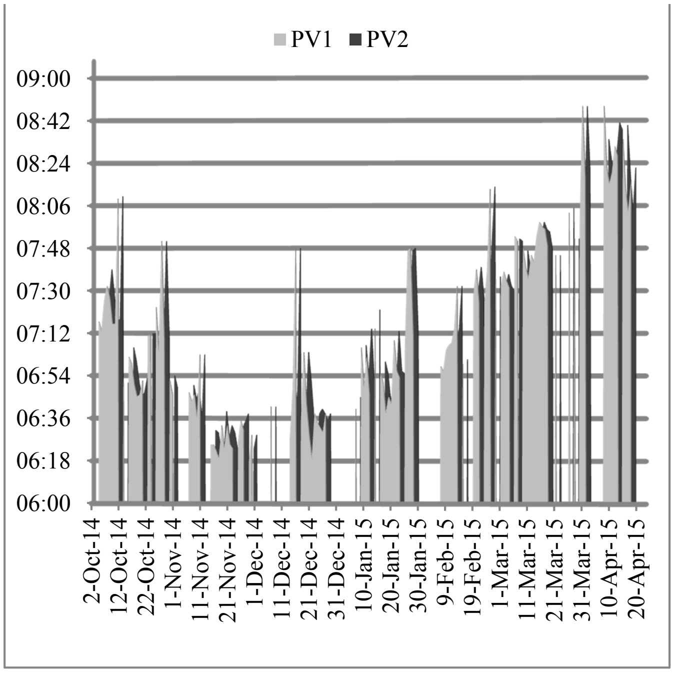

Fig. 6: On-time data for PV1 and PV2 from the 4 October 2014 through the 17 April 2015.

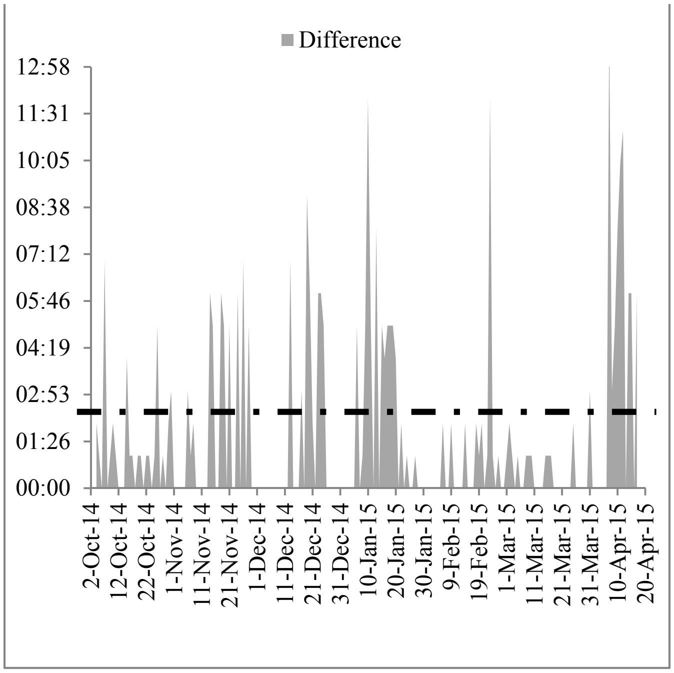

Fig. 7: On-time differences for PV1 and PV2 from the 4 October 2014 through the 17 April 2015.

