Sliding mode control of SEPIC converter based photovoltaic system

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ABSTRACT
Photovoltaic (PV) energy can be considered to be as highly efficient energy source since it is ecofriendly, harmless and available endlessly. In order to improve the output power of photovoltaic cells, the maximum power point tracking technology is used in PV systems. This paper designs a sliding mode controller based on SEPIC converter to implement MPPT. The difference from other methods is that the proposed method uses the circuit output voltage $U_0$ in the closed-loop system, so that the controller has better control effect. The buck-boost feature of the SEPIC widens the applicable PV voltage and thus increases the adopted PV module flexibility. First, the photovoltaic array is modeled and the simulation results are analyzed in this paper. Then model and analyze the SEPIC circuit and derive a sliding mode control strategy based on this circuit. Finally, the results obtained in MATLAB/Simulink were compared with the conventional P&O algorithm and INC algorithm. The results show that the sliding mode controller proposed in this paper has faster speed and less oscillation when tracking the maximum power point (MPP).

1. Introduction
With the rapid development of national economy, renewable energy is becoming more and more important. PV energy is the most important renewable energy since it is clean, pollution free, and inexhaustible. Due to the rapid development of power electronics technology, PV energy is more and more widely used in power systems. How to make the PV system work at the MPP has become a research hotspot (Agarwal et al., 2016; Celik, 2018).

The output characteristics of photovoltaic arrays are affected by irradiance level, temperature and load. Adopting MPPT technology can make it work at the MPP to improve work efficiency and make full use of solar energy resources (Chen et al., 2019). At present, the most commonly methods for MPPT solution are P&O algorithm and INC algorithm. An adaptive P&O algorithm was proposed in Das et al. (2017). The disadvantage of this method is that the oscillation at MPP is relatively large. Compared with this method, the SMC control strategy proposed in this paper has less oscillation. This is proved by the simulation results in Section 4 – 4.1, 4.2, 4.3. An modified incremental conductance (INC) algorithm was proposed in Deepak et al. (2016), which has a better response when the solar irradiation increases. However, when the partial shading condition changes, the response time and oscillation of this method increase. This article makes a detailed comparison with this method in Section 4 – 4.4. A novel fuzzy adaptive proportional-integral-derivative (PID) control strategy with online set-point tracking is presented in Dhimish (2017), which has the range of the membership functions of the fuzzy logic for online PID parameter tuner has been optimized using the relay feedback tuning method. Using the modified Inc Cond algorithm, the authors in Dhimish et al. (2018) proposed a novel algorithm to modulate the duty cycle of the converter. The tracking speed of this method is improved, but there will be oscillation at the MPP. Fuzzy logic control method (FLC) was proposed in El Khateb (2014), which uses Hopfield Neural Network (HNN) instead of trial and error to optimize the fuzzy logic controller to achieve better tracking results. A new IC MPPT algorithm with direct control is introduced in Gonzalez Montoya et al. (2015), which based on a fuzzy duty cycle change estimator. The algorithm reaches the MPP more accurately and faster during all conditions. However, the algorithm has overshoot in the process of tracking. In addition, there is a fuzzy logic control method based on SEPIC converters in Hejri and Mokhtari (2017), which proves that the membership function of the convergent distribution has a faster response speed than the membership function of the symmetrical distribution. The authors in Incremona et al. (2017) reviewed AI-based techniques which are very common in literature for MPPT. This paper introduces different MPPT technologies from many aspects, such as...
the background theory, application to MPPT systems, and important references relating to each method. Some of these methods have great reference value for this paper.

This paper proposes a sliding-mode control (SMC) strategy based on SEPIC converter for photovoltaic systems. Compared with Boost converter, SEPIC used in this paper can not only boost or step down the output voltage, but also maintain the same polarity at the input and output. Compared with P&O algorithm and incremental conductance method (INC), SMC strategy has faster tracking speed and less oscillation. When partial shading condition is changed, the strategy is still applicable.

2. Mathematic modeling of the photovoltaic system

PV cells are usually made of semiconductor materials, also known as solar cells. Their output power varies nonlinearly with the effects of solar irradiation and temperature. It receives the solar energy directly from the sunlight and converted to the electrical energy. Therefore, how to make PV cells work at MPP is one of the core technologies to improve work efficiency (Karanjkar et al., 2014; Mohapatra et al., 2019).

