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Mathematical Modeling of Sliding Mode Reaching Laws for Buck Converter

K.B.Siddesh, Basavaraja Banakara, R.Shivarudraswamy

Abstract**: *In this paper, the load and line variations are analyzed for Sliding Mode reaching laws. Mathematical modeling has been done for all proposed sliding mode reaching laws, they are Exponential reaching law, Sigmoid reaching law, Tan hyperbolic, Robust reaching law, Improved tan hyperbolic reaching law and Double power reaching law. SMC has less sensitive for load and line disturbances. SMC (Sliding Mode Control) gives sensitive for load and line mutations due to chattering phenomenon. The comparative analyses for these reaching laws have been tested in buck converter. Chattering of all reaching laws are depicted. Among these reaching laws, tan hyperbolic reaching law gives efficient and insensitive for line and load mutations, even for parametric uncertainties and simulation results are validated through MATLAB/Simulink***

Keywords: Tanhyperbolic reaching law, buck converter, Double power reaching law, Robust reaching law, Sigmoid reaching law

I. INTRODUCTION

Variables structure system is applied for nonlinear circuits.SMC(sliding mode control) is part of the variables structure system[1].DC-DC buck converter is implemented and controlled by SMC, because SMC is suitable for power electric systems[2] and the fastest switching operation has been done in power electronics systems[3]. Know days usage of electronic gadgets are more. The chattering is the undesirable phenomenon occurs in the power converters due to switching operation and lack of designing closed-loop systems[4]. The DC-DC power converters to obtain smooth and fast operation and less steady error, it requires a dynamic controller for efficient operations [2, 5]. In some research work dc-dc buck converter controlled by classical SMC, chattering is not focused. The chattering is minimized to some extent [6]. The steady-state error is minimized effectively. Global SMC minimized the steady-state error and chattering minimized considerably. Reaching law is implemented but chattering existing on the sliding line, so that steady state error not accurate using reaching law[7].

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* Correspondence Author
K.B.Siddesh*, Department of ECE, SJMIT, VTU, Chitradurga, India.
Dr.Basavaraja Banakara, Department of EEE,UBDTCE, Davangere, VTU India.
R.Shivarudraswamy, Department of EEE, MIT, Manipal, MAHE, India.

In some researchers modified SMC functional to dc-dc power converter to obtain a smooth and less steady-state error even for external disturbances occurs [8,9]. To overcome the drawbacks of the chattering in SMC, and minimizing the steady-state errors and a stable output voltage. Proposed techniques are adopted buck converter and among them, tan hyperbolic reaching law gives steady-state output voltage even for external disturbances.

II. SLIDING MODE CONTROL FOR BUCK CONVERTER

The sliding mode controlled buck converter as shown in figure [10].

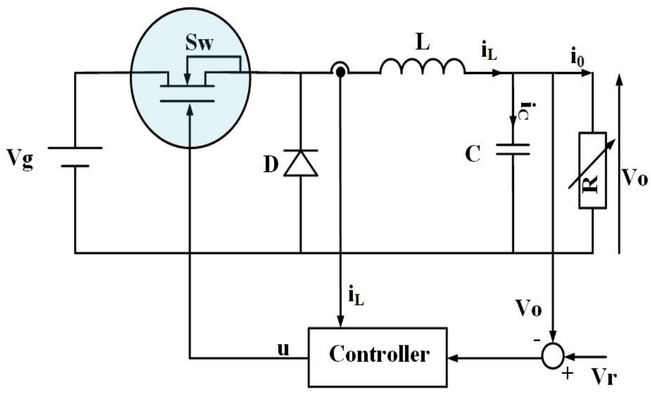

Figure1. A Circuit diagram of SMC for converter.

State equations

$$Xbuck = \begin{pmatrix} X1 \\ X2 \\ X3 \end{pmatrix} = \begin{pmatrix} X1 = Vref - \beta Vo \\ X2 = \dfrac{\beta Vo}{RLC} + \int \dfrac{\beta Vo - \beta ViU}{LC} dt \\ X3 = \int X1dt \end{pmatrix} \quad [10]$$

$$\dot{X} = AX + BU + D \quad (1)$$

X_1 is the error, X_2 is the derivative of the error and X_3 is the integral error.

