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Design of Sliding Mode Control for BUCK Converter

Kruti. R.Joshi[1], Hardik V.Kannad[2]

PG Student [Applied instrumentation], Dept. of I&C, AITS, Rajkot, Gujarat, India[1]

Assistant Professor, Dept. of I&C, AITS, Rajkot, Gujarat, India[2]

ABSTRACT:The main objective of this paper is to design a SM Controller for a buck converter to convert a dc input voltage to the required lower dc output voltage level for lower power application to solve the problem of voltage regulation and high power loss of the linear voltage regulator circuit. The converter uses a switching scheme which operates the switch MOSFET in cutoff and saturation region to reduce power loss across MOSFET. Then, the output voltage is controlled using SM Control technique to get the desired output voltage level. The design is based on low power application such as laptop charger, mobile charger etc. The circuit is simulated using MATLAB/SIMULINK software to obtain desired response.The SM control is a type of nonlinear control introduced initially as a means for controlling variable structure systems. The main advantage of the SM control over other types of nonlinear control methods is its ease of implementation. This makes it well suited for common DC–DC power regulation purposes. The SM control is naturally well suited for the control of variable structure systems. Characterized by switching, power converters are inherently variable structure systems. It is therefore; appropriate to apply SM control on power converters.

KEYWORDS: Buck converter, SM Control, Relay/ SIGNUM function, Hysteresis function

I.INTRODUCTION

In simplest terms, the SM control is a kind of nonlinear control which has been developed primarily for the control of variable structure systems. Technically, it consists of a time-varying state-feedback discontinuous control law that switches at a high frequency from one continuous structure to another according to the present position of the state variables in the state space, the objective being to force the dynamics of the system under control to follow exactly what is desired and pre-determined.

The main advantage of a system with SM control characteristics is that it has guaranteed stability and robustness against parameter uncertainties. Moreover, being a control method that has a high degree of flexibility in its design choices, the SM control method is relatively easy to implement as compared to other nonlinear control methods. Such properties make SM control highly suitable for applications in nonlinear systems, accounting for their wide utilization in industrial applications, e.g., electrical drivers, automotive control, furnace control, etc. In this, we are concerned with a particular class of variable structure system known as Buck Converter.

DC–DC converters are power electronic circuits that accept DC input voltages or currents and produce DC output voltages or currents. This power conversion process is divided as step down conversion (Buck converter), step up conversion (Boost converter), and step up-down conversion (Buck-Boost converter). DC-DC converters are important in portable devices such as cellular phones and laptops. The Buck Converter is most widely used DC-DC converter topology in power management and voltage regulation application. These applications requires that the converter operates with a small steady-state output error, fast dynamical response, low overshoot, and low noise susceptibility, while maintaining high efficiency and low noise emission. They can convert a voltage source in to lower regulated voltage source. For example for computer system voltage needs to be step down and lower voltage needs to be maintained. For this Buck Converter needs to be used. Furthermore, Buck Converter provides longer battery life for mobile systems. Buck regulator is also used as switch mode power supplies for baseband digital core and the RF power amplifier. Suppose we want to use a device with low voltage level and if devices such as laptop or mobile charger directly connected to the supply at home then it may be damaged or not work properly due to overvoltage and over current fluctuation. To avoid this unnecessary damage of devices or equipment's we need to convert the voltage level to the required voltage level and maintain it at same level. In this project the Buck Converter configuration of DC-DC converter is chosen for study. It is suitable for lower power application due to low voltage and current at output.

II. LITERATURE SURVEY

Application of SM controllers in DC–DC converters was first reported in 1983 by Bilalovi´c et al., who demonstrated the feasibility of using SM control in the buck converter. Later, Venkataramanan et al. presented a more complete description the application of SM control to all basic second-order DC–DC converters, and introduced the idea of applying the equivalent control method of SM control theory to the standard duty-ratio control scheme to achieve constant frequency SM controllers.

[1] B. Naik& A. Mehta, *"Sliding Mode Controller with modified sliding function for Buck Type Converters"*, ISIE, ieee international symposium, May 2013

This paper author discussed about the detail mathematical modeling of Buck Converter and modified sliding function to get high performance accuracy. Comparison of conventional and modified SM control is given and its application to control speed of DC Motor is justified using simulation results.

