The study for MPPT of photovoltaic system based on terminal sliding mode control method

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Abstract. Aiming at the problem of the Maximum Power Point Tracking (MPPT) of PV system, based on the requirements of improving the tracking speed and reduce the steady-state oscillation, a terminal sliding mode control method is proposed to complete MPPT control in this paper. Mathematical model of the PV module is realized by four parameters with standard condition. Unlike traditional methods, it is proposed that the tracking current and power reference at the maximum power point at arbitrary conditions can be obtained directly from the established model. It is simple and can avoid the tracking error. In this paper, we tracked the outputs of the PV module under different conditions and compared the proposed method with the Incremental Conductance (INC) algorithm, the results show that the proposed control method can enhance the track speed and accuracy, decrease the steady-state oscillation and improve the efficiency of PV system.

1. Introduction
Solar photovoltaic power generation directly converted solar radiation into electrical energy by applying the photovoltaic effect of the semiconductor materials. The output power is influenced by the ambient temperature and irradiance, the PV model has maximum power points under different conditions, tracking these points and putout the power at the corresponding conditions can improve the efficiency of the PV system and the utilization rate of resources. Therefore, the MPPT control technology has been a hot theoretical research of PV power generation system. In recent years, domestic and foreign scholars have already done a lot of researches, and have made plenty of achievements in this field.

Recently, the main methods of MPPT for the PV system are short circuit current method\cite{1}, fuzzy control\cite{2},\cite{3}, Incremental Conductance (INC) algorithm\cite{4}, Perturb and Observe (P&O) method\cite{5},\cite{6}, constant voltage method\cite{6}, Genetic algorithm\cite{7} and so on. Each of them has its advantages but also has some insufficiencies, difficult to balance tracking speed, convenient and accurate.

Based on the MPPT theorem, combined with above control methods, a terminal sliding mode control method \cite{8} is proposed in this paper. In this paper, the exponential reaching law is used which can guarantee that the system reaches the equilibrium point in finite time, and achieves the real time tracking. Beyond that, a comparison is made between the proposed method and the INC algorithm. The results indicate that the proposed method is feasible and effective.
2. The mathematical model of PV module

The output current of the PV module:

\[ I_{pv} = I_{sc} \left[ 1 - c_1 \exp \left( \frac{V_{pv}}{c_2 V_{oc}} \right) - 1 \right] \]  

The output power of the PV module:

\[ P_{pv} = V_{pv} I_{pv} \left[ 1 - c_1 \exp \left( \frac{V_{pv}}{c_2 V_{oc}} \right) - 1 \right] \]

In above expressions,

\[ c_1 = (1 - \frac{I_m}{I_{sc}}) \exp \left( \frac{V_m}{c_2 V_{oc}} \right), \quad c_2 = (\frac{V_m}{V_{oc}} - 1)[\ln(1 - \frac{I_m}{I_{sc}})]^{-1} \]

\( I_{sc} \) and \( V_{oc} \) are the short circuit current and open circuit voltage at the standard condition respectively; \( V_{pv} \) is the output voltage of the PV model.

According to \( I_{sc} \), \( V_{oc} \), \( I_m \), \( V_m \) under the standard condition, calculate \( I_{sc} \), \( V_{oc} \), \( I_m \), \( V_m \) at arbitrary conditions, then we can get the electrical outputs under these conditions by fed them into the practical expressions [9],[10]. Defining the output voltage reference at the MPP to be \( V_{ref} \), current to be \( I_{ref} \), power to be \( P_{ref} \), then we can obtain:

\[
\begin{align*}
V_{ref} &= V_m \\
I_{ref} &= I_m \\
P_{ref} &= V_{ref}I_{ref}
\end{align*}
\]

This method avoided tracking the MPP under different conditions, can further improve the tracking speed and precision.

3. Designing of terminal sliding mode controller

3.1. Designing of MPPT control circuit

![Figure 1. The topology of the MPPT control circuit.](image)

Establishing the mathematical model by using the switching function, \( u=1 \) indicates that the switch is on, \( u=0 \) indicates off [11].

