dSPACE DS1104 based Proportional Integral Sliding Mode Controller for Continuous Conduction Mode Buck Boost Converter

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ABSTRACT

The buck-boost converter is a popular non-isolated, inverting power stage topology. Buck Boost Converter can be controlled using different control algorithms like PID control, current mode programmed control, conventional sliding mode control etc. But in all these methods, the steady state error is found prominently. With the use of Proportional Integral Sliding Mode Control method (PI-SMC), the disadvantage of steady state error overcomes thereby stable and efficient response of output voltage. This paper focuses on using advanced tool, dSPACE DS1104 based controller and ControlDesk software for controlling the variations in the output voltage of power converter. This paper considers the problem of controlling switched mode buck-boost power converters, in the presence of load uncertainties connected to the converter as well as input voltage variation. The converter is modeled by an average non-linear state-space representation and is controlled according to pulse-width-modulation (PWM). The control purpose is to enforce the output voltage to track any desired reference signal irrespective of uncertainties and external disturbances. The paper shows that the control algorithm represented by PI-SMC in MATLAB/ Simulink and using the dSPACE dsp 1104 controller as control toolbox is able to control the prototype model.

1. INTRODUCTION

Switched mode DC-DC power converters are used in a variety of electric power supply systems such as cars, ships, aircraft and computers among many others. Sliding mode controllers (SMC) are known for their robustness properties. This type of controller provides parameter invariance to the system when system is on the sliding surface. A number of contributions to sliding mode control of power converters are available in the papers [8], [9], [10], [11], [12]. Direct regulation tracking control of the output voltage for buck-boost power converter results in a non minimum phase system and therefore to an unstable performance. In the case of switching power converters, most of sliding mode controller has been designed using hysteresis-modulation (HM) or delta-modulation. The drawbacks of such type of controller are: i) they operate at variable switching frequency operation; ii) they are highly sensitive to noise. When we approach practically, variable switching frequency operation also limit the selection of energy storage component (i.e. when inductor operator at variable frequency it produce noise and highly non-linear in nature). To overcome such types of difficulties instead of constant time circuit switch is implemented into the hysteresis sliding mode controller, constant frequency (pulse width modulation) approach is presented. Due to popularity and advanced development of PWM based digital control [2], [3], [4], [5], [6], it is possible to implement high frequency PWM for power converter. PWM control approach is based on the assumption that, at high switching frequency, the control action generated by a sliding mode controller determines the duty cycle. Hence, the difficulty of a sliding mode controller from being HM-based to PWM-based is made possible.

Many researchers have implemented controllers for power converters with suitable assumptions and particular problem consideration. Using classical controller [7] (i.e. PID control) control has been designed, but such type of controller are prone to uncertainties and external disturbances. One approach to overcome the uncertainties estimation is adaptive sliding mode control based on PWM techniques [1] for regulation of output which can adapt to wide ranges of uncertainties and disturbances.

In the Fig.1, the power converter with simple digital controller based on pulsed width modulation technique is presented. Such types of controller are easy to implement with digital signal processor. In this technique output voltage sampler and the driver of the switches are synchronized, hence the switching frequency is constant and the output voltage is being sampled once in each switching period. These soft switching transitions reduce the switching losses as well as electromagnetic interference (EMI) noise.
The main objective of research and development in the field of DC-DC converter is always to find the most suitable control method to be implemented i.e. to select a control method capable of improving the efficiency of the converter, reducing the effect of disturbances (line and load variation), lessening the effect of EMI and being less effected by component variation. The buck-boost power converter is also called as step up/down chopper because the output voltage can be either higher or lower than the input voltage and the output voltage is inverted from the input voltage. Till now the control strategies have been implemented are based on either pulse adjustment control technique or switching LC tank circuit for attaining zero current switching or zero voltage switching, but the problem of controlling switched mode buck-boost power converters, in the presence of load uncertainties connected to the converter as well as input voltage variation is seen prominently. So to avoid these errors new control strategy implemented is Proportional Integral Sliding Mode Control. In this method, the control is designed in such a way that the control law which is responsible to force the system trajectories is towards the switching surface, because on switching surface, the system is insensitive to parameter variations and unknown disturbances. The controller is built on dSPACE DS1104 controller board. The implementation of the control algorithm in MATLAB/Simulink approaches easy and efficient controller which could be used in controlling the prototype of Buck-Boost Converter in dSPACE ControlDesk.

