IJIREEICE
ISSN (Online) 2321 – 2004
ISSN (Print) 2321 – 5526
INTERNATIONAL JOURNAL OF INNOVATIVE RESEARCH IN ELECTRICAL, ELECTRONICS, INSTRUMENTATION AND CONTROL ENGINEERING
Vol. 4, Issue 3, March 2016

Modeling and Simulation of Hysteresis Modulation Based Sliding Mode Control of DC-DC Buck Converter in CCM

B.Chitra[1], S.Ramprasath[2], P.Ramesh Babu[3]

PG Scholar, Department of Electrical and Electronics Engineering, Saranathan College of Engineering Trichy, Tamil Nadu, India[1]

Assistant Professor, Department of Electrical and Electronics Engineering, Saranathan College of Engineering, Trichy, Tamil Nadu, India[2,3]

Abstract: This paper presents a systematic design procedure for hysteresis modulation based sliding mode control of DC-DC buck converter in continuous conduction mode. SM control is a type of nonlinear control which has been developed primarily for the control of variable structure systems. It has a high degree of flexibility in its design choices; the SM control technique is relatively easy to put into practice as compared to other nonlinear control methods. The design method and mathematical modeling for the Buck Converter has been explained. In this paper the sliding coefficient for the controller has been chosen based on satisfying the hitting, existence and stability conditions. The controller equations for buck converter have been resultant and modeled using MATLAB/SIMULINK.

Keywords: Sliding Mode Control, Sliding coefficient, Buck Converter, Modeling, Hysteresis modulation.

I. INTRODUCTION

One of the most significant features of the sliding mode regime in variable structure systems (VSS) is the capacity to attain responses that are independent of the system parameters[4].

From this vision, the Buck DC/DC converter is appropriate for the application of the SMC, which the system is controllable if every state variable can be exaggerated by an input signal in figure.1.Power electronics circuits transfer electric power from one form to another using electronic device. It has the function of using semiconductor devices as switches, thus controlling a voltage or current. Power electronic converters are key stone in power systems.

All power electronics converters are mostly variable structured in their control methodologies, exist it linear or nonlinear. DC-DC Converter is the circuits which transfer sources of direct current (DC) from one voltage level to another. The calculated output voltage will not be the same to the desired output voltage due to external disturbance like noise, wide input voltage variations, load variations and change in the parameter value. To get the desired output irrespective of the external disturbances control is required.

An application of SMC includes switched-mode power supplies, fuel cells, high voltage dc power transmission, efficient heating and lighting. But SMC is having the chattering event which is exhibited due to the high frequency and non-deterministic switching control signal. The introduction of Hysteresis band with boundary state is to limit this problem of chattering [6].

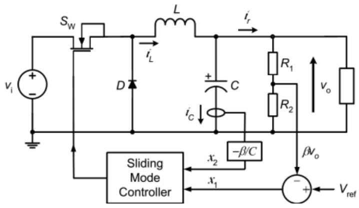

Fig.1. General Control block diagram of buck converter

Mainly DC–DC converters are designed with a closed-loop feedback controller to deliver a regulated output voltage. The main purpose is to guarantee that the converter operates with a small steady-state output error, fast dynamical response, low overshoot, and low noise susceptibility, as maintaining high efficiency and low noise production.

These entire design criterions can be achieved through the proper selection of control strategies, circuit parameters and components [1], [6]. Buck converter is used for the applications where necessary output voltage is lower than the source voltage. The dissimilarity between conventional control methodologies and the actual SM control method can be eminent by the way in which the controllers are being designed.

In this SM control primarily the mathematical representation of the Buck converter for the précised output has been modeled. Then the control parameters are chosen by fulfilling the hitting condition, the existence condition, and the stability condition of the SM control law.

DOI 10.17148/IJIREEICE.2016.4334

The calculation of switching frequency, hysteresis band and the controller equations is derived. The control structure is formed and then it is simulated using MATLAB/SIMULINK.

II. BUCK CONVERTER MODELING

Designing a Buck Converter using the specifications: Input Voltage V_s=24V; Output Voltage V_o=12V; Frequency=25 KHz; Variation in inductor current is about 20% and Output voltage ripple is less than 2%.

For the specifications mentioned above the values are calculated and tabulated:

TABLE I. DESIGN VALUES FOR BUCK CONVERTER

I_L	2A
R	6Ω
L	600μH
C	8.33μF

The Buck Converter is modeled for the above specifications.

