Sliding Mode Controlled DC-DC Buck Converter using Traditional and Proposed Reaching Laws

Siddesh K. B, Basavaraja Banakara, R. Shivarudraswamy

Abstract: ***Comparison analysis of sliding mode controlled dc-dc buck converter for chattering suppression with traditional and proposed reaching laws. A proposed reaching laws and traditional reaching law applied to SMC DC-DC buck converter, the proposed reaching law effectively reduces the chattering, because switching devices are existing in the model, it reduces the switching losses in the switching devices of the dc-dc buck converter. The results of proposed reaching law are compared with traditional reaching law. Proposed method gives less switching losses, in turn efficiency of the buck converter increases, more chattering mitigation by proposed reaching laws as compared to traditional reaching law. And very less sensitive in line and load variation. Simulation done in MATLAB.***

Index Terms: *Slidng mode control, Buck converter, Traditional reaching law, reaching law, Chattering*

I. INTRODUCTION

DC-DC converters are operated at very high switching frequencies, and this allows the use of small inductive and capacitive components which increases the dynamic behavior There are several parameters that have a strong influence on the behavior of the converters. The design of a DC-DC converter, a nominal input voltage and load values are selected [1]. The SMC is derived from VSCS. The physical structure of system is changed intentionally during the time with respect to the present structure control law.The state variables, during which changing of the structure occurs are determined by the current system which offers an alternate way to implement a control action, which completes inherent variable structure nature of DC-DC converter.In practice the converter switches are driven as a function of instantaneous values of the state variables in such way that forces the system trajectory to stay on suitable selected surface in the state space called sliding surface[2].

Applications of sliding mode control, engineers may experience undesirable phenomenon of oscillations having finite frequency and amplitude, which is known as '**chattering**'. At the first stage of sliding mode control theory development the chattering was the main obstacle for its implementation. Chattering is a harmful phenomenon because it leads to low control accuracy, very high heat power losses in circuits [2][3].

In order to overcome the problem of chattering in sliding mode control a reaching law method is implemented to the dc-dc buck converter[4].Proposed a reaching law based sliding mode controller is applied in the proposed system. The exponential stability condition in the form of linear matrix inequality is figured out based on the multi-Lyapunov function method *[5]*. A conventional sliding mode control (SMC) and chattering free improved sliding mode control design strategy for nonlinear systems. The modeling of conventional sliding mode controller as well as chattering free improved sliding mode controller for sample nonlinear equation *[6]* .A sliding mode control (SMC) is a kind of variable structure control, which has strong robustness. However, there exist severe chattering phenomenon, which are caused by frequently discontinuous switching control, in the applications of conventional SMC. And the chattering not only affects control precision, but also arouses unmodeled high-frequency dynamics possibly, or even makes the system unstable [7].A reduction of chatting phenomenon and fastening convergence speed. It is indicated through theoretical analysis with saturation function that the system under the proposed reaching law has existence and accessibility. The convergence speed is high [8].Sliding mode control is a robust control strategy which is suitable for the control of both linear and non-linear systems. Since then it has developed into a widely applicable controller design methodology finding applications in the areas of robotics, process control etc. SMC involves two modes of operations, viz., reaching mode and sliding mode [9]. A variable exponential reaching law based on equivalent error was designed in order to eliminate the influences of parameter variations.To guarantee the actual contour trajectory converges to desired trajectory in finite time [10]. An integral sliding mode surface is used to design the switching function, and the fractional exponential reaching law is designed by using the definition and properties of fractional exponential differential equations and F-functions to achieve high accuracy sliding mode control[11].

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A chattering problem of conventional sliding mode control systems for dc-dc converters.The chattering problem existing in conventional sliding mode can be practically solved due to the fact that the states cannot be stabilized to the origin from engineering point of view [12].A scheme, based on the averaging model and the output signal of the controller is d+ or d-instead of the on or off signal of a direct sliding-mode (SM) controller or the continuous signal. In order to improve the dynamic characteristics of the reaching phase and to alleviate chattering.[13] A novel continuous reaching law for chattering-free sliding mode control by using two hyperbolic functions with similar changing rate and opposite amplitude characteristics. which can guarantee the fast convergence as the initial value of the sliding mode variable is far away from the equilibrium. [14].

II. REACHING LAW METHODS FOR SLIDING MODE CONTROL DESIGN

The reaching law is a differential equation which indicates the dynamics of a switching function S(X). The differential equation of an asymptotically stable S(X) [1][14][15].

The traditional reaching laws:

It directly specifies the dynamics of the switching function. Let the dynamics of the switching function be specified by the differential equation.[1]

The Reaching Law Approach: The crux of the reaching law approach is a new method called the reaching law method.

The three traditional reaching laws

1) The constant rate reaching law

$$\dot{S} = -Q\,\mathrm{sgn}(s) \qquad (1)$$

2) The constant plus proportional rate reaching law(Traditional Reaching laws)

$$\dot{S} = -Q\,\mathrm{sgn}(s) - Ks \qquad (2)$$

3) The power rate reaching law

[2]

$$\dot{S} = -k|s|^{\alpha}\ \mathrm{sgn}\ (si)$$

III. SLIDING MODE CONTROL FOR DC-DC BUCK CONVERTER USING REACHING LAW

The DC-DC Buck converter is specifically suitable for application of the SMC, due to controllable state. The every state variable may be affected by an input voltage, if the system is controllable. The converter output voltage and its derivative are both selected as state variables for DC-DC Buck converter. Figure 1 shows the general structure of SMC for DC-DC converters. [7].

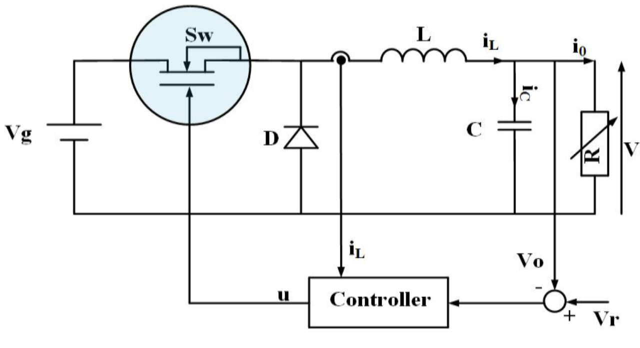

Fig. 1 A schematic diagram of SMC for DC-DC buck converter.

