MPPT control of solar energy collecting circuit based on state estimation of solar cells

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Abstract. In order to maximize the power output efficiency of Solar cells and the solar energy collection efficiency of collecting circuit, it is needed to track the real-time status of Solar cells, and force solar cells to work at its MPPT working point by an appropriate control method. Aiming at the solar energy collecting circuit based on Boost structure DC/DC converter, a MPPT control method based on the state estimation of Solar cells (MPPT-SE) is presented. In the MPPT-SE control method, the MPPT current value of solar cells is estimated by detecting solar cells’ output status and estimating its internal equivalent state, and the actual output current of solar cells is controlled to track its MPPT current value by current closed-loop control, this can force solar cells to work near its MPPT working point and maximize the power output efficiency of Solar cells and the solar energy collection efficiency of collecting circuit. The theoretical analysis and experiment results validate that the solar energy collecting circuit based on MPPT-SE method has higher power output efficiency and solar energy collection efficiency.

1. Introduction

With the rise of clean energy, solar power generation has become a hot spot in the new energy industry [1]. In the key technologies of solar power generation, Maximum Power Point Tracking (MPPT) [2] control is one of the key issues to be solved. The power generation capacity of solar cells is affected by the environmental factors such as light intensity and so on. The precise model of solar cells is extremely complex, and the directed application of precise model in practical engineering is not convenient. When used in practice, solar cells are usually equivalent to a controlled power [3], namely a combination of controlled equivalent electromotive force and controlled equivalent internal resistance. It involves a complex control problem how to make solar cells work near its MPPT working point in real time [4]. In the proposed MPPT control methods of solar power generation system [5], there are commonly used methods such as perturb-observe (P&O)[6], increment conductance (INC)[7] and so on. The MPPT working point of solar cells is tracked in a gradual accumulation way step by step in the above methods. Although they have their own characteristics, there is a contradiction between the tracking rapidity and the steady-state tracking accuracy. The tracking error is accumulated on time dimension, and there exists “over tracking” and “under tracking” phenomenon, which causes some problems such as implement-ability and efficiency [8]. In order to overcome the shortcomings of the existing methods, many improved intelligent control methods [9-10] have been put forward by researchers, but most of them are rather complex, and not convenient for
practical application or high cost. The development of MPPT control technology with better dynamic and static characteristics and high performance-price ratio has become an unremitting pursuit for engineers and technicians. Based on the existing research results [11-12], high frequency Pulse Width Modulation (PWM) control DC/DC converter has the ability to make solar cells work near its MPPT working point, but how to achieve high performance needs to be deeply researched. Aiming at the solar energy collecting circuit based on Boost structure DC/DC converter, this paper proposes a MPPT control method based on real-time state estimation of solar cells (MPPT-SE) and according to the thought of sliding mode control. In MPPT-SE, the equivalent state of solar cells is estimated in the normal running process of collecting circuit, and the MPPT working point is determined. Then, by controlling the switch tube to turn on or turn off, the actual output current of solar cells is forced to maintain near the MPPT working point in real time, which makes the power output efficiency of solar cells and the solar energy collection efficiency of collecting circuit maximized.

