PWM-Based Sliding Mode Controller for DC-DC Boost Converter

Sumita Dhali*, P.Nageshwara Rao,Praveen Mande***, K.Venkateswara Rao******

Department of Electrical And Electronics Engineering, GITAM UNIVERSITY, Visakhapatnam(A.P.)

ABSTRACT-

This paper presents a design and simulation of pulse width modulation (PWM) based sliding mode (SM) controller for DC/DC boost converter operating in continuous conduction mode. The general aspects of the performances and properties of the sliding mode controller is compared with the Proportional Integral Derivative (PID) controller and Proportional Integral (PI) controller. Simulation results shown that the sliding mode control scheme provides good voltage regulation and is suitable for boost DC-to-DC conversion purposes. The derived controller/converter system is feasible for common step-up conversion purposes. Moreover, it is exposed to significant variations which may take this system away from nominal conditions, due to changes on the line voltage and parameters at the input keeping load as a constant.

Keywords: **DC-DC boost converter, Pulse width modulation, sliding mode controller**

1.INTRODUCTION:

Direct current (DC-to-DC) converters are circuits which convert sources of direct current (DC) from one voltage level to another by changing the duty cycle of the main switches in the circuits. Since DC–DC converters are nonlinear systems, they represent a big challenge for control design. Since classical control methods are designed at one nominal operating point, they are not able to respond satisfactorily to operating point variations and load disturbance. They often fail to perform satisfactorily under large parameter or load variations.

The boost type DC-DC converters are used in applications where the required output voltage needed to be higher than the source voltage. The control of this type DC-DC converters are more difficult than the buck type where the output voltage is smaller than the source voltage. The difficulties in the control of boost converters are due to the non-minimum phase structure 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.

Different control algorithms are applied to regulate the DC-DC converters for achieving a robust output voltage. As DC-DC converters are nonlinear and time variant systems. The application of linear control techniques to control these converters is 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. The controllers based on these techniques are simple to implement however, it is difficult to account the variation of systems parameters, because of the dependence of small signal model parameters on the converter operating point. Variations of system parameters and large signal transient such as those produced in the start up or against changes in the load, cannot be dealt with these techniques. A multi-loop control technique, such as current mode control, has greatly improved the dynamic behaviour, but the control design remains difficult especially for higher order converter topologies.

PWM DC-to-DC converters are very popular for the last three decades, and that are widely used at all power levels .Since switching converters constitute a case of variable structure systems, the sliding mode (SM) control technique can be a possible option to control this kind of circuits [3].

Sliding Mode (SM) controllers are well known for their robustness and stability. The nature of the controller is to ideally operate at an infinite switching frequency such that the controlled variables can track a certain reference path to achieve the desired dynamic response and steady-state operation [6]. This requirement for operation at infinite switching frequency, however, challenges the feasibility of applying SM controllers in power converters. This is because extreme high speed switching in power converters results in excessive switching losses, inductor and transformer core losses, and electromagnetic interference (EMI) noise issues.

Sliding mode control has been successfully applied to robot manipulators, underwater vehicles, automotive transmissions and engines, high-performance electric motors and power systems. SMC provides a systematic approach to the problem of maintaining stability and consistent performance in the face of modelling imprecision.

2. CONTROL TECHNIQUES USED IN DC-DC BOOST CONVERTER

2.1 Necessity for controlling of dc to dc converters using PWM (Pulse Width Modulation):

Power conversion is usually achieved by appropriate configuration of the DC to DC converter circuit components and proper operation of the semiconductor switches. Any DC to DC converter will be designed for specific line (input voltage) and load (output) conditions. In other words, the circuit will be operated at steady state condition only. But in practice this may not be possible and there is always a possibility of some disturbances which cause the circuit operation to deviate from the nominal values considerably. These disturbances may be due to the changes in the source, load, circuit parameters, and perturbation in switching time and events such as start up and shut down etc.

This deviation of the circuit operation from the desired nominal behaviour is known as the dynamic behaviour of the circuit. If the above mentioned disturbances have negligible effect on the circuit operation, no action will be required by the designer to correct this situation But in most cases the departure from nominal conditions will affect the circuit operations to large extent and therefore, the designers will be required to design a proper controller or compensator to overcome this situation of the circuit operation.

