REALIZATION OF DC-BUS SENSOR-LESS MPPT TECHNIQUE FOR A SINGLE-STAGE PV GRID-CONNECTED INVERTER

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ABSTRACT
A single-stage photovoltaic (PV) grid connected system is an attractive approach for a distributed energy source due to its simple topology and low cost. However, maximum power point tracking (MPPT) algorithms require measurements on the DC side of the inverter in order to determine the operating point of the PV panel at each instant. This paper presents a sensor-less MPPT algorithm for a single-stage PV grid connected inverter where the MPPT algorithm determines whether the reference inverter operating point is below or beyond the maximum power point (MPP) at different light intensities based upon the current controller action. The proposed algorithm monitors the controller action after each perturbation, if the reference power is beyond the maximum power, the controller would saturate and thus the MPP is at the previous reference power. Changes in insolation are accompanied by changes in the current controller action, which is detected by the algorithm. The overall system has been experimentally implemented and control algorithm has been validated using digital signal processing (DSP) unit. Using simulation and practical implementation results, the performance of the proposed MPPT algorithm is evaluated while limits and merits of the proposed setup have been demonstrated.

INTRODUCTION
The use of PV technology as a stand-alone energy source for grid-connected applications is an attractive approach due to its advantages of being adequately maintenance free and pollution free. The MPPT control technique plays an important role in this application since the system is required to extract maximum available power from the PV panel. Several topologies for grid-connected PV systems have been discussed in literature [1] involving single stage (DC/AC) and two stage (DC/DC/AC) converters. A challenging design target is to minimize the number of power electronic devices used by minimizing the number of power converting stages while maintaining a minimum number of sensing devices to ensure a low cost and less complex system. Typical sensor-less MPPT algorithms discussed in [2-4], involve two stage converters with MPPT controller implemented on the DC/DC converter side by measuring only the DC bus voltage or converter output current while the DC/AC converter controller measures the inverter output current and grid side voltage for the current controller. Single stage converters discussed in [5] involve MPPT control algorithms based on DC bus voltage and PV panel current measurements while grid voltage and current are measured for current controller. In [6], PV panel voltage, grid current and grid voltage are measured for a single stage grid connected converter operating in continuous conduction mode for the configuration. It should be noticed that these MPPT algorithms require at least one sensing element on the DC side of the converter. Measurements on the DC side of the converter require filtering in order to determine the average DC component of the measured variable which eventually requires more processing. In this paper, a current controlled, single-stage, single phase grid connected H-bridge inverter topology is utilized. A sensor-less MPPT algorithm is proposed and implemented based on perturbing the inverter reference output power and observing the inverter current controller action in order to achieve MPP operation.

DERIVATION OF THE PROPOSED TECHNIQUE
A. Single Stage Configuration Response
The proposed setup shown in Fig.1 consists of a typical single-stage PV grid connected inverter controlled via sinusoidal pulse width modulation (SPWM) technique. The \( P_{\text{ref}} \) is the reference output power, \( m_a \) is the amplitude modulation ratio of the SPWM, \( SW_1 \) and \( SW_2 \) are the inverter switches signal. Electrical signals: \( V_s \) and \( I_s \) as the grid voltage and current respectively, \( V_{dc} \) and \( I_{dc} \) are the PV panel voltage and current respectively, \( V_i \) is the inverter output voltage. Passive circuit components \( C_{dc}, R_{dc}, L_1 \) are the dc link capacitor, filter inductor resistance and inductance respectively. Fig.2 depicts the typical simulated response of the proposed setup for nine incremental values of \( P_{\text{ref}} \), while Fig.3 illustrates the relation between PV panel and inverter characteristics for different operating regions. In Fig.4, at operating point 1 and 1', \( V_{dc} \) at that instant is less than the open circuit voltage of the PV panel and \( m_a \) is increased to \( m_a' \). It should be noticed that \( V_{dc} \) should always be greater than \( V_i \) since an inverter operates in buck mode.