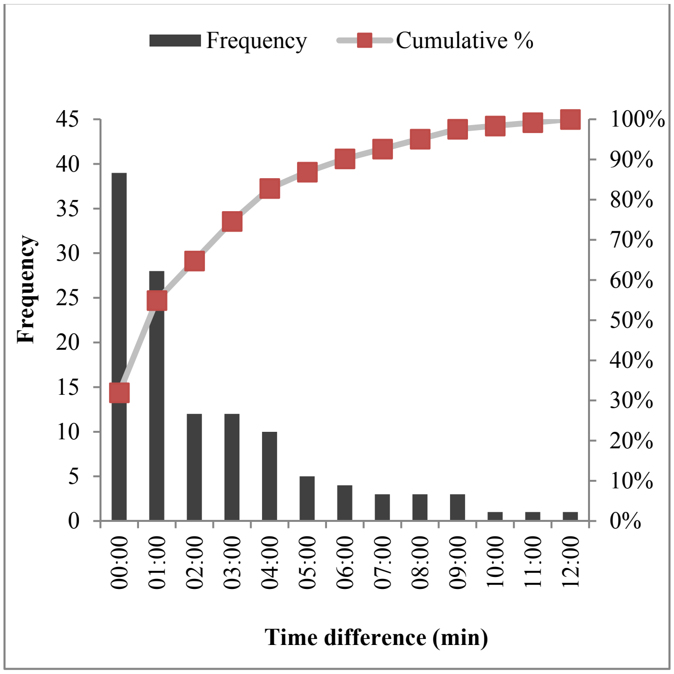

Fig. 8: Histogram showing the frequency of on-time differences in minutes between PV1 and PV2 for the 26 week period

Figure 8 presents a histogram of the most frequent switch-on time differences between the two identical PV modules. The most frequent difference was 0 minutes, accounting for up to 31.97% of the time. On average, less than 65% of the 26 week period indicates a switch-on time difference of less than 2 minutes. In fact, the average difference in switch-on time between PV1 and PV2 is a mere 2 minutes and 27 seconds, as shown by the back dotted line in Figure 7. Using a reference point of 60 minutes yields an average time difference of 4% (147 seconds divided by 3600 seconds x 100%).

Table 1 presents succinct descriptive statistics for the data collected over the 26 week period. Both PV modules have similar Kurtosis and Skewness factors, while a significant statistical relationship exists between the data sets (p = 0.000).

TABLE 1: DESCRIPTIVE STATISTICS OF THE ON-TIME FOR PV1 AND PV2

Start date	04 October 2014	
End date	17 April 2015	
PV module	PV1	PV2
Mean (average on-time)	07:14:00	07:16:27
Standard Error	00:03:23	00:03:19
Median (on-time)	07:07:00	07:10:00
Mode (on-time)	06:46:00	06:51:00
Standard Deviation	00:37:30	00:36:52
Sample Variance	00:00:59	00:00:57
Kurtosis	-0.64	-0.54
Skewness	0.50	0.55
Range	02:30:00	02:29:00
Minimum (on-time)	06:18:00	06:19:00
Maximum (on-time)	08:48:00	08:48:00
Sum	NA	NA
Count	123	123
Pearson correlation	0.996	
Significance	122.382	
p-value	0.000	

VI. CONCLUSIONS

The purpose of this paper was to present a simplified measuring approach to validate the operating performance of two identical PV modules by determining their individual switch-on time early in the morning. The switch-one time difference was calculated to be 2 minutes and 27 seconds (4% when considering an hour period) for these 10 W PV modules. This suggests that no severe manufacturing differences exist between these two PV modules which originate with the same manufacturer.

This would furthermore cause no hotspots to occur in these PV modules if they were used in a PV array, as the results are applicable to the early morning where the PV module has not yet reached its MP for a specified load. However, power mismatches would occur between different PV strings using these PV modules, resulting in a small percentage of overall lost power. These results do suggest that PV system modeling must take into account a small percentage of power mismatch losses so as to continually provide the desired output power.

However, shading in PV arrays will continue to present challenges to engineers, as it contributes to a significant reduction in output power. Mitigating this power reduction may be accomplished by using algorithms to switch in or out specific PV modules within an array that are haphazardly exposed to full uniform shading. Another option may lie in the installation of reflectors that may primarily be used during midday when the solar radiation curve is at is maximum. This may results in alternative paths for the direct beam radiation reaching the PV modules when clouds are present, giving rise to the effect of site diversity that is used in Satellite Communications.

The simplified measuring approach may be used in other applications, such as verifying the acceptance zone of PV modules. It proves to be a valid, reliable and inexpensive method of collecting specific data where motion detection is required.

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