A Novel MPPT Scheme for an Unequally Irradiated Solar Photovoltaic Panels Feeding a Common Load Using Sliding Mode Controller

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\textbf{ABSTRACT:} In this work the maximum power point tracking of solar photovoltaic panels that are operating in the same area for a common load but subjected to an unequal solar insolation levels. It is proposed that a separate DC to DC converter is used for each of the panels. Sliding mode controller is adopted for the MPPT. The MATLAB SIMULINK simulation and the experimental verification validates that the proposed idea harvests more power than the common optimised duty cycle that is used in a single power converter.

\textbf{METHODS:} In the existing scheme where a number of panel are operating in parallel a common DC to DC converter is used. For the purpose of MPPT and optimisation technique is used to arrive at the duty cycle to be adopted in the common DC to DC converter. Such a method guarantees the overall maximum possible power output for that particular method using a single DC to DC converter with a single duty cycle. It does not guarantee the maximisation of the power output of the individual solar PV panels which is the actual maximum power harvestable for the given environmental condition. In the proposed technique, applicable to solar trees where a number of panels are physically arranged in different angles so as to harvest maximum power all through the day, it is more effective to use individual dc to dc converters with individual duty cycles. In this work the sliding mode control based on the PV terminal voltage is adopted.

\textbf{RESULTS:} The proposed idea is simple, no rigorous mathematical implications, requires less number of sensors, and requires no explicitly PWM circuits. It can be used readily in real life applications.

\textbf{KEYWORDS:} Solar photovoltaic tree, MPPT, unequal irradiation, buck-boost converters, sliding mode controller, battery.

1. INTRODUCTION

The Renewable energy system has drawn the attention of energy engineers throughout the world. Many schemes of renewable energy systems are being developed. Among the various renewable energy sources in the forefront, the wind energy and the SPV energy are prominent. Particularly, the SPV power harvesting scheme has many advantages compared to the wind power system. The SPV energy systems in spite of the advantages, there are some disadvantages as well, like the requirement of a large space, initial cost etc. The operational disadvantages of the SPV schemes are that the solar power available is unpredictable and is quite unreliable, although at an average the solar power scheme can deliver viable power. Besides the capacity of the solar PV panels, exhibit degraded power capacity with regard to falling solar insolation. The power output capability of the SPV panels reduces with reduced insolation and increased temperature. In order that the available power at any given solar insolation and temperature may be harvested the load connected to the SPV has to be adjusted automatically. This technique is known as the Maximum Power Point Tracking (MPPT). Many different MPPT techniques have been developed with each method having its own merits and demerits and thus applicable for specific applications and operational constraints.

When Ann SPV panel is subjected to an uniform solar insolation, the voltage power characteristic exhibit unique maximum power point that can be reached by any of the conventional MPPT algorithms like the Perturb and Observe or the Incremental Conductance algorithm. However, if the solar panel is partially shaded then there exist multiple peaks with different maximum power level with one among them being the highest power point. The conventional MPPT techniques do not guarantee to reach this globally best maximum power point rather they may be held up at the locally best maximum power points. For reaching the maximum power point when there are many peaks, soft computing techniques had been suggested by some researchers. Heuristic search algorithms had also been promoted as a solution for the partially shaded conditions. In [1] the authors have used the Particle Swarm Optimisation technique as a solution methodology to track the MPP in the partially shaded conditions. In [2] the authors have compared...
various MPPT techniques for the solar Photovoltaic power harvesting. The authors in [3] have developed a variable step size Incremental Conductance algorithm and have drastically reduced the convergence steps and also have achieved closed MPPT with minimal error. A maximum power operation of PV System Using Fuzzy Logic Control has been carried out by the authors in [4, 5] but the authors have not discussed the case of unequal irradiance case when there are a number of panels operating for a common load. Fuzzy logic based MPPT has been demonstrated by the authors in [6, 7] as well. They have also compared the performance of Fuzzy Logic based MPPT with the performance of the P and O algorithm of MPPT. Some authors [8, 9] have shown interest in the development of MPPT algorithm using the advanced hybrid soft computing technique namely ANFIS. ANFIS demands more software facilities that cannot be implemented in domestic or distributed solar photovoltaic power harvesting systems. An incremental conductance maximum power point tracking algorithm suitable for high perturbation rates has been developed by the authors in [10]. Optimization techniques have been used by [10] and the authors have come out with a Hybrid Algorithm for Tracking of GMPP Based on P&O and the method proved to reduce power oscillations at the Global Maximum Power Point (MPP). The authors in [11] have developed a Second order Sliding Mode Control to attain MPPT for stand lone PV system. Even in this case, the authors have not focused the idea on multiple panel single load system with unequal solar irradiance. A double integral sliding mode controller has been developed and demonstrated by the authors in [12]. The proposed system is mathematically much complicated and it is difficult to be implemented with simple embedded implementations as may be required by small PV power stations. Further in [9] the authors have demonstrated how the fuzzy logic controller can be used as a technique for harvesting maximum power output from the PV panel. In [13] the authors have adopted a novel MPPT technique using the neuro fuzzy techniques which again involves much mathematical overheads and needs either a high speed digital processor or a dedicated computer for that purpose. The authors in [13] have used the fuzzy logic technique for the grid integration of the solar panel with the grid using the line commutated inverter. The classical PI controller besides being a mathematical overhead also cannot be appropriately designed easily as it exhibits a behaviour that depends mainly on the Kp and Ki values. Depending upon the tuning technique of the PI controller, the sliding mode controller that is the best suitable for MPPT and solar PV applications, has the advantage of requiring less mathematical overheads, does not require integrators or differentiators in real hardware and since it is easy to be implemented it can be said that the sliding controller even in large numbers may be deployed where a number of panels are to use and that they might be subjected to an unequal solar insolation.

