Posicast control within feedback structure for a DC–DC single ended primary inductor converter in renewable energy applications

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**A B S T R A C T**

In this paper, modeling, analysis, design, simulation and control of a single ended primary inductor converter (SEPIC) are discussed for renewable energy applications. Because the traditional control methods such as proportional–integral–derivative (PID) and classical half-cycle Posicast controllers based on feed-forward are sensitive to noise and variations in natural frequency, a Posicast control with feedback structure is proposed and designed to reduce or rejection undesirable sensitivity greatly, to suppress measurement noise and to eliminate the overshoot in the output response. The SEPIC converter is modeled using average value modeling analysis. Dynamic modeling and simulation are accomplished using MATLAB Simulink™ 7.2.

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1. Introduction

One of the most applications of converters such as AC/DC converter, named rectifier, DC/AC converter, named inverter, and DC/DC converter, named chopper, is in renewable energy systems such as autonomous wind-solar hybrid power generation system [1,2], shown in Fig. 1. Among these converter, DC–DC converters have important roles for charging or discharging of batteries, adjusting DC-link voltage between rectifier and inverter and etc. Batteries are employed to store superfluous energy derived from wind blowing and solar irradiance during windy or sunny days and then to release during cloudy days or at nights. So, a DC–DC converter is used to charge or discharge the battery. Furthermore, they are also implemented in fuel cell [3,4], photovoltaic and solar system in order to extract the maximum power [5,6] and other applications such as electric vehicle [7].

Various DC–DC converters which can be applied in order to step up and step down output voltage are cascaded buck and boost converters, buck-boost converter, flyback converter, Cuck converter and SEPIC converter [8]. Two needed separate controllers and switches are the most drawbacks in the cascaded buck and boost converters. In the buck-boost and Cuck converters, output voltage is inverted. Furthermore, a required transformer in a flyback converter instead of just an inductor increases the complexity of the development. So, the best option for increasing and decreasing of output voltage is single ended primary inductor converter named SEPIC. A SEPIC is a DC–DC converter allowing the output voltage to change more than, less than, or equal to the input voltage without inverting. Output voltage of a SEPIC is controlled using duty cycle generated by control circuit and applied to the transistor. Thus, the most advantage of a SEPIC over the other converters is a non-inverted output voltage.

In order to control of a SEPIC converter, several controllers are used such as classical PID and Posicast controllers. The Posicast controller improves the steady state performance and damps resonant behavior of responses. It causes that gain parameter of the controller is easily determined and sensitivity to parametric uncertainty and load change have been reduced. Furthermore, Posicast control within a feedback system is proposed and utilized to damp oscillations in lightly damped control systems. It is designed as a feedback structure and dynamic compensator to deal overshoot in the system step response. Also, it is very efficient, robust to modeling uncertainty and is used to minimize vibration in various types of systems and to suppress high frequency noise [9].

In this paper, Mathematical model and description of the SEPIC converter based on average value modeling is accomplished in Section 2. Section 3 illustrates the Posicast control design based on feedback system. Posicast control with feedback structure is proposed and designed to reduce or rejection undesirable sensitivity greatly, to suppress measurement noise and to eliminate the overshoot in the step response of the SEPIC converter. Simulation results are discussed in Section 4. Finally, the conclusion is presented in Section 5.
2. Mathematical model of the SEPIC converter

The SEPIC converter is a kind of DC–DC converter that the output voltage magnitude is more or less than input voltage magnitude. The output voltage is adjusted using duty cycles applied to the transistor. State space equations analysis is utilized for modeling and analyzing of the SEPIC converter shown in Fig. 2. In this analysis, parasitic resistances of the inductors and capacitors are ignored. Based on the MOSFET is on or off, two situations are happen [8,9].