Thus, the mathematical model of the Boost circuit is obtained:

\[
\begin{align*}
\dot{V}_{pv} &= \frac{1}{C_1}(I_{pv} - I_L) \\
I_L &= \frac{1}{L}[V_{pv} + (u-1)V_o] \\
\dot{V}_o &= \frac{1}{C_2}(1-u)I_L - I_o
\end{align*}
\]

Written the above expression in another form: \( \dot{X} = f(X) + g(X)u \)
\[
\begin{align*}
\dot{X} &= \begin{bmatrix}
\dot{V}_{PV} \\
I_L \\
\dot{V}_o
\end{bmatrix}, \\
\dot{f}(X) &= \begin{bmatrix}
\frac{(I_{PV} - I_L)}{C_1} \\
\frac{V_{PV} - V_o}{I_L} \\
\frac{I_L - I_o}{C_2}
\end{bmatrix}, \\
g(X) &= \begin{bmatrix}
0 \\
V_o \\
I_L
\end{bmatrix}
\end{align*}
\]

3.2. Designing of terminal sliding mode control

The follow expression is obtained according to the characteristics of the PV model at MPP.

\[
\begin{align*}
V_{PV} - V_{ref} &= 0 \\
I_{PV} - I_{ref} &= 0
\end{align*}
\]

Defining the current error and get its integral:

\[
e = \int (I_{PV} - I_{ref}) dt
\]

Designing the sliding surface:

\[
S = \dot{e} + ae^p
\]

In above expression, a>0, p and q are positive numbers, p>q.
Applying the exponential reaching law:

\[
S = -WS - K \text{sgn}(S)
\]

The equivalent control is:

\[
u_{eq} = -\frac{f_2(x) + WS + K \text{sgn}(S) + a \frac{q - 1}{p} \dot{e}}{g_2(x)}
\]

3.3. Testifying the finite time convergence

Supposing the time from \(e(t_r)\neq 0\) to \(e(t_r+\tau)\)=0 to be \(\tau\), using the follow expression:

\[
\dot{e} = -ae^p
\]

Thus, we can get the time \(\tau\) from arbitrary initial condition \(e(t_r)\neq 0\) to the balanced state \(e=0\) along the sliding mode.

\[
\tau = \frac{p}{a(p-q)} [e(t_r)]^{(p-q)}_p
\]

By setting the parameters: a, p, q, the system can reach the equilibrium point in finite time \(\tau\), achieving the real time control.

3.4. Robustness analysis:

From the expression (3), obtained that:

\[
f_2 = \frac{V_{PV} - V_o}{L}, g_2 = \frac{V_o}{L}
\]

Making that:

\[
f_2 = \hat{f}_2 + \Delta f_2, g_2 = \hat{g}_2 + \Delta g_2
\]

\[
h = \hat{h}, h = \hat{h} + \Delta h
\]

In above expression, \(0<\epsilon<1\), \(\Delta f_2\), \(\Delta g_2\), and \(\Delta h\) are the uncertainties or disturbances of the PV system. \(\hat{f}_2\), \(\hat{g}_2\) and \(\hat{h}\) are the known and measurable quantities.
When has a disturbance, the equivalent control is:
\[ u_{eq}^* = \frac{\hat{f}_2 + \frac{a}{p} \hat{h} \left( \int_0^t \frac{g}{\dot{\gamma}} \right) \frac{g}{\dot{\gamma}} }{g_2} + \frac{[W + K \text{sgn}(S)]}{g_2} \]  \hspace{1cm} (14)

Then derivate the switch function, fed the above expression into it, obtained that:

\[ S = \left[ \Delta f_2 - \frac{\dot{g}_2}{g_2} (W + K \text{sgn}(S)) \right] \frac{g}{\dot{\gamma}} \left( \int_0^t \frac{g}{\dot{\gamma}} \dot{h} \right) \frac{g}{\dot{\gamma}} + b \left( \int_0^t \frac{g}{\dot{\gamma}} \right) \frac{g}{\dot{\gamma}} \]  \hspace{1cm} (15)