However, in this work, a novel sliding mode control scheme is proposed. The proposed work has been developed for the solar photo voltaic tree in which a number of PV panels are mounted on a common tree-like structure with a number of branches and in each branch, there may be a single or more number of panels. Fig. (1) shows such Solar Panel Tree.

The idea of the solar tree is that since the solar irradiation falling in the location of solar power harvesting is a function of the relative position of the sun with respect to the location of harvesting. Various SPV panels are mounted on the solar tree in such a manner that some of the panels face direct sunlight while some other panels may not. Thus, it is a case of a number of panels operating in parallel but not subjected to the same solar insolation. Under such conditions it is not possible to use the traditional technique of connecting them all in series parallel combination and terminating the end terminals at the input of a DC to DC converter. In the traditional method, a common optimisation technique may be used to arrive at the duty cycle of the power electronic switch that is used in the DC to DC converter. In this case what can be achieved is that an arbitrary maximum power can be harvested but that is not the sum of the maximum possible power output of each of the panels for the prevailing solar irradiation condition. Thus, the traditional method does not ensure that each panel is delivering its maximum power output. However, if a number of DC to DC converters are used each with its own MPPT control scheme then the number of sensors as well as the number of power electronic switches, inductors and the diodes will be of large number. This leads to poor reliability as well as the order of the system gets increased and it becomes difficult to model the whole system and also the associated control systems become complicated. In order to save energy [15], in this work, a trade off is done and the number of inductors and diodes each restricted to one. It is the number of switches which becomes equal to the number of panels. For each panel, only the terminal voltage is measured with the series connected power electronic switch in the off state and then in the on state. Thus for each panel only one sensor is used. The output of each of the solar panel is routed to the battery through a common diode. The battery being the sink and is held at constant terminal voltage, each of the solar PV panel drives a current that is proportional to the power harvested by the panel. The total power harvested is the sum of the individual maximum of each of the solar PV panel.
It is demonstrated in this paper how the proposed idea can be used to charge the battery at nearly constant voltage but with variable current that matches with the instantaneous maximum power point. Next to this, brief introduction a review into the characteristics of the PV panel under partially shaded conditions is discussed in chapter II. A review of the DC to DC buck boost converter is given in Chapter III. The theory behind the proposed technique, which is the sliding mode control is discussed in Chapter IV. The Sliding Mode Controller design proposed in [16, 17] is also considered for designing the SMC in this work. The MATLAB simulation details and the details of the hardware description are given in Chapter V. In this work the five parameter modelling as proposed by the authors in [18] and analytical modeling in [19] have been considered for the simulations of the solar PV panel in the MATLAB SIMULINK environment.

The results of both simulation and hardware are discussed in Chapter VI followed by the conclusion and references sections.