Figure 1 represents the dc-dc buck converter

The mathematical equation

$$\begin{pmatrix} X_1 \\ X_2 \\ X_3 \end{pmatrix} = \begin{pmatrix} X_1 = V_{ref} - \beta Vo \\ X_2 = -\dfrac{\beta ic}{C} \\ X_3 = \int X_1 \end{pmatrix}$$

$$X_{buck} = \begin{pmatrix} X_1 \\ X_2 \\ X_3 \end{pmatrix} = \begin{pmatrix} X_1 = Vref - \beta Vo \\ X_2 = \dfrac{\beta Vo}{RLC} + \int \dfrac{\beta Vo - \beta ViU}{LC} dt \\ X_3 = \int X1dt \end{pmatrix} \quad [15] \qquad (4)$$

$$\dot{X} = AX + BU + D \qquad (5)$$

Where,

$$A = \begin{pmatrix} 0 & 1 & 0 \\ -1/LC & -1/RLC & 0 \\ 1 & 0 & 0 \end{pmatrix}, B = \begin{pmatrix} 0 \\ -\beta Vi/LC \\ 0 \end{pmatrix}, D = \begin{pmatrix} 0 \\ Vref/LC \\ 0 \end{pmatrix} \qquad (6)$$

X_1 is the error, X_2 is the derivative of the error and X_3 is the integral error.The differential of the state variables

The sliding surface is given by

$$S = \alpha 1X1 + \alpha 2X2 + \alpha 3X3 \qquad (7)$$

The derivative of the sliding surface is given by

$$\dot{S} = \alpha 1\dot{X}1 + \alpha 2\dot{X}2 + \alpha 3\dot{X}3 = 0 \quad [15] \qquad (8)$$

where $\alpha 1\ \alpha 2\ \&\ \alpha 3$ represent the sliding coefficients, and X_1, X_2, and X_3 denote the state feedback variables to be controlled.

A. Sliding Mode Control for DC-DC Buck Converter with Proposed method 1: Reaching Law

This reaching law proposed in this work is based on the exponential term that adapts to the switching function, it's derived basically from variable structure system. This reaching law is given by [16].

$$\dot{S} = -T1|S|^{\alpha}\ \mathrm{sgn}(s) - T2|S|^{\frac{1}{\beta}}\ \mathrm{sgn}(s) \qquad (9)$$

T_1 and T_2 are the coefficients, Where α is a positive offset , $\alpha>0$and $\beta>1$, $T_1>0, T_2>0$,β α are positive integers , the sliding line approaching by state vectors, as β increase and α decreases. $-T_1|S|^{\alpha}\ \mathrm{sgn}(s)$ This term up reaching condition for state vectors, in turn reaching speed increases on sliding trajectories. $T_2|S|^{\frac{1}{\beta}}\mathrm{sgn}(s)$ This term mitigates the chattering, when system on the phase plane and makes system stable on switching surface. S approach zero quickly until stable in original point. Therefore the chattering phenomenon can be well mitigated and keep the system on the sliding mode, and it maintained the sliding mode portion of the system.

The sliding surface is given by

$$S=\alpha 1X1+\alpha 2X2+\alpha 3X3 \tag{10}$$

The derivative of the sliding surface is given by

$$\dot{S}=\alpha 1\dot{X}1+\alpha 2\dot{X}2+\alpha 3\dot{X}3=0 \tag{11}$$

Simulation modeling equations

$$\dot{S}=-T1|S|^{\alpha}\operatorname{sgn}(s)-T2|S|^{\frac{1}{\beta i}}\operatorname{sgn}(s)=\alpha 1\dot{X}1+\alpha 2\dot{X}2+\alpha 3\dot{X}3=0$$

$$T1|S|^{\alpha}\operatorname{sgn}(s)-T2|S|^{\frac{1}{\beta i}}\operatorname{sgn}(s)=\alpha 1\left(-\frac{\beta}{C}\right)ic+\alpha 2\frac{\beta ic}{RC^2}-\alpha 2\frac{UVin\beta}{LC}+\alpha 2\frac{\beta V0}{LC}+\alpha 3\left(Vref-\beta Vo\right) \tag{12}$$

$$Ueq=\frac{LC}{\alpha 2Vin\beta}\left[T1|S|^{\alpha}\operatorname{sgn}(s)+T2|S|^{\frac{1}{\beta i}}\operatorname{sgn}(s)-\frac{\alpha 1ic\beta}{C}+\alpha 2\frac{\beta ic}{RC}+\alpha 2\frac{\beta Vo}{LC}+\alpha 3\left(Vref-\beta Vo\right)\right]$$

B. Sliding Mode Control for DC-DC Buck Converter with Proposed method 2: Reaching Law.

Hongtao Ye *et al*. in 2017. Proposed a reduction of chatting alleviation and fastening convergence speed. .
A proposed method 2 reaching law. It is given by

$$\dot{S}=-m1*|s|^{k1}sat(s)-m2|s|^{k2}sat(s) \tag{13}$$

$$sat(s)=\begin{cases}\operatorname{sgn}(s), & |s|>\Delta\\ \frac{s}{\Delta}, & |s|<=\Delta\end{cases}$$

The saturation function is used instead of signum function as used in traditional function. The saturation function is a switching adaptation nature. Its derivative can converge to a neighborhood of the origin very quickly.Where Δ is the length of the sat(s) plus-minus symmetric linear section near the origin, 0<Δ<1.satuartion function is smoothly adapts the switching system. The proposed method 2 reaching law was by using a Lyapunov stability principle. [16][17],

$-m_1*|s|^{k1}sat(s)$, Here m_1 is a constant parameter, by selecting the gain $k_{1,}$ system reaches on the sliding line from any initial state. The convergence speed is high $-m_2|s|^{k2}sat(s)$, m_2 constant parameter, by selecting the gain value of k_2, the state variable reaches the sliding line at greater velocity and moving in phase with sliding line. Till the equilibrium point reach by the system point. If the gain value of k_2 is high, system generates high chattering. The gain value of k_2 is low, system generates low chattering..