In the first state, the MOSFET transistor is on and the diode would not conduct. In this situation, the equivalent circuit is depicted in Fig. 3. Thus, state space equations are obtained as following

\[
\begin{bmatrix}
    i_1 \\
    0 \\
    0 \\
    0
\end{bmatrix}
= \\
\begin{bmatrix}
    0 & 1 & 0 & 0 \\
    L_2 & 0 & 0 & 0 \\
    0 & C_1 & 0 & 0 \\
    0 & 0 & C_2 & 0
\end{bmatrix}
\begin{bmatrix}
    i_1 \\
    i_2 \\
    v_1 \\
    v_2
\end{bmatrix}
\]

\[
\frac{dx}{dt} = \begin{bmatrix}
    R_{on} & 0 & 0 & 0 \\
    -R_{on} & -1 & 0 & 0 \\
    0 & 1 & 0 & 0 \\
    0 & 0 & -1/R & 0
\end{bmatrix} \begin{bmatrix}
    i_1 \\
    i_2 \\
    v_1 \\
    v_2
\end{bmatrix}
\]

(1)

\[
x = \begin{bmatrix}
    x_1 \\
    x_2 \\
    x_3 \\
    x_4
\end{bmatrix} = \begin{bmatrix}
    i_1 \\
    i_2 \\
    v_1 \\
    v_2
\end{bmatrix}
\]

(2)

\[
Kdx/dt = A_1 x(t) + B_1 u(t)
\]

(3)

\[
v_o = v_2
\]

(4)

\[
[y] = \begin{bmatrix}
    0 & 0 & 0 & 1 \\
    c_1 & i_1 \\
    0 & i_2 \\
    v_2
\end{bmatrix} + \begin{bmatrix}
    0 & 0 \\
    v_s \\
    0 \\
    v_o
\end{bmatrix}
\]

(5)

In the second state, the MOSFET transistor is off and the diode will conduct. In this situation, the equivalent circuit is depicted in Fig. 4. Therefore, state space equations are calculated as following

\[
\begin{bmatrix}
    i_1 \\
    0 \\
    0 \\
    0
\end{bmatrix}
= \\
\begin{bmatrix}
    0 & 0 & 0 & 0 \\
    0 & 0 & 0 & 0 \\
    0 & 0 & 0 & 0 \\
    0 & 0 & 0 & 0
\end{bmatrix}
\begin{bmatrix}
    i_1 \\
    i_2 \\
    v_1 \\
    v_2
\end{bmatrix}
\]

\[
\frac{dx}{dt} = \begin{bmatrix}
    0 & 1 & 0 & 0 \\
    0 & 0 & 1 & 0 \\
    1 & 0 & 0 & 0 \\
    0 & 0 & -1/R & 0
\end{bmatrix} \begin{bmatrix}
    i_1 \\
    i_2 \\
    v_1 \\
    v_2
\end{bmatrix}
\]

(6)

\[
Kdx/dt = A_2 x(t) + B_2 u(t)
\]

(7)

\[
v_o = v_2
\]

(8)

\[
[y] = \begin{bmatrix}
    0 & 0 & 0 & 1 \\
    c_2 & i_1 \\
    0 & i_2 \\
    v_2
\end{bmatrix} + \begin{bmatrix}
    0 & 0 \\
    v_s \\
    0 \\
    v_o
\end{bmatrix}
\]

(9)

Using state space equations, small signal model for the control-to-output transfer function are obtained as follow

\[
\begin{align*}
\mathcal{H}(s) &= \frac{V_o}{V_s} \\
&= \frac{1}{1 + \frac{R}{sC}}
\end{align*}
\]
information of step response, depicted in Fig. 6, consisting of Posicast control identified by this name because its desired value is attained as follow. This problem is solved lightly damped system but feedforward construction causes that classical Posicast control is able to cancel oscillatory response of a nonlinear system with slowly time varying such as a large flexible-link robotic arm. Posicast based on feedforward control method relies on dynamic cancellation or model inversion. Thus, sensitivity of classical Posicast control is very high. John Y. Hung shows that the sensitivity problem can be reduced if Posicast compensation is applied within a feedback system rather than in the classical feedforward configuration [10].