In this paper, the design of sliding mode control for switched buck-boost DC-DC power converter is proposed. The PWM method ensures a time-invariant switching frequency. The tracking of the desired output voltage level irrespective of load change to the power converter with sliding mode controller has been designed. In detail, this method retains the advantages of the ability of sliding mode controllers to give invariance in the presence of system parameter variations. The PWM approach has been used to generate the desired output voltage. Comparison of designed controller with traditional hysteresis based sliding mode controller and proportional-integral (PI) are presented with results. It overcomes the steady state error which is presented in the conventional controller. The designed approached is achieved by the concept of equivalent control input can be used as the output of the controller. The output of the controller maintains the duty ratio of fixed frequency pulses.

Major contributions of the paper are:

- Sliding mode control is designed for buck boost converter.
- Comparison of designed method with conventional method via simulation example.
- This method is based on pulse width modulation for tracking the output voltage in the presence of input voltage uncertainties.

This paper is organized as follows. Section II establishes the modeling of buck boost converter for particular problem formulation. Section III is used to derive the PI-SM controller for power converter with stability consideration. In Section IV, the computer simulation of design controller and comparison of designed approached with the conventional method. Section V concludes the paper.

2. BUCK BOOST CONVERTER MODELING

Fig. 2 shows the basic structure of the buck boost power converter which operate according to the principle of PWM techniques. Applying Kirchhoff's Voltage Law (KVL) and Kirchhoff's Current Law (KCL) method for ON state and OFF state on the power circuit. Using state space averaging method, the dynamic equation of buck boost converter in the current continuous model as follows:
When the switch is ON the system is linear and the state-space equations can be written as,

\[
\frac{dI_L}{dt} = -\frac{v_{in}}{L}\\
\frac{dV_C}{dt} = -\frac{1}{RC}v_0
\]

(1)

When the switch is OFF the system is also linear and the state-space equations are given by:

\[
\frac{dI_L}{dt} = -\frac{v_0}{L}\\
\frac{dV_C}{dt} = -\frac{1}{RC}v_0 - \frac{I_L}{C}
\]

(2)

The state-space representation for ON mode by:

\[
\begin{align*}
\dot{x} &= A_1x + B_1u \\
V_C &= C_1x
\end{align*}
\]

(3)

Where, \[A_1 = \begin{bmatrix} 0 & \frac{1}{L} \\ -\frac{1}{C} & -\frac{1}{RC} \end{bmatrix}, \]

\[B_1 = \begin{bmatrix} 0 \\ 0 \end{bmatrix}, \]

\[C_1(x) = [0 \ 1] \text{ and } u = v_{in}\]

The state-space representation for OFF mode by:

\[
\begin{align*}
\dot{x} &= A_2x + B_2u \\
V_C &= C_2x
\end{align*}
\]

(4)

Where, \[A_2 = \begin{bmatrix} 0 & 0 \\ 0 & -\frac{1}{RC} \end{bmatrix}, \]

\[B_2 = \begin{bmatrix} 0 \\ \frac{1}{L} \end{bmatrix}, \]

\[C_2 = [0 \ 1] \text{ and } u = v_{in}\]

The averaged state-space representation of buck-boost converter system is obtained and represented by the following equations:

\[
\begin{align*}
\dot{x} &= [aA_1 + (1-d)A_2]x + [dB_1 + (1-d)B_2]v_{in} \\
V_C &= [dC_1 + (1-d)C_2]x
\end{align*}
\]

(5)

Where \(d\) is the duty cycle of the power MOSFET and value of duty cycle is in between 0 to 1 (0 to 100%). \(I_L\) is the electric current of the inductor \(L\), \(V_C\) is the voltage across the capacitor \(C_{out}\), and \(R\) is the load resistance apply to the converter. From the system point of view \(d\) is the control input, \(E\) is the input voltage, \(R\) is the output resistance.
2.1 Assumptions

The assumptions for derivation of state space model are:

- The power MOSFET and the diode are ideal switches. Switching looses are negligible.
- The transistor output capacitance and the diode capacitance as well as lead inductances are zero.

In matrix form we can write Eq. (1), (3) and (4) as follows.

\[
\begin{bmatrix}
I_L \\
\dot{V}_c
\end{bmatrix}
= 
\begin{bmatrix}
0 & \frac{1-d}{L} \\
-1 - \frac{d}{C} & -\frac{1}{RC}
\end{bmatrix}
\begin{bmatrix}
I_L \\
V_c
\end{bmatrix}
+ 
\begin{bmatrix}
\frac{d}{L} \\
0
\end{bmatrix}v_{in}
\]

For the formulation of state space model let’s choose the state variable as inductor current \( x_1 = I_L \) and capacitor voltage \( x_2 = V_c \). Output of the model is the capacitor voltage \( y = x_2 \).