Simulation modeling equations:

$$-m1*|s|^{K1}sat(s)-m2|s|^{K2}sat(s)=\dot{S}=\alpha 1\dot{X}1+\alpha 2\dot{X}2+\alpha 3\dot{X}3 \tag{14}$$

$$-m1*|s|^{k1}sat(s)-m2|s|^{k2}sat(s)=\alpha 1\left(-\frac{\beta}{C}\right)ic+\alpha 2\frac{\beta ic}{RC^2}-\alpha 2\frac{UVin\beta}{LC}+\alpha 2\frac{\beta V0}{LC}+\alpha 3(Vref-\beta Vo) \tag{15}$$

$$Ueq=\frac{LC}{\alpha 2Vin\beta}\left[-m1*|s|^{k1}sat(s)-m2|s|^{k2}sat(s)-\frac{\alpha 1ic\beta}{C}+\alpha 2\frac{\beta ic}{RC^2}+\alpha 2\frac{\beta Vo}{LC}+\alpha 3\left(Vref-\beta Vo\right)\right] \tag{16}$$

C. Sliding Mode Control for DC-DC Buck Converter with proposed method 3: Reaching law

Liang Tao *et al*. in 2018. Proposed a novel continuous reaching law for chattering control by using two hyperbolic functions.*[13]*
A proposed method 3 reaching law is given by

$$\dot{S}=-m1*|s|^{\alpha}\tanh(s)-m2|s|^{\lambda}\tanh(s) \tag{17}$$

$m_1>0,\ m_2>0, \alpha>0,\ \lambda>0$

The hyperbolic function is mathematical expressions its range from (-1, +1),

$$\tanh(s)=\frac{e^{x}-e^{-x}}{e^{x}+e^{-x}}$$

Here tan hyperbolic used instead of sign and saturation function, it adapts switching function as compared to saturation function .The reaching phase and convergence speed of the hyperbolic function is fast and keep the system state at sliding line. $-m_1*|s|^{\alpha}\tanh(s)$. As α varies, the system bringing on sliding line and hits the sliding surface at greater velocity. $m_2|s|^{\lambda}\tanh(S)$ term keeps system the stable on the phase plane and selecting gain value λ such that chattering will be mitigated at certain point

Stability analysis:

The new hyperbolic reaching law applied to stability condition using a Lyapunov stability principle, as follows,

$$V(s)=\frac{1}{2}S^2 \tag{18}$$

The derivative of both sides of the above formulae

$$\dot{V}(s)=S\dot{S}$$

$$\dot{S}=-m1*|s|^{\alpha}\tanh(s)-m2|s|^{\lambda}\tanh(s)$$

$$\dot{V}(S)=S(-m1*|s|^{\alpha}\tanh(s)-m2|s|^{\lambda}\tanh(s))$$

$$\dot{V}(S)=-m1*S*|s|^{\alpha}\tanh(s)-m2*S|s|^{\lambda}\tanh(s)) \tag{19}$$

From (19), it given by, that
Case 1: when s = 0, $\dot{V}=0$;
Case2: when s > 0, $m_1\tanh(s)>0$, $m_2\tanh(s)>0$, $\dot{V}<0$;
Case 3: when s < 0, $m_1\tanh(s)<0$,$m_2\tanh(s)<0$, $\dot{V}<0$;

This proposed reaching law is a smooth transition for switching action and alleviates the high frequency oscillation in the system.

Simulation modeling equations

$$m1*|s|^{K1}\tanh(s)-m2|s|^{K2}\tanh(s)=\dot{S}=\alpha 1\dot{X}1+\alpha 2\dot{X}2+\alpha 3\dot{X}3$$

$$-m1*|s|^{K1}\tanh(s)-m2|s|^{K2}\tanh(s)=\alpha 1\left(-\frac{\beta}{C}\right)ic+\alpha 2\frac{\beta ic}{RC^2}-\alpha 2\frac{UVin\beta}{LC}+\alpha 2\frac{\beta V0}{LC}+\alpha 3(Vref-\beta Vo)$$

$$Ueq=\frac{LC}{\alpha 2Vin\beta}\left[-m1*|s|^{\alpha}\tanh(s)-m2|s|^{\lambda}\tanh(s)-\frac{\alpha 1ic\beta}{C}+\alpha 2\frac{\beta ic}{RC^2}+\alpha 2\frac{\beta Vo}{LC}+\alpha 3\left(Vref-\beta Vo\right)\right]$$

IV. RESULTS AND DISCUSSION

Sl.No.	Parameter	Symbol	Value
1	Input voltage	Vi	24Volts
2	Capacitance	C	220µF
3	Inductance	L	69µH
4	Switching Frequency	fs	200KHz
6	Maximum load resistance	R_L(max)	10 Ohm
7	Desired Output voltage	Vod	12V
8	Reference voltage	Vref	12V
9	T1 &T2 (Parameters)		2,3
10	K1 and k2		0.9 and 0.5
11	βi α	Parameters of reaching law	2, 1.5
12	Feedback factor	β	0.98
13	Sliding coefficients,	α_1 α_2 α3	3 25 2000
14	Duty cycle	α	0.5
15	Efficiency of the Converter	η	0.91
16	Vknee_Mos		0.8
17	Vknee_D		0.7
18	R_{on_Mos}		0.1
19	R_{on_D}		0.001
20	.λ α		0.5,1

Table-5.1 Specification of Sliding Mode Control DC-DC Buck Converter with reaching laws

D. Sliding Mode Control for DC-DC Buck Converters with Constant plus Proportional Rate Reaching Law (Traditional Reaching law)