The control circuit in Switch Mode Power Supply (SMPS) circuits has several main functions. During steady state operations, the control circuit maintains the output voltage constant, if there is any change either in the input voltage or load. During transient operations, the control circuit protects all the components used in the converter by limiting external stress on them.

In pulse width modulation (PWM) converters the control circuit regulates the output by fixing the switching frequency and varying the on time of the switch, while on the other hand in resonant switched mode power supplies the control circuit regulates the output by varying the switching frequency and fixing the on or off time of the switch[1]. Several control techniques are available for conventional switched mode power supplies which work on PWM method, some of the most common techniques will be discussed here in the later section.

2.2 Control principle:

Modelling the power stage presents one of the main challenges to the power supply designer. A popular technique involves modelling only the switching elements of the power stage. An equivalent circuit for these elements is derived and is called the PWM Switch Model where PWM is the abbreviation for the pulse width modulated [9]. As shown in Figure 2.1, the power stage has two inputs: the input voltage and the duty cycle. The duty cycle is the control input, i.e., this input is a logic signal which controls the switching action of the power stage and hence the output voltage. The three major components of the power supply control loop (i.e., the power stage, the pulse width modulator, and the error amplifier) are shown in block diagram form in Figure2.1.

Most power stages have a nonlinear voltage conversion ratio versus duty cycle.

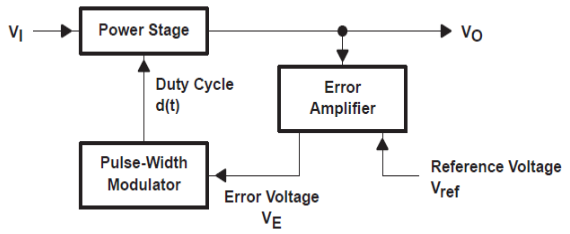

Fig.2.1 power supply control loop components

2.3 Control technique:

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. Various control techniques are there: Fuzzy logic controller, Artificial Neural Network (ANN), PID controller, PI controller, sliding mode controller. In this paper the performance and properties of the sliding mode controller, PID controller and PI controller has been focused.

2.3.1 Proportional, Integral & Derivative Controller (PID):

For control over steady state and transient errors all the three control strategies discussed so far should be combined to get proportional-integral derivative (PID) control. Hence the control signal is a linear combination of the error, the integral of the error, and the time rate of change of the error. All three gain constants are adjustable. The PID controller contains all the control components (proportional, derivative, and integral).

In order to get acceptable performance the constants K_P, K_D and K_I can be adjusted. This adjustment process is called tuning the controller. Increasing K_P and K_I tend to reduce errors but may not be capable of producing adequate stability. The PID controller provides both an acceptable degree of error reduction and an acceptable stability and damping.

2.3.2PI-Controller:

The integral term in a PI controller causes the steady-state error to reduce to zero, which is not the case for proportional-only control in general. The lack of derivative action may make the system more steady in the steady state in the case of noisy data. This is because derivative action is more sensitive to higher-frequency terms in the inputs. Without derivative action, a PI-controlled system is less responsive to real (non-noise) and relatively fast alterations in state and so the system will be slower to reach set-point and slower to respond to perturbations than a well-tuned PID system may be.

2.3.3 Sliding mode control:

Sliding mode controller provides a systematic approach to the problem maintaining stability and consistence performance in the face of modeling imprecision [3]-[4]. For example, the gains in each feedback path switch between two values according to a rule that depends on the value of the state at each instant. The purpose of the switching control law is to drive the nonlinear plant's state trajectory onto a pre-specified (user chosen) surface in the state space and to maintain the plant's state trajectory for the subsequent time. This surface is called the switching surface [6]. When the plant trajectory is above the surface a feedback path has one gain and a different gain if the trajectory drops below the surface. This surface defines the rule for proper switching. This surface is also called a sliding surface (sliding manifold). Ideally, once intercepted, the switched control maintains the plants state trajectory on the surface for all subsequent time and the plants state trajectory slides along this surface. By proper design of the sliding surface, VSC attains conventional goals of control such as stabilization, tracking, regulation etc.