Using the Lyapunov function \( V = S^2/2 \), getting that:

\[ \dot{V} = SS' \]

\[ = S[\Delta f_2 - \frac{\dot{g}_2}{g_2} (W + K \text{sgn}(S))] \frac{g}{\dot{\gamma}} \left( \int_0^t \frac{g}{\dot{\gamma}} \dot{h} \right) \frac{g}{\dot{\gamma}} + b \left( \int_0^t \frac{g}{\dot{\gamma}} \right) \frac{g}{\dot{\gamma}} \]

Then get that:

\[ \dot{V} = SS' \leq S\left| \Delta f \right| + cW \left[ \left( \int_0^t \frac{g}{\dot{\gamma}} \right) \frac{g}{\dot{\gamma}} \right] + cW \left( \int_0^t \frac{g}{\dot{\gamma}} \right) \frac{g}{\dot{\gamma}} + b \left( \int_0^t \frac{g}{\dot{\gamma}} \right) \frac{g}{\dot{\gamma}} \]  \hspace{1cm} (16)

Assuming that:

\[ K^* \geq \frac{1}{c} \left| \Delta f \right| + b \left( \int_0^t \frac{g}{\dot{\gamma}} \right) \frac{g}{\dot{\gamma}} \]  \hspace{1cm} (17)

Fed the above expression into (17), obtaining that:

\[ \dot{V} = S \dot{S} \leq -cW^2 \]  \hspace{1cm} (18)

Thus, if \( K^* \) meets the expression (18), then the PV system can keep a good robustness [12].

4. The simulation results and analysis

The simulations are realized by Matlab/simulink. In standard condition, the open circuit voltage \( V_{oc} \) is 43.7V, short circuit current \( I_{sc} \) is 5.07A, output current at MPP \( I_m \) is 4.65A and output voltage at MPP \( V_m \) is 34.4V. The inductance in Boost circuit is 0.1H, capacitance \( C_1 \) is 0.00005F, \( C_2 \) is 0.0099F.

Figure 2-4 are the simulation results when the temperature \( T \) is 25°C, the initial illumination \( R \) is 1000W/m², then reduced to 800 W/m² at 2th seconds and to 600 W/m² at 3th seconds.

**Figure 2.** PV model output (a) power and Local amplification of it (b) for terminal sliding mode control.
Figure 3. PV array output (a) power and Local amplification of it (b) for (INC) algorithm.

Figure 4. PV array output current (a) for terminal sliding mode control and (b) for (INC) algorithm.

Figure 2-4 shows the P-t and I-t curves of the proposed method and the INC algorithm and the compared results between the output power and current and the reference $P_{ref}$ and $I_{ref}$. From above curves, we can know that when the temperature is constant, the control systems based on above methods can track the maximum power points according to the suddenly changed illumination. The tracking speed of the proposed method is about 0.004s, while that of the INC algorithm is about 0.03s. The steady-state oscillation of the output power of the proposed method is about 0.18%, while that of the INC algorithm is about 0.82%.

Figure 3-4 are the simulation results when the illumination $R$ is 1000 W/m2, environmental temperature $T$ is 10℃, then increased to 25℃at 2th seconds and to 70℃ at 3.5th seconds.

Figure 5. PV array output (a) power, Local amplification of it (b) for terminal sliding mode control.

We can see from Figure 5-6 that the output current increases with the increasing temperature, while the output power is opposite, which consistent with the PV characteristics. The tracking speed of the proposed method is about 0.003s, while that of the INC algorithm is about 0.05s. The steady-state oscillation of the output power of the proposed method is about 0.16%, while that of the INC algorithm is about 0.76%.
Simulating the whole day illumination, then the simulation results based the two methods are showed in Figure 7. They indicate that the proposed method and the INC algorithm all can reach the MPPs in whole day. But we can see that the steady-state oscillation of the proposed method is much smaller than the INC algorithm when these two Figures. are local amplified.

5. Conclusions
In this paper, the terminal sliding mode method is proposed for MPPT control of the PV system. The tracking results and comparisons between the proposed method and the INC algorithm show that the proposed method is feasible and effective. Compared to the INC algorithm, the proposed method can avoid the defects like high sampling requirements, complex control algorithm, sharp steady-state oscillation. However, due to the inevitable chattering of sliding mode control, there are still some fluctuations at steady-state condition, which can lead to the system can only keep operating near the maximum power point. On this basis, further study of this problem will be continued.

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