A New Digital Double Integral Sliding Mode Maximum Power Point Tracker for Photovoltaic Power Generation Application

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Abstract—This paper proposed a new digital double integral sliding mode controller based MPPT (DDISMC-MPPT) for tracking the maximum power point (MPP) of a photovoltaic (PV) panel. In this DDISMC-MPPT, a new double integral sliding surface has been chosen and with PWM mechanism its operation is enhanced with fixed switching frequency. The DDISMC-MPPT controller is designed considering the reaching and stability conditions. It is found that the proposed controller inherent robustness and is stable. Comparing with two available DDISMC-MPPTs such as Tan’s [6] and Jiao’s [7] DDISMCs, this proposed DDISMC-MPPT performs better MPP tracking with less chattering. It is also confirmed that the settling time and chattering yielded in the proposed controller are less compared to that of Tan’s and Jiao’s DDISMC-MPPTs.

Index Terms—PV system, MPPT, SMC, Proposed DISMC-MPPT, Tan’s DISMC-MPPT, Jiao’s DISMC-MPPT.

I. INTRODUCTION

PV systems need to be operated at their MPPs to achieve higher efficiency of energy conversion. To track the MPP, a maximum power point tracker (MPPT) is to be placed between the PV panel and load. Maximum power point tracking is an important aspect in a PV system because at MPP, a PV panel operates most efficiently as it delivers the maximum power.

A number of MPPT techniques are reported in literature [1-3]. Among them, perturb and observe (P&O) and incremental conductance (IC) techniques are straightforward, accurate and easy to apply, hence commonly used. But, both these techniques do not perform well in rapidly changing environmental conditions [4]. SMC is suitable for MPP tracking of a PV system in rapidly changing environmental conditions [5] because SMC possesses inherent robustness, stability. In addition to that, it has high degree of flexibility in design choices and also easy to implement using DSP, microcontroller, FPGA, etc. But, conventional HM based SMC has two major drawbacks, such as the variable operating frequency of SMC and presence of high frequency chattering. To tackle the variable operating frequency problem, a PWM based indirect sliding mode controller and for the high frequency chattering problem, an integral term has been added to the sliding surface. This controller with an integral term is called integral sliding mode controller (ISMC) [6]. To further improve the response, another integral term can be supplemented which is usually referred to as a double integral sliding mode controller (DISMC) [7]. On introducing the double integral of error term in sliding surface of DISMC exhibits fast dynamic responses for a wide range of operating conditions. It also inherent the robustness and stability features of SMC. There exist a number of DISMC with different sliding surfaces [8-10]. Out of which Tan’s [7] and Jiao’s [10] are distinctly applied in output voltage regulation of converters.

Performance of a DISMC design greatly depends on selection of an appropriate sliding surface because accuracy and response time of the controlled system is dependent on the sliding surface. In this paper, DISMC with a new double integral sliding surface has been designed and applied for MPP tracking of a PV system.

II. PROBLEM FORMULATION

Fig.1 describes a simple topology of a stand-alone PV system. It consists of a PV panel, a DC/DC converter, a load and a control circuit to control the switching operation of DC/DC converter. The control circuit has a DDISMC-MPPT so that the power output from PV panel is always the maximum.

Fig.1 A stand-alone PV system topology with DDISMC-MPPT

Fig. 2 Equivalent circuit model of a PV panel

The equivalent circuit of PV panel is shown in Fig.2. In the circuit, the expression for PV panel output current ($i_{pv}$) can be represented as follows.
\[ i_{pv} = I_{pv} - I_o \left[ \exp \left( \frac{v_{pv} + i_{pv} R_{se}}{N_s V_t} \right) - 1 \right] - \frac{v_{pv} + i_{pv} R_{se}}{R_{sh}} \]  

where \( v_{pv} \) is the output voltage of the PV panel. \( I_{pv}, I_o, V_t, N_s, R_{se}, \) and \( R_{sh} \) are photo-generated current, dark-saturation current, thermal voltage, number of series cells in PV panel, series resistance and shunt resistance respectively. The nonlinear model of a DC/DC boost converter system is given by

\[
\begin{align*}
\dot{i}_L & = \frac{v_{pv} - v_o}{L} + \frac{v_o - v_{pv}}{L} u \\
v_{pv} & = \frac{1}{C_1 r_{pv}} v_{pv} - \frac{1}{C_1} i_L + \frac{1}{C_1} i_r u \\
y & = v_{pv} 
\end{align*}
\]

where \( i_L, v_{pv}, v_o \) and \( r_{pv} \) are the inductor current, PV panel voltage, load voltage and dynamic resistance of PV panel respectively. \( C_1 \) and \( L \) are the input capacitor and inductor of the DC/DC boost converter respectively. Since, \( v_o \) is dependent on \( v_{pv} \) and \( i_L \), hence eq (2) can be written as

