Development and Implementation of Modified Power Loss Detection Algorithm for Partial Shading in Real-time Photovoltaic System

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Abstract: The development of maximum power point tracking in solar photovoltaic system is important for obtaining the maximum power, which works satisfactorily when subjected to steady, undisturbed irradiation. Under real-time conditions, the solar panel does not always receive uniform irradiation owing to partial shading, thereby reducing the gross power output from the panel. The presence of partial shading is directly recognized by an occurrence of multiple local peaks in the performance characteristics of the solar panel. During partial shading, conventional maximum power point tracking algorithms fail to detect the global maximum power point, thus operating the panel at a much lower efficiency than desired. This study aimed to accurately detect the occurrence of partial shading condition in the solar Photovoltaic (PV) systems under different irradiation conditions and shading patterns. A partial shading detection mechanism is proposed based on power loss generated from a solar PV array without any sensors incorporated in the real-time platform. The proposed method is cost effective and accurate even under different seasonal and weather conditions, without any empirical constant and sensors. The proposed method is tested experimentally in real-time setup and the results are validated. The method provides a much higher accuracy than the current approximation and power loss method, and it does so by using the minimum number of variables. The proposed detection mechanism is compared with other existing methods in the Maximum Power Point Tracking (MPPT) algorithm, which proves the powerfulness of the algorithm. To test the performance of the proposed method, a real-time PV system with data acquisition using National Instruments LabVIEW is developed. Virtual Bench-8012 is used for data acquisition with a high precision along with intrinsic signal conditioning, and compact RIO-9081 with a Field-Programmable Gate Array (FPGA) Virtex-5 LX150 is used for the MPPT algorithm implementation. The experimental results are also verified under different shading patterns and irradiation conditions for detecting the shading of the panel. Hence, it is shown that the detection algorithm has an efficiency of 97% in detecting the shading conditions of the panel.

Keywords: Solar Photovoltaic, Partial Shading, Global peak, Power loss method

1. Introduction

When the solar panels are not subjected to uniform irradiance throughout the panels, then the system is considered to have partial shading and hence reduction in output power. The non-shading conditions also result in reduction in the output power considering the inconsistency or variation of the irradiation throughout a day. Many authors in the literature have considered setting a threshold power to detect partial shading. In [1-8], the authors have considered the partial shading if the output power exceeds a certain threshold value or else, uniform irradiation is assumed which is not effective. Moreover, the basis on which the current and power threshold values are chosen is not indicated and hence, it is difficult to determine the exact value of the threshold given that no specific equations are involved. These methods scan the entire P-V curve even under uniform irradiation since they cannot differentiate the change in power under uniform irradiance or partial shading conditions. Hence, the converter will operate at a much lower power point rather than tracking the Maximum Power Point (MPP) and cannot compensate for the small shifts in MPP due to a dynamic change of insolation, temperature, and loading. To obtain the maximum output power, the Maximum Power Point Tracking algorithm should be able to discriminate between the global peaks, which indicate the maximum power, and the local peak, which arises during the partially shaded condition. If the threshold power is set very high, the algorithm cannot initiate a global peak search. On the other hand, if it is set very low, the algorithm gives a false trigger.

In [2], the author has assumed the threshold to be 10% to 20% of maximum power. Artificial Neural Network is used for partial shading detection and fault analysis of panels. Due to the number of cases considered by the ANN algorithm, it gives a real-time accuracy of 83% but the method become tedious in designing ANN algorithm under different system conditions. Likewise, threshold power is set to be 5% of the nominal power in [3]. Under the concept of normalized deviation of power presented in [4], threshold power, P_{th} is 15% but in [5], 10% is used. Hence, it is understood that the threshold value allotted is susceptible to change depending on various parameters including the array structure, geographical location etc.

