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Modelling and Simulation of DC-DC Boost Converter using Sliding Mode Control

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Abstract*: *DC-to-DC converter is an electronic circuit that converts direct current (DC) from a given voltage to another. DC-DC converters have a broad range of applications, starting from electronic gadgets to household equipment, adapters of mobile phone and laptops, aero plane control frameworks and communication hardware. This paper illustrates the practical application of DC-DC boost converter using Sliding Mode Control (SMC). DC-DC converters can be categorized into different categories in terms of mechanical, electrical and electronic features. SMC DC-DC converters show better performance compared to other converters under certain conditions. This nonlinear control system is especially well suited for Variable Structure Systems. The most significant advantage of Sliding Mode Control over conventional control systems is its robustness against load, line and parametric uncertainties.

Keywords: Sliding Mode Control, Boost Converter, Power Electronics, Control Systems.

I. INTRODUCTION

A DC-DC boost converter is used where desired output voltage is greater than the input voltage. Control of these types of converters may be difficult compared to other converters due to its non-minimum phase structure where control inputs are prevalent in both voltage and current equations. There are numerous control schemes for the output of voltage regulations of DC-DC power converters. Due to the presence of non-linearity and time variance in the DC-DC converters, linear control techniques for controlling these converters are not suitable. From the state space averaging model small signal mode is derived for designing a linear control system. Though these type of controllers are comparatively easy to implement, it is complicated to account the change of system parameters.

These techniques cannot handle parametric uncertainties and large signal transient that is generated during startup or when the load is changed. A multi-loop control method, such as current mode control, has paved the way to improved dynamic performance, but the designing of controllers remains difficult for converters with higher orders. [1].

Pulse width modulation based DC-DC converters became very much popular in the last few decades. As switching power converters constitute an ease of variable structure system (VSS), the sliding mode control (SMC) can be a good alternative for controlling these circuits

Stability and robustness of sliding mode (SM) controllers make them popular. SMC can operate at an infinite operating frequency range. In this scheme controlled variable

Tracks a reference and eventually attains steady state performance. [2] But operating these converters at unbounded frequency utilizing SMC could be a challenge. This challenge is primarily due to switching losses, transformer's core and copper losses and electromagnetic interference noise (EMI)

II. CONTROL MECHANISM FOR DC-DC

By configuring and orienting different circuit components and operating the switches appropriately power conversion using converter circuits is done. All the DC-DC converters are designed for specified input voltage and output conditions. Alternatively, it can be said that it is operated in steady state conditions only, but in real life it may not be possible as there are some disturbances that causes deviation of circuit operation from nominal conditions. These disturbances can be caused by several reasons. Some of the most common source of disturbances occur due to the changes in line, load, parametric instabilities and small perturbation in switching events such as startup and shut down. These divergences from the nominal conditions of circuit operation is called dynamic behavior of the circuit. No significant action is required when there is negligible amount of disturbance, but in many instances deviation from nominal conditions affects the circuit operation heavily. Therefore, there is a need to come up with a proper controller or compensator to get rid of these problems. The control scheme of switch mode power supply circuits has several features. Output voltage is made constant during the steady state condition. By limiting external stress on circuit components, the control circuitry protects all the components during transient operation.

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In pulse width modulation (PWM) converters output is regulated by the control circuit by means of fixing switching frequency and fluctuating the on time of the switch. On the contrary in resonant switched mode power supply, output is regulated by changing the switching frequency and keeping the ON and OFF time of the switch fixed. [4].

One of the major challenges for a designer is to model the power stages .One of the most common techniques is to model only the power stage's switching elements. Model for this kind of circuit is presented below. [5]

Power stage of the converter is comprised of two inputs-

a) Input voltage.

b) Duty cycle.

Duty cycle works as the control input. Switching action of the power stage of the converter is controlled by the duty cycle. Major elements of the power supply control loop are given in the figure below.