2. Design and analysis of solar energy collecting circuit

2.1. Design of solar energy collecting circuit
Solar cells convert solar energy into electrical energy, and its external characteristics are equivalent to a controlled power source changing with environmental factors. Solar cells can output electrical energy when its output terminal is connected with a load, but how much energy will be output is related to not only the practical equivalent status of solar cells but also the impedance matching degree of the circuit. The maximum power output is achieved only when the impedance matching between solar cells and the collecting circuit is achieved, and at this time, the output voltage and output current of solar cells is marked as the MPPT voltage \( U_{MPPT} \) and MPPT current \( I_{MPPT} \) respectively. In order to maximize the output power of solar cells, especially the high efficiency power output of low voltage solar cells, the main circuit of collecting circuit adopts the Boost structure DC/DC converter, which makes the collection of solar energy maximized through voltage boosting. In order to track the actual equivalent state of solar cells and realize solar cells’ MPPT output in real time, the control circuit detects the output state of solar cells. With help of the detected value of solar cells’ output state, the internal equivalent state of solar cells is estimated, and then the MPPT current value of solar cells is computed. Accordingly, the working state of collecting circuit is switched in order to force the solar cells to work near its MPPT working point by current close-loop control. A Boost structure DC/DC converter controlled with MPPT-SE is used as the solar energy collecting circuit, and the equivalent block diagram of the collecting circuit is shown in Figure 1. In the figure, \( U_i \) represents the equivalent electromotive force of solar cells, \( R_i \) represents the equivalent internal resistance of solar cells, \( L \) is a energy storage inductor, \( Q \) is a switch tube, \( D \) is a one-way isolating diode, \( C \) is a super energy storage capacitor or rechargeable battery, \( R_e \) is the equivalent load of the solar energy collecting circuit, \( R_s \) is a sampling resistor for the output current of solar cells, the “CPU” module is used as an MPPT-SE controller, the “Driver” module is the driving circuit of the switch tube Q, and the two independent A/D converters are the synchronous and independent detecting and digitalizing circuits for the output photovoltaic voltage \( u_{PV}(t) \) and photovoltaic current \( i_{PV}(t) \) of solar cells.

2.2. Analysis of solar energy collecting circuit
The working process of the Boost structure solar energy collecting circuit under the control of MPPT-SE is divided into two stages, namely the energy storage stage of the inductor \( L \) and the energy release stage of the inductor \( L \).

(1) Energy storage stage of inductor
When the switch tube Q is turned on, the current path’s impedance of the solar energy collecting circuit becomes smaller, the inductance current \( i_L(t) \) increases, and the energy storage capacity of \( L \) is increased. At the same time, the energy storage capacity of \( C \) is supplied to the output load, and the voltage \( u_C(t) \) drops.
(2) Energy release stage of inductor

When the switch tube Q is turned off, the current path’s impedance of the solar energy collecting circuit increases, the inductance current \( i_{PV}(t) \) decreases, and the energy storage inductor releases energy, and the released energy is transferred to the energy storage capacitor or rechargeable battery C, so the voltage \( u_C(t) \) increases.

![Figure 1. Boost structure collecting circuit with MPPT-SE.](image)

3. MPPT-SE control of collecting circuit

3.1. MPPT-SE control algorithm

In order to make solar cells work at its MPPT state in real time, the real-time MPPT current \( I_{MPPT}(t) \) is used as the given value of the current control loop for the output current of solar cells, and the current closed-loop control mode is used to turn on or turn off the switch tube Q. When the actual output current \( i_{PV}(t) \) of solar cells is greater than the \( I_{MPPT}(t) \), the switch tube Q is turned off to force the output current \( i_{PV}(t) \) of solar cells to decrease. When the actual output current \( i_{PV}(t) \) of solar cells is less than the \( I_{MPPT}(t) \), the switch tube Q is turned on to force the output current \( i_{PV}(t) \) of solar cells to increase. At the same time, taking into account the needed time to turn on or turn off the switch tube Q, estimate the equivalent state \((U_i(t), R_i(t))\) of solar cells and compute the MPPT current \( I_{MPPT} \) of solar cells, the time interval \( D_t \), namely the control time step is introduced in the control process. The state-switching control of switch tube Q is carried out at every interval of \( D_t \), and the switching state \( S_Q \) of switch tube Q is determined according to formula (1).

![Figure 2. Control flow of MPPT-SE algorithm.](image)
where \( \kappa \) —— The discrete value for time \( t \) at \( D_t \) intervals.

The control flow of the MPPT-SE algorithm is shown in Figure 2.