2. CHARACTERISTICS OF THE SOLAR PHOTO VOLTAIC PANELS

The Solar Photo Voltaic panels are formed by the series and the parallel connection of the solar photo voltaic cells. A basic solar cell which is the building block of the solar photo voltaic panels, is of low terminal voltage in the order of 0.4 V to 0.5 V and it can supply a current in the order of a few amperes which actually depend upon the cross sectional size of the PV cell. When the solar cell is left open and not connected to any electrical load it produces an open circuit voltage and this voltage falls as the PV cell is connected across an electrical load. Depending upon the cross sectional area of each of the cell the current sourcing capacity changes and typically a solar panel is rated as 10, 50, 100 and 200 W. The solar panel name plate carries the information regarding the open circuit voltage, the short circuit current, the maximum power point voltage and the maximum power point current and all these considered for the standard test condition which is 1000 Watt/m², AM 1.5 and 25°C. Fig. (2) gives the single diode model of the photo cell. The series resistance Rs and parallel resistances Rp represents the non-idealities. The basic current equation is given in Equation (1).

\[
I = I_{ph} - I_0 \left[ \exp \frac{qV}{AKT} - 1 \right]
\]

where,

- \( I_{ph} \) - Current generated by the incident light
- \( T \) - Temperature of the PN junction
- \( A \) - Diode ideality factor
- \( I_0 \) - Leakage current of the diode

q - Electron charge \((1.6021 \times 10^{-19} \text{ C})\)

k - Boltzmann constant \((1.38 \times 10^{-23} \text{ J/K})\)

Eqn (1) gives the relationship between the various currents, two equivalent resistances and other constants related to the semiconductor-based solar photovoltaic cell.

The solar PV cell is basically a current source. Electric current gets initiated by the liberation of electron hole pairs when the semi conductor junction is bombarded with the photons of the sun light that falls on the semiconductor junction. The photo current liberated from the PN junction is denoted as \( I_{ph} \) and a part of this current flows through the internal diode and another part of the remaining current flows through the shunt resistance equivalence formed by the recombination of the electron hole pairs.

The ohmic end connections and some other semiconductor factors defined by semiconductor theory as a whole are represented by a series resistance Rs. When the terminals of the Solar Photo Voltaic cell are connected through a resistor or is short-circuited then a voltage drop occurs along the series resistor Rs which influences the output voltage that appears across the load resistor. The characteristics of the solar photo voltaic panel can be observed by conducting experiments on the panel or by modelling the panel in MATLAB. The characteristics obtained from a MATLAB SIMULINK simulation relating to the PV Voltage, Current and Power delivered by the PV panel are given in Figs. (3 and 4).
Fig. (5). The PV current and power for step variation of solar irradiances plotted against continuously varied PV terminal voltages obtained from MATLAB Simulation.

The characteristics as shown in Fig. (3, 4 and 5) have been obtained for the condition that the panel has been uniformly subjected to solar irradiation such that all the solar cells contained in the panel receive the same solar irradiation. There is a unique maximum power point and for the unique combination of voltage and current the PV panel delivers maximum power for the given solar irradiance.

The characteristics as shown in Fig. (10) have been obtained for the condition that the two different panels have been subjected to different solar irradiation such that both the solar panels do not receive the same solar irradiation but different irradiations.

When the solar irradiation falling on one panel is from the other the characteristics differ from the uniform insolation case and will be typically as shown in Fig. (10). The characteristics exhibit multiple peaks with each peak offering a different power and corresponding current levels. Even though there are many peaks with different levels one among them is the globally tall peak and the maximum power point to be reached and maintained.

The conventional MPPT tracking algorithms depend upon the change of direction of power level and based on this direction change they identify the peak point. In the case of multiple peaks, which typically occur with partial shading the peak point reached depends upon the starting point and the algorithm will settle down at the first peak it encounters irrespective of whether or not there is an another peak nor the height of the unnoticed peaks.

The problem at hand is therefore, that the operating point is to be correctly identified as that peak point that is the best operating point in terms of the maximum possible power harvest.

3. THE BUCK BOOST CONVERTER

The buck boost converter is a generic DC to DC converter and its topology is shown in Fig. (6). The main components of the converter are the power electronic switch that comes in series with the DC power source, the boost inductor and the current routing diode. Since the power electronic switch comes in series with the DC source the converter can be shut down by turning off the Power electronic switch.