A. Control Technique for boost converter

Control technique used for DC-DC converters should be able to withstand the intrinsic non linearity and parametric uncertainties such as load and line voltage variations, ensuring stability in all operating conditions. Numerous control techniques are there to control the load of the boost converters. Most common controller are PI controller, PID controller, Fuzzy logic controller, artificial neural network controller. In this paper a comparison between PI controller, PID controller and sliding mode controller has been shown

B. PI Controller

The integral term of a PI controller reduces the steady state term to zero unlike proportional only controller. The absence of derivative action makes the system stable in the presence of disturbances, because it exhibits more sensitivity to higher frequency terms in the input. Derivative control can be thought as a crude prediction of the error in future, based on the current slope of the error. It makes the system less responsive. Hence, it will take relatively more time to reach the set point compared to a properly tuned PID system.

C. PID Controller

To eliminate steady state error and transient errors all the three techniques need to be merged together to get PID controller. Hence, the control signal becomes a linear combination of the error, integral of the error and rate of change of the error. All these gain values are modifiable.

To get acceptable performance the gain parameters K_p, K_i *and* K_d are adjusted. This adjustment process is known as gain tuning. Increasing K_p *and* K_i reduces steady state error but it may not be able to exhibit proper stability. PID controller reduces the error as well as provides acceptable damping and stability

D. Sliding Mode Controller

Sliding mode control gives a systematic approach to obtain stability and constant output in the presence of parametric uncertainties. In SMC, trajectories starting from any point are pressured to attain and stay on a predefined surface called sliding surface. When the trajectory is confined to the sliding surface, system's dynamical behavior depends on the sliding manifold. Since the sliding surface doesn't depend on system parameters, it shows a robust characteristics in terms of load and line disturbances. Thus the sliding mode control technique involves the construction of an appropriate sliding manifold and a corresponding law which forces the trajectories to attain the sliding surface in finite time and stay on the manifold for all future time by properly implementing and designing the sliding manifold. VSS attains traditional goals of control ranging from tracking, stabilization and adjustment etc.

E. Sliding Mode Control for DC-DC Boost Converter

The voltage error, rate of change of voltage error and integral of voltage error are assumed to be the three states of the boost converter. Following expressions are derived under continuous conduction mode

$$X_1 = V_{ref} - \beta V_0 \tag{1}$$

$$X_2 = \dot{X}_1 = \frac{\beta}{C}\left[\frac{V_0}{R_L} - \int \frac{uV_i - V_0}{R_l}\, dt\right] \tag{2}$$

$$X_3 = \int X_1 dt \tag{3}$$

$$X_{boost} = \begin{bmatrix} V_{ref} - \beta V_0 \\ \frac{\beta}{C}\left[\frac{V_0}{R_L} - \int \frac{uV_i - V_0}{R_l}\, dt\right] \\ \int V_{ref} - \beta V_0 dt \end{bmatrix} \tag{4}$$

$$\dot{X}_{boost} = AX_{boost} + Bu \tag{5}$$

$$A = \begin{bmatrix} 0 & 1 & 0 \\ 0 & \frac{1}{R_l C} & 0 \\ 1 & 0 & 0 \end{bmatrix} \tag{6}$$

$$B = \begin{bmatrix} 0 \\ \frac{\beta V_0}{LC} - \frac{\beta V_i}{LC} \\ 0 \end{bmatrix} \tag{7}$$

Sliding mode controller has a switching function

$$u = \begin{cases} 1 \; when \; \sigma > 0 \\ 0 \; when \; \sigma < 0 \end{cases} \tag{8}$$

Where S is the instantaneous state variables trajectory and is represented as

$$\sigma = \alpha_1 X_1 + \alpha_2 X_2 + \alpha_3 X_3 \tag{9}$$

With

$$J^T = [\alpha_1 \quad \alpha_2 \quad \alpha_3]$$

In order to make sliding mode controller work equation (9) should be satisfied

$$\lim_{\sigma \to 0} \sigma \dot{\sigma} < 0 \tag{10}$$

Substituting the values of x_1, x_2, x_3 into equation (9) gives

$$\sigma = \propto_1 \frac{d}{dt}\left(v_{ref} - \beta \frac{1}{C} \int i_c dt\right) + \propto_2 \frac{d}{dt}\left(\frac{\beta v_0}{R_L C} + \frac{\beta}{LC} \int (v_0 - v_i) \dot{u} dt\right) + \propto_3 \frac{d}{dt} \int (v_{ref} - \beta v_0) dt \tag{11}$$

