A new general controller for DC-DC converters based on SMC methods

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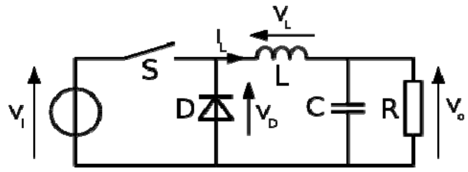
***Abstract*— A new general sliding mode controller is proposed for a DC-DC converter that can regulate the output voltage. Due to nature of some non-minimum-phase converters, an indirect method is used to control the output voltage. A robust nonlinear controller is employed that uses the output voltage error integral and provides zero steady state error. The proposed method was simulated in MATLAB / Simulink, and the controller, buck converter, boost, buck/boost, and fly back responses were determined. The proposed sliding mode control can cover the operating range of load variations, input voltage, and other parameters to provide robust and steady output voltage.**

Keywords*— *DC-DC converters, Sliding mode control, Nonlinear controller, Boost converter, Buck converter, Flyback converter.

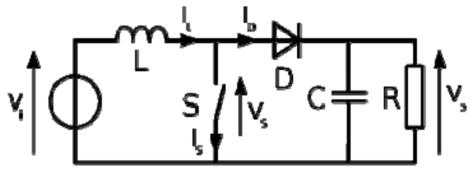
INTRODUCTION

Sliding mode control (SMC) was first proposed for variable structures in the early 1950s in the former Soviet Union [1–3]. Since then, variable structure systems and their control methods have been used in a broad range of different applications, such as non-linear discrete models; and multi-input/multi-output, large scale, and stochastic systems. The main control goal for variable structure systems is to improve the closed-loop stability. In recent years, nonlinear controllers have been largely replaced by linear controllers for DC-DC power converters, using feedback linearization [4], adaptive back stepping control [5], non-active based control [6], and SMC [7] to regulate the output voltage. Robust SMC has attracted consider-able attention because of the simplicity of implementation, relatively low volume calculations, and the controller can be practically implemented using basic analog circuits rather than digital processors. Applying sufficient controller power switches, the power converter is tuned so the output voltage tracks the reference value (V_{ref}). The effects of parasitic elements were not considered in the modeling phase. For example, the voltage drop across the power switch, semiconductor diode, and output capacitor equivalent series resistance in dynamic and steady state equations governing the behavior of the converter were neglected. The proposed method was simulated in MATLAB / Simulink, and the controller, buck converter, boost, buck/boost, and fly back responses were determined. The proposed sliding mode control can cover the operating range of load variations, input voltage, and other parameters to provide robust and steady output voltage.

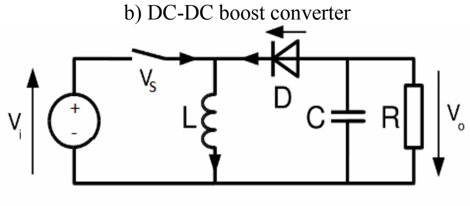
GENERAL MODEL



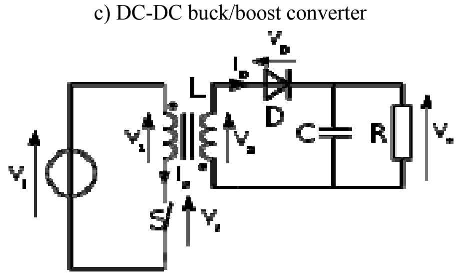
a) DC-DC buck converter



b) DC-DC boost converter



c) DC-DC buck/boost converter



d) DC-DC flyback converter

Fig.1. Basic DC-DC converter topologies.

Fig. 1 shows the main DC-DC converter topo-logies, Assuming CCM operation, there are two inductor current regions to consider. Considering the buck converter (Fig.1(a)), state space models for each region can be expressed as

$$X = (i_L, v_C) = (i_L, V_{out}) = (x_1, x_2) \quad (1)$$

Where X is state variable. When the power switch is ON,

$$\begin{pmatrix} \dot{x}_1 \\ \dot{x}_2 \end{pmatrix} = \begin{pmatrix} 0 & -\frac{1}{L} \\ \frac{1}{C} & -\frac{1}{RC} \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \end{pmatrix} + \begin{pmatrix} \frac{V_{in}}{L} \\ 0 \end{pmatrix} \quad (2)$$

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where L is inductor, R is resistor, C is capacitor, and V_{in} is input voltage, and when the power switch is OFF and $x_1 > 0$,

$$\begin{pmatrix} \dot{x}_1 \\ \dot{x}_2 \end{pmatrix} = \begin{pmatrix} 0 & -\frac{1}{L} \\ \frac{1}{C} & -\frac{1}{RC} \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \end{pmatrix} + \begin{pmatrix} 0 \\ 0 \end{pmatrix} \quad (3)$$