It is given by

$$\dot{S} = -Q\operatorname{sgn}(S) - kS \tag{20}$$

Where Q and k are constants, Q and K helps to obtain fast convergence ,but makes the system increased chattering, but on the other hand it leads disturbance on the sliding mode portion. By adding the proportional rate term –ks, the state is forced to approach the switching surface. [9]

$$\dot{S}=-Q\operatorname{sgn}(S)-kS=\alpha1\dot{X}1+\alpha2\dot{X}2+\alpha3\dot{X}3 \tag{21}$$

$$-Q\operatorname{sgn}(S)-kS = \alpha1\left(-\frac{\beta}{C}\right)ic + \alpha2\,\frac{\beta ic}{RC^2} - \alpha2\,\frac{UVin\beta}{LC} + \alpha2\frac{\beta V0}{LC}+\alpha3(Vref-\beta Vo) \tag{22}$$

$$Ueq=\frac{LC}{\alpha2Vin\beta}\left[\begin{matrix} Q\operatorname{sgn}(S)+kS-\dfrac{\alpha1ic\beta}{C}+\alpha2\dfrac{\beta ic}{RC^2}+ \\ \alpha2\dfrac{\beta Vo}{LC}+\alpha3\left(Vref-\beta Vo\right)\end{matrix}\right] \tag{23}$$

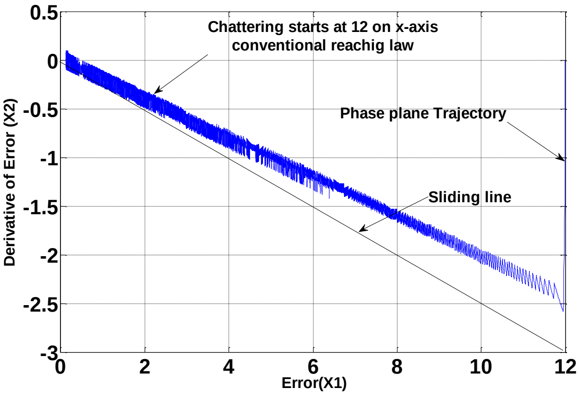

Fig..2. Phase plane trajectory of the Constant plus proportional rate reaching law (CPPRRL)

Fig.2.Shows the derivative of error (X_2) v/s Error (X_1). It is observed that phase plane trajectory of the conventional reaching law on the sliding line, here chattering exists more on the sliding line to origin. It starts from 12 on x-axis with high oscillations.

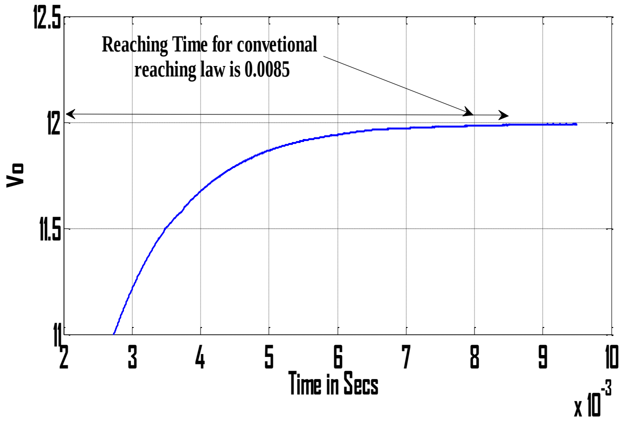

Fig.3. Output voltage of constant plus proportional rate reaching law

Fig.3.Shows the output voltage v/s Time in secs. It is observed that output voltage of conventional reaching law and it takes 8 mSecs to reach the steady state, it makes the delay due to chattering.

E. Sliding Mode Control for DC-DC Buck Converters with Proposed method 1: Reaching Law

This reaching law is given by [14].

$$\dot{S}=-T1|S|^{\alpha}\operatorname{sgn}(s)-T2|S|^{\frac{1}{\beta}}\operatorname{sgn}(s) \tag{24}$$

T_1 and T_2 are the coefficients, Where α is a positive offset , $\alpha>0$and $\beta>1$, $T_1>0, T_2>0$

β α are positive integers , the sliding line approaching by state vectors, as β increase and α decreases. $-T_1|S|^{\alpha}\operatorname{sgn}(s)$ This term up reaching condition for state vectors, in turn reaching speed increases on sliding trajectories. $T_2|S|^{\frac{1}{\beta}}\operatorname{sgn}(s)$ This term mitigates the chattering, when system on the phase plane and makes system stable on switching surface. S approach zero quickly until stable in original point.

Therefore the chattering phenomenon can be well mitigated and keep the system on the sliding mode, and it maintained the sliding mode portion of the system.

The sliding surface is given by

$$S=\alpha 1X1+\alpha 2X2+\alpha 3X3 \tag{25}$$

The derivative of the sliding surface is given by

$$\dot{S}=\alpha 1\dot{X}1+\alpha 2\dot{X}2+\alpha 3\dot{X}3=0 \tag{26}$$

$$\dot{S}=-T1|S|^{\alpha}\,\mathrm{sgn}(s)-T2|S|^{\frac{1}{\beta i}}\,\mathrm{sgn}(s)=\alpha 1\dot{X}1+\alpha 2\dot{X}2+\alpha 3\dot{X}3=0$$

$$-T1|S|^{\alpha}\,\mathrm{sgn}(s)-T2|S|^{\frac{1}{\beta i}}\,\mathrm{sgn}(s)=\alpha 1\left(-\frac{\beta}{C}\right)ic+\alpha 2\frac{\beta ic}{RC^2}-\alpha 2\frac{UVin\beta}{LC}+\alpha 2\frac{\beta V0}{LC}+\alpha 3\left(Vref-\beta Vo\right) \tag{27}$$

$$Ueq=\frac{LC}{\alpha 2Vin\beta}\left[T1|S|^{\alpha}\,\mathrm{sgn}(s)+T2|S|^{\frac{1}{\beta i}}\,\mathrm{sgn}(s)-\frac{\alpha 1ic\beta}{C}+\alpha 2\frac{\beta ic}{RC}+\alpha 2\frac{\beta Vo}{LC}+\alpha 3\left(Vref-\beta Vo\right)\right]$$

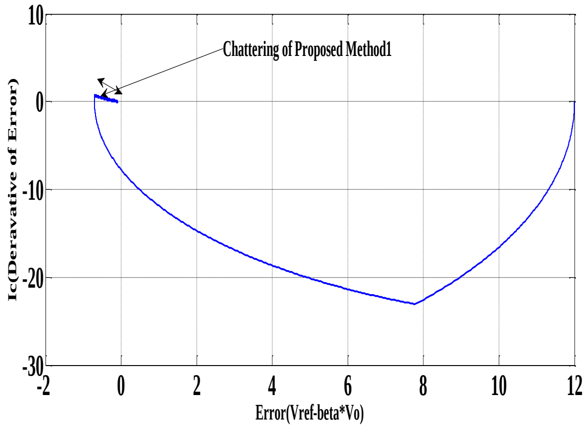

Fig.4.Chattering on Phase plane trajectory of the proposed method1

Fig.4. Shows that Deravative of error v/s Error chattering of proposed method 1 here chattering is occurred at the near the origin.