There are two possibilities

Condition 1

$$\sigma \to 0^+ \; and \; \dot{\sigma} < 0$$

(12)

Substituting equation (8) into

equation (11) gives us

$$-\alpha_1 \frac{\beta i_c}{C} + \alpha_2 \left(\frac{\beta i_c}{C}\right) + \alpha_3 \left(v_{ref} - \beta v_0\right) < 0$$

(13)

Condition 2:

$$\sigma \to 0^- \ and\ \dot{\sigma} > 0$$

Substituting equation (8) into equation (11) again gives us

$$-\alpha_1 \frac{\beta i_c}{c} + \alpha_2 \left(\frac{\beta i_c}{c} + \frac{\beta v_0}{LC} - \frac{\beta v_i}{LC}\right) + \alpha_3 \left(v_{ref} - \beta v_0\right) > 0 \quad (14)$$

From equation (13) and (14) existence condition for boost converter can be written as

$$0 < \beta L \left(\frac{\alpha_1}{\alpha_2} - \frac{1}{R_L C}\right) i_c - LC\frac{\alpha_3}{\alpha_2}\left(v_{ref} - \beta v_0\right) < \beta\left(v_0 - v_i\right) \quad (15)$$

From equation (13) the ramp and control voltages are selected

$$v_{ramp} = \beta(v_0 - v_i) \quad (16)$$

$$v_c = -k_{p1} i_c + k_{p2}\left(v_{ref} - \beta v_0\right) + \beta\left(v_0 - v_i\right)$$

Where

$$k_{p1} = \beta L\left(\frac{\alpha_1}{\alpha_2} - \frac{1}{R_L C}\right)$$

$$k_{p2} = LC\frac{\alpha_3}{\alpha_2}$$

β Is the feedback factor

System model of the sliding mode controller can be found from the control voltage equation given in equation (16) and the corresponding diagram is shown in fig.

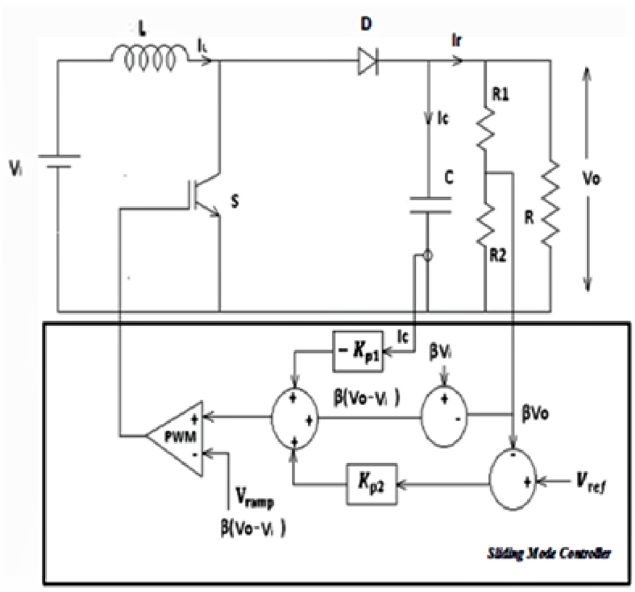

Fig. 1. System Modeling of SMC boost Converter

PWM based sliding mode controller is simulated in this section. Response of this controller under parametric uncertainties like input and load change is observed. The coefficients $\alpha_1, \alpha_2, \alpha_3$ are found from the following equations:

$$\frac{\alpha_1}{\alpha_2} = \frac{10}{T_s}$$

$$\frac{\alpha_3}{\alpha_2} = \frac{25}{\delta^2 T_s^2}$$

Here δ is the damping constant and T_s is the expected settling time. The damping constant can be selecting peak overshoot voltage M_p

$$\delta = \sqrt{\frac{(\ln\frac{M_p}{100})^2}{\pi^2 + (\ln\frac{M_p}{100})^2}}$$