We obtain the simple form of the system (6) as follows:

\[
\dot{x} = Ax + Bu
\]  
(7)

Where, the system parameter matrix is,

\[
A = \begin{bmatrix}
0 & \frac{1-d}{L} \\
-1 - \frac{d}{C} & -\frac{1}{RC}
\end{bmatrix},
\]

State dependent input matrix as,

\[
B = \begin{bmatrix}
\frac{d}{L} \\
0
\end{bmatrix}
\]

and the state matrix is, \( x = \begin{bmatrix} I_L \\ V_c \end{bmatrix} \)

Our aim is to voltage across capacitor (or load) kept constant at desired level irrespective of input voltage to the system. We have adjusted the duty cycle such that our output kept constant or within certain limit. Our desired voltage is level assumed to be constant.
3 CONTROL LAW DESIGN

The objective of the sliding mode controller is to design switching surface and control law which is responsible to force the system trajectories towards the switching surface. On switching surface, the system is insensitive to parameter variations and unknown disturbances. First we define sliding surface by PWM based sliding mode controller and then afterward proof of stability is presented.

We choose sliding surface as,

\[ \sigma = k_1(x_1 - x_{1\text{ref}}) + k_2(x_2 - x_{2\text{ref}}) + k \int (x_2 - x_{2\text{ref}}) \]  

(8)

Here \( k_1, k_2 \) are chosen by the designer. So we get \( \dot{\sigma} \) as,

\[ \dot{\sigma} = k_1 \dot{x}_1 + k_2 \dot{x}_2 \]

(9)

When system enters into the sliding \( \dot{\sigma} \) becomes zero. When we design the control for the system, last term of (9) will come into the control. Which eliminate the steady state error in the system output.

Substituting the values of \( \dot{x}_1 \) and \( \dot{x}_2 \) from (7) into the (9), simplifying the equation.

Where \( u_{eq} \) caters the nominal terms or known terms of system and \( u_n \) will nullify the uncertainties of the system. Here uncertainties come into the input voltage which varies into the system model.

\[ \dot{\sigma} = k_1 \left( -\frac{x_2}{L} + \frac{x_2 + E}{L} u \right) + k_2 \left( \frac{x_1}{C} - \frac{x_2}{RC} - \frac{I_L}{C} \right) \]

(10)

Split our control into two parts, \( d = d_{eq} + d_n \)

(11)

Substituting the (11) into (10) and simplifying the equation,

\[ \dot{\sigma} = -\frac{k_1 x_2}{L} + \frac{k_2 x_1}{C} - \frac{k_2 x_2}{RC} - k_3 x_2 + k_3 V_{ref} + \{ \frac{x_2}{L} + \frac{E}{C} - \frac{I_L}{C} \} (d_{eq} + d_n) \]

(12)

Choosing \( u_{eq} \) as,

\[ u_{eq} = \frac{k_1 x_2 - k_2 x_1 - k_2 V_C}{\frac{x_2 + E L}{C} - \frac{I_L}{C}} \]

(13)

The next step is to design the control input so that the state trajectories are driven and attracted toward the sliding surface and then remain sliding on it for all subsequent time. Let us consider the positive definite Lyapunov function \( V \) defined as follows:

\[ V = \frac{1}{2} S^2 \]

(14)

The time derivative \( \dot{V} \) of \( V \) must be negative definite \( \dot{V} < 0 \) to insure the stability of the system and to make the surface \( S \) attractive. Such condition leads to the following inequality:
\[
\dot{V} = S\dot{S} < 0
\]

To satisfy the condition given by the inequality (12) the non-linear control component can be defined as follows:

\[
u_n = k_3 \cdot \text{sgn}(\sigma)
\]

(15)

Where, \(k_3\) is chosen as negative constant. If our control \(u_n\) is able to generate control which attract the state trajectory to the sliding. After enter into the sliding our control such that in will remain on the sliding surface irrespective of any system parameter changes or external disturbance to the system. If we are able to prove that \(\dot{\sigma}\sigma < 0\) then system will enter into the sliding.

Where \(\text{sgn}\) function is defined as follows:

\[
\text{sgn}(e) = \begin{cases} 
1 & |e| > 0 \\
-1 & |e| \leq 0
\end{cases}
\]

This type of control has term, \(x_2 - x_{2\text{ref}}\), it will eliminate the steady state error. When we choosing the designer parameter \(k > 0, k_1 > 0, k_2 > 0, k_3 < 0\) it should be set such that our effective control will not cross the maximum or minimum limit (i.e. 0 to 1).