Combining (2) and (3), the average state space model of the DC-DC buck converter can be expressed as

$$\dot{x}_1 = -\frac{1}{L}(1-u)x_2 + \frac{V_{in}}{L}u \quad (4)$$

and

$$\dot{x}_2 = \frac{1}{C}(1-u)x_1 - \frac{1}{RC}x_2 \quad (5)$$

Where $\dot{x}_1$ denote inductor current and $\dot{x}_2$ is output capacitor voltage similarly, state the averaged state space model for the DC-DC boost, buck/boost and flyback with leakage inductor (L_m) are shown in Table I.

TABLE I. STATE VARIABLES FOR BOOST, BUCK/BOOST, AND FLYBACK DC-DC CONVERTERS WITH LEAKAGE INDUCTOR.

Converter Type	State Variable	
Boost converter	$\dot{x}_1 = -\frac{1}{L}(1-u)x_2 + \frac{1}{L}ux_2 + \frac{V_{in}}{L}(1-u)$	(6)
	$\dot{x}_2 = \frac{1}{C}(1-u)x_1 - \frac{1}{C}ux_1 - \frac{1}{RC}x_2$	(7)
Buck/boost converter	$\dot{x}_1 = -\frac{1}{L}(1-u)x_2 + \frac{1}{L}ux_2 + \frac{V_{in}}{L}u$	(8)
	$\dot{x}_2 = \frac{1}{C}(1-u)x_1 - \frac{1}{C}ux_1 - \frac{1}{RC}x_2$	(9)
Fly back converter	$\dot{x}_1 = -\frac{n_1}{n_2}\frac{1}{L}(1-u)x_2 + \frac{1}{L}ux_2 + \frac{V_{in}}{L}u$	(10)
	$\dot{x}_2 = \frac{n_1}{n_2}\frac{1}{C}(1-u)x_1 - \frac{1}{C}ux_1 - \frac{1}{RC}x_2$	(11)

.

TABLE II. UNCERTAIN PARAMETERS OF DIFFERENT CONVERTERS

	Uncertain parameters					
	θ_1	θ_2	θ_3	θ_4	θ_5	θ_6
Buck Converter	$-1/L$	0	$1/L$	$1/C$	0	$-1/RC$
Boost Converter	$-1/L$	$1/L$	$1/L$	$1/C$	$-1/C$	$-1/RC$
Buck/Boost Converter	$-1/L$	$1/L$	$1/L$	$1/C$	$-1/C$	$-1/RC$
FlyBack Converter	$1/L$	$1/L$	$1/L$	$1/C$	$-1/C$	$-1/RC$

SIMULATION RESULTS

Simulation results for DC-DC converters are presented incorporating the controller design of (22) with parameters from (12) and (13), converter circuitry as shown in Fig. 1, and orbital elements and numerical values shown in Table II. Converters are stable with the assumptions in Table I. In a DC-DC converter, it is presumed that the input voltage and load parameters are indefinite. It is obvious that the ability to adjust the converter controller's output voltage provided in various situations with various output reference voltage. In the remainder of this section, simulation results are presented to prove the items listed.

TABLE III. NOMINAL SPECIFICATIONS FOR DC-DC CONVERTERS

	Buck	Boost	Buck/Boost	Flyback
Input voltage (V_{in}):	24 V	12 V	12 V	12 V
Inductor (L):	550 µH	550 µH	550 µH	550 µH
Output capacitor (C):	330 µF	330 µF	330 µF	330 µF
Load resistor (R):	23 Ω	23 Ω	23 Ω	23 Ω
Switching frequency (f_s):	9.25 kHz	9.25 kHz	9.25 kHz	9.25 kHz
Diode bias voltage (V_D):	0.7 V	0.7 V	0.7 V	0.7 V

A. Buck converter

A buck or step-down converter steps down the voltage, while stepping up the current, from its input (supply) to its output (load). It is a class of switched-mode power supply (SMPS) typically containing at least two semiconductors (a diode and a transistor, although modern buck converters frequently replace the diode with a second transistor used for synchronous rectification) and at least one energy storage element (a capacitor, inductor, or the two in combination). To reduce voltage ripple, capacitor-based filters (sometimes in combination with inductors) are normally added to the output (load side filter) and input (supply side filter) [15]. Test 1: We assume the nominal values as shown in Table 3, and converter reference voltage changes from V_{ref} =12–5 V at time t = 0.3 s. Figure 3 shown the simulation results. The proposed produces zero steady state error and its dynamic response is acceptable.