MODE1 :(S-On)

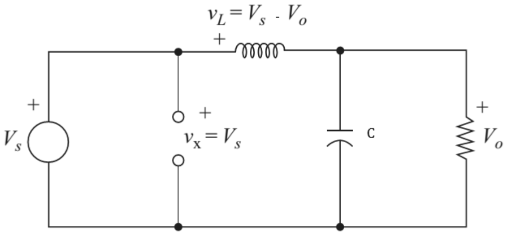

Fig.2. Equivalent circuit when switch is on

$$\frac{di_L}{dt} = \frac{V_s - V_o}{L} \tag{1}$$

$$\frac{dV_o}{dt} = -\frac{V_o}{RC} + \frac{i_L}{C} \tag{2}$$

MODE 2: (S-Off)

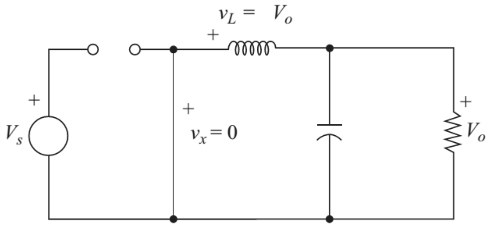

Fig.3. Equivalent circuit when the switch is off

$$\frac{di_L}{dt} = -\frac{V_o}{L} \tag{3}$$

$$\frac{dV_o}{dt} = -\frac{V_o}{RC} + \frac{i_L}{C} \tag{4}$$

Combining equations (1), (2), (3), (4)

$$\frac{di_L}{dt} = \frac{Vi*D}{L} - \frac{V_o}{L} \tag{5}$$

$$\frac{dV_o}{dt} = \frac{i_L}{C} - \frac{V_o}{RC} \tag{6}$$

By using the above equations (5) and (6) the Buck Converter for continuous conduction mode have modeled

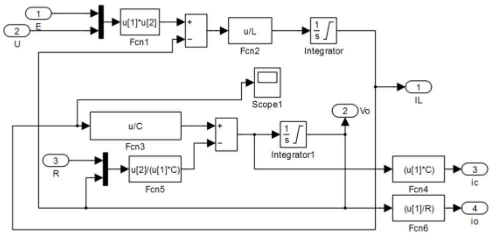

Fig. 4.Simulink model of Buck Converter

III. DESIGN PROCEDURE

Step1: Structure modeling.

Step2: Controller Design.

(i) Derivation of hitting and existence Conditions

(ii) Design of a practical SM voltage controller

(iii) Derivation of controller equations for Hysteresis Modulation based SM Controllers.

STEP1:(STRUCTURE MODELING)

To classify the state variables and to formulate gives the state space explanation necessary for the controller design

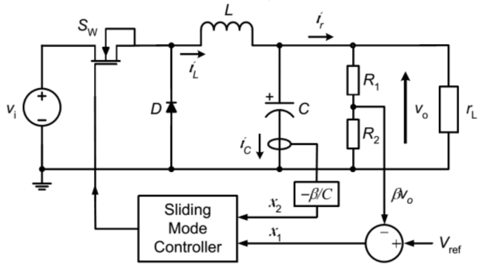

Fig.5. General Block Diagram of the SM Voltage controlled Buck Converter

Where

i_C, i_L, i_r →Instantaneous currents of C, L and load resistance

C,L,r_L →capacitance, inductance and load resistance

β →feedback ratio

V_{ref}, V_i, V→ reference, instantaneous input, instantaneous output voltages

The state variables are:

$$X = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} V_{ref} - \beta V_o \\ \frac{d}{dt}(V_{ref} - \beta V_o) \end{bmatrix} \tag{7}$$

x_1 → Voltage error

x_2 → Change in the voltage error

As of the Buck Converter model, the values for control variables are obtained.