The sliding surface is given by

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

The derivative of the sliding surface as

$$\dot{S} = \alpha 1\dot{X}1 + \alpha 2\dot{X}2 + \alpha 3\dot{X}3 = 0 \quad [10] \quad (3)$$

Where α1 α2 & α3 are constants.

Chattering: It is undesirable or unwanted oscillation occurs in the sliding surface of SMC.Fig.1 depicts the chattering of SMC.

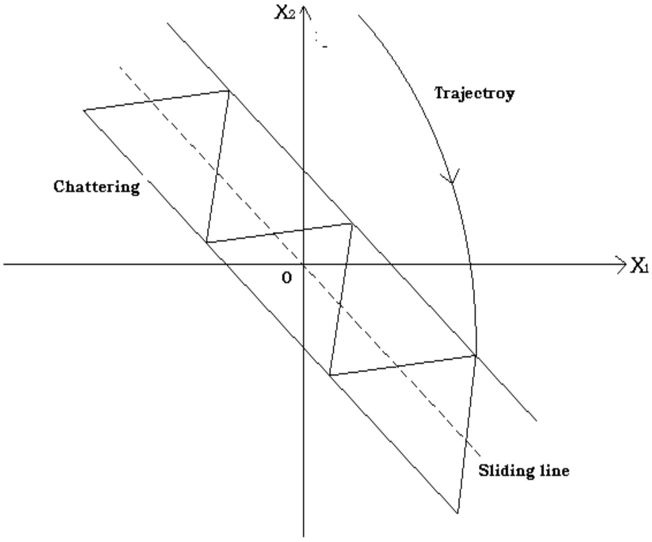

Figure 1: Chattering of SMC

III. Proposed reaching laws method for SMC based reaching law in buck converter

A. Proposed reaching law: SMC based buck converter using Exponential reaching law

This reaching law is given by [11].

$$\dot{S} = -K*\mathrm{sgn}(S) \quad \dot{S} = -K*\mathrm{sgn}(S) \tag{4}$$

$$\dot{S} = -\frac{K}{N(S)}*\mathrm{sgn}(S), \quad K>0 \tag{5}$$

$$N(S) = \delta 0 + (1-\delta 0)e^{-\alpha|S|p} \tag{6}$$

$\delta 0<1$, $P>0$, $\alpha>0$

$$\text{in } \dot{S}(\delta 0 + (1-\delta 0)e^{-\alpha|S|p}) = -K\mathrm{sgn}(S) \tag{7}$$

$$\dot{S} = -\frac{K\,\mathrm{sgn}(S)}{N(S)} \tag{8}$$

Equating eqn. (9) and (8)

Mathematical modeling:

$$\dot{S} = -\frac{K\mathrm{sgn}(S)}{N(S)} = \alpha 1\dot{X}1 + \alpha 2\dot{X}2 + \alpha 3\dot{X}3 = 0 \tag{9}$$

$$-K\frac{1}{N(S)}\mathrm{sgn}(S) = \alpha 1\left(-\frac{\beta}{C}\right)ic + \alpha 2\frac{\beta ic}{RC^2} - \alpha 2\frac{UVin\beta}{LC} + \alpha 2\frac{\beta V0}{LC} + \alpha 3(Vref - \beta Vo) \tag{10}$$

$$Ueq = \frac{LC}{\alpha 2 Vin\beta}\left[K\frac{1}{N(S)}\mathrm{sgn}(S) - \frac{\alpha 1 ic\beta}{C} + \alpha 2\frac{\beta ic}{RC^2} + \alpha 2\frac{\beta Vo}{LC} + \alpha 3(Vref - \beta Vo)\right] \tag{11}$$

$$Vc = \frac{LC}{\alpha 2}\left[K\frac{1}{N(S)}\mathrm{sgn}(S) - \frac{\alpha 1 ic\beta}{C} + \alpha 2\frac{\beta ic}{RC^2} + \alpha 2\frac{\beta Vo}{LC} + \alpha 3(Vref - \beta Vo)\right] \tag{12}$$

