Journal of Applied Sciences

ISSN 1812-5654

Journal of Applied Sciences 5 (3): 588-592, 2005
ISSN 1812-5654

Sliding Mode Control of Dc-Dc Boost Converter

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Abstract: Control of Dc-Dc boost converter is a complex task due to the nonlinearity inherent in the converter and introduced by the external changes. A robust sliding mode controller for the control of Dc-Dc boost converter were described in this study. Dynamic equations describing the boost converter are derived and sliding mode controller is designed. The robustness of the sliding mode controlled boost converter system is tested for step load changes and input voltage variations. The computer-aided design software tool Matlab/Simulink is used for the simulations. The simulation results are presented. The simulation results show a fast dynamic response of the output voltage and robustness to load and input voltage variations.

Key words: Switched-mode power supplies, boost converter, Dc-Dc converter, sliding mode control

INTRODUCTION

The boost type Dc-Dc converters are used in applications where the required output voltage is higher than the source voltage. The control of this type Dc-Dc converters are more difficult then the buck type where the output voltage is smaller than the source voltage. The difficulty in the control of boost type Dc-Dc converters are due to their non-minimum phase structure i.e. since, the control input appears both in voltage and current equations, from the control point of view the control of boost type converters are more difficult than buck type[1].

Different control algorithms are applied to regulate Dc-Dc converters to achieve a robust output voltage. As Dc-Dc converters are nonlinear and time variant systems, the application of linear control techniques for the control of these converters are not suitable. In order to design a linear control system using classical linear control techniques, the small signal model is derived by linearization around a precise operating point from the state space average model[2]. The controllers based on these techniques are simple to implement however, it is difficult to account the variation of system parameters, because of the dependence of small signal model parameters on the converter operating point[3]. Variations of system parameters and large signal transients such as those produced in the start up or against changes in the load, cannot be dealt with these techniques. Multiloop control techniques, such as current mode control, have greatly improved the dynamic behavior, but the control design remains difficult especially for higher order converter topologies[4].

A control technique suitable for Dc-Dc converters must cope with their intrinsic nonlinearity and wide input voltage and load variations, ensuring stability in any operating condition while providing fast transient response[3]. Since switching converters constitute a case of variable structure systems, the sliding mode control technique can be a possible option to control this kind of circuits[5]. The use of sliding mode control enables to improve and even overcome the deficiency of the control method based on small signal models. In particular, sliding mode control improves the dynamic behavior of the system, endowing it with characteristics such as robustness against changes in the load, uncertain system parameters and simple implementation[6].

THE MATHEMATICAL MODEL OF Dc-Dc BOOST CONVERTER

The mathematical model of the boost type Dc-Dc converter in state space form is obtained by application of basic laws governing the operation of the system. A basic converter topology is shown in Fig. 1.

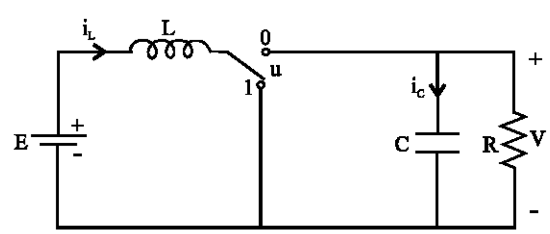

Fig. 1: Boost Dc-Dc converter

The dynamics of this converter operating in the continuous conduction mode can be easily obtained by applying Kirchhoff's voltage law on the loop containing the inductor:

$$\frac{di_L}{dt} = -(1-u)\frac{v}{L} + \frac{E}{L} \quad (1)$$

and Kirchhoff's current law on the node with the capacitor branch connected to it.

$$\frac{dv}{dt} = (1-u)\frac{i_L}{C} - \frac{v}{RC} \quad (2)$$

Letting x_1=i and x_2 = v, the state equations become

$$\dot{x}_1 = -(1-u)\frac{1}{L}x_2 + \frac{E}{L} \quad (3)$$

$$\dot{x}_2 = (1-u)\frac{1}{C}x_1 - \frac{1}{RC}x_2 \quad (4)$$

In the state space represantation:

$$\dot{x} = Ax+Bu \quad (5)$$

$$\begin{bmatrix}\dot{x}_1\\ \dot{x}_2\end{bmatrix} = \begin{bmatrix}0 & -(1-u)\frac{1}{L}\\ (1-u)\frac{1}{C} & -\frac{1}{RC}\end{bmatrix}\begin{bmatrix}x_1\\ x_2\end{bmatrix} + \begin{bmatrix}\frac{1}{L}\\ 0\end{bmatrix}E \quad (6)$$

where, i_L represents the inductor current and v is the output capacitor voltage. The control input u, representing the switch position function, is a discrete-valued signal taking values in the set {0;1}. The system parameters are constituted by L, which is the inductance of the input circuit; C the capacitance of the output filter; and R, the output load resistance. The external voltage source has the constant value E. It is assumed that the circuit is in continuous conduction mode, i.e. the average value of the inductor current never drops to zero, due to load variations. Figure 2 shows the block diagram representing the solution of the state equation given by Eq. 6.