Above equations can be used to find out the gain factor K_{p1} and K_{p2}

Table 1

List of different parameters

Description	Parameter	Nominal Value
Input Voltage	V_{in}	24
Capacitor	C	2000μF
Inductor	L	1mH
Switching frequency	F	100kHz
Sliding mode controller gain	K_{p1}	0.149
	K_{p2}	1.35
PID controller gain (Proportional Constant)	K_p	1
PID controller gain (Integral constant)	K_i	100
PID controller gain (Derivative constant)	K_d	0.05
PI controller gain (Proportional constant)	K_p	0.17
PI controller gain (Integral constant)	K_i	15
Desired voltage	V_o	48V

III. SIMULATION RESULT

To verify the response of the converter a dynamic model of the DC-DC boost converter is simulated in Simulink. It has been simulated for variation of the resistive load from 24 ohms to 240 ohms. The block diagram of boost converter and corresponding sliding mode controller is shown in figure 2. To maintain the output voltage, closed loop control is necessary

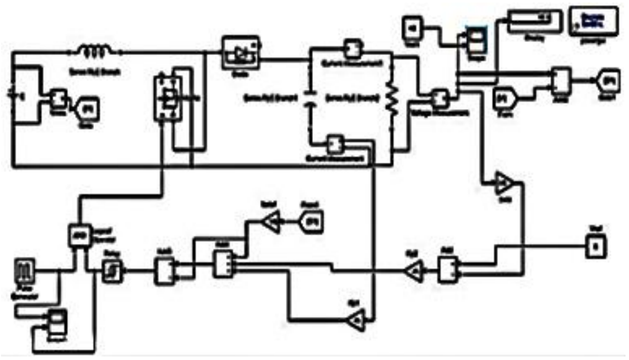

Fig. 2. System Modeling of SMC in MATLAB

Table 2
Simulation result of SMC under changing line condition

Input voltage	Output Voltage
24	46.52
25	46.76
26	46.83
27	46.93
28	47.07
29	47.15
30	47.18
31	47.25
32	47.33
33	47.36
34	47.44
35	47.49
36	47.54
37	47.61
38	47.64
39	47.69
40	47.73
41	47.77
42	47.82
43	47.85
44	47.87
45	47.94
46	47.97
47	47.99
48	48.01

Table 3
Simulation result of SMC under changing load condition

Load resistance	Output Voltage
24	46.72
100	47.61
200	47.72
240	47.74
400	47.78
600	47.85
800	47.88
1000	47.91
1200	47.92
1300	47.92
1320	48