From equation (3)

$$\mathbf{i_L = -\int \frac{V_s D - V_o}{L} dt} \tag{8}$$

Control Variable x_2 in terms of control parameters

$$\mathbf{x_2 = \frac{d}{dt}(V_{ref} - \beta V_o)} \ ;$$

$$x_2 = -\frac{d}{dt}\beta V_o$$

$$\frac{dV_o}{dt} = -\frac{x_2}{\beta}$$

$$\mathbf{x_2} = \beta\frac{V_o}{r_L C} + \boldsymbol{\beta} \int \frac{V_s D - V_o}{LC} \, dt \tag{9}$$

DOI 10.17148/IJIREEICE.2016.4334

Control Parameter for Buck Converter is:

$$x_{buck} = \begin{bmatrix} x_1 = (V_{ref} - \beta V_o) \\ x_2 = \beta \frac{V_o}{r_L C} + \beta \int \frac{V_s D - V_o}{LC}\, dt \end{bmatrix} \quad (10)$$

In differentiation of equation (10) with respect to time gives the state space explanation required for the controller design of Buck Converter

$$\dot{\mathbf{x}}_\mathbf{1} = \frac{\mathbf{d}}{\mathbf{dt}}(\mathbf{V_{ref}} - \boldsymbol{\beta}\mathbf{V_o}) = \boldsymbol{X_2} \quad (11)$$

$$\dot{\mathbf{x}}_\mathbf{2} = -\frac{\mathbf{1}}{\mathbf{r_L C}}\mathbf{x_2} - \frac{\mathbf{1}}{\mathbf{LC}}\mathbf{x_1} + \frac{\boldsymbol{\beta}\mathbf{V_s D}}{\mathbf{LC}} + \frac{\mathbf{V_{ref}}}{\mathbf{LC}} \quad (12)$$

Writing equations (11), (12) in matrix form

$$\dot{x} = Ax + Bu + D$$

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ \frac{-1}{LC} & \frac{-1}{RC} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{-\beta V_s}{LC} \end{bmatrix} D + \begin{bmatrix} 0 \\ \frac{V_{ref}}{LC} \end{bmatrix} \quad (13)$$

Where $u =$ Duty ratio

STEP 2:(CONTROLLER DESIGN)

The general SM control rule that adopts a switching function

$$\mathbf{u} = \begin{cases} \mathbf{1 = ON;\ s > 0} \\ \mathbf{0 = OFF;\ s < 0} \end{cases} \quad (14)$$

s → instantaneous state trajectory

$s = \alpha x_1 + x_2$ (15)

$= J^T x$

$J = [\alpha, 1]$

α→ sliding coefficient

The sliding coefficient for the SM Voltage Controller is acquired, and then we have to find out with the conditions

1) HITTING CONDITION

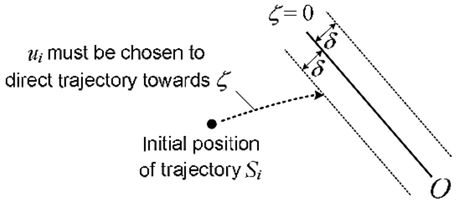

Fig.6. Trajectory S converging to the sliding manifold in SM control method when the hitting state is satisfied.

The purpose of hitting condition is to guarantee that in spite of the initial condition, the trajectory of the scheme is moved to the sliding surface according to the SM control process. From figure (6) the initial position of the trajectory (S_i) is moved to the sliding surface S(S=0), which is situated at a distance away from sliding manifold ζ=0 then it is moved to the sliding surface S.

At first state

Vector x_i = x (t = 0)

Trajectory S_i = S (t = 0)

The required condition to satisfy the hitting condition is the resulting control $u_i = u\ (t > 0)$ produces a state variable vector x (t > 0) and a controlled trajectory S (t > 0), which satisfies the variation:

$$\mathbf{S}\frac{\mathbf{dS}}{\mathbf{dt}} < \mathbf{0}(\mathbf{for\ t} > 0) \ \mathbf{and}\ |\mathbf{S}| \geq \boldsymbol{\delta} \quad (16)$$

The above condition is a partial consequence of the Lyapunov second theorem on stability.

DERIVATION OF EXISTENCE CONDITION

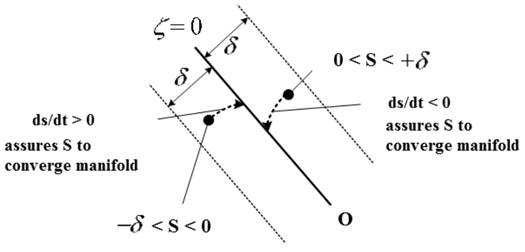

Fig.7. Trajectory S is converging to sliding manifold in SM control process

Existence condition which ensures that the trajectory point S converges to sliding manifold and reaches the origin, irrespective of the initial state.

