PWM-BASED SLIDING MODE CONTROL OF DC-DC BOOST CONVERTER

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ABSTRACT
This paper explores brief idea of the Design and simulation of DC/DC Boost Converter using Pulse Width Modulation based Sliding Mode Controller operating in Continuous Conduction Mode is discussed. The performance and properties of Sliding Mode Controller is compared with conventional controllers Proportional Integral Derivative (PID) controller and Proportional Integral (PI) controller. The derived Controller/Converter system is feasible for step up purposes, as it is exposed to significant variations and input changes.

KEYWORDS: Boost converter (DC-DC), Pulse width Modulation, Sliding Mode Controller.

I. INTRODUCTION
DC-DC converter is the circuits which convert sources of direct current (DC) from one voltage level to another. There are six basic DC-DC converters. Buck, boost, buck-boost, cuk, Septic, & zeta. DC-DC converters are nonlinear system. Therefore they represent a big challenge for control system. As classical control methods are designed at one operating point, they don’t give satisfactory performance under operating point variations, large parameter variations & load variations [1].

Boost converter converts an input (DC) voltage to higher output (DC) voltage by changing the duty cycle of the main switches in the circuit. Boost converters are used in battery powered devices, where the circuit requires a higher operating voltage than the battery can supply, e.g. laptops, mobile phones, camera flashes & battery powered vehicles. The function of boost converter is like during ON time of switch inductance is charged with energy & during the OFF time of the switch this energy is transferred from the inductor through the diode to the output capacitor. Control of this type of converter is more difficult than buck converter, where output voltage is smaller than input voltage.

Control of boost converter is difficult due to their non-minimum phase structure, since control input appears in voltage as well as current equations.

Pulse width modulation (PWM) is a modulation technique that conforms the width of a pulse, formally the pulse duration, based on modulator signal information. It is used to allow the control of power supplied to electrical devices, especially to internal loads such as motors. The average value of voltage (or current) fed to the load is controlled by turning the switch between supply and load. The longer the switch is on compared to the off periods; the power supplied to the load is high. Advantage of PWM is that power loss in switching devices is very low. When a switch is off practically there is no current, and when it is on, there is no voltage drop across switch. Power loss, being the product of voltage and current, is thus in both cases close to zero. PWM has also been used in communication systems where its duty cycle has been used to convey information over a communication channel. It also used in motor drives for fans, pumps robotic servos, electric stoves and lamp dimmers.
Sliding mode control or SMC is a nonlinear method of control. It alters the dynamics of any nonlinear system by application of a discontinuous control signal. State feedback control law is a discontinuous function of time. Hence it switches from one continuous structure to another. Hence sliding mode control is a variable structure control method. Discontinuous signal forces the system to slide along cross section of the system’s normal behaviour.

The multiple control structures are designed so that trajectories always move toward adjacent region with a different control structure so, ultimate trajectory will not exist entirely within one control structure, but it will slide along the boundaries of control structures. The motion of system that slides along the boundaries is called sliding mode and geometrical locus consisting of the boundaries is called sliding surface.

II. Pulse Width Modulation (PWM)

2.1 Necessity for Controlling Dc/Dc Boost Converter using PWM

Control circuit regulates output by varying on time of switch and fixing switching frequency, in pulse width modulation (PWM) Technique. Control circuit regulates output by varying switching frequency and fixing on or off time of switch, in resonant switch mode power supplies [2]. Control circuit in switch mode power supplies has several main functions. Control circuit maintains output voltage constant even if there is any change in input voltage or load, during steady state operation. Control circuit protects all components, during transient operation by limiting external stress on them [1]. The main function of DC-DC converter is power conversion and appropriate operation of semiconductor switches. DC-DC converters are generally designed for input voltage and load conditions that is they must operate in steady state conditions only. But, practically it may not be possible due to possibility of some disturbances which causes system to deviate from nominal values [1]. These disturbances may be due to changes in circuit parameters, source, load, disturbances in switching such as shut down and start up.

![Power supply components](image)

Fig. 1 power supply components

2.2 Control Principle

The fig. 2.1 [1] describes control principle of pulse width modulation. Power stage has two inputs: input voltage and duty cycle. Duty cycle is control input i.e. it controls the switching action of power stage and hence output. Error amplifier amplifies error and regulates output voltage. In pulse width modulation rectangular pulse wave is used which results in the variation of the average value of the waveform. If we consider a pulse waveform f(t) with its minimum value $y_{\text{min}}$, a maximum value $y_{\text{max}}$ and a duty cycle $D$, then the average value of the waveform can be given by the expression,

$$Y = \frac{1}{T} \int_0^T f(t) \, dt$$

Where, $y_{\text{max}}$ is $0 < t < D.T$ and $y_{\text{min}}$ is $D.T < t < T$. Therefore,

$$Y = \frac{1}{T} (\int_0^{DT} Y_{\text{max}} \, dT + \int_{DT}^T Y_{\text{min}} \, dT)$$

$$= \frac{D.T.Y_{\text{max}} + (1-D)Y_{\text{min}}}{T}$$

$$= D.Y_{\text{max}} + (1-D)Y_{\text{min}}$$
It can be simplified by putting $y_{\text{min}} = 0$ so, $y = D.y_{\text{max}}$. Therefore average value of signal is directly dependant on duty cycle $D$.