(12)

B.Proposed Reaching Law: Buck converter using SMC based Sigmoid Variable Reaching Law

This reaching law is given by [12].

$$\mathrm{sig}(X,\alpha,\theta) = (1 + e^{-\alpha X+\theta})^{-1} \tag{13}$$

$$\|X\| = \sum_{i=1}^{n}|X_i|, \varepsilon > 0, K > 0$$

$$\dot{S} = -\varepsilon\mathrm{sig}(\|X\|)\,\mathrm{sgnS}(X) - K1S(X) \tag{14}$$

$$\dot{S} = -\varepsilon\mathrm{sig}(\|X\|)\,\mathrm{sgnS}(X) - K1S(X) = \alpha 1\dot{X}1 + \alpha 2\dot{X}2 + \alpha 3\dot{X}3 = 0 \tag{15}$$

Mathematical modeling:

Equate (4) and (15), we get

$$-\varepsilon\mathrm{sig}(\|X\|)\,\mathrm{sgnS}(X) - K1S(X) = \alpha 1\left(-\frac{\beta}{C}\right)ic + \alpha 2\frac{\beta ic}{RC^2} - \alpha 2\frac{UVin\beta}{LC} + \alpha 2\frac{\beta V0}{LC} + \alpha 3(Vref - \beta Vo) \tag{16}$$

$$Ueq = \frac{LC}{\alpha 2 Vin\beta}\left[\varepsilon\mathrm{sig}(\|X\|)\mathrm{sgnS}(X) + K1S(X) - \frac{\alpha 1 ic\beta}{C} + \alpha 2\frac{\beta ic}{RC^2} + \alpha 2\frac{\beta Vo}{LC} + \alpha 3(Vref - \beta Vo)\right] \tag{17}$$

(16)

$$Vc = \frac{LC}{\alpha 2}\left[\varepsilon\mathrm{sig}(\|X\|)\,\mathrm{sgnS}(X) + K1S(X) - \frac{\alpha 1 ic\beta}{C} + \alpha 2\frac{\beta ic}{RC^2} + \alpha 2\frac{\beta Vo}{LC} + \alpha 3(Vref - \beta Vo)\right] \tag{18}$$

C. Proposed Reaching law: Buck converter using SMC based Tan hyperbolic reaching law

It is given by

$$\dot{S} = -m1*|s|^{g}\tanh(s) - m2|s|^{f}\tanh(S) \tag{19}$$

$m_1>0$, $m_2>0$, $g>0$, $0<f<1$

Convergence speed of the hyperbolic function is fast and keep the system state on the sliding line $-m1*|s|^{g}\tanh(s)$. $-m2|s|^{f}\tanh(S)$ term alleviates the chattering. [13].

Mathematical modeling:

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

$$-m1*|s|^{g}\tanh(s) - m2|s|^{f}\tanh(s) = \alpha 1\left(-\frac{\beta}{C}\right)ic + \alpha 2\frac{\beta ic}{RC^2} - \alpha 2\frac{UVin\beta}{LC} + \alpha 2\frac{\beta V0}{LC} + \alpha 3(Vref - \beta Vo) \tag{20}$$

The control equation is given by [10]

$$U_{eq} = \frac{LC}{\alpha 2 Vin\beta}\begin{bmatrix} -m1*|s|^{g}\tanh(s) - m2|s|^{f}\tanh(s) - \frac{\alpha 1 ic\beta}{C} + \alpha 2\frac{\beta ic}{RC} + \\ \alpha 2\frac{\beta Vo}{LC} + \alpha 3\left(Vref - \beta Vo\right) \end{bmatrix} \quad (21)$$