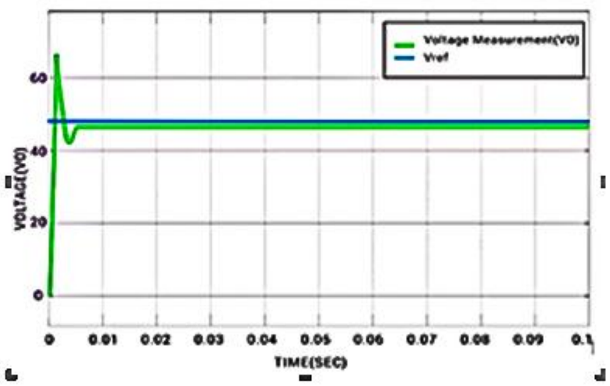

Fig 3: Sliding mode control of boost converter with 24 ohm load

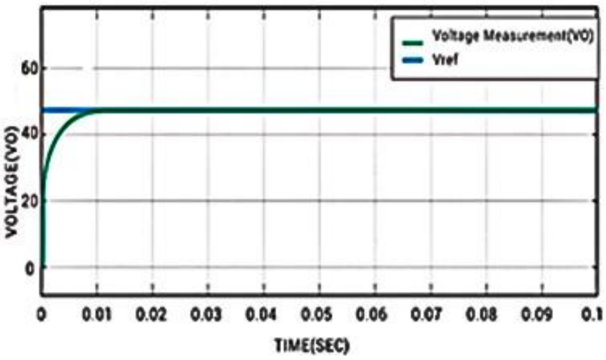

Fig 4: Sliding mode control of boost converter with 1000 ohms

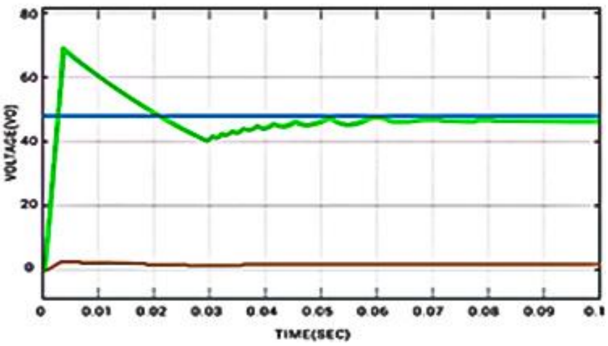

Fig 5: PI controller with 24 ohm load

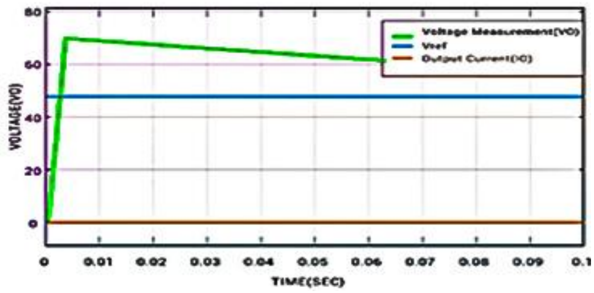

Fig 6: PI controller with 240 ohms load

From the simulation result it is evident that sliding mode controller performs better compared to PI controller under changing line and load conditions

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IV. HARDWARE IMPLEMENTATION

Designed boost converter was implemented on hardware to check the real time system performance. Partial setup of the circuit without connecting the DC source is shown below. Simulation was slightly modified to be implemented on the hardware as the previous simulation was not possible to be implemented directly. This simulation also exhibits the same result and proves robustness of the system.

Components were assembled in a bread board and code was written accordingly for the controller portion and burnt into Arduino board. After completing the setup output voltage of the boost converter was measured across the output resistor network. Full hardware setup is shown below

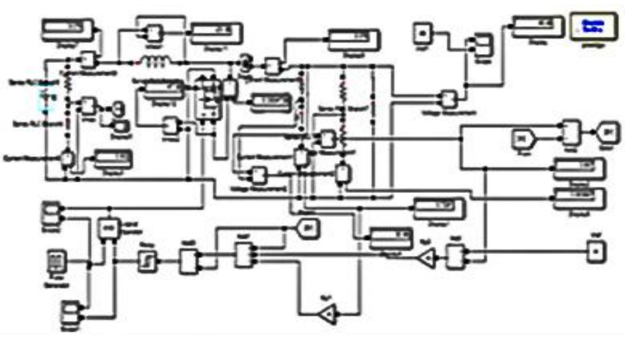

Fig 7. Modified SMC for hardware implementation

Fig 8. Hardware implementation of SMC boost converter

V. RESULT AND DISCUSSION

A relation between the PWM based sliding mode controller, PID and PI controllers for a DC-DC boost converter is demonstrated. Performance analysis for controlling DC-DC boost converters are evaluated in simulation under line voltage variation, internal losses and parametric uncertainties. Sliding mode controller and PI controller have the same overshoot voltage but voltage drop is more when PI controller is used. PID controller has maximum settling time in comparison to SMC and PI controller. In order to test the robustness of the sliding mode control technique, the line voltage is changed from 24v to 47v.

Controller	Input	Load	Settling time
Sliding Mode Controller	24	24	0.005
		240	0.01
PI controller	24	24	0.06
		240	0.2
PID controller	24	24	0.03
		240	0.2

VI. CONCLUSION

PWM based sliding mode controller exhibits better performance than PID and PI controller having the lowest deviation from reference voltage under internal losses, parametric uncertainties and input voltage variations

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