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Voltage Ripple Reduction of Buck Converter Using Sliding Mode Control Technique

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Abstract: This paper presents a design and simulation of sliding mode controller for DC-DC buck converter. The performances comparison of DC-DC buck converter with open loop control, PID control and sliding mode control are presented. It is shown that sliding mode control technique can give good results in terms of robustness toward load and input voltage variations, while maintaining a dynamic response to standard control techniques.

Key words: Buck Converter · PID Control · Sliding Mode Control

INTRODUCTION

In recent years DC-DC converters have been increasingly used in many applications due to low weight, compactness and high efficiency. DC-DC converters are widely used in most of the power supply systems such as computers, aircrafts and electronic equipment. They are the most efficient way to implement actuators for electromechanical systems. A DC-DC converter must provide a regulated dc output voltage even subjected to load and input voltage variations. DC-DC buck converter is one of the most important converters which step down the input voltage. In buck converter, a high speed switching devices are used for better efficiency.

Since the DC-DC converters are nonlinear and time invariant system, the linear conventional control techniques applied for the control of these converters are not suitable. Variation of system parameters and large signal transients produced during start up or against changes in the load cannot be handled with these techniques. 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 [1]. Therefore, nonlinear and advanced non-conventional robust control structures to improve the performance of the DC-DC converters became the attractive research topic of the researchers. Sliding Mode Controllers (SMC) are well known for their robustness and stability [2]. It is a nonlinear control approach which complies with the nonlinear characteristic inherent in the DC-DC converters.

Application of sliding mode for dc-dc converters is promising because a switching control strategy is employed in the converters [3]. The sliding mode control of dc-dc converters is simple to implement and it is studied in many papers [4- 6]. It is robust against changes in the load and uncertain system parameters and characterized by a good dynamic response [7].

Buck Converter: In the Figure 1 shows the principle scheme for a buck converter. For buck converter presented is working in continuous-conduction mode. A Buck converter operates in continuous mode if the current through the inductor does not fall to zero during the commutation cycle. By varying the duty-cycle of the switch, the output voltage can be controlled. The simulation model of DC-DC buck converter using Matlab / Simulink is shown in Fig. 1. It consists of the input DC supply, MOSFET, Pulse Generator, inductor (L), Capacitor(C) and the load resistance(R). The values are given in Table 1. The desired output from this converter is 12 V DC.

Open Loop Control: To understand the steady state and transient performance of the buck converter, the open loop control is analyzed. In continuous-conduction mode,

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Table 1: Buck Converter Parameters

Input Voltage (V_{in})	24 V
Output Voltage (V_o)	12 V
Capacitor (C)	220 µF
Inductor (L)	69 µH
Load Resistance (R)	13 Ω
Nominal Switching Frequency (Fs)	100 kHz

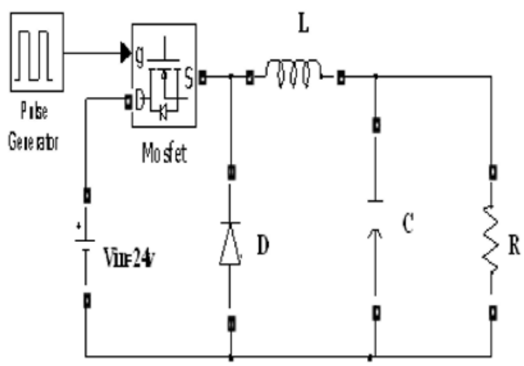

Fig. 1: Buck Converter

since in steady state the time integral of the inductor voltage over one time period must be zero. Consequently, in average value over the switching period (T) given by the following equation.

$$(V_{in} - V_o)T_{on} = V_o(T - T_{on}) \quad (1)$$

Where, $V_o/V_{in} = T_{on}/T = D$ (2)

This means that the output voltage varies linearly with the duty-cycle D. In a lossless circuit, the input power P_{in} must be equal to the output power Po.
So that,

$$V_{in}I_{in} = V_oI_o \quad (3)$$

and

$$I_o/I_{in} = V_{in}/V_o = 1/D \quad (4)$$

The average output voltage is given as,

$$V_o = DV_{in} \quad (5)$$

Critical inductance is given as

$$L_{Critical} = \frac{V_o^2 T_s}{2P_o}\left(1 - \frac{V_o}{V_{in}}\right) \quad (6)$$

For the continuous conduction mode $L \geq L_{critical}$

Based on the value of duty cycle the switch is operated to get the required output voltage. In this the value of duty cycle is selected as 0.5 to obtain 12 V output voltage (V_o) from 24 V input voltage (V_{in}).