III. CONTROL TECHNIQUES USED IN DC-DC BOOST CONVERTER

A control technique suitable for DC-DC converter must match with their nonlinearity and input voltage and load variations, ensuring stability in any operating condition. There are various control techniques such as, fuzzy logic controller, artificial neural network (ANN) controller, sliding mode controller (SMC), PI controller, PID controller, P controller. But here for DC-DC boost converter we compare the properties of sliding mode controller, PI controller and PID controller.

3.1 Proportional, Integral and Derivative (PID) Controller

Three control strategies proportional, integral and derivative are combined to get proportional integral derivative (PID) controller to control over steady state and transient errors. Therefore in this controller control signal is a linear combination of the error, integral of the error, and rate of change of error. The constants used in PID controller are $k_p$, $k_i$, $k_d$. These constants can be adjusted to get acceptable performance. If we increase $k_p$ & $k_i$ errors will be reduced but we cannot get adequate stability. Thus PID controller provides both acceptable degree of reduction in error and acceptable stability.

3.2 Pi Controller

Two control strategies proportional and integral are combined to get proportional integral (PI) controller. The integral term in PI controller causes steady state error to reduce to zero. Due to lack of derivative term system becomes more steady in steady state operation, also it is less responsive to real and fast changes in state, so system will be slower as compared to PID controller.

3.3 Sliding Mode Controller

Sliding mode controller maintains stability and provide consistence performance. In general the function of switching control law is to drive nonlinear plant’s state trajectory onto a pre-specified surface and to maintain plant’s state trajectory for subsequent time. The surface is known as switching surface which defines rules for proper switching. This surface is also called sliding surface. Feedback path has one gain when plant trajectory is above the surface and a different gain when trajectory is below the surface. Conventional controls such as stabilization, regulation, tracking can be obtained by proper design of sliding surface.

3.3.1 control law for dc-dc boost converter

Let’s consider, voltage error be $X$, rate of change of voltage error be $Y$ & integral of voltage error be $Z$. Under continuous conduction mode, derived in [7] can be expressed as,

$$X = (v_{\text{ref}} - \beta V_0)$$

$$Y = \frac{\beta V_0}{C} \int \frac{u(V_i - V_0)}{RL} \, dt$$

$$Z = \int X \, dt$$

$$X_{\text{boost}} = \left[ \begin{array}{c} \frac{\beta V_0}{C} \int \frac{V_i - V_0}{RL} \, dt \\ \int \frac{V_i - V_0}{RL} \, dt \\ \frac{V_{\text{ref}} - \beta V_0}{C} \end{array} \right]$$

$$X_{\text{boost}} = AX_{\text{boost}} + Bu$$

Where,

$$A = \begin{bmatrix} 0 & \cdots & 1 & 0 \\ 0 & \ddots & \frac{1}{RL} & \vdots & 0 \\ 1 & \cdots & 0 & 0 \end{bmatrix}$$

$$B = \begin{bmatrix} \frac{\beta V_0}{LC} \\ \frac{\beta V_i}{LC} \\ 0 \end{bmatrix}$$
For this system, it is appropriate to have a general SM control law that adopts a switching function such as,

\[
  u = \begin{cases} 
    1 & \text{when } S > 0, \\
    0 & \text{when } S < 0,
  \end{cases}
\]

\[
  u = \frac{1}{2(1+\text{sign } s)}
\]

Where \( S \) is the instantaneous state variable’s trajectory and is described as,

\[
  S = \alpha_1 X_1 + \alpha_2 \dot{X}_2 + \alpha_3 \ddot{X}_3 = J^T X
\]

With, \( J^T = [\alpha_1 \quad \alpha_2 \quad \alpha_3] \)

where, \( \alpha_1, \alpha_2 \) and \( \alpha_3 \) are representing control parameter termed as sliding coefficients.

A sliding surface can be obtained by enforcing, \( S = 0 \). Finally, the mapping of the equivalent control function onto the duty ratio control \( d \), where

\[
  0 < d = \frac{V_C}{\text{Vramp}} < 1
\]

gives the following relationship for the control signal \( V_C \) and ramp signal \( V_{\text{ramp}} \), where

\[
  V_C = U_{\text{eq}} = -\beta L \left( \frac{\alpha_1}{\alpha_2} \right) i_c + L C \left( \frac{\alpha_3}{\alpha_2} \right) (V_{\text{ref}} - \beta V_o) + \beta (V_o - V_i)
\]

\[
  V_C = -k p_1 i_c + k p_2 (V_{\text{ref}} - \beta V_o) + \beta (V_o - V_i)
\]

\[
  k p_1 = \frac{\alpha_1}{\alpha_2} - \frac{1}{R_1 C} \quad \text{&} \quad k p_2 = L C \left( \frac{\alpha_3}{\alpha_2} \right)
\]

\[
  V_{\text{ramp}} = \beta (V_o - V_i)
\]