D. Proposed Reaching Law: Robust Reaching law: buck converter using SMC based Robust Reaching law

The robust reaching law is given by

$$\dot{s} = -d1*|s|^{h1}\,sat(s) - d2|s|^{h2}\,sat(s) \quad (22)$$

d1>0, d2>0, h1>0, 0>h2>1

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

S is a sliding mode variable, where Δ is the length of the sat(s) plus-minus symmetric linear section near the origin, 0< Δ< 1[14]. Apart from this a boundary layer approach is followed. Instead of sgn(s), sat(s) is used such that switching from -1 to 1 or vice versa is followed through a linear path. $-d1*|s|^{h1}\,sat(s)$, Here d_1 is a constant, by proper selecting the h_1, the system arrives on the phase plane quickly, $d_2|s|^{h_2}\,sat(s)$ d2 is a constant. Selecting a optimistic value of h2, it alleviates the chattering [14, 17, 18].

Mathematical modelling:

$$-\alpha 1*|s|^{h1}\,sat(s) - \alpha 2|s|^{h2}\,sat(s) = \dot{s} = \alpha 1\dot{x}_1 + \alpha 2\dot{x}_2 + \alpha 3\dot{x}_3 \quad (23)$$

$$-d1*|s|^{h1}\,sat(s) - d2|s|^{h2}\,sat(s) = \alpha 1\left(-\frac{\beta}{C}\right)ic + \alpha 2\frac{\beta ic}{RC^2} - \alpha 2\frac{UVin\beta}{LC} + \alpha 2\frac{\beta V0}{LC} + \alpha 3(Vref - \beta Vo) \quad (24)$$

The control equation given by after equating with proposed reaching law

$$U_{eq} = \frac{LC}{\alpha 2 Vin\beta}\begin{bmatrix} -\alpha 1*|s|^{h1}\,sat(s) - \alpha 2|s|^{h2}\,sat(s) - \frac{\alpha 1 ic\beta}{C} + \alpha 2\frac{\beta ic}{RC} + \\ \alpha 2\frac{\beta Vo}{LC} + \alpha 3\left(Vref - \beta Vo\right) \end{bmatrix} \quad (25)$$

E. Proposed Improved Tan Hyperbolic Reaching Law: Buck Converter Using improved Tan hyperbolic Reaching Law

The tan hyperbolic reaching law is given by [15, 19, 20]

$$\dot{s} = -k1*|s|^{a}\tanh(s) - k2|s|^{b}\tanh(s) - Ts \quad (26)$$

$$k1 > 0, k2 > 0, a > 0, b > 0, T > 0$$

The Equation (25) in the improved tan hyperbolic reaching law the bigger the value of b, the greater the velocity of the system state trajectory far the sliding mode surface (s>1) and the smaller the velocity of the system state path near the sliding mode surface (s<1). Correspondingly, the larger the rate of 'a', the lesser the velocity of the method state path near the sliding mode surface. It can be known from Eq. (1) that when s=0, $\dot{s}$= 0 =0. The first two terms in Eq. (1) are corresponding to the phased control useful to the system. The third term -Ts is added to mitigate the discontinuity of the system at the separation point, exponentially attenuates the system chattering and ensures the stability of the system.The equation (26) equated with equation (3),

$$-k1*|s|^{a}\tanh(s) - k2|s|^{b}\tanh(s) - Ts = \dot{s} = d1\dot{x}_1 + d2\dot{x}_2 + d3\dot{x}_3 \quad (27)$$

control equation given by after equating with proposed reaching law

$$U_{eq} = \frac{LC}{d2 Vin\beta}\begin{bmatrix} -k1*|s|^{a}\tanh(s) - k2|s|^{b}\tanh(s) - Ts - \frac{d1 ic\beta}{C} + d2\frac{\beta ic}{RC} + \\ d2\frac{\beta Vo}{LC} + d3\left(Vref - \beta Vo\right) \end{bmatrix} \quad (28)$$

F.Proposed Double Power Reaching Law: buck converter using double power reaching law

$$\dot{s} = -R_1*|s|^{F_1}\,sgn(s) - R_2|s|^{F_2}\,sgn(s) \quad (29)$$

$F_1 > 1$, $0 < F_2 < 1$, $R_1 > 0$, $R_2 > 0$.