[2] H. Guldemir, *"Study of Sliding Mode Control for DC-DC Buck Converter"*, Energy and Power Engineering, 2011, 3, 401-406, Scientific Research.

In this paper author discussed about the robustness of SM Controller for Buck Converter by designing and analyzing it's performance characteristics. Author checked the o/p voltage and inductor current of buck converter by changing the step load and input variation. The test was performed using MATLAB/Simulink and result shows fast dynamic response of o/p voltage and robustness to load and i/p voltage variations.

[3] S. verma, S.K. Singh & A.G. Rao, *"Overview of Control Techniques for DC-DCConverters",* Research Journal of Engineering SciencesVol. 2(8), 18-21, August (2013)

In this paper author summarized few of the available control technique i.e. voltage control mode (VMC), current mode control (CMC), PID, SM Control and Fuzzy Logic Control. Author discussed about advantage and disadvantage of all mention control technique based on their basic principle. As per requirement of our application we can select any one or combination of it.

[4] Siew-Chong Tan, M.Lai, and Chi K.Tse, *"General Design Issues of Sliding Mode Controllers in DC-DC Converters",* IEEE transactions on industrial electronics, Vol. 55, no. 3,March 2008

In this paper author examined the practical design issues of SM controllers as applied to the control of dc–dc converters. Author investigated the major problems that prevent the use of SM control in dc–dc converters for industrial and commercial applications. Possible solutions are derived, and practical design procedures are outlined. The performance of SM control is compared with that of conventional linear control in terms of transient characteristics. It has been shown that the use of SM control can lead to an improved robustness in providing consistent transient responses over a wide range of operating conditions.

[5] L. Martinez-Salamero, A. Cid-Pastor, A. El Aroudi, R. Giral, J. Calvente, and G. Ruiz-Magaz, *"Sliding-Mode Control of DC-DC Switching Converters"* 18th IFAC, September 2011.

In this paper author discussed SM Control in contrast to the traditional PWM method. The problem with PWM method is that the controller design in the frequency domain and that is based on averaged small signal model of converter which valid for low modulation frequency. In contrast SM Control designed in time domain which can be used to compensate both small and large signal perturbations.

[6] C. Batard. F.Poitiers, C.Millet and N.Ginot, *"Simulation of Power Converter using MATLAB, chapter 3",*MATLAB - A Fundamental Tool for Scientific Computing and Engineering Applications - Volume 1

This chapter discussed about the MATLAB/Simulink toolbox used for power converter design. Author mentioned in detail how to implement power converter using Simulink toolbox which avoid the purchasing of complex and expensive software. Implementation of Buck Converter is given in detain with necessary equations and figures.

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II.MATHEMATICALMODEL of BUCK CONVERTER &PARAMETERS

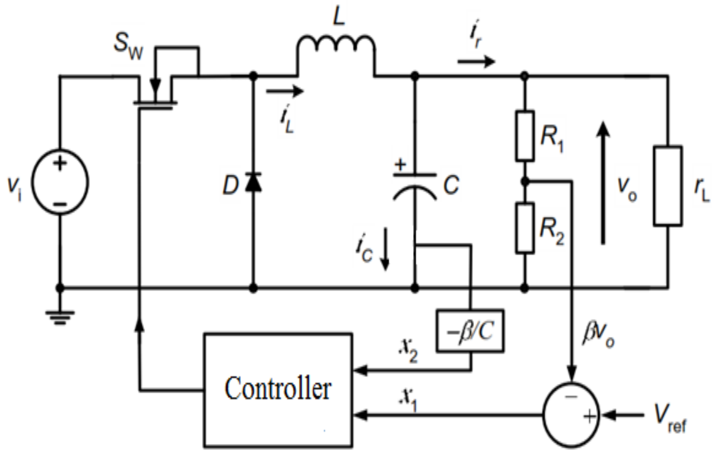

Fig. 1 BUCK Converter Model

A mathematical model of Buck Converter as shown in figure 1 in open loop can be derived using basic circuit analysis laws. The converter is with pure resistive load whose output voltage is to be controlled using SMC. The converter is assumed to be operated in continues current conduction mode.
The state space model of the electrical system can be derived by defining the states as follows:

$$x_1 = V_{ref} - \beta V_o \qquad (1)$$
$$x_2 = \dot{x_1} \ (2)$$

Where, $\beta = \frac{R_2}{R_1 + R_2}$ is the voltage divider ratio.
$V_{ref} = \beta V_d$, is the reference voltage corresponding to desired load voltage V_d.