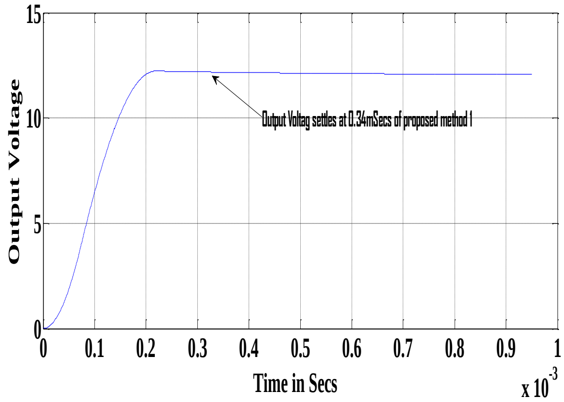

Fig.5.Shows the output voltage of proposed method 1.

Fig.5 observes that output voltage v/s time in secs.the output voltage of proposed method1.It setlles at 0.34mSecs, it makes the small delay due to chattering, to reach the steady state.

Results comparison:

Proposed method 1 with constant proportional reaching law**:**

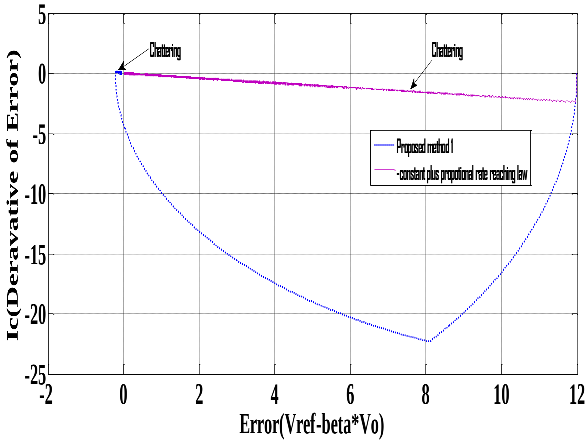

Figure 6 Error v/s Deravative of error

Fig. 6 observed that the chattering of proposed method 1 and constant plus proportional rate reaching law on phse plane trajectory. Here chattering exist at 12 on x-axis to origin

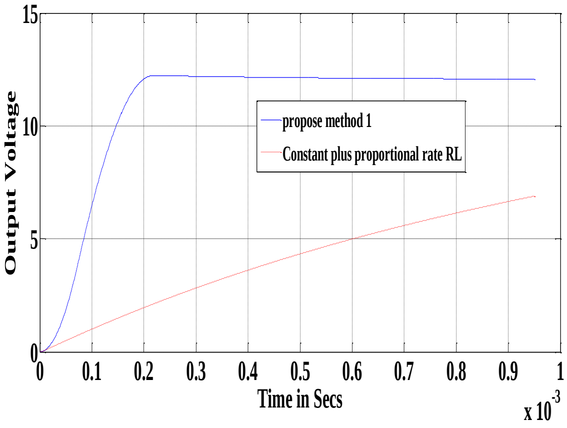

Fig..7 Output voltage v/s Time in secs of proposed method1andcont.plusproportional rate reaching law

Summary:

The proposed method 1 gives constant output voltage reaches steady state with fast reaching time and it mitigates chattering, it covers entire sliding mode portion of the phase plane trajectory as a result of this less switching losses. The constant plus proportional rate reaching law gives more chattering and takes more time to reach the steady state, this is due to chattering on the phase plane, in turn more switching losses in the dc-dc buck converter.

F. Sliding Mode Control for DC-DC Buck Converters with Proposed method 2: Reaching Law

A proposed method 2 reaching law. It is given by

$$\dot{S}=-m1*|s|^{k1}\,\mathrm{sat}(s)-m2|s|^{k2}\,\mathrm{sat}(s) \tag{28}$$

m1 >0 m2>0 k1>0& k2>0 are positive constants.

$$\mathrm{sat}(s)=\begin{cases}\mathrm{sgn}(s), |s|>\Delta\\ \frac{s}{\Delta}, |s|<=\Delta\end{cases}$$

The saturation function is used instead of signum function as used in traditional function. The saturation function is a switching adaptation nature. Its derivative can converge to a neighborhood of the origin very quickly.Where Δ is the length of the sat(s) plus-minus symmetric linear section near the origin, 0<Δ<1.satuartion function is smoothly adapts the switching system. The proposed method 2 reaching law was by using a Lyapunov stability principle. $-m_1 * |s|^{k1}\,\mathrm{sat}(s)$, Here m_1 is a constant parameter, by selecting the gain k_1, system reaches on the sliding line from any initial state. The convergence speed is high $-m_2|s|^{k2}\,\mathrm{sat}(s)$, m_2 constant parameter, by selecting the gain value of k_2, the state variable reaches the sliding line at greater velocity and moving in phase with sliding line. Till the equilibrium point reach by the system point. If the gain value of k_2 is high, system generates high chattering. The gain value of k_2 is low, system generates low chattering.