Fig.1. Proposed setup for sensor-less PV grid-connected MPPT system
Assuming sinusoidal \( I_c \) and \( V_{dc} \), the relationship between \( V_i \) and \( V_{dc} \) is given by (1) and (2).

\[
|V_i| = m_a V_{dc}
\]  
\[|V_i| = \sqrt{(R_s|I_c| + |V_{dc}|)^2 + (L_{dc}|I_c|)^2}
\]

As \( P_{ref} \) increases to operating point 2 and 2', \( V_{dc} \) further decreases while \( V_i \) increases thus according to Equation (1), \( m_a \) would increase to \( m_{am} \). This can also be observed in Fig.2 in Region (3-4). In Fig.3, when the \( P_{ref} \) is equal to the MPP at operating point 3 and 3', \( m_a \) indicates the maximum amplitude modulation ratio \((m_{am})\) to operate the panel at the MPP. If \( P_{ref} \) is beyond MPP, \( V_{dc} \) would collapse as shown in Fig.2 in Region(6-9) and Fig.3. At this point, to achieve \( P_{ref} \), a greater \( V_i \) is required which the PV panel is incapable of supplying. Thus it can be seen in Fig.2 that \( m_a \) increases beyond the linear region and saturates at the maximum value of linearity set by the controller. If a SPWM technique is used, \( m_{am} \) for linear operation would be 1.

![Fig.2. Typical response of the proposed system with incremental \( P_{ref} \)](image)

\[ \text{PV Power & Reference Power} \]
\[ \text{PV Voltage} \]
\[ \text{PV Current} \]
\[ \text{Amplitude Modulation Ratio} \]
\[ \text{Saturation} \]

![Fig.3. Inverter with filter and PV panel characteristics at different operating points](image)

**B. Effect of Change in Insolation**

Changes in insolation would directly affect \( V_{dc} \) as shown in Fig.4. For a step increase in insolation in Region B\( \rightarrow \)A, \( V_{dc} \) is increased and the controller would reduce \( m_a \) in order to maintain the same \( V_i \), for the set \( P_{ref} \) as shown in Fig.5 (a). Whereas when insolation decreases there are two possible operation cases shown in Fig.4. If the current operating point (A) is less than the MPP at the lower insolation (B'), then \( m_a \) is expected to increase since the available \( V_{dc} \) has decreased as shown in Fig.5(b). Whereas if the current operating point (C) is greater than the MPP at the lower insolation (B'), the controller would eventually saturate, since \( V_{dc} \) is collapsing as shown in Fig.5(c).

![Fig.4. Effect of change in insolation on PV characteristics](image)

![Fig.5. Change in \( P_{dc} \), \( V_{dc} \), \( I_c \), and \( m_a \) (from top to down) referring to cases in Fig.4 for change in insolation (a) Point B to A (b) Point A to B and (c) Point C to D](image)

It can be concluded from the previous analysis that \( m_a \) can be taken as an indicator for the PV operating region. This observation is utilized in the development of the proposed MPPT technique.

**PROPOSED CONTROL ALGORITHM**

**A. Configuration**

In the proposed setup shown in Fig.1, \( P_{ref} \) is perturbed based on the feedback information of \( m_a \). The response of \( m_a \) is analyzed based on the MPPT algorithm and \( P_{ref} \) is then varied accordingly to always get the maximum available power from the PV panel.
B. Algorithm

The proposed MPPT algorithm given as a flowchart in fig.6 explains the method of decision making of increment/decrement to $P_{ref}$ based on the feedback $m_a$. The algorithm is based upon the following three processes:

Tracking process, as the $P_{ref}$ is incremented, on regular basis, and $m_a$ is observed. In the tracking process, the algorithm does not perform an increment to $P_{ref}$ unless $m_a$ is settled within a tolerance band. This is essential to avoid multiple increments during a slow transient state of the current controller yielding $P_{ref}$ far beyond the MPP. In case $m_a$ is settled and below $m_{amax}$, $P_{ref}$ is stored as the maximum power ($P_{MPP}$) and then $P_{ref}$ is perturbed while $m_a$ is observed in the next sampling interval. The process stops when $m_a$ increases beyond the permissible $m_{amax}$ which indicates a voltage collapse.