The commonly used method is to set a threshold for both voltage and current [6-7] parameters but the changes in current depend greatly on the irradiation value. In [8], detection is done by measuring a voltage mismatch in the PV module. This requires the use of a voltage sensor in every module, which leads to high cost. In [9], the MPPT algorithm scans three specific points based on a predetermined duty cycle with current threshold, I_{th} as 0.2 and voltage threshold, V_{th} as 0.1. Though this method holds good for most cases it needs tuning for some shading conditions. In [10], the detection is based on the state of shading where both current and voltage are kept as tuning parameters, but temperature affects both voltage at MPP, V_{mpp} and current at MPP, I_{mpp} to a certain extent. Another method involves P_{th} [11] which can be varied depending on weather conditions but dependency on temperature is not preferred since it requires frequent changing of the threshold. Ahmed et al [12]

implemented a more reliable detection method by scanning the short circuit current and the MPP current to calculate irradiation. As we know, the relationship between current and irradiation is not always linear and hence current rapidly changes whenever irradiance, G changes abruptly. In addition, two values of irradiances are calculated from the current values at 0.8 open circuit voltage of a single module, (V_{oc}) and 0.8 open circuit voltage of an array (V_{oc_array}) at standard test conditions. The mismatch between two G values and irradiation are plotted against each other and the threshold of the mismatch is determined to be $40W/m^2$. If the difference is less than 40, uniform irradiation is assumed. Sufficient information is not given on how this threshold is chosen and the threshold may vary depending on the panel structure.

Murtaza et al [13] uses multiples of open circuit voltage ($0.8 V_{oc}$) model that originates from the assumption that the local peaks, under partial shading condition occur at multiples of V_{oc} . The advantage is that tracking is confined only to a particular range. But the overall tracking speed is slow. A two-stage Global MPPT (GMPPT) Method based on characteristic curves is reported in [14] in which V_{mpp} is considered equal to voltage at Global MPP, V_{gmpp} under shading condition, which may not be true. Li et al [15] propose a two-stage GMPPT method, which tracks an intermediate variable (β) other than the power. Though no threshold parameter is required, it requires the generation of an equivalent PV string module for various shading patterns which can be tedious. Recent methods include Thermography based fault detection [16], which is useful to identify faults and visualize PV panel temperature. But thermal imaging faces the challenge of device aging and is not cost effective. In [17], flash test method is used to determine the fault detection based on I-V, P-V curves of solar panel. The drawback is that flash test is time consuming, and it requires the knowledge of PV datasheet. In [18], the partial shading detection algorithm is based on the geometric pattern of the shadow, and activation of bypass diodes depending on isolation. Though this curve scanning method gives a direct indication of the number of peaks in the I-V, P-V characteristics, but it is time-consuming. Also, this requires an already inbuilt reference, I-V curve to compare the actual I-V curve to detect shading. In [2], Artificial Neural Network (ANN) is used for partial shading detection and fault analysis of panel. Due to the number of cases considered by the ANN algorithm, it gives a real-time accuracy of 83% but the method become tedious in designing ANN

algorithm under different system conditions. In [19], the PV reconfiguration under partial shading is not proved under practical situations. Even though drawback in shading is avoided by dispersing a shadow range of cells, it cannot be assured and is design specific. Qi et al [20] have provided a partial shading detection mechanism only in the left side of IV curve that is irrelevant under real-time PV setup. The power variation is considered as the parameter for shading detection which tries only to fit the curve and not very effective in detection.

A summary of different partial shading detection algorithms is presented in Table 1. This paper proposes a modified power loss method, which is tested both in simulation and in two real-time test beds. The proposed detection mechanism is accurate, as it directly taps the power loss from the solar panel, which is primarily due to the presence of blocking diodes. As a result, in this work the threshold value for detecting partial shading has been omitted. The paper is organized as follows: The power loss in different combinations of PV modules is presented in section 2. The proposed shading detection algorithm is presented in section 3 and the details of the experimental setup are provided in section 4. The simulation and the experimental results are provided in section 5 and the conclusions are given in section 6.

2. Illustration of power loss in different combinations of PV modules under partial shading condition:

2.1 Four series connected solar PV modules

To analyze the effects of partial shading on solar PV modules, four 300W solar PV modules are modelled using a single diode equation and are simulated under uniform irradiance and partial shading condition. Initially all 4 modules are subjected to uniform irradiation of about $1000 \frac{W}{m^2}$ and then two modules are shaded with irradiation reduced to $500 \frac{W}{m^2}$ as shown in Figure 1.