To ensure the existence of SM process, the local reach ability condition is

$$\mathbf{lim_{s \to 0}\ s.\dot{s} < 0} \quad (17)$$

Equation (17) must be fulfilled for the existence of SM control process.

This can be expressed as,

$$\dot{S} = \begin{cases} J^T Ax + J^T Bu_{s\to 0^+} + J^T D < 0 \\ J^T Ax + J^T Bu_{s\to 0^-} + J^T D \ \ > 0 \end{cases} \quad (18)$$

CASE1: $(s \to 0^+; \dot{s} < 0)\ u_{s\to 0^+};\ u = 1$

$$= [\alpha\ \ 1] \begin{bmatrix} 0 & 1 \\ \frac{-1}{LC} & \frac{-1}{RC} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + [\alpha\ \ 1] \begin{bmatrix} 0 \\ \frac{-\beta V_s}{LC} \end{bmatrix} D + \begin{bmatrix} 0 \\ \frac{V_{ref}}{LC} \end{bmatrix}$$

$$= \frac{-1}{LC}x_1 + \left(\alpha - \frac{1}{Rc}\right)x_2 + \left(\frac{V_{ref} - V_o}{LC}\right) < 0$$

$$x_1 = V_{ref} - \beta V_o \quad (19)$$

$$x_2 = \beta[\frac{V_o}{r_L C} + \frac{1}{LC}\int (V_s D - V_o)dt] \quad (20)$$

$$\lambda_1 = \left(\alpha - \frac{1}{r_{LC}}\right)x_2 - \frac{1}{LC}x_1 + \frac{V_{ref} - \beta V_o}{LC} < 0 \quad (21)$$

CASE2 :$(\ s \to 0^-; \dot{s} > 0)\ u_{s\to 0^-} = u = 0$

$$\dot{s} = J^T Ax + J^T Bu \qquad (J^T B\bar{u} = 0)$$

$$= [\ \alpha\ \ 1] \begin{bmatrix} 0 & 1 \\ \frac{-1}{LC} & \frac{-1}{RC} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}$$

$$= \left(\frac{-1}{LC}\right)x_1 + \left(\alpha - \frac{1}{r_L C}\right)x_2 + \frac{V_{ref}}{LC} \quad (22)$$

$$\lambda_2 = \left(\alpha - \frac{1}{r_{LC}}\right)x_2 - \frac{1}{LC}x_1 + \frac{V_{ref}}{LC} > 0 \quad (23)$$

Where

$$\lambda_1 = J\dot{x} < 0 \quad for\ 0 < S < \varepsilon$$

$$\lambda_2 = J\dot{x} > 0 \quad for - \varepsilon < S < 0$$

DOI 10.17148/IJIREEICE.2016.4334

As discussed in [6] the maximum existence region will occur when $\alpha = \frac{1}{r_L C}$.

2) DESIGN OF A PRACTICAL SM VOLTAGE CONTROLLER

$$S = \alpha X_1 + X_2$$

From equation (19) and (20)

$$S = \frac{1}{r_L C}(V_{ref} - \beta V_o) + \left(\frac{-\beta}{C}\right) i_C \tag{24}$$

$$S = k_{p1}(V_{ref} - \beta V_o) + k_{p2} i_C$$

Where $k_{p1} = \frac{1}{r_L C}$ and $k_{p2} = \left(\frac{-\beta}{C}\right)$

Capacitance C in the DC–DC converters is typically in the microfarad (μF) range, its inverse expression will be considerably higher than β and r_L .The overall gains k_{p1} and k_{p2} will become too high for practical implementation. If forcibly implemented, the feedback signals may be determined into saturation, thereby causing equation (24) to give unreliable information for the control.

Reconfigure the switching function:

$$S = \frac{C}{\beta}\alpha x_1 + \frac{C}{\beta}\alpha x_2 = Q_x \tag{25}$$

$$\text{Where,} Q = \begin{bmatrix} \frac{C}{\beta}\alpha & \frac{C}{\beta} \end{bmatrix}$$

$$x = [x_1 \quad x_2]^T$$

from equation (19) and (23) we get,

$$S = \frac{C}{\beta}\left(\frac{1}{r_L C}\right)(V_{ref} - \beta V_o) + \frac{C}{\beta}\left(\frac{-\beta}{C}\right) i_C$$

$$S = \frac{1}{\beta r_L}(V_{ref} - \beta V_o) - i_C \tag{26}$$

The modified switching function is independent of C, thereby reducing the amplification of the feedback signals. With this sliding line, the conditions for SM control to exist are

$$\lambda_1 = \left(\frac{C}{\beta}\alpha - \frac{1}{\beta r_L}\right)x_2 - \frac{1}{\beta L}x_1 + \frac{V_{ref} - \beta V_s}{\beta L} < 0$$

$$\lambda_2 = \left(\frac{C}{\beta}\alpha - \frac{1}{\beta r_L}\right)x_2 - \frac{1}{\beta L}x_1 + \frac{V_{ref}}{\beta L} > 0$$