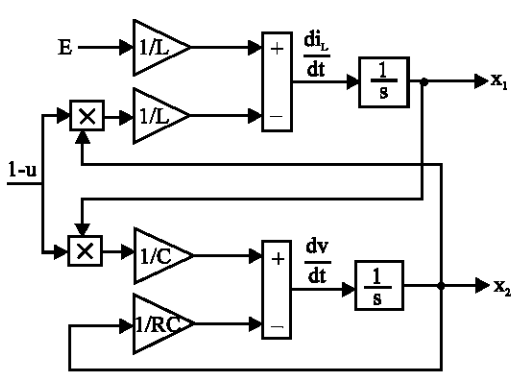

Fig. 2: Block diagram of a boost converter

SLIDING MODE CONTROL

The sliding mode control theory of the VSC system provides a method to design a system in such a way that the controlled system is to be insensitive to parameter variations and external load disturbances[5,6]. The approach is realized by the use of a high speed switching control law which forces the trajectory of the system to move to a predetermined path in the state variable space (called Sliding or Switching Surface and it is a line in case of two dimensions) and to stay in that surface thereafter. Before the system reaches the switching surface, there is a control directed towards the switching surface which is called reaching mode. The regime of a control system in the sliding surface is called Sliding Mode. In sliding mode a system's response remains insensitive to certain parameters variations and unknown disturbances.

The Variable Structure System (VSS) theory has been applied to nonlinear systems. One of the main features of this method is that one only needs to drive the error to a switching surface, after which the system is in sliding mode and robust against modeling uncertainties and disturbances[7,8]. A Sliding Mode Controller is a Variable Structure Controller (VSC). Basically, a VSC includes several different continuous functions that map plant state to a control surface and the switching among different functions is determined by plant state that is represented by a switching function.

Consider the following state equation:

$$\dot{x}(t) = Ax(t) + Bu(t) \quad (7)$$

which can be rewritten as:

$$\dot{x}(t) = f(x, t, u) \quad (8)$$

where, x is the state vector of the system, u is the control input and f is a function vector. If the function vector f is discontinuous on a surface S(x)=0 called sliding surface in the sliding mode theory then:

$$f(x, t, u) = \begin{cases} f^+(x, t, u^+) & \text{if} \quad S>0 \\ f^-(x, t, u^-) & \text{if} \quad S<0 \end{cases} \quad (9)$$

The system is in sliding mode if its representative point moves on the sliding surface S(x)=0. The sliding surface is also called as switching function because the control action switches depending on its sign on the two sides of the sliding surface.

In sliding mode theory, the control problem is to find a control input u such that the state vector x tracks a desired trajectory x* in the presence of model uncertainties and external disturbance. The sliding surface may then be set to be of the form:

$$S(x) = x - x^* \tag{10}$$

If the initial condition S(0)=0 is not satisfied then the tracking can only be achieved after a transient phase called reaching mode.

Since the aim is to force the system states to the sliding surface, the adopted control strategy must guarantee the system trajectory move toward and stay on the sliding surface from any initial condition if the following condition meets[9],

$$S\dot{S} \le -\eta|S| \tag{11}$$

where, η is a positive constant that guarantees the system trajectories hit the sliding surface in finite time[10]. The required sliding mode controller achieving finite time convergence to the sliding surface is given by:

$$u = \begin{cases} 1 & \text{for } S>0 \\ 0 & \text{for } S<0 \end{cases} \tag{12}$$

SLIDING MODE CONTROLLER DESIGN

Taking $x_1 = i_L$ and $x_2 = v$ as the states of the systems and using the state equations given in equations (3) and (4), now the aim is to achieve a desired constant output voltage V*. That is, in steady state the output voltage should be the desired voltage V*. Thus,

$$x_2 = V^* \tag{13}$$

$$\dot{x}_2 = \dot{V}^* = 0 \tag{14}$$

From the general sliding mode control theory, the state variable error, defined by difference to the reference value, forms the sliding function:

$$S = x_1 - x_1^* = 0 \tag{15}$$

This means that the control forces the system to evolve on the sliding surface[3]. The reference value x_1^* is derived internally to the controller from the output of the linear voltage controller.