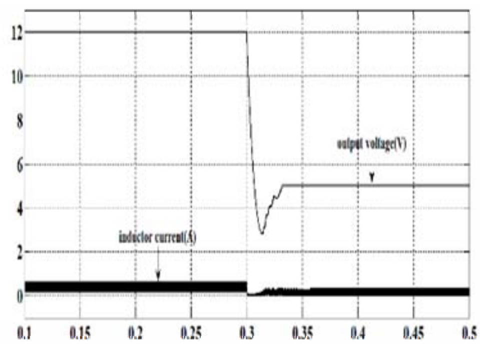

Fig. 3. Output voltage and inductor current waveforms for test 1

Test 2: Suppose the converter elements are initialized in stable condition as R = 23 Ω, C = 330 µF, and V_{ref} = 12 V. We apply a step change in load resistance and output capacitance (R = 100 Ω and C = 660 µF at t = 0.15 s). The resultant reference and input voltage were V_{ref} = 5 V at t = 0.25 s and V_{in} = 20 V at t = 0.4 s, and the final results of simulations are shown in Fig. 4. The proposed controller produces zero steady state error and its dynamic response is acceptable.

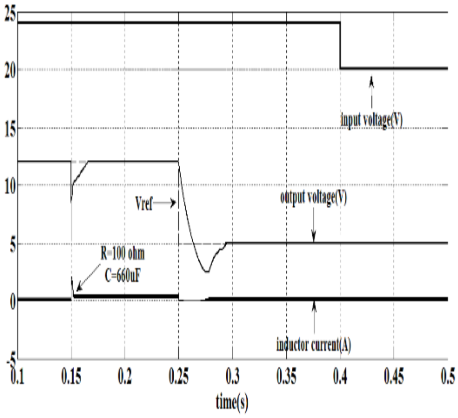

Fig. 4. Output, input, and reference voltage, and inductor current waveforms for test 2

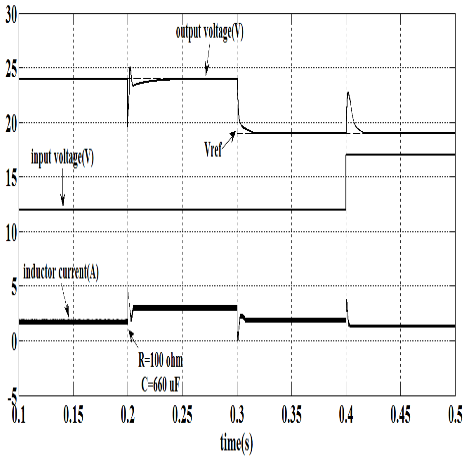

Fig. 6. Output voltage and reference voltage and inductor current waveforms for test 4

B. Boost converter

A boost or step up converter steps up the voltage, while stepping down the current, from its input (supply) to its output (load). It is a class of switched-mode power supply (SMPS) containing at least two semiconductors (a diode and a transistor) and at least one energy storage element (a capacitor, inductor, or the two in combination). To reduce voltage ripple, capacitor based filters (sometimes in combination with inductors) are commonly added to the converter output (load side filter) and input (supply side filter) [15]. Test 3: We assumed the nominal values provided in Table 3. The converter reference voltage was changed from V_{ref} = 19–28 V at t = 0.3 s. The results of simulations are shown in Fig. 5. The proposed controller produces zero steady state error and its dynamic response is acceptable.

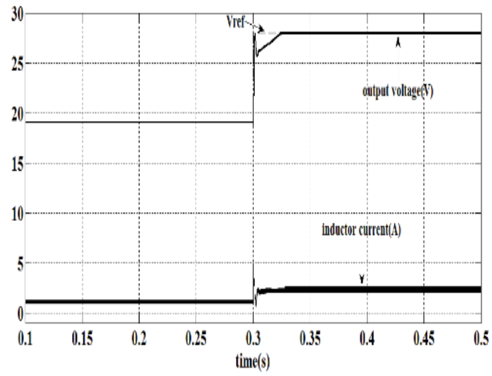

Fig. 5. Output voltage and inductor current waveforms for test 3

Test 4: The converter elements were initialized in stable condition as R = 23 Ω, C = 330 μF and V_{ref} = 24 V. A step change was applied to the load resistance and output capacitance (R = 100 Ω and C = 660 μF at t = 0.2 s). The resultant reference and input voltages were V_{ref} = 15 V at t = 0.3 s and V_{in} = 17 V at t = 0.4 s, with final results of simulations as shown in Fig. 6. The proposed controller produces zero steady state error and its dynamic response is acceptable.