### 3.2. State estimation and parameter determination

#### 3.2.1. Estimation of the equivalent state of solar cells

In the MPPT-SE control algorithm, the internal equivalent state \((U_i(t), R_i(t))\) of solar cells is estimated by real-time detecting the output voltage \( u_{PV}(t) \) and output current \( i_{PV}(t) \) of solar cells, then the expected MPPT current \( I_{MPPT-SE}(t) \) of solar cells is determined. The relationship between the equivalent state of solar cells and its output state can be expressed by formula (2).

\[
 u_{PV}(t) = U_i(t) - R_i(t)i_{PV}(t)
\]  

At adjacent time point \( t=(k-1)D_t \) and \( t=kD_t \), the relationship between the equivalent state of solar cells and its output state is described by formula (3).

\[
\begin{align*}
 u_{PV}(k) &= U_i(k) - R_i(k)i_{PV}(k) \\
 u_{PV}(k-1) &= U_i(k-1) - R_i(k-1)i_{PV}(k-1)
\end{align*}
\]  

In order to facilitate the real-time estimation of equivalent state \( U_i(k) \) and \( R_i(k) \) of solar cells, formula (3) can be expressed to formula (4) by the variation of the solar cells’ equivalent state.

\[
\begin{align*}
 u_{PV}(k) &= U_i(k) - \Delta U_i(k) - (R_i(k) - \Delta R_i(k))i_{PV}(k-1) \\
 u_{PV}(k-1) &= U_i(k-1) - R_i(k-1)i_{PV}(k-1)
\end{align*}
\]  

where \( \Delta U_i(k), \Delta R_i(k) \) —— The variation quantity of the equivalent state of solar cells at the adjacent interval of \( D_t \).

According to the formula (4), the internal equivalent state of solar cells can be calculated by formula (5).

\[
\begin{align*}
 R_i(k) &= \frac{u_{PV}(k)-u_{PV}(k-1)}{i_{PV}(k)-i_{PV}(k-1)} + \frac{\Delta U_i(k) - \Delta R_i(k)\Delta R_i(k)}{i_{PV}(k)-i_{PV}(k-1)} \\
 U_i(k) &= \frac{i_{PV}(k)u_{PV}(k)-i_{PV}(k)u_{PV}(k-1)}{i_{PV}(k)-i_{PV}(k-1)} + i_{PV}(k)\frac{\Delta U_i(k) - \Delta R_i(k)\Delta R_i(k)}{i_{PV}(k)-i_{PV}(k-1)}
\end{align*}
\]  

The formula (5) shows that the first part of the internal equivalent state’s calculation value is only related to the output state values of solar cells, and the output state values can be obtained by real-time detection. The second part of the internal equivalent state’s calculation value is related to not only the output state values of solar cells, but also the variation quantity of the internal equivalent state. Because the variation of solar cells’ equivalent state is relatively slow compared with the speed of electronic circuit, the main part of the internal equivalent state’s calculation value is located in the first part of the formula (5), and can be used as the rough estimated value of the internal equivalent state of solar cells, such as formula (6).

\[
\begin{align*}
 \bar{R}_i(k) &= \frac{u_{PV}(k)-u_{PV}(k-1)}{i_{PV}(k)-i_{PV}(k-1)} \\
 \bar{U}_i(k) &= \frac{i_{PV}(k)u_{PV}(k)-i_{PV}(k)u_{PV}(k-1)}{i_{PV}(k)-i_{PV}(k-1)}
\end{align*}
\]  

For the second part of the equivalent state’s calculation value in the formula (5), it can be approximately calculated according to the rough estimated value of the equivalent state, which is
expressed as the formula (7), and this can be used to correct the rough estimated value of the equivalent state to further improve the accuracy of estimation.

\[
\begin{align*}
\delta_R(k) & \approx \frac{\delta_I(k) - \delta_I(k-1) - i_{PV}(k-1)(R_i(k) - R_i(k-1))}{i_{PV}(k) - i_{PV}(k-1)} \\
\delta_U(k) & \approx \frac{i_{PV}(k)(\delta_I(k) - \delta_I(k-1) - i_{PV}(k-1)(R_i(k) - R_i(k-1)))}{i_{PV}(k) - i_{PV}(k-1)}
\end{align*}
\]  