\[
\dot{X} = f(X) + g(X) u
\]

where,

\[
X = \begin{bmatrix} i_L \\ v_{pv} \end{bmatrix} \quad f(X) = \begin{bmatrix} \frac{v_{pv} - v_o}{L} + \frac{v_o - v_{pv}}{L} - \frac{1}{C_1} i_L \\ -\frac{v_o}{L} + \frac{i_L}{C_1} \end{bmatrix} \\
g(X) = \begin{bmatrix} \frac{1}{C_1 r_{pv}} v_{pv} \\ \frac{1}{C_1} \end{bmatrix}
\]

III. DESIGN OF THE PROPOSED DISMC-MPPT

For a DC/DC converter, the switching function \( u \) is the duty-ratio and \( 0 \leq u \leq 1 \). The proposed DISMC-MPPT has the PWM-based switching function \( u \) such that it has only two logic-states 0. Referring to Fig.2, this switching function adopts the following switching law.

\[
u = \frac{1}{2} \left[ 1 + \text{sgn}(S) \right]
\]

where \( S \) is the proposed sliding surface and defined as

\[
S = a_1 e_1 + a_2 e_2 + a_3 e_3 + a_4 e_4
\]

The terms \( a_1, a_2, a_3, a_4 \) denote the sliding coefficients and the \( e_1, e_2, e_3, e_4 \) are various error signals and are defined as follows.

Differentiating the above state variables leads to

\[
\begin{align*}
\dot{e}_1 & = \frac{d}{dt} \left[ i_{ref} - i_L \right] = -\frac{\beta K_1}{a_1} i_L - v_{pv} + v_o + \frac{v_o - v_{pv}}{L} u \\
\dot{e}_2 & = \frac{d}{dt} \left[ V_{ref} - \beta v_{pv} \right] = -\frac{\beta}{C_1} i_L \\
\dot{e}_3 & = V_{ref} - \beta v_{pv} \\
\dot{e}_4 & = \int [V_{ref} - \beta v_{pv}] dt
\end{align*}
\]

Taking derivative of \( S \) gives

\[
\dot{S} = a_1 \dot{e}_1 + a_2 \dot{e}_2 + a_3 \dot{e}_3 + a_4 \dot{e}_4
\]

Applying eq (9) in eq (10), \( u_{eq} \) is obtained as follows.

\[
u_{eq} = 1 - K_1 \left( \frac{i_{ref}}{v_o} - \frac{v_{pv}}{v_o} + K_2 \frac{e_2}{v_o} + K_3 \frac{e_3}{v_o} \right)
\]

where

\[
K_1 = \frac{\beta L}{a_1} \left( \frac{a_1 K + a_2}{C_1} \right)
\]

Here, \( K_1, K_2 \) and \( K_3 \) are selected empirically such that existence and stability conditions should be satisfied. The structure of this DDISM-MPPT is shown in Fig.3. In this figure, \( G_s \) is a factor multiplied with \( V_{ref} \) to make it of chip-level for ease in hard-ware implementation of the proposed controller. To further simplify the controller implementation, it is assumed that \( G_s = \beta \). The basic idea behind the proposed DDISM-MPPT is that the voltage \( (v_{c1}) \) across the capacitor \( C_1 \) is made equal to \( v_{pv} \) and current \( (i_c) \) across \( C_1 \) is reduced to zero so that the total panel output current \( (i_{pv}) \) flows through the inductor \( L \). Thus, we have
A. Reaching Condition

We need to ensure that the state trajectory of the system should be directed always towards the sliding surface from any initial state. For this, from reaching conditions we have

\[ S\dot{S} < 0 \]  

(14)

Referring to eq (14), if \( S > 0 \), then \( \dot{S} < 0 \) and vice-versa. Further, referring eqs (7-11), in a boost converter the following conditions are valid. When,

\[ S > 0, \dot{S} < 0 \Rightarrow u = 0 \]

\[ K_i i_c + v_{pr} + K_3 e_2 + K_3 e_3 < 0 \]  

(15)

and when

\[ S < 0, \dot{S} > 0 \Rightarrow u = 1 \]

\[ K_i i_c + v_{pr} + K_3 e_2 + K_3 e_3 > 0 \]  

(16)

At steady state eqs (15-16) are modified as follows.

\[ K_i i_{c_{\text{max}}} + K_3 e_{2_{\text{max}}} + K_3 e_{3_{\text{max}}} > v_{pr_{\text{max}}} \]  