Where

$$\lambda_1 = Q\dot{x} \quad for\, 0 < S < \varepsilon$$

$$\lambda_2 = Q\dot{x} \quad for - \varepsilon < S < 0$$

3) DERIVATION OF CONTROLLER EQUATIONS FOR HYSTERESIS MODULATION BASED SM CONTROLLERS

The introduction of hysteresis band with the boundary condition S=k and S=-k is to control the switching frequency of the converter.

This scheme is developed to limit the chattering effect of SM control. To solve these problems, the control rule in equation (14) is redefined as,

$$u = \begin{cases} 1 = '\,\mathrm{ON}' & \text{when } s > 0 \\ 0 = '\,\mathrm{OFF}' & \text{when } s < 0 \\ unchanged & otherwise \end{cases}$$

Where κ is an arbitrarily small value

Relation between switching frequency and k:

(Figure 10) shows the magnified view of the phase trajectory when it is operating in SM. f^- and f^+ are the vectors of state variable velocity for $u = 0$ and $u = 1$, respectively.

$$\Delta t_1 = \frac{2k}{\nabla S \cdot f^-} \tag{27}$$

$$\Delta t_2 = \frac{2k}{\nabla S \cdot f^+} \tag{28}$$

Where

Δt_1 is the time taken for vector f^- to move from position *x* to *y*

Δt_2 is the time taken for vector f^+ to move from position *y* to *z*.

$$\nabla S \cdot f \sum_{i=1}^{n} \frac{\partial S}{\partial x_i}\frac{dx_i}{dt} = \frac{dS}{dt} = \dot{S}$$

$$f = \begin{cases} f^- & for\, u = 0 \\ f^+ & for\, u = 1 \end{cases}$$

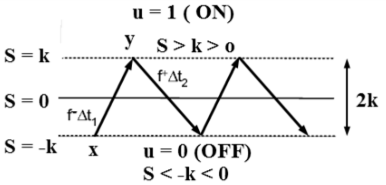

Fig.8.the phase trajectory in SM operation.

$$\Delta t_1 = \frac{2k}{\dot{S}_{u=0}} = \frac{2k}{\lambda_2} \tag{29}$$

$$\Delta t_2 = \frac{-2k}{\dot{S}_{u=1}} = \frac{-2k}{\lambda_1} \tag{30}$$

By substituting equation (19) and (20) in the above equations,

$$\Delta t_1 = \frac{2k}{\left(\frac{C}{\beta}\alpha - \frac{1}{\beta r_L}\right)x_2 - \frac{1}{\beta L}x_1 + \frac{V_{ref}}{\beta L}} \tag{31}$$

$$\Delta t_2 = \frac{-2k}{\left(\frac{C}{\beta}\alpha - \frac{1}{\beta r_L}\right)x_2 - \frac{1}{\beta L}x_1 + \frac{V_{ref} - \beta V_s}{\beta L}} \tag{32}$$

$$T = \Delta t_1 + \Delta t_2$$

$$T = \frac{-2kV_s}{\left[\left(\frac{C}{\beta}\alpha - \frac{1}{\beta r_L}\right)x_2\right]^2 L + \left[\left(\frac{C}{\beta}\alpha - \frac{1}{\beta r_L}\right)x_2\right](2V_o - V_s) + \frac{V_o(V_0 - V_s)}{L} - \frac{1}{\beta L}x_1}$$

$$f_S = \frac{1}{T}$$

$$f_S = \frac{\left[\left(\frac{C}{\beta}\alpha - \frac{1}{\beta r_L}\right)x_2\right]^2 L + \left[\left(\frac{C}{\beta}\alpha - \frac{1}{\beta r_L}\right)x_2\right](2V_o - V_s) + \frac{V_o(V_0 - V_s)}{L} - \frac{1}{\beta L}x_1}{-2kV_s}$$