In order to enforce sliding mode in the manifold S=0, the corresponding control signal for the ideal switch in Fig. 1[11]:

$$u = \frac{1}{2}(1 - \text{sign}(S)) \tag{16}$$

Since the aim is to guarantee that the state trajectory of the system is directed to the sliding surface s = 0 and slides over it, this is achieved with a suitable design of control law using the reaching condition:

$$S\dot{S} < 0 \tag{17}$$

since:

$$\dot{S} = \dot{x}_1 - \dot{x}_1^*$$

The steady state values of state variables coincide with the corresponding reference values and they are constants then, $\dot{x}_1^* = 0$, replacing Eq. 15 in Eq. 17 and solving it we get:

$$x_2 > E \tag{18}$$

This means that the sliding mode exists if the output voltage is higher than the source voltage.

SIMULATIONS

The closed-loop control is necessary to maintain the output voltage when the input voltage has some variation. The analysis of converter shows that the system dynamics can be divided into fast (current) and slow (voltage) motion. In this study two-loop control, an inner current control loop and an outer voltage control loop, is used. The voltage loop controller is a linear PI type controller. Since the motion rate of the current is much faster than that of the output voltage, a sliding mode controller is used in the inner current loop. The block diagram of the overall system is shown in Fig. 3.

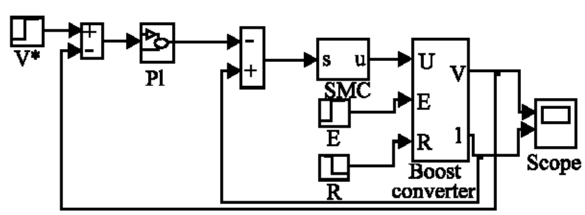

Fig. 3: Simulink block of sliding mode controlled boost converter

Simulations were performed on a typical 'boost' converter circuit with the following parameter values: E= 20 V, L= 40 mH, C= 4 μF, R= 40 W.

Figure 4 shows output voltage and current transient response during a change in the reference voltage from 30 to 40 V at time t= 0.025 sec.

It is known that the sliding mode control is regarded as a robust feedback control technique with respect to matched unmodelled external perturbation signals and

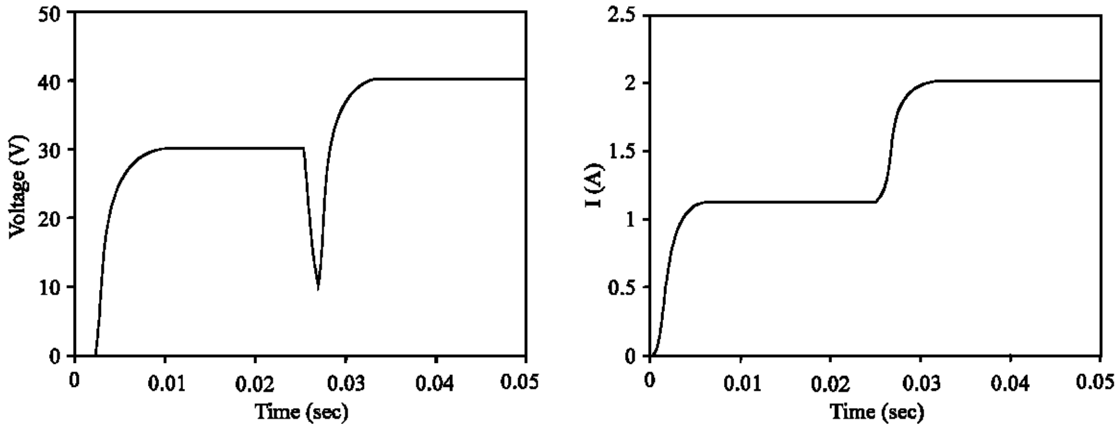

Fig. 4: Output voltage and input current waveforms for step change in reference voltage