(17)

\[ K_i i_{c_{\text{min}}} + K_3 e_{2_{\text{min}}} + K_3 e_{3_{\text{min}}} > v_{pr_{\text{min}}} \]  

(18)

\[ v_{pr_{\text{min}}}, v_{pr_{\text{max}}}, i_{c_{\text{min}}}, i_{c_{\text{max}}}, v_{c_{\text{max}}}, \text{are minimum and maximum PV panel voltages respectively, } i_{c_{\text{min}}}, \text{ are minimum and maximum inductor currents respectively.} \]

B. Stability Condition

To ensure that the state trajectory remains in the sliding surface, we need to verify the stability condition of the PV system with the proposed controller. This controller has both the current and voltage state variables. Hence, the sliding motion equation cannot be solved analytically. The stability condition can be obtained analytically if the sliding motion equation is represented linearly. This is possible by first by rewriting the combined state equations of the PV system and boost converter in Laplace form as follows.

\[ s^2 I_z (s) + \frac{1}{L} \left[ K_1 I_z (s) I_z (s) - K_2 E_z (s) \right] s \]

\[ - K_3 E_z (s) = 0 \]  

(19)

and

\[ s v_{pr} (s) + \frac{1}{C_{pr}} v_{pr} (s) - \frac{I_z (s)}{C_i} v_{pr} (s) + K_1 I_z (s) I_z (s) - K_2 I_z (s) E_z (s) \]

\[ - K_3 E_z (s) = 0 \]  

(20)

Applying Routh-Hurwitz stability criterion to eq (19), we have

\[
\begin{array}{ccc}
S^2 & I_L (s) & - K_3 E_2 (s) \\
S + \frac{1}{L} \left[ K_1 I_z (s) I_z (s) - K_2 E_z (s) \right] & 0 \\
S^0 & K_3 E_2 (s) & 0
\end{array}
\]  

(21)

Similarly, applying Routh-Hurwitz stability criterion to eq (20), we have

\[
\begin{array}{ccc}
S^2 & V_{pr} (s) & - K_3 E_2 (s) \\
S + \frac{1}{C_{pr}} v_{pr} (s) - \frac{I_z (s)}{C_i} v_{pr} (s) + K_1 I_z (s) I_z (s) - K_2 I_z (s) E_z (s) & 0 \\
S^0 & K_3 E_2 (s) & 0
\end{array}
\]  

(22)

Referring to eqs (21-22), the following condition must be satisfied for achieving stability of the PV system with the proposed controller.
The above three conditions such as existence, reaching and stability conditions should be satisfied to ensure the close-loop stability of the PV system. $K_1$, $K_2$ and $K_3$ are selected such that eqs (15-16) and eq (23) are valid.

IV. Results and Discussions

The performance of the proposed DDISMC-MPPT was verified on a SSI-M6-205 PV system [11]. I-V and P-V characteristics of the panel are shown in Fig.4.

![Fig.4](image)

(a) P-V Characteristics, (b) I-V Characteristics of SSI-M6-205 solar panel at different solar radiations

The tracking performance of the proposed controller was evaluated and tested using MATLAB/SIMULINK. In this paper, the PV panel voltage at MPP is taken as $V_{ref}$ of the controller and is calculated online for every change in solar irradiance or temperature using the MPPT algorithm proposed by [12]. The values of $V_{ref}$ for different solar irradiance or temperature are listed in Table-I. For efficient tracking of the $V_{ref}$ of the studied PV panel, the parameters of the values of different components are shown in Table-II. In this table, the values of the components of the given DC/DC boost converter i.e.; inductor ($L$) and capacitors ($C_1$ and $C_2$) are constant. Taking these values of $L$, $C_1$ and $C_2$, the parameters $K_1$, $K_2$, and $K_3$ are empirically chosen such that eqs (15-16 and 23) are satisfied.

<table>
<thead>
<tr>
<th>$G$ (watts/m²)</th>
<th>$V_{ref}$ (volts)</th>
</tr>
</thead>
<tbody>
<tr>
<td>250</td>
<td>25.99</td>
</tr>
<tr>
<td>500</td>
<td>27</td>
</tr>
<tr>
<td>750</td>
<td>27.59</td>
</tr>
<tr>
<td>1000</td>
<td>28.04</td>
</tr>
</tbody>
</table>

Table I. Values of $V_{ref}$ of the studied PV Panel calculated at different solar radiations