Using $\alpha = \frac{1}{r_L C}$, the above equation becomes,

$$f_S = \frac{V_o\left(1 - \frac{V_o}{V_s}\right)}{2kL} \tag{33}$$

Re-arranging the above equation,

$$k = \frac{V_{od}\left(1 - \frac{V_{od}}{V_s}\right)}{2 f_{sd}\, L} \qquad (34)$$

TABLE II CONTROL PARAMETER FOR HSM CONTROLLER

f	25kHz
T_s	$4 * 10^{-5}$s
α	$200008.003 s^{-1}$
β	0.275
k	0.15
V_{ref}	3.3

IV. SIMULATION RESULTS

By fulfilling all the control parameter values are chosen for Controller, using these values the mathematic model for Hysteresis Modulation Based SM Voltage Controller for Buck Converter was simulated using MATLAB software. The response for source variation and load variations was obtained for the designed specifications Vi = 24V, load R_L=6Ω and f_s = 25 KHz.

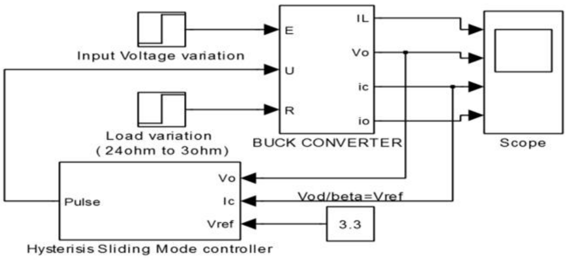

Fig. 9.Simulink Model of HSM Buck Converter

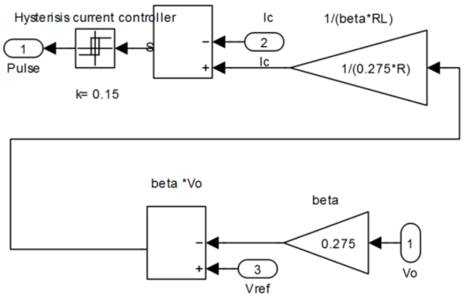

Fig. 10.Simulink Model of Hysteresis SM Controller

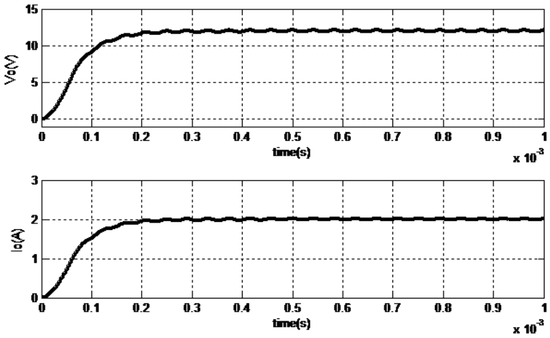

Fig.11. Output Voltage (V_o) and output Current (I_o) waveform

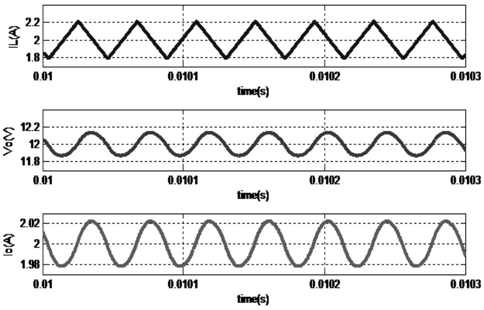

Fig.12. Peak to peak ripple in inductor current (0.4A), output voltage (0.2V) and output current is about (0.04A)

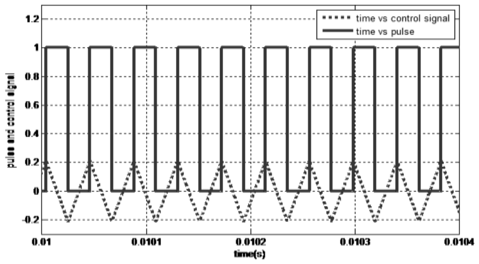

Fig.13. Comparison of Pulse and Control Signal

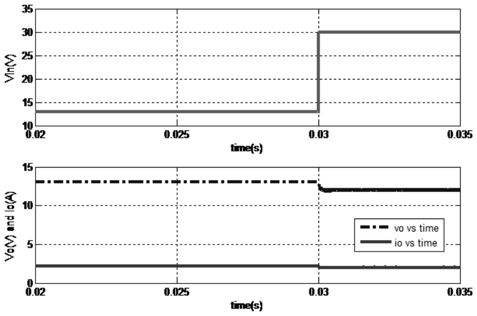

Fig.14. Output voltage and current waveform for a change in input voltage at 0.03 sec from 13V to 30V