2.3.3.1 Sliding mode control law for DC-DC boost converter:

Here, the voltage errorX_1, the voltage error dynamics (or the rate of change of voltage error) X_2, and the integral of voltage error X_3, under continuous conduction mode (CCM) operation, derived in [8] can be expressed as

$$X_1 = (V_{ref} - \beta V_o) \tag{2.1}$$

$$X_2 = \dot{X}_1 = \frac{\beta}{C}\left[\frac{Vo}{RL} - \int \frac{uVi - V_o}{RL}\, dt \right] \tag{2.2}$$

$$X_3 = \int X_1 \, dt \tag{2.3}$$

$$X_{boost} = \begin{bmatrix} V_{ref} - \beta V_o \\ \frac{\beta}{C}\left[\frac{V_o}{RL} - \int \frac{uV_i - V_o}{RL}\, dt \right] \\ \int V_{ref} - \beta V_o \, dt \end{bmatrix}$$

$$\dot{X}_{boost} = A\, X_{boost} + B\, u$$

where,

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

$$B = \begin{bmatrix} 0 \\ \frac{\beta V_o}{LC} - \frac{\beta Vi}{LC} \\ 0 \end{bmatrix}$$

For this system, it is appropriate to have a general SM control law that adopts a switching function such as

u= 1 when S > 0,
= 0 when S < 0,

$$u = \frac{1}{2(1 + \text{sign} S)} \tag{2.4}$$

Where S is the instantaneous state variable's trajectory and is described as

$$S = \alpha_1 X_1 + \alpha_2 X_2 + \alpha_3 X_3 = J^T x \tag{2.5}$$

With, $J^T = [\ \alpha_1 \ \ \alpha_2 \ \ \alpha_3]$
where, $\alpha_1,\ \alpha_2$ *and* α_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 $0 < d = \frac{V_C}{V_{ramp}} < 1$, gives the following relationship for the control signal V_C and ramp signal V_{ramp} , where
$V_C = U_{equ}$ =

$$-\beta L \left[\left(\frac{\alpha_1}{\alpha_2}\right) - \left(\frac{1}{R_l C}\right)\right] i_c + LC\left(\frac{\alpha_3}{\alpha_2}\right)(V_{ref} - \beta V_o) + \beta(V_o - Vi) \tag{2.6}$$

$$V_C = -kp_1\, i_c + kp_2(V_{ref} - \beta Vo) + \beta(V_o - Vi) \tag{2.7}$$

$kp1 = \left(\frac{\alpha_1}{\alpha_2}\right) - \left(\frac{1}{R_l C}\right)$ and
$kp2 = LC\left(\frac{\alpha_3}{\alpha_2}\right)$

$$V_{ramp} = \beta (V_o - Vi) \tag{2.8}$$

Using control voltage equation, the sliding mode controller for boost converter can be modelled as shown in fig.2.2

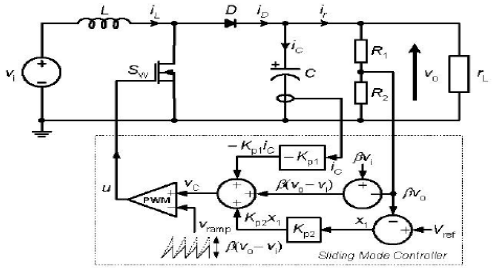

Fig. 2.2 System modelling of sliding mode controller

TABLE-1
LIST OF PARAMETERS

DESCRIPTION	PARAMETER	NOMINAL VALUE
Input voltage	Vin	24 v
Capacitance	C	2000µF
Inductance	L	300µH
Switching frequency	F	100kHz
Load resistance	Rl	240 Ω
Sliding mode controller gain	Kp1	0.149
	Kp2	1.35
PID controller gain, proportional constant	Kp	25
Integral constant	Ki	12
Derivative gain	Kd	0.05
PI controller gain proportional constant	Kp	0.17
Integral constant	Ki	15
Expected voltage	Vo	48v

3. SIMULATION RESULT AND DISCUSSION

3.1Basic model of Boost converter:

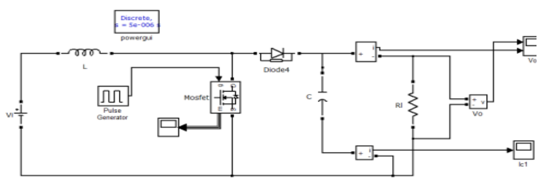

Fig.3.1 Simulated block diagram of boost converter

Result: For input voltage of Vin=24v, output voltage, Vo=30 and output current, Io=0.11 amp with nonlinearity up to 0.8 sec.