The Equation (29), The double power reaching law, It has two terms, the first term makes the system bringing into wherever, the initial conditions on to sliding manifold and reach to equilibrium point. [13, 14, 16, 21]

Mathematical modelling:

$$-R_1*|s|^{F_1}\,sgn(s) - R_2|s|^{F_2}\,sgn(s) = \dot{s} = \alpha_1\dot{x}_1 + \alpha_2\dot{x}_2 + \alpha_3\dot{x}_3$$

$$U_{eq} = \frac{LC}{\alpha 2 Vin\beta}\begin{bmatrix} -R_1*|s|^{F_1}\,sgn(s) - R_2|s|^{F_2}\,sgn(s) - \frac{\alpha_1 ic\beta}{C} + \alpha_2\frac{\beta ic}{RC} + \\ \alpha_2\frac{\beta Vo}{LC} + \alpha_3\left(Vref - \beta Vo\right) \end{bmatrix} \quad (30)$$

IV. RESULTS AND DISCUSSIONS:

A. Comparison of all proposed methods:

Table-1 shows the parameters of buck converter and reaching laws.

Sl. No.	Parameter	Symbol	Value
1	Input voltage	Vi	24Volts
2	Capacitance	C	220μF
3	Inductance	L	69μH
5	Maximum load resistance	R_L(max)	10 Ohm
6	Desired Output voltage	Vod	12V
7	Reference voltage	Vref	12V
8	m1 &m2 (Parameters)		2,3
9	Feedback factor	β	0.99
10	sliding coefficients,	α_1, α_2, α3	3,25,2000

11	F1,F2,R1,R2		1, 0.5, 0.7,1
12	k1, k2 ,a ,b,T		1, 0.5 ,0.7, 0.4,1
13	m1,m2,g f		0.5, 1
14	K,		0.02,3
15	d1,d2,h1 ,h2		1, 0.5,0.8,1

Table-2 Comparative analysis of output voltage of reaching laws

Sl.No.	Reaching laws	Deviated output voltage after disturbances	Actual output Voltage
		Line variations	
1	Exponential	11.62V(more)	12V
2	Sigmoid	11.79V	12V
3	Tan hyperbolic reaching law	11.82V(less)	12V
4	Improved tan hyperbolic reaching law	11.71V	12V
5	Robust reaching law	11.73V	12V
6	Double power reaching law	11.9V (Not Reached the Steady State) still arrive to steady state	12V
		Load variations	
9	Exponential	11.98V	12V
11	Sigmoid	11.97V	12V
12	Tan hyperbolic reaching law	11.99V(less)	12V
13	Improved tan hyperbolic reaching law	11.96V(more)	12V
14	Robust reaching law	11.97V	12V
15	Double power reaching law	11.90V(not reached steady state) still arrive to steady state	12V

From table-2 it is observed that tan hyperbolic reaching law give a smaller amount deviated output voltage as of the actual output voltage, among all the reaching laws. The recovery time of tan hyperbolic reaching law is less, it reaches steady state very quickly even after the disturbances of both load and line variations.

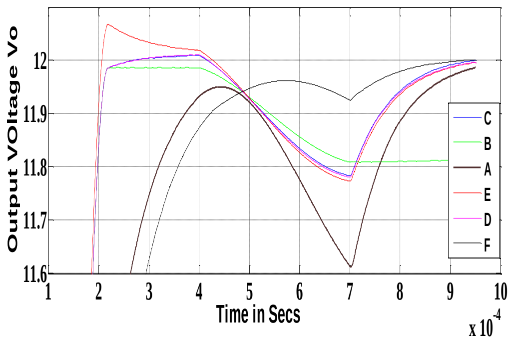

Figure 3: Output voltage of line variations occurred at 0.4mSecs from 24V to 5V and 0.7mSecs from 5V to 24V. SMC Reaching laws: 1) A (Exponential Reaching law 2) B (sigmoid Variable Reaching law) 3) C (Tan hyperbolic Reaching law) 4) D (Robust reaching law) 5) E (Improved tan hyperbolic reaching law) 6) F (Double power reaching law).From fig.3 depicts the output voltage versus of tan hyperbolic reaching law and it gives a better response than other reaching laws. Output voltage recovered very quickly from 24V to 5V at 0.4mSecs and 5V to 24V at 0.7mSecs.When compared to other reaching laws.