Recharging process, as the algorithm shifts to this process when $P_{ref}$ is greater than the maximum available power point which is detected when $m_a$ increases beyond $m_{amax}$. In order to move to the previous operating point, the DC link capacitor is required to be recharged since the current operating point voltage is below the MPP voltage. $P_{ref}$ is reduced in order to recharge the DC link capacitor until $m_a$ is below $m_{amax}$. At this state the MPP has been detected which is the last stored power increment ($P_{MPP}$) before the voltage collapsed. When the DC link capacitor has been recharged, $P_{ref}$ is set to $P_{MPP}$ and the algorithm shifts to the observation process while operating at the MPP.

Observation process, as in the final observation process the algorithm constantly checks $m_a$ for changes which indicates a change in insolation. If $m_a$ suddenly increases to $m_{amax}$, this would indicate a decrease in insolation and $P_{ref}$ is beyond the MPP. The corrective action taken is to reduce $P_{ref}$ to zero and starting the tracking process again. Whereas, when operating at the MPP and $m_a$ decreases, this would indicate an increase in insolation which indicates that the MPP is beyond the current operating point. The corrective action would be to continue to the tracking process again.

C. Controller

The controller action is required to have a minimum overshoot in order to avoid $m_a$ increasing beyond $m_{amax}$ during the tracking process. The proposed controller shown in fig.7 illustrates the implemented controller structure. The integrator eliminates the error caused by the variable $V_{dc}$ due to the non-linear $V$-$I$ characteristics of the PV.

D. Parameters

The algorithm includes three parameters that are required to be adjusted; the settlement range, algorithm sampling rate and reduction range.

E. Working Area

Fig.8 illustrates the inverter current controller action due
to an increase in insolation together with the associated variation of modulation index \( m_a \). The MPPT algorithm is required to detect the change in amplitude modulation ratio \( \Delta m_a \) in order to recognize that a new maximum power is available. A small change in insolation would lead to a decreased \( \Delta m_a \) and vice versa. \( \Delta m_a \) is described in (4) where \( V_{inv}(G_{n-1}) \) represents the inverter voltage to obtain the maximum output power at low insolation \( G_{n-1} \) while \( V_{pv}(G_{n-1}) \) is the PV voltage at that insolation. As insolation increases from \( G_{n-1} \) to \( G_n \), the PV voltage at which the same output power is required increases to \( V_{pv}(G_n) \). Using PV characteristics at different insolations and temperatures combined with the inverter characteristics a relationship can be established between change in insolation \( \Delta G \) and \( \Delta m_a \) at several temperatures \( T \), as:

\[
\Delta m_a = \frac{V_{inv}(G_{n-1}) - V_{inv}(G_{n-1})}{V_{pv}(G_{n-1}) - V_{pv}(G_n)} (4)
\]

It should be noted that the permissible working area of the proposed set is located under the intersection between the inverter and PV characteristics as given in figure 8.

**SIMULATION RESULTS**

The proposed algorithm has been simulated on a system with the specifications given in Table I. The inverter voltage was calculated using Equation (2) for the entire operating range and checked to satisfy the PV output voltage throughout different insolations, and the L-filter has been adopted based on the method introduced by the authors in [7].