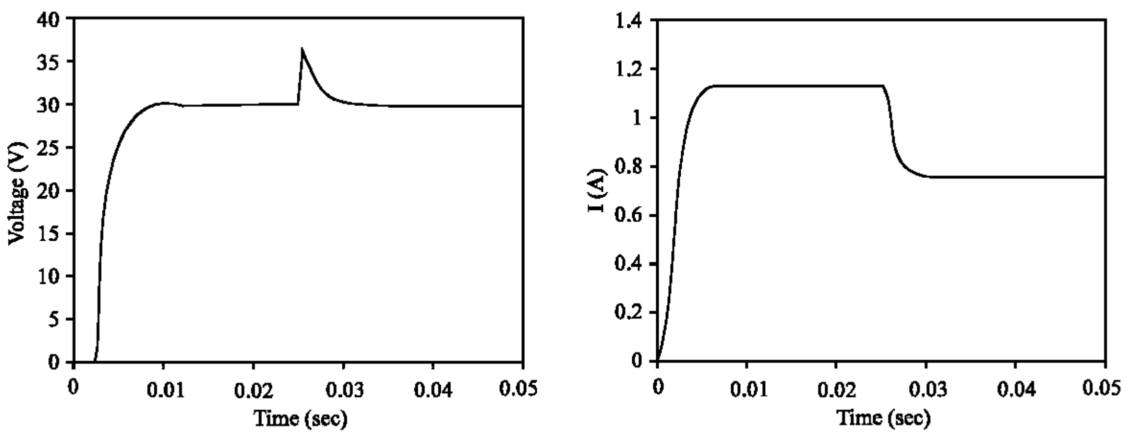

Fig. 5: Output voltage and input current waveforms for step load variations

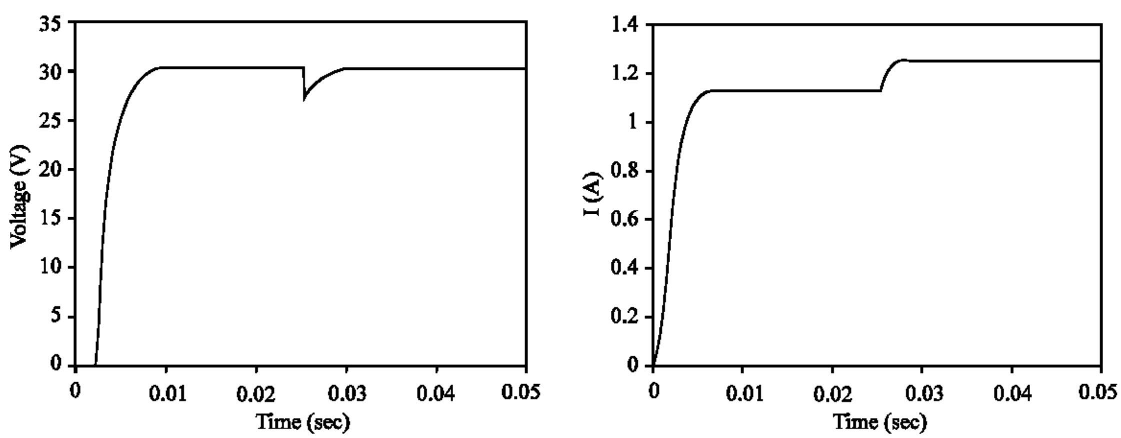

Fig. 6: Output voltage and input current waveforms for step changes in input voltage

plant parameter variations. In order to test the robustness of the sliding mode control scheme, the load resistor R has been let to change 50% of its nominal value of 40 Ω. This variation took place, at time, t = 0.025 sec, while the system was already stabilized to the desired voltage value of 30 V.

Figure 5 shows the recovering features of the proposed controller to the imposed load variation. As expected, the output voltage is robust when the load resistance was subject to a sudden unmodelled variation from R = 40 W to R= 60 W at time t = 0.025 sec.

Figure 6 shows the performance of the sliding mode based control scheme, when the input voltage E is changed from 20 to 18 V at the time t = 0.025 sec with a desired steady state output voltage of 30 V.

Figure 5 and 6 allows proving the robustness of the sliding mode control against changes in the load and variations in the input voltage.

As the boost converter systems are in the non-minimum phase structure, the voltage waveforms first change in opposite direction with the change in parameters then recovers to the desired value. This case can be seen in all simulation results.

The voltages and currents throughout the simulation are low pass filtered in order to avoid the low amplitude high frequency oscillations; however, this has an adverse effect on the control performance.

CONCLUSIONS

The simulation of a sliding mode controlled Dc-Dc boost converter is presented in this study. The proposed control scheme was shown to be robust with respect to load and supply parameter step variations. The simulation results show the validity of the sliding mode controlled boost converter model and the robustness of this control technique against changes in the load or variations in the input voltage. Therefore the system achieves a robust output voltage against load disturbances and input voltage variations to guarantee the output voltage to feed the load without instability. The approach has several advantages: stability even for large supply and load variations, robustness and good dynamic behavior.

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