The SW is the MOSFET switch turned ON or OFF with the output of SM Controller which is in the form of pulses.
Note that when u = 1 means SW is closed and u = 0 means SW is open.
L is an inductor.
C is a capacitor
D is a free-wheeling diode.
V_o is the output voltage.
V is the input voltage.
r_L is the load resistance.

From equation 2
$$x_2 = -\beta \frac{dV_o}{dt}$$
$$x_2 = -\frac{\beta}{C} i_C$$

Where, i_C is the capacitor current which can be measured as shown in figure 1.

Let, i_L and i_r be the inductor current and load current respectively.
So above equation can be written as:

$$x_2 = -\frac{\beta}{C}(i_L - i_r) \qquad (3)$$

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Let the voltage dropped across inductor be v_L then,

$$v_L = (uV - V_o) = L\frac{di_L}{dt}$$

$$\Rightarrow \quad i_L = \int \frac{uV - V_o}{L} dt$$

So equation (3) can be rewritten as,

$$x_2 = \dot{x_1} = \frac{\beta}{C}\left(\frac{V_o}{r_L} - \int \frac{uV_i - V_o}{L} dt\right) (4)$$

Hence,

$$\dot{x}_2 = -\frac{1}{LC}x_1 - \frac{1}{r_L C}x_2 - \frac{\beta V}{LC}u + \frac{V_{ref}}{LC} (5)$$

From equation (2) & (5), the state-space model of Buck Converter system is obtained

$$\begin{bmatrix}\dot{x_1}\\ \dot{x_2}\end{bmatrix} = \begin{bmatrix}0 & 1\\ -\frac{1}{LC} & -\frac{1}{r_L C}\end{bmatrix}\begin{bmatrix}x_1\\ x_2\end{bmatrix} + \begin{bmatrix}0\\ -\frac{\beta V}{LC}\end{bmatrix}u + \begin{bmatrix}0\\ \frac{V_{ref}}{LC}\end{bmatrix} (6)$$

Buck Converter Parameter formula:

Duty cycle $D = \frac{T_{on}}{T_{sw}} = \frac{Vout}{Vin}$

Current ripple $\Delta I_L = V_{out}(T_{sw} - T_{on})/L$

Critical value of inductance $L_c = \frac{(1-D)R_L}{2F_{sw}}$

By assuming 10% to 20% ripple current $L = \frac{(V_{in} - V_{out})\frac{D}{F_{sw}}}{I_{ripple}}$

By assuming 1% to 2% ripple voltage in output $C = \frac{\Delta I_L T_{sw}}{8\Delta V}$

TABLE I: BUCK Converter parameter

TOPOLOGY	BUCK CONVERTER
INDUCTOR (L)	69 µH
CAPACITOR (C)	220 µF
DC INPUT VOLTAGE (Vin)	24 V
DC OUTPUT VOLTAGE (Vo)	12 v
LOAD RESISTANCE (RL)	POTENTIOMETER
SWITCH	N- MOSFET (IRF 520)
DIODE	SCHOTTKY DIODE (1N5826)

III.MATHEMATICAL FORMULATION OF SM CONTROL

Consider a non-linear time dependent switching-system defined by the equation:

$$\dot{x}(t) = g(x(t)) + \varphi(x(t))u(t) \quad (7)$$

Where, x(t) is the state vector in n dimensional space R^n.

g (.) and φ (.) are smooth vector fields in the same space.

u(t)is the discontinuous control action expressed as

$$u(t) = \begin{cases} U^+ & if\ S(x,t) > 0\\ U^- & if\ S(x,t) < 0\end{cases} (8)$$

Where, U^+ and U^- are either scalar values or scalar functions ofx(t).