The equivalent circuit of the PV cell under standard conditions is shown in Figure 1.

The equation of the PV model is as follows (Radjai et al., 2014).

\[ I = I_{ph} - I_o \left\{ \exp \left( \frac{q(U + IR_s)}{AKT} \right) - 1 \right\} - \frac{U + IR_s}{R_{sh}} \]  

(1)

In the ideal case, \( R_s \) can be approximated to zero and \( R_{sh} \) can be approximated to infinity, (1) can be simplified as:

\[ I = I_{ph} - I_o \left( \exp \left( \frac{qU}{AKT} \right) - 1 \right) \]

(2)

the output power of the photovoltaic cell can be obtained as

\[ P = U_{PV} \cdot I_{PV} = U_{PV} \left\{ I_{ph} - I_o \left( \exp \left( \frac{qU}{AKT} \right) - 1 \right) \right\} \]

(3)

where \( I \), cell output current and voltage; \( I_{ph} \), light-generated current; \( I_o \), cell reverse saturation current; \( q \), charge of an electron; \( A \), ideality factor of the p-n junction; \( K \), Boltzmann’s constant; \( T \), cell temperature; \( R_s \), intrinsic series resistance of the PV array; \( R_{sh} \), shunt resistance.

Based on the above analysis, the PV cell model was built in MATLAB/Simulink. I-V curve and P-V curve obtained by changing the irradiation are shown in Figure 2.

From the I–V curve, it can be seen that with the increase of irradiation at the same temperature, the short-circuit current increases and the open-circuit voltage decreases. It can be seen from the P–V curve that the MPP increases with the increase of irradiation.

3. SEPIC converter with sliding mode control

Sliding mode control mainly includes two movement processes: approach phase and sliding phase (Sangeetha & Joseph, 2016). The approach phase refers to the process of designing a sliding mode surface. Its control law can introduce the state variables to the sliding mode surface within a limited time. The sliding phase means that the state variables of the system are maintained on the
sliding surface along a predetermined trajectory. Therefore, the sliding mode surface and control law must be determined before designing the sliding mode controller (Seyedmahmoudian, 2016).

3.1. Modeling SEPIC

At present, the most common dc/dc converter circuit topology used in PV systems includes boost circuits, buck circuits, buck-boost circuits, SEPIC circuits, etc (Subiyanto et al., 2012; Tey & Mekhilef, 2014). The input of the Buck circuit works in discontinuous mode. If the energy storage capacitor is not added, the PV cells will be discontinuous during operation and cannot reach the optimal working state. Boost and Buck circuits can only work in a single boost mode and buck mode, while the SEPIC circuit can work in both boost mode and buck mode. The SEPIC circuit can also maintain the output voltage with the same polarity as the input voltage. The PV system based on the SEPIC circuit is shown in Figure 3.

When the SEPIC circuit works in continuous conduction mode (CCM), the current flowing through the inductor $L_1$ and the voltage $U_0$ across the capacitor $C_2$ are taken as state quantities, and the state equation is obtained as

$$
\begin{align*}
\frac{di_{L_1}}{dt} &= \frac{U_{PV}}{L_1} - \left( \frac{U_{L_1} + U_0}{L_1} \right) \mu \\
\frac{dU_0}{dt} &= -\frac{U_0}{RC_2} + \left( \frac{i_{L_1} + i_{L_2}}{C_2} \right) \mu
\end{align*}
$$

In the formula, $\mu$ is the control quantity of the switch $S$. When $\mu = 0$ switch on, $\mu = 1$ switch off. Select state quantity as

$$
X = [x_1 \ x_2]^T = [i_{L_1} \ U_0]^T
$$

Therefore (4) can be rewritten into the general form as

$$
\dot{X} = \frac{dx}{dt} = f(x, t) + g(x, t)\mu
$$

3.2. Selection of sliding surface

From the P–V curves in Figure 2, it can be known that when the PV cell works at the maximum power point

$$
\frac{dP_{PV}}{dU_{PV}} = \frac{dI_{PV}}{dU_{PV}} U_{PV} = 0
$$

So the sliding surface is chosen as

$$
S(x) = \frac{dP_{PV}}{dU_{PV}} = I_{PV} + \frac{dI_{PV}}{dU_{PV}} U_{PV} = 0
$$