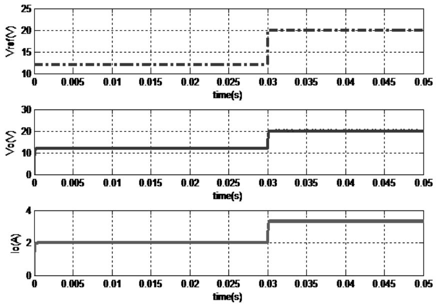

Fig.15. Output voltage waveform for a change in reference voltage at 0.03 sec from 12V to 20V

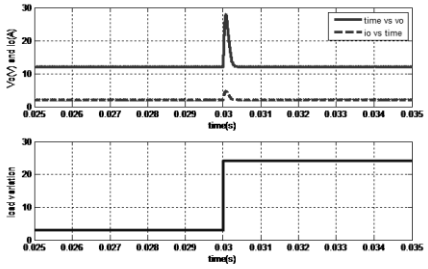

Fig.16. Output voltage and current waveform for a change in load resistance variation 3Ω to 24Ω at 0.03 sec from 12V to 20V

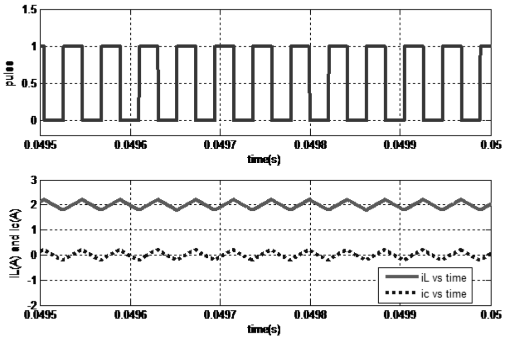

Fig.17. Inductor current and capacitor current waveform comparing with pulse for a steady state input voltage

V. CONCLUSION

In this paper we have discussed in detail about the controller equations, calculation of switching frequency and the design method for the Hysteresis modulation based SM controller for Buck Converter in Continuous Conduction Mode and with the design values a mathematic model of SM Controller was obtained and the controller have been simulated using MATLAB /SIMULINK.

REFERENCES

[1]. Alberto Cavallo and Beniamino Guida, “Sliding mode control for DC/DC converters”51st IEEE Conference on Decision and Control Maui, Hawaii, USA December 2012.

[2]. Arnab Ghosh, Student Member, IEEE, Mangal Prakash, Sourav Pradhan, and Subrata Banerjee, Member, IEEE,(2014) “A Comparison among PID, Sliding Mode and Internal Model Control for a Buck Converter”Department of Electrical Engineering, National Institute of Technology, Durgapur.

[3]. Benoit Labbe, Member, IEEE, Bruno Allard, Senior Member, IEEE, and Xuefang Lin-Shi, Member, IEEE,(September 2014)“Design and Stability Analysis of a Frequency Controlled Sliding-Mode Buck Converter” IEEE Transactions On Circuits and Systems—I: Regular Papers, Vol. 61, No. 9.

[4]. Kruti.R.Joshi1,Hardik V.Kannad (May 2015) “Design of Sliding Mode Control for Buck Converter ” ISSN (Print): 2320-3765, ISSN (Online): 2278–8875, ISO 3297:2007, International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering , Vol. 4, Issue 5.

[5]. Shelgaonkar (Bindu) ArtiKamalakar, N.R.Kulkarni (January 2012) “Performance Verification of DC-DC Buck Converter using Sliding Mode Controller for Comparison with the Existing Controllers – A Theoretical Approach” International Journal of Advances in Engineering & Technology (IJAET). ISSN: 2231-1963258 Vol.2, Issue 1.

[6]. Siew-Chong Tan,Y. M. Lai,and Chi K. Tse,(May 2011),who published the book about “ Sliding Mode Control of Switching Power Converters, Techniques and Implementation”.

DOI 10.17148/IJIREEICE.2016.4334