(7)

Finally, the estimated value of the equivalent state of solar cells can be expressed as formula (8).

\[
\begin{align*}
R_i(k) & \approx \frac{u_{PV}(k-1) - u_{PV}(k)}{i_{PV}(k) - i_{PV}(k-1)} + \delta_R(k) \\
U_i(k) & \approx \frac{i_{PV}(k)(u_{PV}(k-1) - i_{PV}(k-1)) - u_{PV}(k)}{i_{PV}(k) - i_{PV}(k-1)} + \delta_U(k)
\end{align*}
\]  

(8)

where \(u_{PV}(k), u_{PV}(k-1), i_{PV}(k), i_{PV}(k-1)\)——The detection value of the output state of solar cells.

3.2.2. Determination of the MPPT current value \(I_{MPPT}\). After obtaining the equivalent state’s estimation value of solar cells, according to the maximum power transmission condition of electric network, the MPPT current value \(I_{MPPT}\) of solar cells can be approximately calculated by formula (9).

\[I_{MPPT-SE}(k) = \frac{U_i(k)}{2R_i(k)}\]  

(9)

3.2.3. Determination of the control time step \(D_t\). The selection of \(D_t\) is related to many factors, which are mainly in the following aspects and need to be considered in a comprehensive way.

a) It is related to the needed tracking precision of the output current of solar cells. In order to improve the tracking precision of the output current of solar cells, \(D_t\) should be as small as possible.

b) In order to avoid the case of \(i_{PV}(k) - i_{PV}(k-1) = 0\) in the calculation formula of equivalent state, should take \(D_t < (3~5)\tau_{min}\). Among them, \(\tau_{min}\) is the minimum time constant of solar energy collecting circuit under various working state. In \((3~5)\tau_{min}\) time, the output of collecting circuit has not yet reached the steady state, \(i_{PV}(t)\) is still in the stage of variation, and there is no case of \(i_{PV}(k) - i_{PV}(k-1) = 0\).

c) It is restricted by the changing speed of the equivalent state of solar cells. In order to ensure the accuracy of the estimation of the solar cells’ equivalent state, the variation of the equivalent state of solar cells should be smaller in the time interval \(D_t\).

d) It is related to the reliable turning on/ off speed of the switch tube. The selection of \(D_t\) should ensure that the switch tube can be turn on and turn off safely, and avoid the switching loss too high.

e) It is related to the processing speed of CPU. The selection of \(D_t\) should take into account the processing speed of CPU, and avoid excessive demand for CPU and lead to increase the cost of implementation excessively.

4. Example analysis

For the given circuit shown in the Figure 1, the main component and control parameters are shown in Table 1. Among them, \(U_{Dth}\) is the dead zone voltage of the diode D.

| \(D_t\) | Solar cells | L    | C    | \(R_S\) | \(U_{Dth}\) | \(R_S\) | CPU           |
|-------|-------------|------|------|--------|------------|--------|---------------|
| 25\mu s | 24V         | 330\mu H | 3000\mu F | 100\Omega | 0.2V       | 0.5\Omega | STC89C52     |

For the given circuit and parameters, and under the scene of solar cells’ internal state dynamically changing with the frequency of 20Hz, the performances of MPPT-SE control algorithm are analyzed by the simulation software of MATLAB and Proteus. Compared with P&O, the real-time tracking process of MPPT-SE control algorithm to the MPPT working state of solar cells, the output efficiency
of solar cells and the solar energy collection efficiency of collecting circuit are analyzed. The main experimental results are shown in the Figure 3-6.

From the results, in the shorter time of starting process, the error of the output current of solar cells tracking its MPPT current is large under the two kinds of control methods, and the output efficiency of solar cells is low. With the growth of time, current tracking error gradually decreases, and the output efficiency gradually increases, but the output efficiency of P&O is obvious lower than that of MPPT-SE. Under the P&O control method, the actual output current of solar cells fluctuates significantly around its MPPT current, and the output efficiency of solar cells is obviously lower than the ideal value of 50%.