![Fig. (6). The buck boost converter.](image)

The polarity of the output DC voltage is reversed with respect to the polarity of the input DC source. The voltage gain of the buck boost converter is given as

\[ V_{out} = -V_{in} \times \frac{D}{1-D} \]  

(2)

where \( V_{in} \) is the source voltage and \( D \) is the duty cycle. The negative sign indicates the reversal of polarity of the output voltage with respect to the polarity of the source side DC voltage. The value of the inductor used in this application is 500 Micro Henry. The load is a battery of nominal voltage with 150 AH capacity. In this application, a set of two buck boost converters are used in parallel across each of the solar PV panels and they share a common load. The schematic representation is shown in Fig. (7).

![Fig. (7). The circuit arrangement used to harvest the maximum power from the two PV panels to charge a common battery.](image)

4. SLIDING MODE CONTROLLER

The sliding mode controller works on the basic principle that when a solar PV panel is operated at the maximum power point, there exits across the terminals of the PV panel a certain voltage and a certain current flows through the PV panel. The maximum power transfer occurs only when this unique combination of this specific voltage is maintained across the PV panel and the specific current flows through the PV Panel.

For example with reference to the basic specifications of the PV panel as given in chapter 4, for a solar insolation of
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1000 Watt/m² and temperature of 25°C the maximum power is derived when the panel voltage is maintained at 17.2 V and the load current is 4.95 A. The open circuit voltage for the given environmental condition is 22.2 V. For a solar Photovoltaic Panel the ratio between the $V_{p_{max}}$ and $V_{oc}$ is constant and is typically $17.2/22.2 = 0.7747$.

When the solar panel is connected through a power electronic converter, like the DC to DC buck boost converter, as used in this application, when the power electronic switch is turned on the PV panel supplies power and current flows through the panel causing a voltage fall across the terminals of the PV panel. Eventually, the terminal voltage across the PV panel falls below the critical voltage $V_{p_{max}}$.

As it happens the power electronic switch is opened and the PV current becomes zero, suddenly rising the terminal voltage across the PV panel to the $V_{oc}$ level and the power electronic switch is again turned on.

The algorithm of the sliding mode controller is as follows.

1. Keep the Power Electronic Switch S in the off state.
2. Measure the Open circuit voltage. ($V_{oc}$).
3. Turn on S.
4. Wait until the PV terminal voltage just falls below 0.7747*$V_{oc}$.
5. Turn Off the switch S.
6. Goto step 1

The same algorithm is followed for each of the solar PV panel and the associated power electronic switch. The MATLAB implementation of the sliding mode controller is shown in Fig. (8). The sliding mode controller just uses only one sensor that measures the terminal voltage of the PV panel. If there are N panels then N voltage sensors are required. The sliding mode controller does not use any explicit carrier.

**5. RESULTS AND DISCUSSIONS**

The proposed scheme uses a novel technique that ensures maximum power harvest from each of the solar panels when a number of solar PV panels operating in parallel are subjected to different solar insolation levels. In this work, two solar panels have been used and each of the panels is rated as follows.

Open circuit voltage $V_{oc} = 22.2$ V; Short circuit current $I_{sc} = 5.45$ A; Voltage at $P_{max} = 17.2$ Current at $P_{max} = 4.95$ A

These ratings are specified by the manufacturers for standard test condition that stipulates the solar irradiation at 1000 W/m² and ambient temperature 25°C. The maximum power output rating of the panel is 85W. With the two panels subjected to the same insolation of 900 watts/m² the total maximum power output as found from the characteristics will be 153 watts. The voltage versus Power curve is shown in Fig. (9). These values and the characteristics have been obtained from the solar panel model. However, the output of the sliding mode controlled system after power being passed on through the buck boost converter that reaches the battery, is calculated to be 12.5V * 11.5A = 143.75W.

**Fig. (9).** The power Vs voltage when the two panels are subjected to the same insolation of 900 W/m².

For an insolation of 600 W/m² for the first panel and 400W/m² for the second panel the characteristics was observed to be 71.67 W and the characteristics are given in Fig. (10).

**Fig. (10).** The power Vs voltage when the two panels are subjected to different insolation levels of 600 W/m² and 400 W/m².