SMC dc-dc buck converter Modeling

$$-m1*|s|^{K1}\,\mathrm{sat}(s)-m2|s|^{K2}\,\mathrm{sat}(s)=\dot{S}=\alpha 1\dot{X}1+\alpha 2\dot{X}2+\alpha 3\dot{X}3 \tag{29}$$

$$-m1*|s|^{k1}\,\mathrm{sat}(s)-m2|s|^{k2}\,\mathrm{sat}(s)=\alpha 1\left(-\frac{\beta}{C}\right)ic+\alpha 2\frac{\beta ic}{RC^2}-\alpha 2\frac{UVin\beta}{LC} \tag{30}$$

$$+\alpha 2\frac{\beta V0}{LC}+\alpha 3\left(Vref-\beta Vo\right)$$

$$Ueq=\frac{LC}{\alpha 2Vin\beta}\begin{bmatrix}-m1*|s|^{k1}\,\mathrm{sat}(s)-m2|s|^{k2}\,\mathrm{sat}(s)-\frac{\alpha 1ic\beta}{C}+\alpha 2\frac{\beta ic}{RC^2}+\\ \alpha 2\frac{\beta Vo}{LC}+\alpha 3\left(Vref-\beta Vo\right)\end{bmatrix}$$

Simulation Modeling.of proposed method 2
Using a Lyapunovs stability analysis

$$V(s)=\frac{1}{2}S^2 \tag{31}$$

The derivative of both sides of the above formulae

$$\dot{V}(s)=S\dot{S}$$

$$\dot{S}*S=S*(-m1*|s|^{k1}\,\mathrm{sat}(s)-m2|s|^{k2}\,\mathrm{sat}(s))$$

$$\dot{S}*S=(-m1*s|s|^{k1}\,\mathrm{sat}(s)-m2*s|s|^{k2}\,\mathrm{sat}(s))$$

Case 1: when s = 0, $\dot{V} = 0$;
Case2: when s > 0, m_1 sat(s) > 0 and m_2 sat(s) > 0, $\dot{V} < 0$;
Case 3: when s < 0, m_1 sat(s) < 0 and m_2 sat(s) < 0, $\dot{V} < 0$;

The following comparison criteria are given.

1) The value of Integrated Absolute Sliding Mode Variable is(IASV) $= \int |S(t)|\,dt$, which can effectively represent the convergence accuracy of sliding mode variable S. *[15]*.

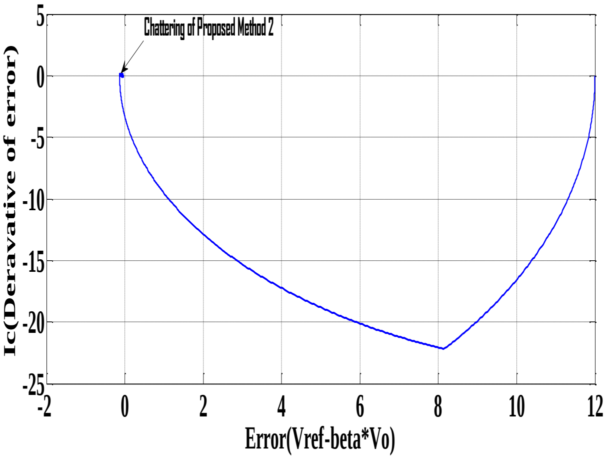

Fig..8 shows that derivative of error v/s error.

Fig.8 It is observed that chattering of proposed method 2 exists nearby origin as shown in the fig.8.the least chattering is occurred.

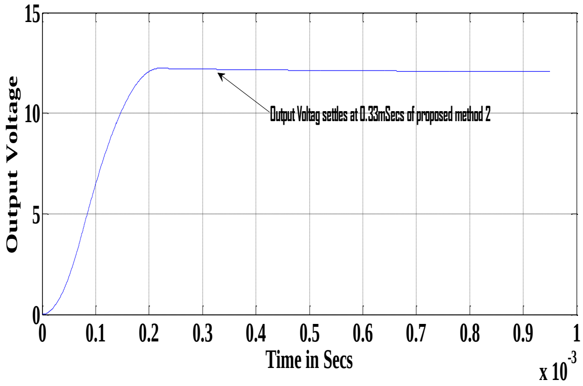

Fig. 9 Output Voltage v/s time in Secs

Fig.9. Shows the output voltage v/s time in Secs.. It is observed output voltage of proposed method 2 settles at 0.33mSecs.Here output voltage reaches steady state quickly, this is due to less chattering occurred and makes the system to reach the steady state and keep the system on phase plane.

Results comparison:

Proposed method 2, Proposed method 1with constant plus proportional reaching law:

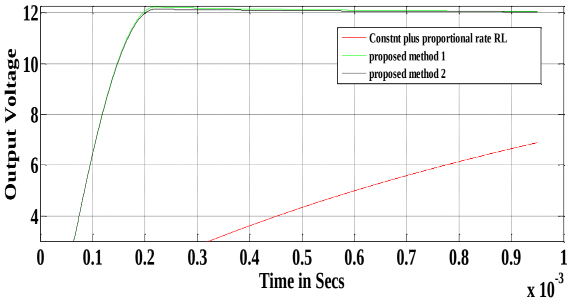

Fig. 10 Shows the Output voltage of v/s time in secs of proposed method1, proposed method2 and constant plus proportional rate reaching law

The fig.10 shows the comparison of proposed method1,proposed method 2 and constant plus proportional rate reaching law v/s time. Here Constant plus proportional rate reaching law is not reached the desired output voltage ,whereas the proposed metohd1reaches nearby the steady state with overshoot, proposed method 2 reaches the steady state quickly as compared to method1 and constant plus proportional rate reaching law with
less overshoot. This is due to less chattering occurred by method 2, as compared to method1 and constant plus proportional rate reaching law.

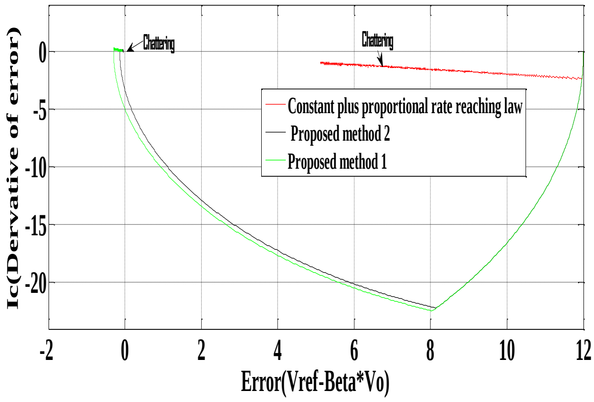

Fig. 11 shows the Derivative of error v/s error

Fig.11 shows the Chattering of proposed method1, method2 and constant plus proportional rate reaching law on the phase plane trajectory. Here method 2 produces a very less chattering and chattering occurs nearby origin as shown in figure.11, when compared to method1 and constant plus proportional rate reaching law.