The electrical P-V and I-V characteristics are displayed in Figures 2(a) and 2(b). In these figures, three regions are mentioned as follows: Power (P_{EGMPP}), Voltage (V_{EGMPP}) and Current (I_{EGMPP}) in Expected Global Maxima region, Power (P_{GMPP}), Voltage (V_{GMPP}) and Current (I_{GMPP}) in Global Maxima region, Power (P_{LMPP}), Voltage (V_{LMPP}) and Current (I_{LMPP}) in Local maxima region. It is seen that between uniform and partial

Table 1. Review of Different Shading Detection Algorithms

ALGORITHM	THRESHOLD	REAL-TIME	ACCURACY	LIMITATIONS
CURVE SCANNING [18]	Yes	No	Works for specific I-V,P-V curves	Time consuming, prior knowledge of I- V,P-V curves
THERMAL IMAGING [16]	No	Yes	Works for two shading patterns	Cost
VOLTAGE MISMATCH SCHEME [8]	Yes	Yes	Works for selected cases	Requirement of voltage sensor for all cells
DIRECT DUTY CYCLE METHOD [9]	Yes	No	Works for select I-V,P-V curves	Predicted duty cycle, Approximations and empirical threshold set
ANN BASED [2]	Yes	Yes	Works for uniform irradiation, continuous and rapidly changing shadowing patterns	Cost and training samples, complexity of the system
IRRADIATION VARIATION [12]	Yes	No	Works for select I-V,P-Curves	Empirical thresholds set
L-ARRAY METHOD [11]	Yes	Yes	Specific to geographic location and temperature conditions	Empirical thresholds set.
NORMALISED DEVIATIONSCHEME [4]	Yes	No	Works for select curves	No theoretical basisfor threshold values
STATE OF SHADING [10]	Yes	No	Works for limited number of shading patterns	Prior knowledge of shading pattern

Fig. 1. Schematic diagram of series connected solar PV module

shading conditions, the power extracted from the solar PV panel undergoes the maximum change. At uniform irradiation of about $1000 \frac{W}{m^2}$, it is seen that the general MPPT algorithm, identifies the MPP and it is about 1200 W. Under partial shading conditions, due to non-generation of some cells, the entire power extracted from the solar PV setup drops to a maximum of 600 W. This is visible from the difference in power generated at Local Maxima (LM) and Expected Global Maxima (EGM) as shown in Figure 2a. This shows that the effect of partial shading is not limited to the shaded cell alone, but rather expands its effect through the entire series connected module. This affects the efficiency of power generation as whole rather than just individual cells. The I-V characteristics under such conditions are plotted in Figure 2b. It is seen that there is a difference between the generated current at uniform irradiation condition and that of partial shading. Once a module is partially shaded, it is understood that the conventional algorithms get stuck at the local maxima point. It is seen that, generated currents at local and expected global maxima are different, although the voltage being the same. This is due to the fact, that once a solar module is shaded in series connection, power output is less than the expected power during uniform irradiation condition.

2.2 Two series and Two parallel connected solar PV modules

In this case, the arrangement of the solar PV modules is as shown in Figure 3. Under uniform and partial shading conditions, the electrical characteristics of the system are

(a) PV Curves

(b) IV Curves

Fig. 2 Power Voltage (PV) curves and Current Voltage (IV) curves for four 300 W series connected modules under uniform and partial shading conditions

studied. The P-V characteristics of the solar PV system of series and parallel connection are shown in Figure 4. It is seen that under shading conditions, the shaded module's characteristics dominate the operation of the solar PV array. This is reflected in the solar PV array's voltage, which is closer to open circuit voltage of operation and the drawn current which is that generated by the shaded module. In other words, the effect of shading is spread rather than concentrated over the specified shaded region.

Fig. 3. Schematic diagram of series and parallel connected PV system

This leads to the fact that at uniform stable irradiation of $1000 \frac{W}{m^2}$, the generated power from the PV array remains 1200W whilst that obtained during shading conditions is only about 600W at $500 \frac{W}{m^2}$. The region of operation of the PV array is in and around the LM region, resulting in huge power difference when compared with Expected Global Maxima region of operation.

The conclusions that can be drawn from the case studies are the following:

- 1) The effect of partial shading, due to the presence of bypass and blocking diodes affects power generation of the series and parallel connected module as a whole and is not centralized to only the shaded portion.
- 2) In a series connected module, the effect of shading ensures that the generated current is forced to a minimum value by a virtue of series connection of shaded cell to the unshaded ones. Thus, affecting the power generated from the solar

Fig. 4. P-V characteristics of series-parallel connected PV modules

PV module. Therefore, the operating point of the module is near to the Local Maxima, (LM) region than the Global Maxima, (GM) region. This is far from the Expected Global Maxima, (EGM) region and hence there is a huge power difference as shown in Figure 2(a).