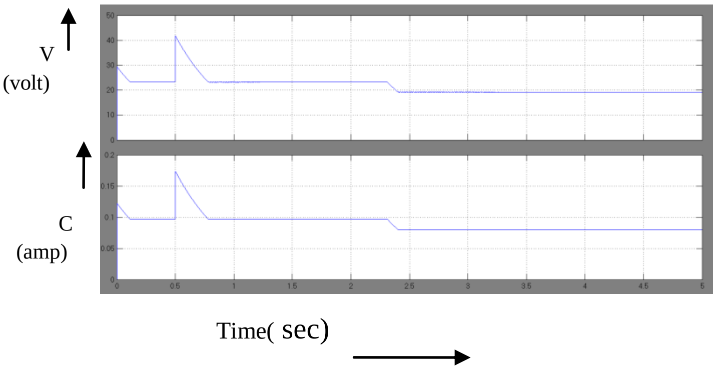

Fig.3.2 Simulation result for basic boost-converter

3.2 Boost converter using sliding mode controller:

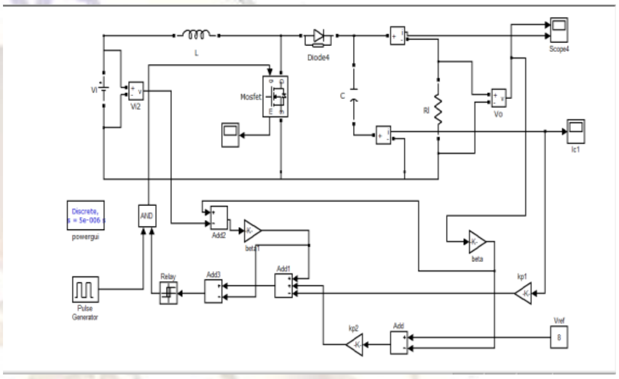

Fig.3.3simulated block diagram of boost converter using sliding mode controller

Result: For input voltage of Vin=24v,Vo=48.5v,Io=0.2 with linear curve.

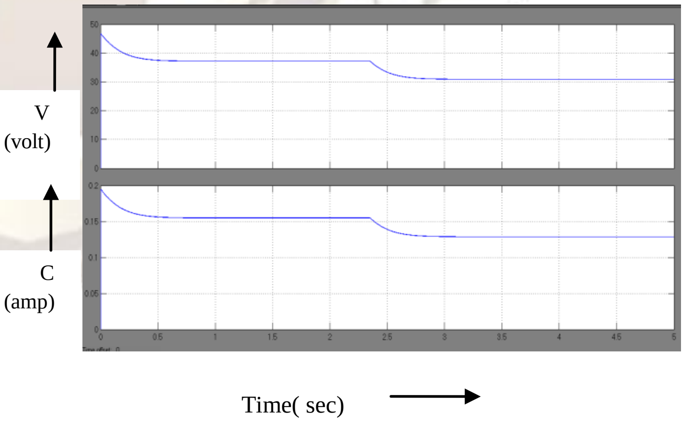

Fig. 3.4simulation result for sliding mode controller

3.3 Simulated block diagram of boost converter using PID controller

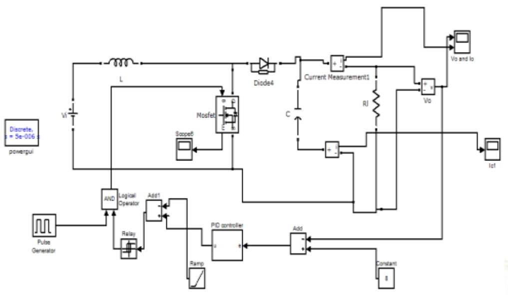

Fig.3.5 Simulated block diagram for boost converter using PID controller

Result: For input voltage of Vin=24v,Vo=48v,Io=0.2amp,with nonlinearity up to 0.8 sec.