Summary:

The proposed method 2 gives constant output voltage reaches steady state with fast reaching time and it mitigates chattering, it covers entire sliding mode portion of the phase plane trajectory as compared to method 1 and constant plus proportional rate reaching law. As a result of this less chattering and takes less time to reach the steady state, in turn less switching losses in the dc-dc buck converter.

G. Sliding Mode Control for DC-DC Buck Converters with Proposed method 3: Reaching law

A proposed method 3 reaching law is given by

$$\dot{S} = -m1*|s|^{\alpha}\tanh(s) - m2|s|^{\lambda}\tanh(s) \qquad (32)$$

$$m_1>0,\ m_2>0, \alpha>0,\ \lambda>0$$

A new hyperbolic function reaching law is proposed .the hyperbolic function is mathematical expressions its range from (-1, +1),

$$\tanh(s) = \frac{e^{x}-e^{-x}}{e^{x}+e^{-x}}$$

Here tan hyperbolic used instead of sign and saturation function, it adapts switching function as compared to saturation function .The reaching phase and convergence speed of the hyperbolic function is fast and keep the system state at sliding line. $-m_1*|s|^{\alpha}\tanh(s)$. As α varies, the system bringing on sliding line and hits the sliding surface at greater velocity. $m_2|s|^{\lambda}\tanh(S)$ term keeps system the stable on the phase plane and selecting gain value λ such that chattering will be mitigated at certain point[18][19][20]

Stability analysis:

The new hyperbolic reaching law applied to stability condition using a Lyapunov stability principle, as follows,

$$V(s) = \frac{1}{2}S^2 \qquad (33)$$

The derivative of both sides of the above formulae

$$\dot{V}(s) = S\dot{S}$$

$$\dot{S} = -m1*|s|^{\alpha}\tanh(s) - m2|s|^{\lambda}\tanh(s)$$

$$\dot{V}(S) = S(-m1*|s|^{\alpha}\tanh(s) - m2|s|^{\lambda}\tanh(s))$$
$$\dot{V}(S) = -m1*S*|s|^{\alpha}\tanh(s) - m2*S|s|^{\lambda}\tanh(s)) \qquad (34)$$

From (34), it given by, that

Case 1: when s = 0, then $\dot{V} = 0$;

Case2: when s > 0, it can be obtained $m_1 \tanh(s) > 0$, $m_2 \tanh(s) > 0$, then $\dot{V} < 0$;

Case 3: when s < 0, we have $m_1 \tanh(s) < 0$, $m_2\tanh(s) < 0$, $\dot{V} < 0$;

This proposed reaching law is a smooth transition for switching action and alleviates the high frequency oscillation in the system.

Simulation modeling equations

$$-m1*|s|^{K1}\tanh(s) - m2|s|^{K2}\tanh(s) = \dot{S} = \alpha1\dot{X}1 + \alpha2\dot{X}2 + \alpha3\dot{X}3$$

$$-m1*|s|^{K1}\tanh(s) - m2|s|^{K2}\tanh(s) = \alpha1\left(-\frac{\beta}{C}\right)ic + \alpha2\frac{\beta ic}{RC^2} - \alpha2\frac{UVin\beta}{LC}$$
$$+\alpha2\frac{\beta V0}{LC} + \alpha3(Vref-\beta Vo)$$

$$Ueq = \frac{LC}{\alpha2 Vin\beta}\begin{bmatrix} -m1*|s|^{\alpha}\tanh(s) - m2|s|^{\lambda}\tanh(s) - \frac{\alpha1 ic\beta}{C} + \alpha2\frac{\beta ic}{RC^2} + \\ \alpha2\frac{\beta Vo}{LC} + \alpha3(Vref-\beta Vo) \end{bmatrix} \qquad (35)$$

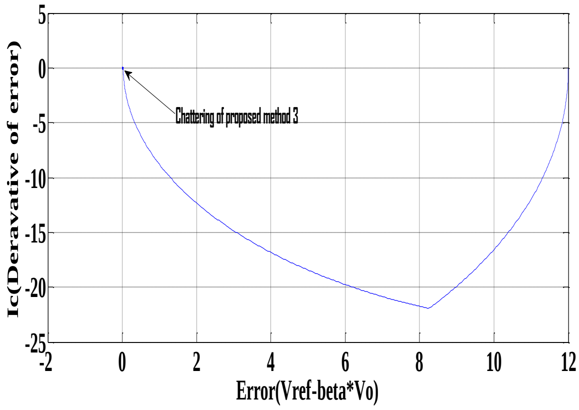

Fig.12. Shows derivative of error v/s error.

Fig.12. Shows that derivative of error v/s error on the phase plane. It is observed that a very less chattering occurred at the origin of the sliding surface. It covers complete sliding mode portion.

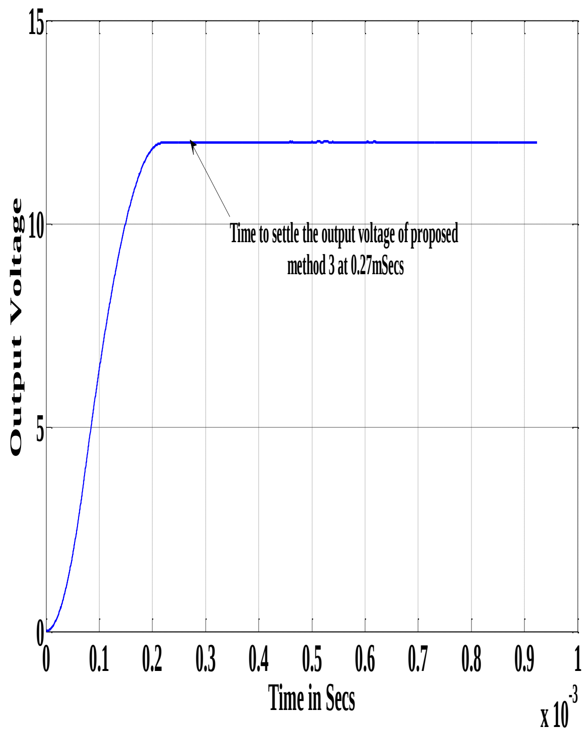

Fig. 13 Shows output voltage v/s Time in Secs

Fig. 13. Shows the output voltage v/s time in Secs It is observed that output voltage reaches steady state with convergence fast at 0.27mSecs and gives constant output voltage without overshoot