Consider invariance conditions

$$
\begin{align*}
S(x) &= 0 \\
\frac{dS(x)}{dt} &= 0
\end{align*}
$$

3.3. Design of control law

According to equivalent control rules, the control law can be selected as switching control which can be expressed as

$$
\mu = \mu_{eq} + \mu_{VSS}
$$

The dynamic part $\mu_{eq}$ can keep the dynamic variables on the sliding surface. The variable structure control term $\mu_{VSS}$ can overcome various disturbances. Then we can get the derivative based on the sliding surface as follows:

$$
\dot{S} = \frac{dS(x, t)}{dt} = \frac{1}{dt} \left( \frac{\partial S}{\partial x} \cdot \dot{x} + \frac{\partial S}{\partial t} \cdot \dot{t} \right) = \frac{\partial S}{\partial x} \cdot \dot{x} + \frac{\partial S}{\partial t} \cdot \dot{t}
$$

Substituting (6) into (12) gives:

$$
\dot{S} = J \cdot f(x, t) + J \cdot g(x, t) \cdot \mu + \frac{\partial S}{\partial x} \cdot \dot{x} + \frac{\partial S}{\partial t} \cdot \dot{t}
$$

where $J = \frac{\partial S}{\partial x}$.
From the above analysis, we can know that on the sliding surface:

\[
\dot{S} = J \cdot (f(x, t) + g(x, t) \cdot \mu_{eq}) + \frac{\partial S}{\partial t} = 0 \tag{14}
\]

Get the law of control:

\[
\mu_{eq} = -[J \cdot g(x, t)]^{-1} \left[ J \cdot f(x, t) + \frac{\partial S}{\partial t} \right] \tag{15}
\]

Now, substituting (11) into (13) yields:

\[
\dot{S} = \left[ J \cdot (f(x, t) + g(x, t) \cdot \mu_{eq}) + \frac{\partial S}{\partial t} \right] + \frac{\partial S}{\partial x} \cdot g(x, t) \cdot \mu_{VSS} \tag{16}
\]

Then substituting (15) into (16) to gives

\[
\dot{S} = \frac{\partial S}{\partial x} \cdot g(x, t) \cdot \mu_{VSS} \tag{17}
\]

According to convergence conditions:

\[
S \cdot \dot{S} = S(x, t) \cdot \frac{\partial S}{\partial x} \cdot g(x, t) \cdot \mu_{VSS} < 0 \tag{18}
\]

Using discrete nonlinear control

\[
\mu_{VSS} = k \cdot \text{sign}[S(x, t)] \tag{19}
\]

Substituting (19) into (18) gives:

\[
S \cdot \dot{S} = S(x, t) \cdot \frac{\partial S}{\partial x} \cdot g(x, t) \cdot k \cdot \text{sign}[S(x, t)] < 0 \tag{20}
\]

Therefore, as long as the sign of \(k\) is different from that of \(\frac{\partial S}{\partial x} \cdot g(x, t)\), the existence and reachability of the system can be guaranteed.

Then substituting (7) into (15) yields:

\[
\mu_{eq} = \frac{U_0}{U_0 + U_{PV}} = D \tag{21}
\]

\(D\) is the duty cycle of the SEPIC converter in steady state.

The control law of the sliding mode controller can be obtained as:

\[
\mu = \mu_{eq} + \mu_{VSS} = D + k \cdot \text{sign}[S(x, t)] \tag{22}
\]

Therefore the control law can be expressed as:

\[
\begin{align*}
\mu &= D + k, \ S > 0 \\
\mu &= D, \ S = 0 \\
\mu &= D - k, \ S < 0
\end{align*} \tag{23}
\]

During control: \(0 \leq \mu \leq 1\).

4. Parameter and simulation analysis

As shown in Figure 4, output of the system can be optimized with the use of SMC. A converter is required for matching the operating points of the load attached and PV module. A SEPIC type of converter is used due to its advantages of having a non-inverted output, ability of responding satisfactorily to a short circuit output and capability of a true shutdown. The SMC MPPT controller takes \(U_{PV}, i_{PV}, U_0\) as inputs, and generates a duty cycle to control the switch \(S\). A LC type of filter has been used in order to obtain smooth output waveform. The main parameters of the converter are shown in Table 1.