- 3) In a parallel connected solar PV module using conventional MPPT algorithm, the effect of shading ensures that the voltage of the module, stays closer to the open circuit voltage of the setup, and hence forcing the current generated to be less. There is no occurrence of multiple maxima due to the operation of the blocking diodes, therefore there is no need to specify an actual GM region. Both LM and GM regions can be used interchangeably. In view of the context, the name LM region has been chosen. Thus, the operating point of the solar PV module remains at the LM region rather than the EGM region. Thus, the generated power is still very low in comparison to the expected power at Expected Global Maximum Power Point, (EGMPP) as shown in Figure 4.
- 4) It is clear from the above three conclusions, that in a given series/parallel connected setup, all measurable electrical parameters, solar current, voltage and power, undergo changes when there is a transition from uniform irradiation to partial shading condition. But there is a prominent difference in the electrical power drawn from the solar panel. Current and voltage parameters are not overlooked by doing so, but the changes in them are visible in a magnified manner when the power term is considered. Thereby, there is a need to take account of the loss in power due to shading effects.

3. Proposed Modified Power Loss method based partial shading detection:

It is known that a conclusive evidence of shading occurrence is the point where the shaded cells act as load to the generating cells. Deploying bypass diodes is essential to save the shaded cells from potential hotspots and in turn damage the surface of the solar PV panel. Activation of the bypass diodes upon occurrence of partial shading is a protective measure that safeguards the shaded cells and PV panel from potential failures and serves as a clear indication of the occurrence of partial

shading depicted as flowchart in Figure 5. In this condition, it is safe to assume that zero current or rather minimal current is generated from the shaded cell. By virtue of the series combination, the actual power generated by a shaded series module drops. When a combination of series and parallel modules is chosen, it is seen that, both voltage and current are forced to a low value near the LM region as depicted in Figure 2. Upon comparison with the power to be generated under uniform irradiance conditions, it is seen that there is a huge difference. Formulating the power loss term under both series and/or parallel combinations is vital in determining the occurrence of shading, as it is directly influenced by the activation of the bypass and/or blocking diodes.

In Figure 3, it is depicted that two series modules are under shading condition and the rest are unshaded. Therefore, it is reasonable to assume that the unshaded modules (M1 and M2) receive an irradiance of $G1 \frac{W}{m^2}$ which is greater than the irradiance $G2 \frac{W}{m^2}$ received by the shaded modules (M3 and M4). Therefore, by the P-V characteristics of the modules and virtue of series connection, the combined voltage of the system is $V_1 + V_2$, where V_1 and V_2 are the voltages of modules M1 and M2, M3 and M4 respectively. Due to shading, it is understood that current I_2 , from modules M3 and M4 dominate, and hence the total power generated at the LM region of operation ($G2 \frac{W}{m^2}$) is $P_{act} = (V_1 + V_2)I_2$. Whereas, the expected power to be generated at the EGM region of operation at irradiance $G1 \frac{W}{m^2}$ is,

$$P_{gen} = V_1 I_1 + V_2 I_2$$

Where $V_1 = V_2 = \frac{V_{EGMPP}}{N}$ and $I_1 = I_2 = I_{EGMPP}$ under uniform irradiation conditions and, V_{EGMPP} and I_{EGMPP} are Voltage and current at Expected Global Maximum Power Point.

Therefore, the power loss is computed as,

$$\begin{aligned} P_{loss} &= P_{gen} - P_{act} \\ &= (V_1 I_1 + V_2 I_2) - (V_1 + V_2) I_2 \\ &= V_1 I_1 + V_2 I_2 - V_1 I_2 - V_2 I_2 \\ &= V_1 (I_1 - I_2) \end{aligned}$$

Considering the power loss term to be L_{array} , we see that the minimum value being 0 at EGM region and maximum being $V_1 I_1$ at LM region. The power loss of N series modules can be calculated as follows:

The power that is expected to be generated at EGM region of operation (uniform irradiance level $G1 \frac{W}{m^2}$) is,

$$P_{gen} = V_1 I_1 + V_2 I_2 + \dots + V_N I_N$$

Assuming that module 2 is shaded, it is seen that actual power generated is

$$P_{act} = (V_1 + V_2 + \dots + V_N) I_2$$

Fig. 5. Process flow in the occurrence of partial shading in solar PV panel

The power loss calculated from the solar PV array, at LM region of operation is,

$$P_{loss} = P_{gen} - P_{act}$$

$$P_{loss} = V_1 I_1 + V_2 I_2 + \dots + V_N I_N - V_1 I_2 - V_2 I_2 - \dots - V_N I_2$$

$$P_{loss} = V_1 (I_1 - I_2) + V_3 (I_3 - I_2) + \dots + V_N (I_N - I_2)$$

Analyzing the power difference term, in the LM region of operation during occurrence of partial shading the power loss is greater than the actual power generated which can be calculated as:

$$\begin{aligned}
 P_{loss} - P_{act} &= V_1 (I_1 - I_2) + V_3 (I_3 - I_2) + \dots + V_N (I_N - I_2) - \\
 &\quad [(V_1 + V_2 + \dots + V_N) I_2] \\
 &= V_1 I_1 - V_1 I_2 + V_3 I_3 - V_3 I_2 + \dots + V_N I_N - V_N I_2 - V_1 I_2 - \\
 &\quad V_2 I_2 - \dots - V_N I_2 \\
 &= [V_1 I_1 + V_3 I_3 + \dots + V_N I_N] - [V_1 I_2 + V_2 I_2 + \dots + V_N I_2] > 0
 \end{aligned}$$

The obtained difference is definitely greater than 0 because all expected currents in the EGM region of operation will definitely be greater than the generated current I_2 at LM region of operation. Hence, it is proved that L_{array} or P_{loss} is greater than P_{act} under partial shading conditions. The same can be extended to series and parallel combination of solar PV modules.

Let us assume a stand-alone solar PV setup, having N series modules and M such series modules in parallel. Whilst operating in the EGM region, the expected power to be generated by the setup is given as:

$$P_{gen} = V_1 I_1 + V_2 I_2 + \dots + V_M I_M = M (VI),$$

where, VI depicts the power generated by one module

$$\begin{aligned}
 \text{At EGMPP, } V_1 = V_2 = \dots = V_M = V_{EGMPP} \text{ and} \\
 I_1 = I_2 = \dots = I_M = \frac{I_{EGMPP}}{M}
 \end{aligned}$$

Assuming that row number 2 is shaded, either fully or partly,

initially through operation of conventional MPPT algorithm, the operating point is in the LM region of the P-V curve closer to the system's open circuit voltage. Thereby, it is observed that the shaded row, dominates the system's operating characteristics under shading conditions. This forces the generated power and voltage to be low and almost same as the power and voltage of row 2, (P_2 and V_2). Therefore, the generated power from the PV module at the LM region of operation is

$$P_{act} = V_2 (I_1 + I_2 + \dots + I_M) = M (V_2 I_2)$$

The generated power loss at the LM region of operation during shading condition is given as:

$$P_{loss} = P_{gen} - P_{act}$$

$$P_{loss} = M(VI) - M(V_2 I_2)$$

$$P_{loss} = M(VI - V_2 I_2)$$

Comparing power loss and actual power generated, we get,

$$P_{loss} - P_{act} = M(VI - V_2 I_2) - M(V_2 I_2)$$

$$= M(VI - 2V_2 I_2)$$

The difference in power loss and actual power can be of positive, negative or 0 values. Under the cases of negative or zero values, which means that, the power generated from each of the series row has to be in their respective EGM region of operation, as only in such a case, the electrical parameters are not altered much which occurs during irradiance changing conditions. Even though load variation may exist, the difference would be such that, the operation region is not altered. Under partial shading conditions, the solution is positive which leads to the case where the operating points of the series connected modules is in the LM region. Hence, the equation that $P_{loss} > P_{act}$ proves to be an accurate indicator for the detection of shading occurrence. The designed case studies and the obtained interferences therein do not limit the applicability of the power loss theorem method. Constraints like different patterns of shading, combinations of series parallel modelling can be introduced to check its validity. Although, the case studies introduced help in understanding the effects of partial shading and the resulting consequences.