Classical half-cycle, shown in Fig. 5, is the most typical types of Posicast control identified by this name because its desired value is one-half of the natural period of the plant. It is design based on information of step response, depicted in Fig. 6, consisting of damped response period ($T_d$) and overshoot ($\delta$). Fig. 7 illustrates the frequency response of Posicast control ($1 + P(s)$). Although classical Posicast control is able to cancel oscillatory response of a lightly damped system but feedforward construction causes that its sensitivity to modeling errors is high. This problem is solved using feedback construction of Posicast control shown in Fig. 8.

$$\frac{\nu_0(s)}{d(s)} = \frac{1}{D^2} \left( 1 - \frac{1}{C_1} \frac{\partial^2}{\partial t^2} \right) \left( 1 - \frac{1}{R} \frac{C_1 + C_2}{\partial^2} \right) \left( 1 + \frac{x}{C_1} + \frac{x^2}{C_1^n} \right) \left( 1 + \frac{1}{C_1} \frac{\partial^2}{\partial t^2} + \frac{x^2}{C_1^n} \right)$$

(10)

$\omega_0$ and $Q_c$ cut-off frequency and quality factor respectively, are obtained as follow

$$\omega_0 = \frac{1}{\sqrt{(L_1 + C_2 + L_2(C_1 + C_2))}}$$

(11)

$$Q_1 = \frac{R}{\omega_0 \cdot (L_1 + L_2)}$$

(12)

$$Q_2 = \frac{1}{\sqrt{(L_2 + L_1 C_1 C_2)}}$$

(13)

$$Q_3 = \frac{R}{Q_{14} \cdot (L_1 + L_2) C_1 C_2}$$

(14)

where $D$ is duty cycle and $D' = 1 - D$.

3. Posicast control design based on feedback system

O.J.M. Smith proposed classical half-cycle Posicast control for canceling the oscillatory behavior of linear lightly damped systems and dealing the overshoot in step response in 1957 [11,12]. Not only Posicast is applied in linear systems but also it is utilized in a nonlinear system with slowly time varying such as a large flexible-link robotic arm. Posicast based on feedforward control method relies on dynamic cancellation or model inversion. Thus, sensitivity of classical Posicast control is very high. John Y. Hung shows that the sensitivity problem can be reduced if Posicast compensation is applied within a feedback system rather than in the classical feedforward configuration [10].

The undamped natural frequency, $\omega_n$, and the damping ratio, $\zeta$, are expressed by the following equations

$$\omega_n = \frac{1}{\sqrt{(L_1 + C_2 + L_2(C_1 + C_2))}}$$

(15)

$$\zeta = \frac{\omega_d}{\omega_n \sqrt{1 - \zeta^2}}$$

(16)

Also, damped natural period $T_d$ and step response overshoot $\delta$ are stated as follows

$$T_d = \frac{2\pi}{\omega_n \sqrt{1 - \zeta^2}}$$

(17)

$$\delta = \exp \left( -\frac{\pi^2}{\sqrt{1 - \zeta^2}} \right)$$

(18)
Two steps implemented in designing feedback-based Posicast control are the function \( P(s) \) and the controller \( C(s) \). \( P(s) \) is determined for the SEPIC converter using equations of (17) and (18) and the controller \( C(s) \) is designed to compensate the combined model \([1 + P(s)]G(s)\). Ziegler–Nichols method is applied to design the controller of \( C(s) \) stated as a pure integrator type compensator. Thus, the Posicast transfer function will be as following equation:

\[
G_c(s) = \frac{C(s)}{1 + \frac{P(s)}{1 + \frac{1 + \delta}{1 + \delta} \left( \exp(-sT_d/2) - 1 \right)}}
\]  

(19)

Frequency response of the Posicast compensated function \( G_c(s) \) is shown in Fig. 9.

### 4. Simulation results and discussions

MATLAB Simulink™ 7.2 is utilized to evaluate the performance of the Posicast controllers for the SEPIC DC–DC converters. A band-limited white noise is generated in order to consider the effects of measurement noise. Fig. 10 shows the implemented measurement noise. The SEPIC converter parameters are shown in Table 1. Parameters of the Posicast control is calculated as \( T_d = 25.8 \text{ ms} \) and \( \delta = 0.789 \) using Eqs. (17) and (18).

In order to get the proper response without overshoot in the simulation, the compensator gain \( K \) is chosen as 24.5. Using Eq. (19), the Posicast transfer function is characterized by

\[
1 + P(s) = 1 + \frac{1 + \delta}{1 + \delta} \left( e^{-sT_d/2} - 1 \right) \approx 1 + 0.44(e^{-12.95} - 1)
\]  

(20)

Output voltage for two amount of input is depicted in Fig. 11. The first input, \( V_{in} = 120 \text{ V} \), is less than reference voltage, \( V_{ref} = 140 \text{ V} \), and the second input voltage, \( V_{in} = 160 \text{ V} \), is more than the reference voltage. In order to compare with classical controller, a PID type feedback controller is implemented and designed. Zeros of the PID controller are designed to cancel the lightly damped. Output voltage is plotted in Figs. 12 and 13 for various values of the input voltage \( V_{in} = 130 \text{ V} \) and \( V_{in} = 150 \text{ V} \).