PID Control: The standard procedure was followed to design the PID Controller. In the proportional control, only gain adjustment is available to improve the system performance. The limitations of its ability to achieve both satisfactory accuracy and acceptable relative stability are understandable. If a P controller cannot meet the performance specifications, it should be replaced by a dynamic controller or a dynamic compensator to provide more flexibility.

The focus is on series compensation using proportional plus integral plus derivative controllers as a dynamic compensator. Among the control methods the PID controller is traditionally used to control DC-DC converters. A good understanding of the proportional, integral and derivative actions is therefore important to evaluate how a dynamic compensation can change the system behaviour. The derivative action has an effect on the converter response at high frequencies and is used to improve the phase margin and a step must be taken to ensure that the closed loop system remains equal to unity at the desired crossover frequency. The D transfer function must contain high frequency poles. The pole has also the beneficial effect of attenuating the high frequency noise.

The converter response can be further improved by adding a lag compensator. This is known as the integral action, which produces a high gain at low frequencies, thus reducing the error in steady state. An inverted zero is added to the loop gain.

The advantages of lead and lag compensators can be combined in order to obtain both a wide bandwidth and a zero steady-state error. At low frequencies, the compensator integrates the error signal, which causes a large low-frequency loop gain and an accurate regulation of the low-frequency components of the output voltage. At high frequencies, the compensator introduces the phase lead into the loop gain, which improves the phase margin. This type of compensator is called PID controller. Fig. 2 shows the simulation block diagram of PID controller for a DC-DC buck converter.

Sliding Mode Control: The sliding mode theory provides a method to design a controller for a system so that the controlled system is to be insensitive to parameter variations and external load disturbances [5, 6].

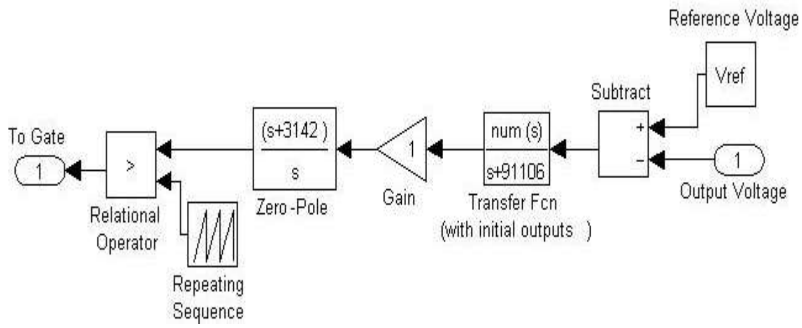

Fig. 2: PID controller

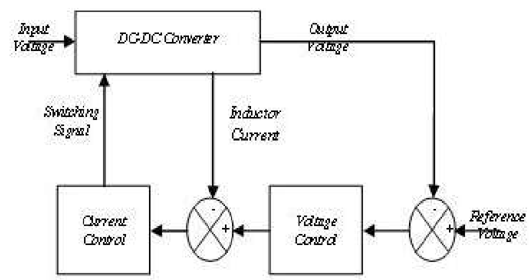

Fig. 3: Structure of SMC

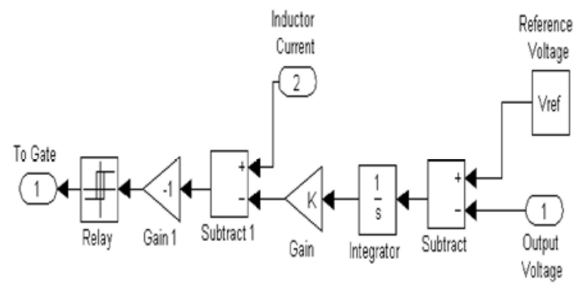

Fig. 4: Sliding mode controller

The details of the Sliding Mode control method, equivalent control and application to converters can be found in references [8-12]. 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 Surface 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. 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 [13, 14]. 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.

Fig. 3 shows a block diagram showing the implementation of this control for DC-DC converters. For most DC-DC converters used in practice, the motion rate of the current is much faster than the motion rate of the output voltage. Using cascaded control structure with two control loops can solve the control problem: an inner current control loop and an outer voltage control loop. The voltage control is usually realized with standard linear control techniques, where as the current control is implemented using either PWM or hysteresis control. Here we use the sliding mode approach for the control of inductor current.