The measured solar PV current and voltage are used to compute the expected power to be obtained at EGM region of operation at that specified irradiation level. This is known as expected power.

$$\text{Expected power from panel} = P_m \left(\frac{G}{G_0} \right)$$

Where P_m is the Rated Panel power at 1000 W/m², G is the average value of monthly irradiation and G_0 is 1000 W/m². The generated power at the current irradiation level, which may lead to either EGM region or LM region of operation is given by:

$$\text{Generated power from panel} = V_{pv} * I_{pv}$$

Where, V_{pv} and I_{pv} are the voltage and current at the PV panel. Power loss is then calculated as Expected power – Generated power, and if it is greater than the generated power, then the system is under shading condition else it is not shaded.

$$P_m \left(\frac{G}{G_0} \right) - V_{pv} * I_{pv} > V_{pv} * I_{pv}$$

The proposed method has an advantage that, it does not depend on any empirical constant. In addition, the proposed power loss method is accurate even with average value of monthly irradiation which makes the algorithm very effective even in the absence of irradiation sensor. This gives the method an added advantage as it is cost effective and accurate even under different seasonal and weather conditions. The power loss method will remain accurate under different temperature conditions as well, as it only plays on the observed intrinsic electrical characteristics of the panel, rather than any external disturbances.

5. Results and Discussion:

The experimental setup for PV testbed is developed using National Instruments hardware and their interfacing software LabVIEW as shown in Figures 6. The PV real-time hardware setup is designed and tested under different conditions for the solar panel in the research lab of SRM Institute of Science and Technology, kattankulathur. The algorithm has been implemented in a real-time PV test bed as shown in Figure 6 for panel rating of 60W (2 series of 30W modules). The partial shading detection algorithm is embedded in a real-time operating system NI-cRIO 9081. The system has a very high processing speed in the order of 1.33GHz making it very accurate for measurement and control of solar panel parameters. The measurement system consists of two Virtual Benches (VB-8012) for measurement of current from the 60W solar panel and boost converter output voltage, and, generation of reference voltage for PWM generation and NI Elvis II+ for measuring panel voltage and a buck-boost converter of 60W (30V, 2A) was used for boosting the panel voltage. Boosted voltage is applied to an electrical load of 120Ω, 2.8A.

Fig. 6. Real time PV testbed setup at SRM Institute of Science and Technology

5.1. Pattern 1: Emulating total shading of solar module, due to cloud cover.

The power vs time for the real-time PV test bed with the shading detection algorithm is shown in Figure 7 for the shading pattern 1. This shading pattern is used to replicate completely shaded conditions due to cloud cover directly above the solar module. In this case, the monthly average irradiance level is found to be 500 W/m². Under stable irradiation of 500 W/m², the PV module provides an output of 16.02 W. There is a small variation in power output due to small changes in natural irradiation. This does not affect the

partial shading detection algorithm, which continues to detect no occurrence of partial shading. During shading pattern 1, where most of the module is shaded as in Figure 7, the generated power drops to about 3W.

Fig. 7. Power Versus Time under shading pattern 1

5.2 Pattern 2: Emulating partial shading of solar module, due to cloud cover and shadow of buildings

The shading detection algorithm is then tested under high, stable irradiation conditions for the shading pattern 2 as shown in Figure 8. This pattern is chosen to replicate the shading pattern produced by some tall objects like buildings. This condition is also used for validation of the proposed algorithm because one cannot expect pattern 1 of shading to always occur. Under normal irradiation conditions of 500 W/m², the generated power from the solar PV module is about 16W and the algorithm does not detect the occurrence of partial shading condition. Once pattern 2 of artificial shading is applied, the system generated power drops to 6.5W. As the string power loss is greater than the generated power, the proposed method detects the occurrence of partial shading condition accurately.

Fig. 8. Power Versus Time under shading pattern 2

The algorithm is validated for a run time of 2 hours (from 2 PM- 4 PM). It is subjected to constant, dynamic and irregular irradiance conditions as shown in Figure 9. The experimental dataset for the figure 9 is given in table 2. The algorithm accurately predicts the partial shading under actual shading conditions and does not produce erratic results under natural irradiation reduction. The current approximation method produces erratic results in this condition and often does not discriminate between actual shading and natural irradiation

variation. The power loss method also fails in this case, due to the presence of a threshold value which is summarized in Table 3.

Table 2. Experimental dataset of the proposed method.