4 IMPLEMENTATION ON dSPACE DS1104 AND CONTROLDESK

Recently, software tools for real-time control became available. Using these software tools it is possible to output values while the simulation program is running, and also to add signals obtained from external sensors. This scheme is known as "hardware in the loop" simulation. Control and supervisory strategies are designed graphically in the Simulink block diagram environment. Then, control algorithms are downloaded to a real-time prototyping system, instead of designing specific hardware. However, a complete and integrated environment is required to support a designer throughout the development of a control system, from initial design phase until the final steps of code generation. In response, several rapid control prototyping modules have been proposed using MATLAB/Simulink. Controller board like dSPACE DS1104 is appropriate for motion controls and is fully programmable from the MATLAB/Simulink environment. The dSPACE uses its own real-time interface implementation software to generate and then download the real-time code to specific dSPACE boards. It enables the user to design digital controller simply by drawing its block diagram using graphical interface of Simulink. The model of the converter and the control algorithm is developed using MATLAB/Simulink module. The code for the dSPACE board is generated using the Real Time Workshop toolbox. The Real-Time Workshop produces code directly from Simulink models and automatically builds programs that can be run in a variety of environments, including real-time systems and stand-alone simulations. After downloading the software in the real time platform the data and system parameters can be observed and modified using ‘ControlDesk’. The software allow to create graphic user interfaces using predefined objects like plots, buttons, sliders, labels, etc. This virtual environment allows the user not only to control or monitor any control algorithm parameter during the real time simulation, but also to access any I/O signal connected to the hardware components.

Here we have implemented the prototype and PI-SMC control on Simulink and with the help of Real time workshop we produced the code for Control-Desk. The graphical user interface is also designed for monitoring the parameters.

For comparison purpose conventional sliding mode control and designed sliding mode control has been described in this section. Nominal values of the physical parameter has been describe in the table.
Table 1: Nominal value of plant and other parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Nominal value/ Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inductance</td>
<td>180 mH</td>
</tr>
<tr>
<td>Capacitance</td>
<td>2200 μF</td>
</tr>
<tr>
<td>Load range</td>
<td>1 to 10 Ω</td>
</tr>
<tr>
<td>Input voltage</td>
<td>5 to 20 V</td>
</tr>
<tr>
<td>Output voltage</td>
<td>15 V</td>
</tr>
<tr>
<td>control input</td>
<td>0 to 1</td>
</tr>
</tbody>
</table>

Fig. 3: Layout of Control Desk Panel to monitor the parameters

Fig. 4 and 5 show the plot of capacitor voltage and reference voltage with step change in input voltage for Conventional SMC and designed controller respectively.

Fig. 6 shows the plot of inductor current for PI-SMC. Fig. 7 shows the plot of control input (or duty ratio) for PI-SMC. The range of control input is in between 0 to 1. It compensate the input voltage changes effect to the system.

Fig. 8 shows the plot of sigma line for PWM based PI-SMC. From plot we can clearly observer that it eliminate the steady state error due to the integral term comes into the definition of sliding surface. Due to the robustness of sliding mode control with designed sliding surface definition give better results. Irrespective of any input voltage changes to the system it remains to zero.

From the comparison of conventional method and designed method we can clearly see that in conventional method steady state error is present. It has been overcome in designed method for this particular problem.
Fig. 4: Plot of capacitor voltage using Conventional SMC

Fig. 5: Reference Voltage and Actual voltage with input voltage step change

Fig. 6: Plot of current across inductor
DC-DC converters can be controlled with various control methods. Each control method has its own advantages and drawbacks with respect to dynamic performances, cost and efficiency. Proportional Integral Sliding mode control based on the pulse width modulation techniques has been designed for buck boost power converter. The dynamical model of buck boost converter is first set up, and then the control law design has been derived with stability proof for designed PI-SMC controller. From the results it can be seen that the designed PI-SMC gives superior, robust performance to variable input voltage. With the help of Control-Desk and dSPACE DS1104Controller Board the real time simulation is achieved.

REFERENCES


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ABBREVIATIONS

SMC: Sliding Mode Control

PI-SMC: Proportional Integral Sliding Mode Control

PWM: Pulse Width Modulation

PID: Proportional Integral Derivative

HM: Hysteresis Modulation