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$S(x,t)$is the instantaneous feedback tracking trajectory of system and is a predetermined function of the state variable. Typically, for ease of design and implementation, $S(x,t)$is chosen as a linear combination of the weighted values of the state variables, and is given as:

$\mathrm{S(x,t)} = \sum_{i=1}^{m} \alpha_i x_i(t)$(9)

Where, α_i foe i = 1 to m denotes the set of control parameters known as sliding coefficient
$x_i(t) \in X(t)$
A system with this description is said to exhibit SM property when all the required conditions i.e. hitting condition, existence condition and stability condition are met.

For an SM-controlled system whose trajectory is made up of the state variables, their time derivatives/sub derivatives, and/or time integrals, its equivalent sliding manifold is basically a linear motion equation, which can be obtained by substituting S = 0 into (9), i.e.,

$$\alpha_1 x_1(t) + \alpha_2 x_2(t) + \cdots + \alpha_m x_m(t) = 0 \quad (10)$$

Since the state variable $x_{n=1,2,3\ldots m}$ are in phase canonical form such that

$$x_{n+1}(t) = \frac{dx_n(t)}{dt}$$

So equation 10 can be rewritten as

$$\alpha_1 X_1(s) + \alpha_2 s X_1(s) + \cdots + \alpha_m s^{m-1} X_1(s) = 0 (11)$$

Where, $X_1(s)$ is Laplace transform of$x_1(t)$
Equation 11 can be rearranged and simplified as

$$\alpha_m s^{m-1} + \cdots + \alpha_3 s^2 + \alpha_2 s + \alpha_1 = 0 (12)$$

By applying the Routh-Hurwitz stability criterion to this m-1th order linear polynomial, the condition for stability which requires that all roots of this characteristic equation have negative real parts can be obtained.
For example, for a second-order polynomial, the stability condition would be:
$\alpha_1 > 0$ And $\alpha_2 > \alpha_3 > 0$

A typical SM controller for switching power converters has two control modes: voltage mode and current mode. Here, voltage mode control is employed, i.e. output Voltage V_o is the parameter to be controlled. Figure 1 shows the schematic diagram of a SM voltage controlled buck converter. Here the state space description of the buck converter under SM voltage control, where the control parameters are the output voltage error and the voltage error dynamics is described in section II.
In SM controller, the controller employs a sliding surface to decide its input states to the system. For SM controller, the switching states U which corresponds the turning on and off of the converter‟ switch is decided by sliding line. The sliding surface is described as a linear combination of the state variables. Thus the switching function is chosen as per equation 10. This equation describes a sliding line in the phase plane passing through the origin, which represents the stable operating point for this converter (zero output voltage error and its derivative).
The sliding line acts as a boundary that splits the phase plane into two regions. Each of these regions is specified with a switching state to direct the phase trajectory toward the sliding line. When the phase trajectory reaches and tracks the sliding line towards the origin, then the system is considered to be stable, i.e.,$X_1 = 0$ & $X_2 = 0$.
Substituting $X_2 = \dot{X}_1$ in equation 10 results in

$$S = \alpha_1 X_1 + \alpha_2 X_1^{\cdot} = 0 (13)$$

This describes the system dynamic in sliding mode. Thus, if existence and reaching conditions of the sliding mode are satisfied, a stable system is obtained.To ensure that a system follows its sliding surface, a control law is proposed. The

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control law only provides the information that the system trajectory is driven toward the sliding line. In order to ensure that the trajectory is maintained on the sliding line, the existence condition of SM operation, which is derived from Lyapunov's second method to determine asymptotic stability, must be satisfied.
The existence condition can be expressed in standard form as:

$$\dot{S} = \alpha^T \dot{X} = \alpha^T (AX + Bu + D) \quad (14)$$

Using SM theory, equations in two cases gives,

$$S_{\dot{S}>0} = \alpha^T AX + \alpha^T B + \alpha^T D < 0$$
$$S_{\dot{S}<0} = \alpha^T AX + \alpha^T D < 0 \quad (15)$$