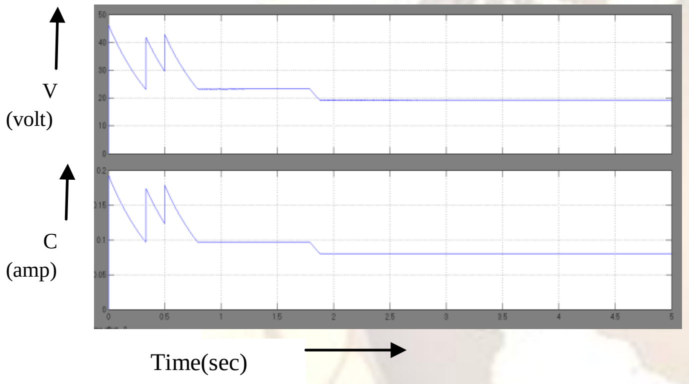

Fig 3.6 simulation result using PID controller

3.4 Simulated block diagram of boost converter using PI controller

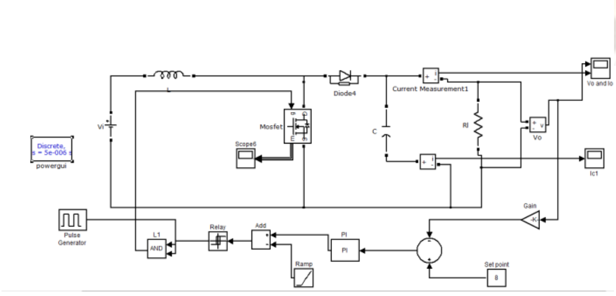

Fig 3.7 simulated block diagram of boost converter using PI controller

Result: For input voltage of Vin=24v,Vo=49 v, Io=0.2amp,with maximum drop of voltage from 24v to 25v at 0.4 sec

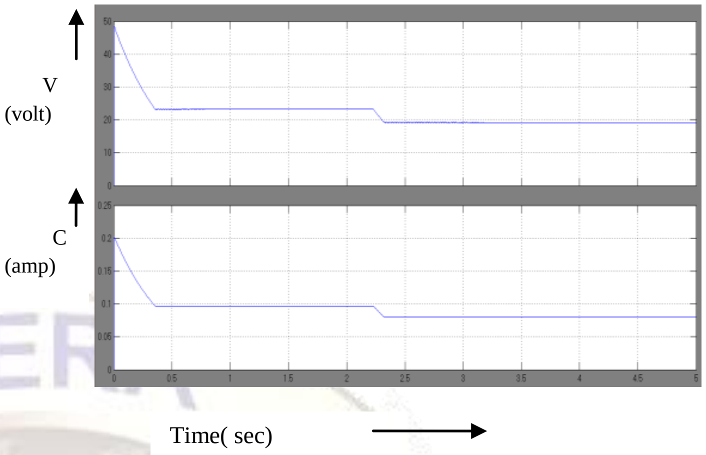

Fig 3.8 simulation result of boost converter using PI controller

TABLE-2
COMPARISON BETWEEN SLIDING MODE, PID AND PI CONTROLLER

Controller	Voltage profile	Settling time	Current profile
Without controller	30 volt with non linearity	0.8 sec	0.11 amp
Sliding mode controller	48volt with linearity	0.01sec	0.2amp
PID controller	48volt to 25 volt with non-linearity	0.8sec	0.2amp
PI controller	49volt to 25volt with linearity	0.4sec	0.2amp

4. CONCLUSION

A comparison between the PWM based sliding mode controller, PID and PI controllers for dc-dc boost converter are highlighted. Performance analysis for controlling of dc-dc boost converter is evaluated in simulation under the internal losses and input voltage variation. Sliding mode controller and PI controller have the same overshoot voltage but voltage drop is more using PI controller.PID controller has maximum settling time as compared to sliding mode controller and PI controller. In order to test the robustness of the sliding mode control scheme, the input voltage is changed from 24v to 20v. This variation took place, at t =2.3sec, while the system was already stabilized to the desired voltage value. Due to the internal losses, the variation took place at 0.05 sec.

PWM based sliding mode controller shows acceptable performance than PID and PI controller having lowest deviation from reference voltage under internal losses and input voltages changes. Using the sliding mode controller, the non-linearity and un-stability of power converters can be improved which is applicable in many engineering applications.

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