However, in the circuit model with the buck boost converter scheme with the proposed MPPT technique, the power output of each of the panels was observed to be 47 W and 29 W respectively as against the values obtained directly
from the PV panel models respectively as 51.2 W and 33.3 W.

Different combinations of solar insolation were setup and the output of the individual panels from the mathematical model of the panels and the corresponding output of the circuit model comprising of the buck boost converter and the sliding model controllers in action have been observed and recorded and are presented in Table 1.

The observations to get the maximum power from the mathematical model has been carried out by a model shown in Fig. (10). The relevant data including the PV power Output, the Voltage across the PV panel and the current flowing through the panel have been collected at the workspace by using the send to workspace blocks used for these variables. The following segment of MATLAB commands was used to get the maximum power and the corresponding values of voltage and current.

```matlab
>> [value ind] = max (P)  
value = 74.2226  
ind = 8869  
>> volt = V(8869)  
volt = 16.7394  
>> Current = I(8869)  
Current = 4.4340
```

![Fig. (11). The MATLAB SIMULINK mathematical model for the observation of the behaviour of two PV panels subjected to different solar irradiances.](image1)

![Fig. (12). The location and the placement of the two PV panels at two different angles.](image2)

However, the results of the circuit model including the maximum power the corresponding PV voltage and PV current have been obtained by using the relevant measurements blocks as shown in Fig. (11). A full rating experimental verification setup was constructed with power rating similar to the power rating used in the simulation studies. Two solar PV panels of rating 85 Ww were placed with different angles of incidence of solar irradiance as shown in Fig. (12). The circuit arrangement of the hardware setup is shown in Fig. (13).

![Fig. (13). Hardware setup.](image3)

### Table 1. Observations.

<table>
<thead>
<tr>
<th>Solar Insolation (W/m²)</th>
<th>Results from Mathematical Model</th>
<th>Results from Circuit Model</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Vpv (V)</td>
<td>Ipv (A)</td>
</tr>
<tr>
<td>Panel 1</td>
<td>Panel 2</td>
<td></td>
</tr>
<tr>
<td>400</td>
<td>600</td>
<td>36.67</td>
</tr>
<tr>
<td>700</td>
<td>300</td>
<td>16.92</td>
</tr>
<tr>
<td>300</td>
<td>900</td>
<td>16.74</td>
</tr>
</tbody>
</table>
Table 2. Observations.

<table>
<thead>
<tr>
<th>Solar Insolation (W/m²)</th>
<th>Results from Circuit Model</th>
<th>Results of Experimental Verification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Panel 1</td>
<td>Panel 2</td>
<td>Vpv (V)</td>
</tr>
<tr>
<td>235</td>
<td>470</td>
<td>36.82</td>
</tr>
<tr>
<td>337</td>
<td>560</td>
<td>35.82</td>
</tr>
<tr>
<td>684</td>
<td>785</td>
<td>35.56</td>
</tr>
</tbody>
</table>

For the periodic observations made every half an hour the solar insolation levels were randomly distributed and had been as shown in the Table 2.

When the two panels are subjected to different solar irradiance the switching rate depends on the insolation falling on each of the two panels and they are typically as shown in Fig. (13). The solar insolation on panel 1 is more than that on panel 2 and hence the difference in the duty cycle of the two switching pulses.

The change in the total battery charging current as shown in Fig. (15) when there is a change in the insolation levels from (235, 470) to (337, 560) W/m² conditions was observed to be from 0.98A to 1.6A and it has been recorded in the DSO as shown in Fig. (14).

For the appreciation of the proposed system, a comparison has been made by substituting the observed real time solar insolation in the mathematical models of the solar panel and the expected results from the MATLAB model has also been found. An overall comparison is presented in Table 2.

CONCLUSION

A novel sliding mode control for a set of two solar PV panels has been developed with minimal components while harvesting the maximum of each of the panels. As compared to the heuristic search algorithm based MPPT schemes, the proposed scheme can harvest more power for the given solar insolation pattern encountered by the two panels. The MATLAB SIMULINK based simulation and the experimental verification validate the proposed idea.

CONSENT FOR PUBLICATION

Not applicable.

CONFLICT OF INTEREST

The authors declare no conflict of interest, financial or otherwise.

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REFERENCES