For BUCK CONVERTER $S \to 0^+$ So switch q = 1 &$S \to 0^-$ so switch q = 0. By substituting the matrices A, B, and D, and state variable *x* above inequality becomes:

CASE 1: $\to 0^+ , \dot{S} < 0$

$$\gamma_1 = \left[\alpha_1 - \frac{\alpha_2}{RC}\right] X_2 - \frac{\alpha_2}{LC} X_1 + \frac{Vref - Vin}{LC} \alpha_2 < 0 \quad (16)$$

$CASE\ 2: S \to 0^- , \dot{S} > 0$

$$\gamma_2 = \left[\alpha_1 - \frac{\alpha_2}{RC}\right] X_2 - \frac{\alpha_2}{LC} X_1 + \frac{Vref}{LC} \alpha_2 > 0 \quad (17)$$

Defining $\gamma_1 = 0$ & $\gamma_2 = 0$ which satisfying lines with same slope in phase plane by solving these two equations we get sliding coefficient $\alpha_1 \& \alpha_2$.

IV.IMPLEMENTATION OF SM CONTROL USING RELAY/SIGNUM FUNCTION

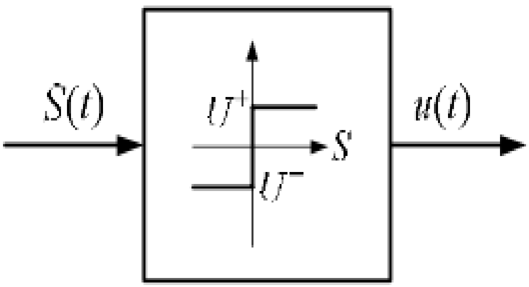

Fig. 2 Relay/SIGNUM function

In many application where control law involves only a positive or negative decision i.e. $U^+ = 1$ and $U^- = -1$. The signum function can be used for the relay i.e.

$$u(t) = sgn\big(S(x,t)\big) \quad (18)$$

Where the signum function $sgn(.)$ function is defined as

$$u(t) = \begin{cases} 1 & if\ s(x,t) > 0 \\ 0 & if\ s(x,t) = 0 \\ -1 & if\ s(x,t) < 0 \end{cases} \quad (19)$$

For the application where the control involves only digital logic equation 19 is replaced by:

$$u(t) = \begin{cases} 1 & if\ S(x,t) > 0 \\ 0 & if\ S(x,t) \le 0 \end{cases} \quad (20)$$

In general, the implementation of the control using this approach is straightforward and simple. However, the direct implementation of this control law results in systems that are switched at a very high frequency giving an unwanted chattering effect in the system. This makes it unsuitable for some applications which see this as an undesired high-

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frequency noise. Therefore, for such systems, it is necessary to restrict the range of the operating frequency, for instance, by using a hysteresis function.

V. RESULT AND DISCUSSION

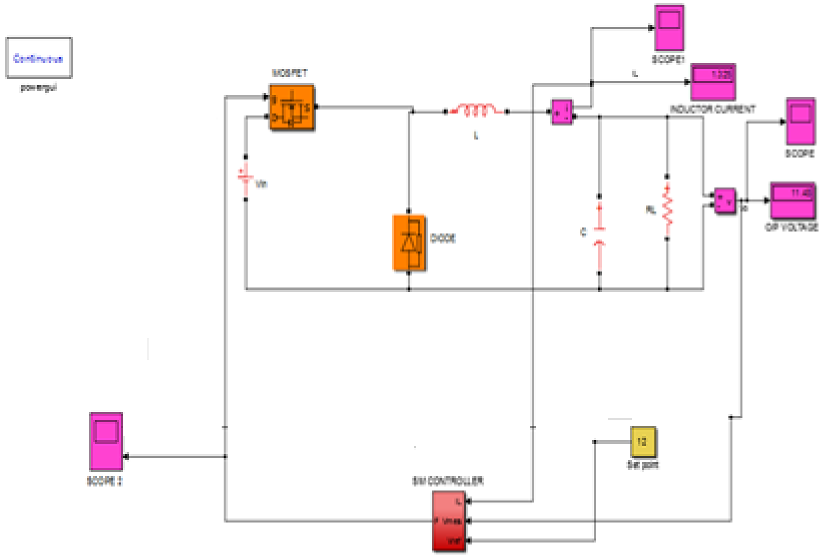

Fig. 3 Simulation model of BUCK Converter model using SMVC

Figure 3 shows the simulation model of buck converter using SMVC. Buck converter is consists of inductor (L), capacitor (C) and two switches one is of MOSFET type and one is of diode type. Variable resistor is used as a load resistance. Variable DC source is used as supply voltage v_{in}.