Using control voltage equation, the sliding mode controller for boost converter can be modeled as shown in fig 3.1

**IV. SIMULATION RESULTS**

**TABLE 1. List of Parameters**

<table>
<thead>
<tr>
<th>Description</th>
<th>Parameter</th>
<th>Nominal Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input voltage</td>
<td>Vin</td>
<td>12V</td>
</tr>
<tr>
<td>Capacitance</td>
<td>C</td>
<td>50( \mu )F</td>
</tr>
<tr>
<td>Inductance</td>
<td>L</td>
<td>120( \mu )H</td>
</tr>
<tr>
<td>Switching frequency</td>
<td>F</td>
<td>100KHz</td>
</tr>
<tr>
<td>Load resistance</td>
<td>Rl</td>
<td>50( \Omega )</td>
</tr>
<tr>
<td>Sliding mode controller gain</td>
<td>Kp1</td>
<td>0.149</td>
</tr>
<tr>
<td></td>
<td>Kp2</td>
<td>1.35</td>
</tr>
<tr>
<td>PID controller gain, proportional constant</td>
<td>Kp</td>
<td>25</td>
</tr>
<tr>
<td>Integral constant</td>
<td>Ki</td>
<td>12</td>
</tr>
<tr>
<td>Derivative constant</td>
<td>Kd</td>
<td>0.05</td>
</tr>
<tr>
<td>Pi controller, proportional constant</td>
<td>Kp</td>
<td>0.17</td>
</tr>
<tr>
<td>Integral constant</td>
<td>Ki</td>
<td>15</td>
</tr>
<tr>
<td>Expected voltage</td>
<td>V0</td>
<td>30V</td>
</tr>
</tbody>
</table>
4.1 Basic model of Boost Converter

![Simulated block diagram of boost converter](image)

**Result:** for input voltage of $V_{in} = 15v$, output voltage $v_0 = 30v$, and output current $i_0 = 0.01amp$ with nonlinearity upto 0.4 sec.

![Simulation result for basic boost converter](image)

4.2 Boost Converter using Sliding Mode Controller

![Simulated block diagram for boost converter using sliding mode control](image)
Result: for input voltage of \( v_{in} = 15v \), output voltage of \( v_0 = 30v \), & output current of \( i_0 = 0.1 \) with linear curve.

**Fig. 6** Simulation result for boost converter using sliding mode controller

### 4.3 Boost Converter using PID Controller

**Fig. 7** Simulated block diagram for boost converter using PID control

Result: for input voltage of \( v_{in} = 15v \), output voltage \( v_0 = 30v \) & output current \( i_0 = 0.1\)amp with nonlinearity 0.4sec.
Fig. 8 Simulation result for boost converter using PID controller

4.4 Boost Converter using PI Controller

Result: for input voltage of $v_{in} = 15v$, output voltage, $v_0 = 31v$ & output current 0.1 amp with maximum voltage drop between 15v to 16v at 0.2 sec.

Fig. 9 Simulated block diagram for boost converter using PI control

Fig. 10 Simulation result for boost converter using PI controller
TABLE 2. Comparison between sliding mode control, pi control & pid controller

<table>
<thead>
<tr>
<th>Controller</th>
<th>Voltage Profile</th>
<th>Settling time</th>
<th>Current Profile</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without controller</td>
<td>25V with nonlinearity</td>
<td>0.4sec</td>
<td>0.01A</td>
</tr>
<tr>
<td>Sliding mode controller</td>
<td>30V with linearity</td>
<td>0.01sec</td>
<td>0.1A</td>
</tr>
<tr>
<td>PID controller</td>
<td>30V to 16V with nonlinearity</td>
<td>0.4sec</td>
<td>0.1A</td>
</tr>
<tr>
<td>PI controller</td>
<td>31v with linearity</td>
<td>0.2sec</td>
<td>0.1A</td>
</tr>
</tbody>
</table>

V. CONCLUSION

In present work comparison between Sliding Mode Controller, PID Controller & PI Controller is to be evaluated under internal losses & input voltage variation. Sliding Mode Controller and PI Controller have same overshoot voltage but only difference is that PI Controller has more voltage drop than Sliding Mode. PID Controller has maximum settling time as compared to Sliding Mode & PI Controller. To test the robustness of Sliding Mode Controller input voltage is varied from 15V to 10V, it takes place at T = 1.1 sec, though the system was already stabilized to desired voltage value. PWM based Sliding Mode Controller shows acceptable performance than PI & PID Controller under internal losses & Input voltage variation. Nonlinearity & instability can be improved using Sliding Mode Controller.

REFERENCES


AUTHOR

Swarada Shrikant Muley received BE (Electrical, Electronics & Power Engineering) from P.E.S. College of Engineering, Aurangabad. She is pursuing M. E. (Control System) from M. B. E. S. College of Engg. Ambajogai, Maharashtra, India.