C. Buck/boost converter

The buck/boost converter has output voltage magnitude either greater than or less than the input voltage magnitude. It is equivalent to a flyback converter using a single inductor rather than a transformer. Two different topologies are considered as buck/boost converters. Both produce a range of output voltages, from an output voltage much larger (in absolute magnitude) than the input voltage, down almost to zero [15]. Test 5: We assumed the nominal values provided in Table 3. The converter reference voltage changed from V_{ref} = 5–10 V at t = 0.3 s, and simulation results are shown in Fig. 7. The proposed controller produces zero steady state error and its dynamic response is acceptable.

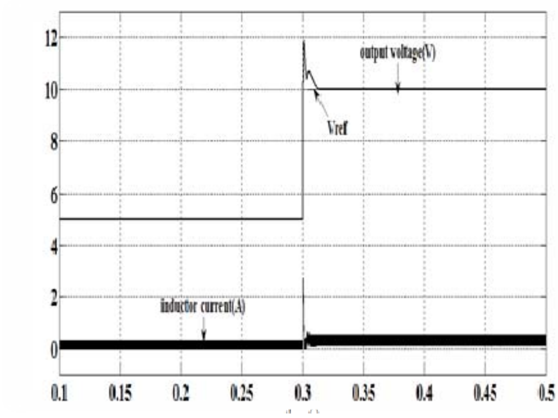

Fig. 7. Output voltage and inductor current waveforms for test 5

D. Buck converter

Test 6: The converter elements were initialized in stable condition as R = 23 Ω, C = 330 μF and V_{ref} = 5 V. A step change was applied in load resistance and output capacitance (R = 100 Ω and C = 660 μF at t = 0.25 s). The resultant reference and input voltages are shown in Fig. 6. The proposed controller produces zero steady state error and its dynamic response is acceptable.

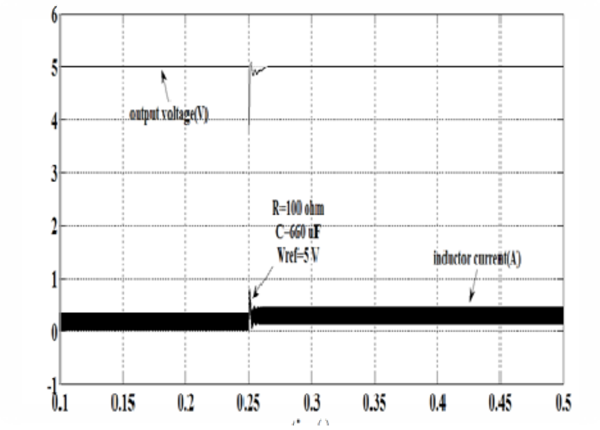

Fig. 8. Output, input, and reference voltage, and inductor current waveforms for test 6

Test 7: The output reference voltage was $V_{ref} = 5$ V, and

simulation results for step change in input voltage (12–18 V at t = 0.3 s) are shown in Fig. 9. The proposed controller produces zero steady state error and its dynamic response is acceptable.

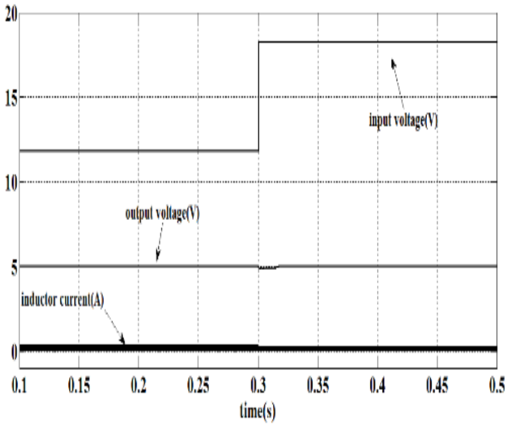

Fig. 9. Output and input voltage, and inductor current waveforms for test 7

E. *Boost converter*

Test 8: Suppose the converter elements are initialized in stable condition as R = 23 Ω, C = 330 μF, and V_{ref} = 18 V. A step change in load resistance and output capacitance was applied (R = 100 Ω and C = 660 μF at t = 0.25 s), and the simulation results are shown in Fig. 10. The proposed controller produces zero steady state error and its dynamic response is acceptable.