<table>
<thead>
<tr>
<th>DDISM C Components</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load</td>
<td>100 Ω</td>
</tr>
<tr>
<td>$L$</td>
<td>18 mH</td>
</tr>
<tr>
<td>$C_1$</td>
<td>850 μF</td>
</tr>
<tr>
<td>$C_2$</td>
<td>525 μF</td>
</tr>
<tr>
<td>Switching frequency ($f_s$)</td>
<td>40KHz</td>
</tr>
<tr>
<td>$K_1$</td>
<td>5</td>
</tr>
<tr>
<td>$K_2$</td>
<td>10</td>
</tr>
<tr>
<td>$K_3$</td>
<td>0.001</td>
</tr>
<tr>
<td>$\beta$</td>
<td>0.8</td>
</tr>
<tr>
<td>$v_{pv}$</td>
<td>0-36 volts</td>
</tr>
<tr>
<td>$r_{pv}$</td>
<td>2-14 Ω</td>
</tr>
</tbody>
</table>

Table II. Values of Comparison of the proposed DDISMC with Tan’s DISMC and Jiao’s DDISMC-MPPT

To test the $V_{ref}$ tracking mechanism of the proposed DDISMC, the MATLAB/SIMULINK model of the SSI-M6-205 PV panel as shown in Fig.5 has been developed. The proposed DDISM C-MPPT (Fig.3) is applied in this circuit. The tracking response is shown in Fig.6 (a). It needs only one current sensor for measurement of $i_C$ as Jiao’s DDISMC-MPPT. Their tracking responses have been compared in Fig.6 (a).
Fig. 5  Block diagram of PV system with Double Integral Sliding Mode Current Controller with two current sensors based MPPT

Fig. 6  Comparison of (a) Chattering, (b) Settling time of MPP tracking response for Proposed DDISMC-MPPT, Jiao’s DDISMC-MPPT and Tan’s DDISMC-MPPT at different solar irradiances
Fig. 6 (b) shows a comparison between settling times of the PV panel output voltage signals. From the set figures shown in Fig 6 (b), it is clear that, the proposed DDISMC-MPPT with single current sensor has faster response than that of Tan’s DDISMC-MPPT. This is because during the start-up, the sliding surface of the DISMC with single current sensor is crossing the origin and the system representing point is very close to origin. Hence, the reaching time is less. Also, the steady state error for the proposed controller is less than that of Tan’s DDISMC-MPPT and almost same with Tan’s DDISMC-MPPT. Therefore in this controller the magnitude of steady state error of the output voltage is less. Hence, the proposed DDISMC-MPPT has fast response without affecting its accuracy. Performances of two existing DISMCs together with the proposed DDISMC-MPPT have been provided in Table III.

Table III. Comparison of the proposed DDISMC-MPPT with Tan’s DDISMC-MPPT and Jiao’s DDISMC-MPPT

<table>
<thead>
<tr>
<th>Controller Properties</th>
<th>Tan’s DDISMC-MPPT</th>
<th>Jiao’s DDISMC-MPPT</th>
<th>Proposed DDISMC-MPPT</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of Current sensors</td>
<td>Two</td>
<td>One</td>
<td>One</td>
</tr>
<tr>
<td>Complexity</td>
<td>More</td>
<td>Less</td>
<td>Less</td>
</tr>
<tr>
<td>Control Variables</td>
<td>( V_{pv}, V_{o}, i_L ) &amp; ( i_C )</td>
<td>( V_{pv}, V_{o}, i_C )</td>
<td>( V_{pv}, V_{o} ) &amp; ( i_C )</td>
</tr>
<tr>
<td>Expensive</td>
<td>More</td>
<td>Less</td>
<td>Less</td>
</tr>
<tr>
<td>Reaching time</td>
<td>22 msecs</td>
<td>&lt; 5 msecs</td>
<td>8 msecs</td>
</tr>
<tr>
<td>Chattering</td>
<td>Less</td>
<td>More</td>
<td>Less</td>
</tr>
</tbody>
</table>

IV. CONCLUSIONS

This paper proposed a DDISMC-MPPT with a new double integral sliding surface for tracking MPPs of a PV system. This DDISMC-MPPT possesses a very simple and efficient PWM-based control structure. The PWM mechanism of this DDISMC-MPPT adds advantages such as simple control structure and fixed frequency operation. Further, the selection of the sliding mode control coefficients taking account the reaching and stability conditions facilitates with fast response and guaranteed stability. The efficacy of the proposed DDISMC-MPPT was verified comparing with two existing DDISMC-MPPTs such as Tan’s and Jiao’s DDISMC-MPPTs. It is found that with less number of components and control variables compared to Tan’s DDISMC-MPPT, the proposed DDISMC-MPPT’s reaching time is less than that of Tan’s DDISMC-MPPT. Similarly, the proposed DDISMC-MPPT has less chattering compared to the Jiao’s DDISMC-MPPT. Hence, the proposed DISMC-MPPT is found to be an efficient MPP tracker for PV system.

REFERENCES