S. No.	Irradiance levels (W/m ²)	Shading Detection	Normal / irradiation
1	575	Yes	Normal
2	583	No	Irradiation
3	600	Yes	Normal
4	623	Yes	Normal
5	876	No	Irradiation
6	656	No	Irradiation
7	344	Yes	Normal
8	987	No	Irradiation
9	786	Yes	Normal
10	776	Yes	Normal
11	976	Yes	Normal
12	455	Yes	Normal
13	608	Yes	Normal
14	989	No	Irradiation
15	587	Yes	Normal
16	347	Yes	Normal
17	786	No	Irradiation
18	876	No	Irradiation
19	654	No	Irradiation
20	433	Yes	Normal

Fig.9. Partial shading condition detection under actual shading and natural irradiation reduction

Table 3. Comparison of Proposed method with existing detection methods

Comparison Parameter	Current Approximation Method	Power Loss Method	Proposed Power Loss Method
Accuracy (%)	35.9	37.9	97.1342383
Standard deviation	0.46249	0.4858	0.17058
Detection during irradiation reduction	Erroneous	Erroneous	No
Detection during natural shading condition	Erroneous	Erroneous	Yes
Detection time	<0.1s	>1 min	<0.1s
Threshold value	0.00512	$L_{array} > 100$ W	Not Essential

The Boolean graph depicting the performance of the proposed algorithm is shown in Figure 10. In this figure, logic 1 depicts shading detected, and logic 0 depicts no detection conditions. The proposed algorithm is checked continuously for two hours and it accurately predicts the actual partial shading condition.

Fig.10. Boolean graph depicting the performance of proposed algorithm for pattern 2.

5.5 Statistical analysis of Experimental Data:

As a measure of accuracy of the mathematical model developed for shading detection a statistical analysis was conducted using the ANOVA and F-Tests where, the experimental data was compared for variance and ANOVA value to prove the dependence of shading on L_{array} and the independence of shading on P_{pv} . These tests are conducted to study the correlation between the variables in play, in order to strengthen the validation of the power loss theorem. Null hypothesis assumes the three samples namely P_{pv} , L_{array} and shading belong to the same population. Firstly, one way ANOVA was conducted to find the significance of the three

samples. It can be noted from the Table 4 that f (96.77) is greater than $F_{critical}$ (3.049). Since $f > F_{critical}$, null hypothesis is rejected, and it can be concluded that at least one of the three samples have significantly different means and thus belong to an entirely different population. To obtain further information on which sample is out of population, F-Test is conducted. It can be noted that $F_{critical}$ is greater than f ($F_{critical} < f$) when shading and L_{array} are taken as samples. Hence, null hypothesis is accepted, and it can be concluded that L_{array} and shading are dependent on each other. Furthermore, it implies that P_{pv} and shading are not dependent which implies that proposed algorithm is accurate in detecting partial shading condition. Therefore, the power loss theorem clearly points out that, only power loss matters in any given condition of shading, and not just power generated from the solar panel. This is the guiding key point for the algorithm, which enables its success.

Table 4 Statistical analysis of Experimental Data

ANOVA: Single Factor						
Groups	Count	Sum	Average	Variance		
Shading	58	27	0.4655	0.2532		
Ppv	58	3912.728	67.4608	1505.446		
Larray	58	3085.595	53.1999	733.500		
ANOVA Output Parameters						
Source of Variation	Sum of Squares	df	Mean Square	F	P-value	Fcrit
Between Groups	144471.5	2	72235.73	96.7789	7.76517 x 10 ⁻²⁹	3.0488
Within Groups	127634.4	171	746.4	--	--	--
Total	272105.8	173	--	--	--	--

6. Conclusion and Future work:

This paper proposes a modified power loss method for detecting the occurrence of partial shading. The proposed detection mechanism is accurate, as it directly taps the power loss from the solar panel, which is primarily due to the presence of blocking diodes. A threshold value, to detect partial shading is, therefore, eliminated in this work. The proposed algorithm detects that measured power from the panel and provides a detection accuracy of 97% under stable as well as dynamic irradiation conditions. The proposed partial shading detection algorithm is found to be more efficient in detecting partial shading under both uniform irradiance and dynamic irradiance conditions, without producing any erratic results in case of natural irradiation reduction. The proposed detection algorithm is compared with existing algorithms and promising results are produced. The modified power loss method is also validated theoretically, and experimental results are obtained in two different real-time testbeds which further emphasis the accuracy

of the method in partial shading detection in solar panels. The algorithm can also be employed for fault analysis on the panel, to determine the exact causes of partial shading. The detection algorithm can be extended to find fill factor in fault detection, different shading patterns and reasons for the loss in power.

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