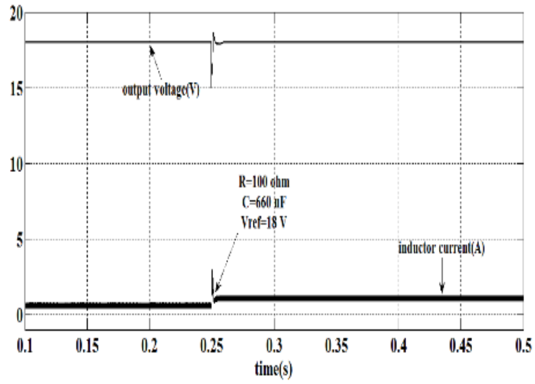

Fig. 10. Output voltage and inductor current waveforms for test8

Test 9: The output reference voltage $V_{ref} = 18$ VVref=5V,

and the simulation results for a step change in input voltage (12–18 V at t = 0.3 s) are shown in Fig. 11. In this experiment, input voltage will change from. The proposed controller produces zero steady state error and its dynamic response is acceptable.

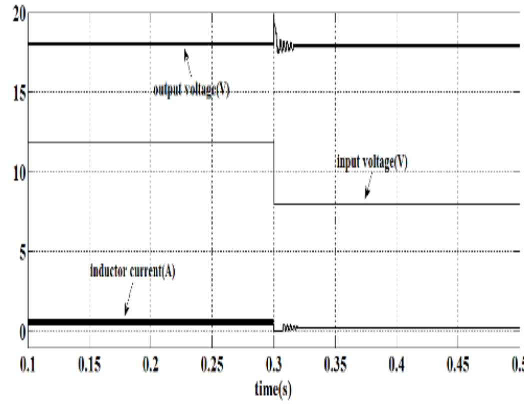

Fig. 11. Output and input voltage, and inductor current waveforms for test 9

F. Flyback converter

Test 10: We assumed the nominal values provided in Table 3. The converter reference voltage was changed (20–28 V at t = 0.3 s), and the results of simulations are shown in Fig. 12. The proposed controller produces zero steady state error and its dynamic response is acceptable

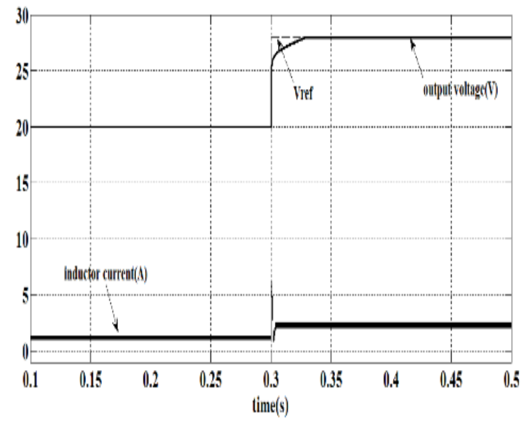

Fig. 12. Output, input, and reference voltage, and inductor current waveforms for test 10

Test 11: The converter elements were initialized in stable condition as R = 23 Ω, C = 330 μF, and V_{ref} = 20 V. A step change in load resistance and output capacitance was applied (R = 100 Ω and C = 660 μF at t = 0.2 s). The resultant reference voltage and input voltage were V_{ref} = 24 V at t = 0.3 s and V_{in} = 17 V at t = 0.4 s, and the terminating simulation is shown in Fig. 13. The proposed controller produces zero steady state error and its dynamic response is acceptable.

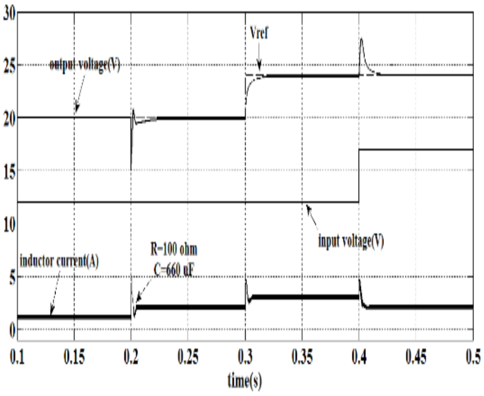

Fig. 13. Output, input, and reference voltage, and inductor current waveforms for test 11

CONCLUSIONS

A general sliding mode controller was designed for DC-DC converters in continuous conduction mode. An indirect method was used to control the converter output voltage because boost, buck/boost and flyback converters are non-minimum phase, requiring indirect control, and the controller can also be used for buck converters. A suitable PI controller was applied in sliding mode to change converter power switching from on to off so the output voltage reaches the reference voltage. The proposed controller produces zero error in steady-state for various output voltage references, variable loads and variable inputs along with acceptable dynamic response. The main advantages of the proposed controller are stability and robustness of the system parameters in the presence of uncertainty, and load and input voltage variations with constant frequency. Buck, boost, buck/boost, and flyback converters were simulated in MATLAB/Simulink software to evaluate the proposed controller response

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