Figure 3 shows the ideal MPPT current $I_{MPPT}$ of solar cells and the estimated MPPT current $I_{MPPT-SE}$ in MPPT-SE algorithm. It can be seen that the error of the estimated MPPT current is larger at the starting stage. After the starting period, the estimated MPPT current $I_{MPPT-SE}$ is basically consistent with the ideal MPPT current $I_{MPPT}$, and there are large errors only in a few intermittent time points, this is because the change of output current of solar cells at the two adjacent detection points is small or the calculation error from the equivalent state of solar cells tending to change abruptly is larger. The estimation accuracy can be improved by reducing the time interval $D_t$.

Figure 4 shows the situation of the actual output current $i_{PV}(t)$ of solar cells tracking its MPPT current $I_{MPPT}$ in MPPT-SE. It can be seen from the figure, after the starting period, despite the presence
of error between the $I_{\text{MPPT-SE}}$ and $I_{\text{MPPT}}$ at a few interrupted time points, the collecting circuit has a good tracking performance for the MPPT working state according to the $I_{\text{MPPT-SE}}$. The output current $i_{PV}(t)$ of solar cells has a large error only in the starting stage, and the tracking error is very small in other time periods. This is because the estimation error of $I_{\text{MPPT-SE}}$ does not exist the accumulation in MPPT-SE. Moreover, the current of inductor does not change abruptly, so the influence of the MPPT current estimation error at a few intermittent time points is not very significant for the actual output current of solar cells.

Figure 5 shows the situations of the output efficiency $\eta_f$ of solar cells and the solar energy collection efficiency $\eta_S$ of collecting circuit under the control of MPPT-SE method. From the figure, after a certain time since the collecting circuit starts working, the output efficiency $\eta_f$ of solar cells is about 49.5%, slightly lower than the ideal output efficiency of 50%, this is because the actual output current $i_{PV}(t)$ of solar cells has been fluctuating around the ideal MPPT current $I_{\text{MPPT}}$ in a small amplitude. The solar energy collection efficiency $\eta_S$ of the collecting circuit is about 45%, lower than the solar cells’ output efficiency of 49.5%, this is because there is consumption of energy on the components of collecting circuit such as the sampling resistor $R_S$, isolating diode D and so on. Compared with the P&O method under the same scene (shown in Figure 6), the efficiency of MPPT-SE is high by about 4%, and this has great economic benefit for the long-running solar energy collecting circuit.

![Figure 5](image1)

**Figure 5.** Output efficiency in MPPT-SE.

![Figure 6](image2)

**Figure 6.** Output efficiency in P&O.

5. **Conclusions**

The Boost structure DC/DC conversion circuit under the high frequency PWM control can maximize the energy collection of solar cells, and is suitable to be used as the collecting circuit of solar energy. Using the MPPT-SE method to control the working status of the Boost structure solar energy collecting circuit can track the MPPT current of solar cells in real time, this forces the solar cells to work near its MPPT working point in real time, and improves the output efficiency of solar cells and the solar energy collection efficiency of collecting circuit. Compared with P&O method, the MPPT current estimation error of MPPT-SE does not exist the accumulation in the time dimension, so the large error of individual time points does not affect the estimation accuracy of other time points. At the same time, because the Boost structure circuit itself has certain inertia, the inductor current does not change abruptly, so the MPPT current estimation error at intermittent time points does not affect the output current tracking for the MPPT current excessively. Therefore, the efficiency is relatively high, and the computation cost can be reduced because of the low computation complexity. If want to further improve the solar energy collection efficiency of collecting circuit, decrease the tracking error of MPPT current and output current, the integrated control of the MPPT-SE and the traditional method can be considered, and the parameters of the circuit components can be synthetically optimized. These will be the next step of inquiry.
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