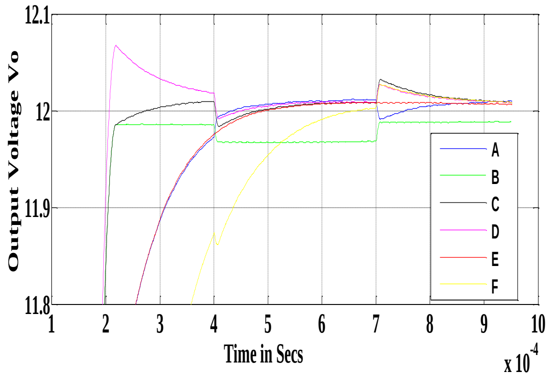

Figure 4: Shows the output voltage of load variations occurred at 0.4mSecs from 10Ω to 2Ω and 0.7mSecs from 2Ω to 10Ω. SMC Reaching laws 1) A (Exponential Reaching law 2) B (sigmoid Variable Reaching law) 3) C (Tan hyperbolic Reaching law) 4) D (Robust reaching law) 5) E (Improved reaching law) 6) F (Double power reaching law).From the figure 4 it is observed that output voltage versus time in secs. Tan hyperbolic reaching law gives a better response than other reaching laws. Output voltage is recovered very quickly from 10Ω to 2Ω, disturbances occur at o.4mSecs and 2Ω to 10Ω, disturbances occurs at 0.7 msec. When compared to other reaching laws, tan hyperbolic reaching law gives better results.

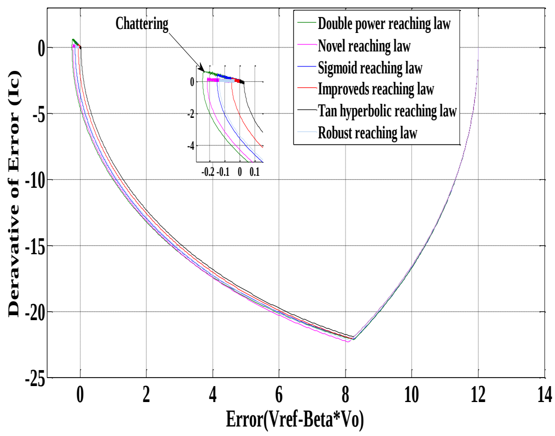

Figure 5 : shows derivative of error v/s error of chattering of Sigmoid, Novel, Improved tan hyperbolic reaching law, Tanhyperbolic reaching law, Double power reaching law and Robust reaching law. Figure 5 depicts the chattering being on the phase plane trajectory. The double power reaching law gives a error length of 0.240 and reaching time for steady state of 0.340msecs, Novel reaching law gives error length of 0.217 and reaching time of 0.310, Sigmoid reaching law gives a error length of 0.140 and reaching time of 0.372msecs,

Robust reaching law gives a error length of 0.130 and reaching time of 0.320msecs,Improved reaching law gives a error length of 0.050 and reaching time of 0.270msecs and tan hyperbolic reaching law gives a error length of 0.20 and reaching time of 0.275msecs respectively. As the error length decreases, reaching time also decreases .Effect of chattering existence on the error length causes a delay in approaching the steady state and switching losses in the switching devices in the buck converter.

V. CONCLUSION

In this article, a relative scrutiny has been done for load and line variations for proposed reaching laws. Among all other reaching laws, tan hyperbolic reaching gives dynamic and robustness response even for parametric uncertainties. Hence the chattering in the system reduced. The tan hyperbolic reaching law adapts the switching system very quickly and covers the sliding mode portion phase plane, it exhibits the property of the SMC, due to less chattering that provides a less sensitive for external disturbances.

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