Fig. 4 explains in detail the internal structure of the control part in Fig. 3 used as a control for the DC-DC buck converter in Matlab/Simulink To construct the simulation model for the sliding mode controlled Buck converter, system model for the main power circuit has to be made. For the Buck converter, it is convenient to use a system description, which involves the output error and its derivative.

$$x_1 = v - v^* \quad (7)$$

$$x_2 = \frac{dx_1}{dt} = \frac{dv}{dt} = \frac{i_c}{c} \quad (8)$$

The system equations, in terms of state variables x_1 and x_2 and considering a continuous conduction mode operation can be written as,

$$\dot{x}_1 = x_2 \quad (9)$$

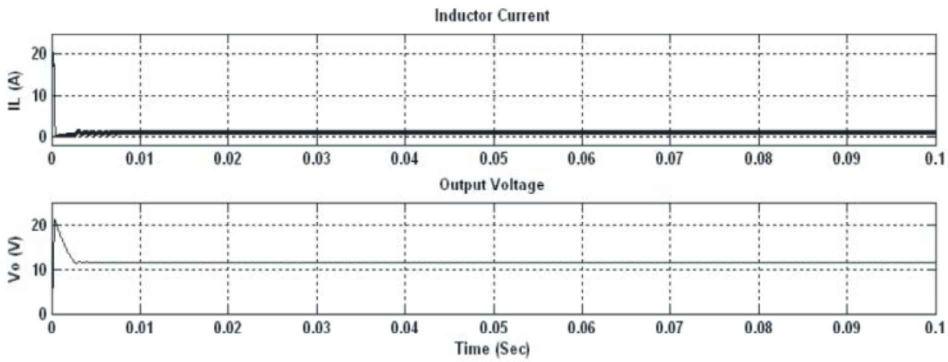

Fig. 5: Inductor current and Output voltage of open loop Buck converter.

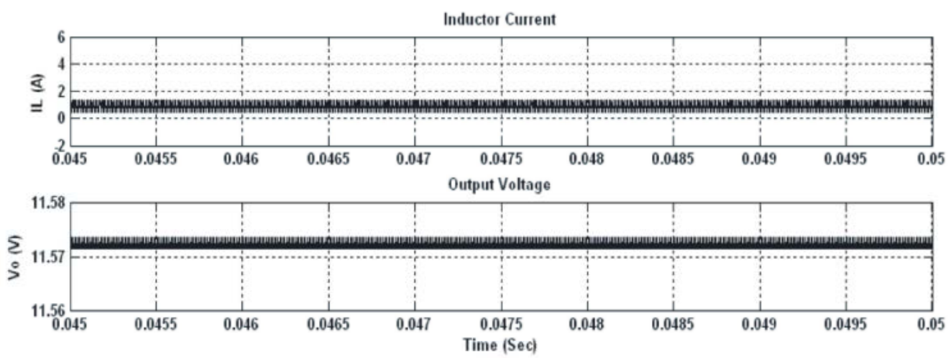

Fig. 5: Inductor current and Output voltage of open loop Buck converter (Expanded View).

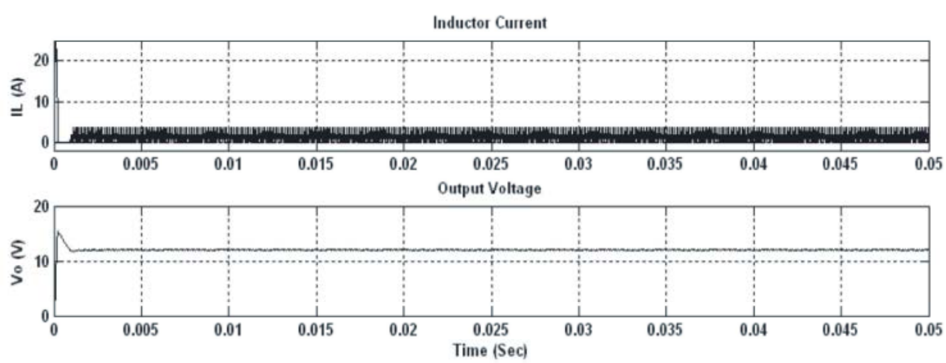

Fig. 6: Inductor current and Output voltage of PID Buck converter.

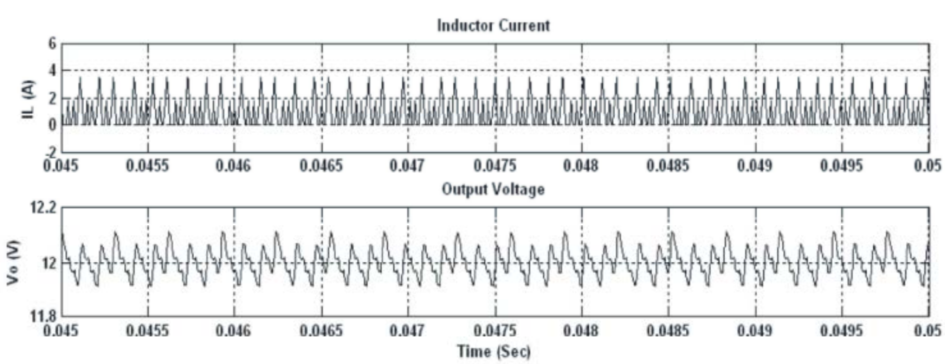

Fig. 6: Inductor current and Output voltage of PID Buck converter (Expanded View).