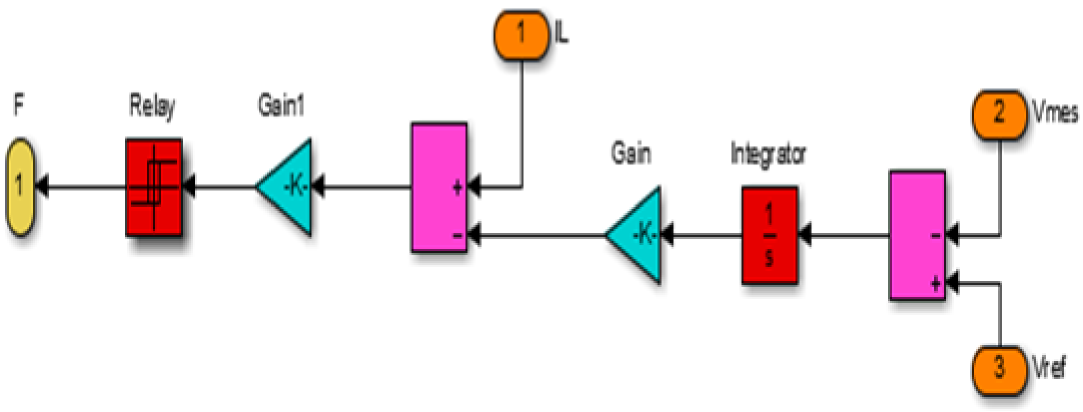

Fig. 4SM Control block using relay/signum function

In the fig 4, it shows Simulink implementation block of SM control using relay as nonlinear element.

To see the performance of SM Controller for Buck converter model set of reading taken as shown in Table II, III & IV for three different conditions i.e. line variation when load is constant, load variation when line is constant and variation in both line and load parallel.

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TABLE II: Result for load variation (o/p variation)

SM CONTROLLER (Vi = 24V)				
LOAD RESIS. (RL)ohm	INDUCTOR CURRENT (IL)amp	LOAD VOLTAGE (Vo) volt	PEAK OVERSHOOT volt	SETTLING TIME (Ts) sec
10	11.75*e-3	11.56	19.26	6.0*e-3
13	2.28*e-3	12.17	19.73	7.1*e-3
15	1.731	11.97	20.14	10*e-3
18	0.226*e-3	12.14	20.10	13.5*e-3
20	1.70	12.20	20.35	14*e-3

TABLE III: Result for line variation (i/p variation)

SM CONTROLLER (RL = 13 ohm)			
I/P VOLT. (Vi) volt	LOAD VOLTAGE (Vo) volt	PEAK OVERSHOOT volt	SETTLING TIME (Ts) sec
18	11.94	20.20	7.5*e-3
21	11.46	19.50	8.8*e-3
24	12.17	19.73	7.1*e-3
26	11.28	19.64	9.2*e-3
28	12.19	19.64	12*e-3
30	12.20	20	12.23*e-3

TABLE IV: Result for line variation (i/p variation) & load variation (o/p variation)

CONTROLLER	I/P VOLT. (Vi) volt	LOAD RESIS. (RL)ohm	LOAD VOLTAGE (Vo) volt
SM CONTROLLER	28	15	12.50
	22	20	12.05

VI.CONCLUSION

Thus from the Table II, III & IV it shows that o/p voltage (Vo) is almost near to the reference voltage (12V) in all three cases. This shows the accuracy of SM Control. From the table it is clear that settling time (Ts) is higher which shows the chattering phenomena of the SM Control which can be eliminated using hysteresis control in place of simple relay based control.

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