**Table I: System Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( V_g )</td>
<td>220</td>
</tr>
<tr>
<td>Number of series PV modules</td>
<td>20</td>
</tr>
<tr>
<td>PV array total maximum power</td>
<td>800W</td>
</tr>
<tr>
<td>( L_I )</td>
<td>80mH</td>
</tr>
<tr>
<td>( C_{dc} )</td>
<td>10mF</td>
</tr>
<tr>
<td>( m_{amax} )</td>
<td>0.98</td>
</tr>
<tr>
<td>Settlement Range</td>
<td>±0.002</td>
</tr>
<tr>
<td>( \Delta m_a )</td>
<td>0.005</td>
</tr>
<tr>
<td>Algorithm Sampling Rate</td>
<td>0.1 sec</td>
</tr>
</tbody>
</table>

**A. The Proposed Sensor-less Configuration**

In Fig.9, the simulation is presented where the algorithm was executed and tracking process is active from 3 to 22 seconds with noticeable increase in \( m_a \) as shown in Fig.10. The algorithm switches to recharging process during 22 to 26 secs due to increase of \( m_a \) beyond the limits while DC link capacitor recharges as shown in Fig.10. After \( m_a \) settlement the algorithm sets \( P_{ref} \) to the previous maximum operating point (MPP(1)) and maintains the current operating point as illustrated in Fig.9 at 26 to 40secs during the Observation process. After 40 secs, the insolation is increased to maximum, the algorithm returns back to the tracking process repeating the entire sequence up to the observation process again (MPP(2)). After 75 secs, the insolation is decreased to half the maximum. The voltage collapses and \( m_a \) increases beyond \( m_{amax} \). The algorithm shifts to zero output power and waits for \( m_a \) to settle while the DC link capacitor recharges. The tracking process restarts again in order to achieve (MPP(1)). In Fig.11 it is seen that \( I_g \) is constant at each MPP with no perturbation.
B. Configuration with Sensors
The classical method for MPPT, using perturb and observe algorithm with both voltage and current measurements on the DC side, has been also simulated for comparison. The simulation results in Fig.12 show that the response of the configuration with sensors due to insolation changes and MPPT is much faster than the proposed technique. This is due to the fact that the sensor-less algorithm requires a low sampling rate in order to detect changes in $m_c$. Meanwhile, the sensor-less algorithm current oscillations are minimal; since when the system yields maximum power, the algorithm halts until changes occur. Whereas, the sensor-less technique in Fig.13 keeps on perturbing the system to determine changes in the maximum power which yields grid side current oscillations.

![Image](image1.png)

**Fig.12. Simulation results of the classical perturb and observe algorithm with sensors during insolation changes**

![Image](image2.png)

**Fig.13. Simulation result for $I_g$ with sensors for MPPT**

EXPERIMENTAL RESULTS
The proposed configuration has been implemented based on Table 1 parameters scaled down by 20. A Texas Instruments TMS320F28335 32-bit microcontroller was used as a controller and a FAIRCHILD Smart Power Module FSBB15CH60C as the inverter. The output grid current waveform shown in Fig.14 was recorded on a digital oscilloscope and then redrawn. Fig.14 consists of 8 operation regions. In Region (2) the algorithm was executed and started the tracking process. In Region (3), the algorithm shifts to recharging process and then to observation process where the algorithm moves directly to the previous output power noted by (MPP(2)). At $T=40$ sec, partial shading was applied to imitate the effect of decrease in solar insolation. Region (4) shows the reduction in the output power up to the maximum output power at (MPP(1)) to the observation process in Region(5). At $T=55$ sec, partial shading was removed and the tracking process is continued in Region (6). Region (7) represents operation at the MPP during the observation process at MPP(2). Finally in Region (8) the controller was switched off.

![Image](image3.png)

**Fig.14. Experimental results of the output grid current using the proposed technique (without any DC bus sensor) during variation of the PV available MPP**

CONCLUSION
A new sensor-less PV MPPT algorithm was developed and evaluated for a single-stage grid connected inverter. The proposal has been simulated and experimentally tested where the obtained results showed the effectiveness of the set to nearly track the maximum available PV power without using any sensors in DC side. The main limiting disadvantage is the slow response of the system comparing with same set using sensors. This slow response could be accepted for PV tracking application particularly as it also has the advantage of providing lower ripple grid current.

REFERENCES