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>( L_1 )</td>
<td>Filter inductance</td>
<td>2500</td>
<td>( \mu \text{H} )</td>
</tr>
<tr>
<td>( L_2 )</td>
<td>Filter inductance</td>
<td>1250</td>
<td>( \mu \text{H} )</td>
</tr>
<tr>
<td>( C_1 )</td>
<td>Filter capacitance</td>
<td>2500</td>
<td>( \mu \text{F} )</td>
</tr>
<tr>
<td>( C_2 )</td>
<td>Filter capacitance</td>
<td>1200</td>
<td>( \mu \text{F} )</td>
</tr>
<tr>
<td>( R )</td>
<td>Load resistance</td>
<td>10</td>
<td>( \Omega )</td>
</tr>
<tr>
<td>( T_d )</td>
<td>Damping natural period</td>
<td>25.8</td>
<td>ms</td>
</tr>
<tr>
<td>( \delta )</td>
<td>Open loop overshoot</td>
<td>0.789</td>
<td></td>
</tr>
<tr>
<td>( R_m )</td>
<td>Transistor resistance</td>
<td>0.1</td>
<td>( \Omega )</td>
</tr>
<tr>
<td>( V_i )</td>
<td>Input voltage</td>
<td>100–180</td>
<td>V</td>
</tr>
<tr>
<td>( f_s )</td>
<td>Switching frequency</td>
<td>20</td>
<td>kHz</td>
</tr>
<tr>
<td>( K )</td>
<td>Gain in compensator ( C(s) )</td>
<td>24.5</td>
<td></td>
</tr>
</tbody>
</table>

---

Fig. 9. Frequency response of proposed Posicast, \( C(s) \) \( [1 + P(s)] \), for \( \delta = 0.789 \) and \( T_d = 25.8 \text{ ms} \).

Fig. 10. Band-limited white noise signal.

Fig. 11. Output voltage of the SEPIC for various input voltages.

Fig. 12. Performance of the Posicast and PID controllers on output voltage for \( V_{in} = 130 \text{ V} \).

Fig. 13. Performance of the Posicast and PID controllers on output voltage for \( V_{in} = 150 \text{ V} \).
The response due to the proposed controller is depicted with a solid curve (red curve). According to this figure, the PID controller has faster than in rise time response in comparison with the Posicast controller, and can be tuned to give even faster response, but the PID controller cannot delete the high overshoot in the output response. Furthermore, responses of Posicast and PID for various values of load resistances \( R \) are shown in Fig. 14. It indicates that the proposed Posicast controller maintains good transient response while load resistance changes.

Finally, the effect of measurement noise, simulated by additive band-limited white noise, is shown in Fig. 15. The output signal calculated by the PID controller is much noisier than the proposed Posicast controller because the PID controller has greater high frequency gain. Thus, the PID-based feedback controller does not perform on suppression of noise but the Posicast control based on feedback suppress the noise properly.

5. Conclusion

In this paper, a Posicast control based on feedback structure has been designed and implemented to eliminate the peak overshoot of the SEPIC DC–DC converter, to improve the settling time of step response and to reduce the sensitivity of classical feedforward Posicast control. \( T_d \) and \( \delta \), the Posicast elements have been determined using the dynamics of the SEPIC converter. The measurement noise has been highly suppressed using the proposed Posicast controller while the PID controller cannot cancel the noise effect because of a lower gain at a higher cross over frequency. An integral compensator with a gain \( K \) accompanied by the Posicast element is utilized to ensure the proper steady state response. In Comparison with PID control, the propounded Posicast control improved the gain and phase margins. Its narrow open loop bandwidth caused that the high frequency noise has been suppressed. The proposed system maintains a suitable transient response while load change in a wide range.

References


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1 For interpretation of color in Figs. 1, 7, 9, 10–15, the reader is referred to the web version of this article.