Results Comparison:

Proposed method 3, Proposed method 2 and method1 with constant proportional reaching law:

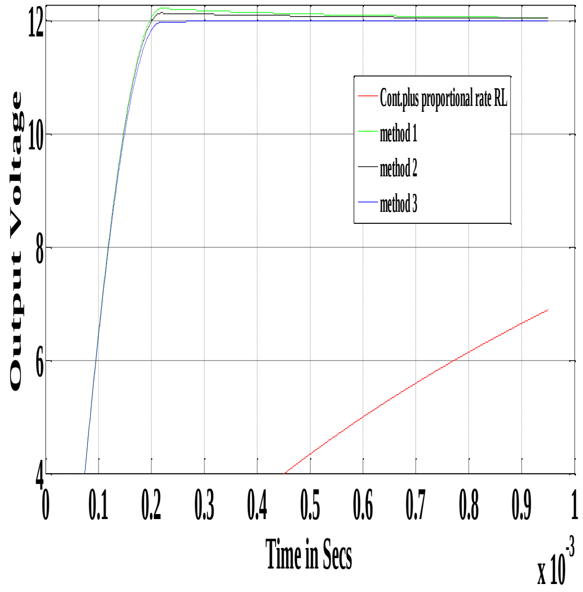

Fig. 14 shows the Output voltage of v/s time in Secs.

The fig.14. Shows the comparison of proposed method 3, proposed method 2, method1 and constant plus proportional rate reaching law v/s time. Here Constant plus proportional rate reaching law is not reached the desired output voltage ,whereas the proposed metohd1reaches nearby the steady state with overshoot, proposed method 2 reaches the steady state with small variation and overshoot .The method 3 reaches the steady state output voltage and settles very fast at 0.27msecs.This is due to less chattering occurred at the origin as compared method1,method2 and constant plus proportional rate reaching law

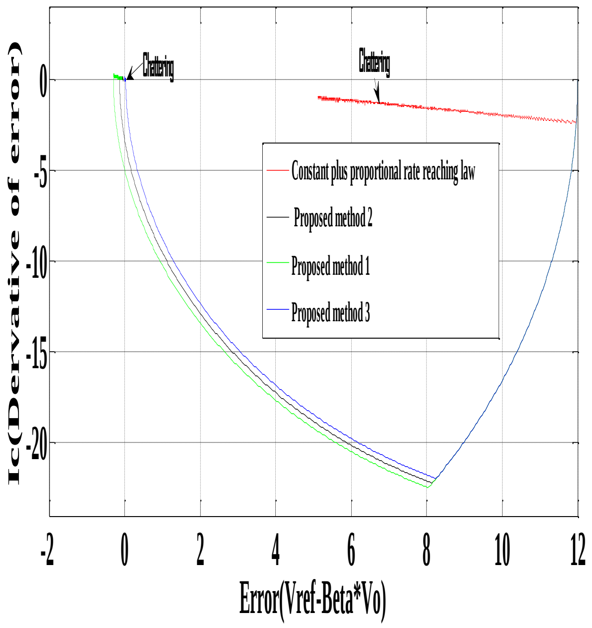

Fig.15. shows the Chattering of proposed method1, method2, method3 and constant plus proportional rate reaching law on the phase plane trajectory.

Here method 3 produces a very less chattering, and chattering occurs nearby origin, when compared to method1, method 2 and constant plus proportional rater reaching law. Proposed method3 produces a less switching losses in buck converter as compared to proposed method1,proposed method 2 and constant plus proportional rate reaching law.

Table-1 Comparison of proposed method 1, proposed method2, proposed method3 and constant plus proportional rate reaching law

Parameters	Constant plus proportional reaching law	Chattering of Constant plus proportional reaching law	A proposed method1 reaching law	Chattering of proposed method1	A proposed method 2 reaching law	Chattering of proposed method 2	A proposed method 3 reaching law	Chattering of proposed method 3
Chattering	on x-axis 12 to 0 on y-axis -0.25 to 0.25	0.5	on x-axis 0 to - 0.3 on y-axis -0.008 to 0.0085	0.0165	on x-axis 0 to - 0.3 on y-axis -0.0075 to 0.008	0.0155	on x-axis 0 to - 0.3 on y-axis -0.0065 to 0.0078	0.0143
Reaching time To steady state	8mSecs		0.34mecs		0.33mSecs		0.27mSecs	
Output Voltage	12.090V		11.91V		12.065V		12.01V	
IASV	400		284		283		281	
Switching loss	0.55W		0.35W		0.32W		0.29W	

Table-1 Comparison of proposed method 1, proposed method2, proposed method3 and constant plus proportional rate reaching law. The proposed method 3.Among these proposed methods and cont.plus proportional rate reaching law the proposed method 3 gives least chattering, desired output voltage, quick arriving time to steady state, least integrated absolute sliding mode value and least switching losses occurred. Proposed method 3 suppresses the chattering.

V. CONCLUSION

The proposed method 3 gives constant output voltage, reaches steady state with fast convergence time and it mitigates chattering, it covers entire sliding mode portion of the phase plane trajectory as compared to method 1, method 2 and constant plus proportional rate reaching law. The integrated absolute sliding mode variable is applied to all three methods and constant plus proportional rate reaching law. Among these proposed methods, the method 3 gives less absolute value of sliding mode variable, as a result of this less chattering and takes less time to reach the steady state. In turn less switching losses in the buck converter.

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