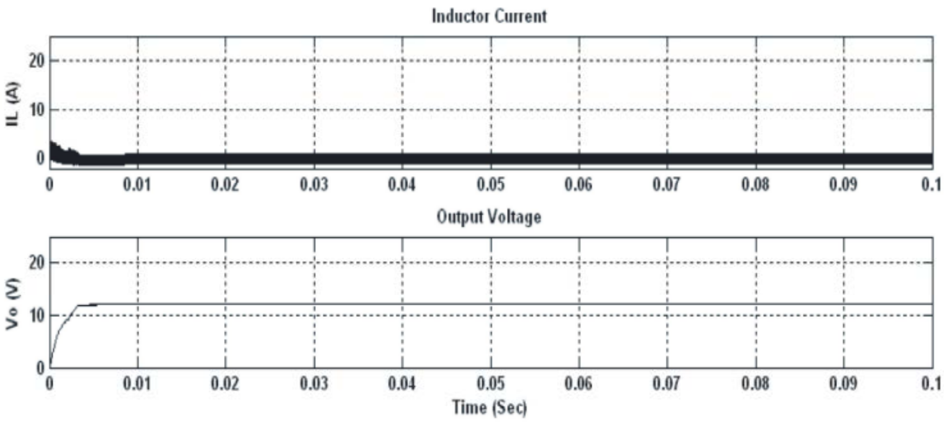

Fig. 7: Inductor current and Output voltage of SMC Buck converter..

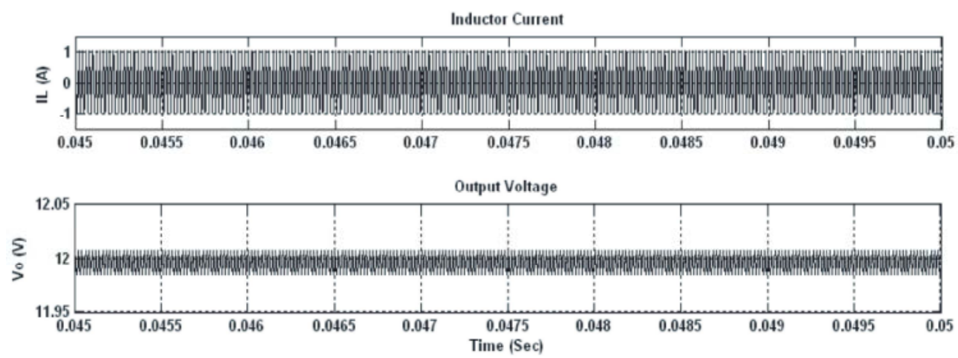

Fig. 7: Inductor current and Output voltage of SMC Buck converter (Expanded View).

Table 2: Simulation Outputs

Control	Settling Time (msec)	I_L(Peak) (A)	Output Voltage (V) Min.	Max.
Open	13.4	26.83	11.572	11.574
PID	4.45	20.25	11.915	12.110
SMC	2.23	3.95	11.985	12.007

Table 3: Voltage Ripples

Control	Ripple Voltage (V)	% Ripple
PID	0.195	1.625
SMC	0.022	0.183

$$x_2 = -\frac{x_1}{LC} - \frac{x_2}{RC} + \frac{V_{in}}{LC}u - \frac{v^*}{LC} \quad (10)$$

Where,
v^* - Output Voltage
u - Discontinuous input

Direct implementation of the simulation model of the sliding mode control of DC-DC buck converter can be derived from equations (7) to (10) and the control block diagram presented in Fig. 4.

RESULTS

DC-DC buck converter with open loop, with PID controller and with sliding mode controller has been simulated using MATLAB/ SIMULINK. The output voltage, inductor current and capacitor voltage are plotted for comparison. Fig. 5 shows the inductor current and output voltage of the open loop DC-DC buck converter and Fig. 6 shows the same graph for using PID controller and Fig. 7 shows the graph for sliding mode controller using Matlab/Simulink. It shows that the peak voltage and the inductor ripple current are very low in sliding mode control method compared with others.

CONCLUSION

The open loop controller, PID controller and the Sliding Mode Controller for DC-DC buck converter is presented. The application of the SMC technique to DC-DC buck converter is analyzed in detail. The simulation model in Matlab/Simulink for the system is developed.

The simulation results showed, that the sliding mode control can stabilize the power supply and that the output voltage and inductor current have very less ripple compared to other methods. SMC is gaining increasing importance as a design tool for the robust control of linear and non-linear systems. SMC provides inherent order reduction, robustness against system uncertainties disturbances and an implicit stability proof, *so* it could be said that the design allows high performance control system at low cost.

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