4.1. Results under the same irradiation and temperature

When the irradiation is 1000 W/m² and temperature is 25°C, the results obtained by the proposed method and

![Figure 4. MPPT structure of sliding mode control photovoltaic system.](image)
Table 1. SEPIC converter parameter.

| SEPIC converter parameter | Value       |
|---------------------------|-------------|
| Inductance \(L_1, L_2\)   | 1 \(\mu\)H |
| Capacitance \(C_0, C_1, C_2\) | 100 \(\mu\)F |
| Load resistance (R)       | 20 ohm      |
| Switching frequency       | 20 KHz      |

P&O algorithm are shown in Figures 5 and 6. Compared with the P&O algorithm, the output power and output voltage of the SMC controller proposed in this paper has less oscillation and faster response time.

4.2. Results under different temperature

Ensure that the irradiation unchanged and verify the applicability of the proposed method by changing the temperature. Irradiation is 1000 W/m² and does not change. The temperature changes from 25°C to 30°C at 0.02 s and from 30°C to 35°C at 0.035 s. The tracking results obtained are shown in Figures 7 and 8.

Compared with the P&O algorithm, the output power and output voltage of the control strategy proposed in this paper has less oscillation and smaller overshoot. Therefore under the condition that the temperature changes, the control strategy proposed in the article is still applicable.

4.3. Results under different irradiances

The theoretical parameters of photovoltaic arrays under different solar irradiation are shown in Table 2. Irradiation in the natural environment is constantly changing. In order to prove the applicability of the SMC controller when the irradiation changes. This paper reduces the irradiation from 1000 W/m² to 600 W/m² at \(t = 0.02\) s, and increases the irradiation to 800 W/m² at \(t = 0.03\) s.

The simulation results obtained are shown in Figures 9 and 10. The simulation results show that the waveform of the SMC strategy has less oscillation in the MPP and track the MPP faster.
4.4. Results under partially shaded conditions

This paper connects four photovoltaic cells in series, and simulates different partial shading conditions (PSCs) by changing the irradiation of the cells. The shading conditions are changed at different times to verify the tracking effect of the proposed method. The results are compared with the perturb and observe (P&O) algorithm and the incremental conductance method (INC). The PV cells series model is shown in Figure 11.

Under the following three partial shading conditions, the corresponding irradiation of each PV cell is shown in Table 3.

| PSC  | PV1 | PV2 | PV3 | PV4 |
|------|-----|-----|-----|-----|
| PSC1 | 1000| 1000| 1000| 1000|
| PSC2 | 1000| 1000| 800 | 800 |
| PSC3 | 1000| 1000| 800 | 400 |

The partial shading condition will be changed from PSC1 to PSC2 at 0.01 s, and from PSC2 to PSC3 at 0.15 s. The tracking results of the three methods under partial shading conditions are shown in Figure 12. When the shading conditions change, compared with the other two methods, the sliding mode control algorithm designed in this paper has a better tracking effect.

5. Conclusion

The SMC controller based on SEPIC is proposed here to improve the tracking speed and reduce the oscillation.
Compared with other control strategies, the method proposed in this article has better performance in many aspects. In the ripple control environment, the SEPIC converter can avoid the ripple content in the solar cell array (SCA) current. Moreover, compared to Boost converter, the buck-boost feature of the SEPIC widens the applicable PV voltage and thus increases the adopted PV module flexibility.

However, the proposed control method also has limitations. First, oscillation still exists at the MPP, but the oscillation is smaller than other methods. Second, tracking to the maximum power point requires response time but the time is very short. Finally, the method is relatively complicated and takes a long time to calculate.

The difference from other methods is that the proposed method uses the circuit output voltage \( V_0 \) in the closed-loop system, so that the controller has better control effect. Moreover, the results obtained in MATLAB Simulink were compared with the P&O and INC algorithm. The results show that the tracking speed of the SMC controller is faster and the oscillation in the MPP is smaller. Moreover, the results obtained in MATLAB Simulink were compared with the P&O and INC algorithm. The results show that the tracking speed of the SMC controller is faster and the oscillation in the MPP is smaller. Furthermore, it can be coupled with an uninterruptible power supply system in commercial buildings or it can be used to supply power to the electrical grid through a dc/ac converter.

**Disclosure statement**

No potential conflict of interest was reported by the author(s).

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