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Comparison analysis of chattering in smooth sliding mode controlled DC-DC buck converter using constant plus proportional reaching law and proposed reaching laws

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ABSTRACT

This paper presents a comparative analysis of chattering in sliding mode controlled DC-DC buck converter for chattering suppression using constant plus proportional reaching law and proposed reaching laws. A smooth SMC is used for chattering suppression in buck converter. The different switching functions are used in proposed reaching laws and constant plus proportional reaching law applied to SMC buck converter, the tan hyperbolic reaching law, sigmoid reaching law and constant plus proportional rate reaching law. The proposed method tan hyperbolic gives less switching loss among the reaching laws and stable output voltage. Inturn, performance of the buck converter increases, tanhyperbolic reaching law is more sensitive to matched, mismatched disturbance and parameter uncertainties. Loading conditions are also applied to the buck converter to measure the disturbances and parametric variations. The results are verified by MATLAB/Simulink.

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1. 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 and alleviate the size of the converter. The DC-DC converter working with a sliding mode controller based reaching law. Even though many parameters influence the operating points of the converters.1) Line and load variation. 2) Electromagnetic interferences (EMI). 3) Chattering. The SMC is derived from VSCS (variable structure control systems) and applied to many non linear applications, using reaching laws, the objective structure of a system is changed intentionally during the time concerning the present structure control law. The traditional reaching laws are explained [1]. The applications and survey given in [2], the variable structure applied with reaching laws, it can minimize the chattering in the systems but not removed from the system. The design and analysis of DC-DC converter done using adaptive SMC, here not mentioned the chattering of converter [3]. Using fixed-frequency modulation for quasi sliding mode control (QSMC) has been done through experimental and simulation verifications [4]. Analysis of new improved reaching law with chattering reduction in SMC based on many applications [5]. In this work comparative study of sliding mode control (SMC) with PID controller, derivative sliding surface with three different reaching laws, namely, constant rate, exponential and power rate reaching law to control a two-link robotic manipulator [6].

An improved traditional SMC in positive invariant ones, the sliding surfaces enters by the variables, it will not move away from the sliding line [7]. In this work presents a new methods based on a novel reaching law to overcome slow convergence rate and reduce the chattering in sliding mode control of permanent magnet synchronous motors (PMSM). The constant reaching law converges slowly. Although the power reaching law converges fast during large error [8].

This work proposes a novel continuous reaching law for chattering-less sliding mode control by using two hyperbolic functions with like changing rate and contradictory amplitude characteristics. The earliest function is an inverse hyperbolic sine function, which can guarantee the quick convergence as the first value of the sliding mode variable is far away from the equilibrium. When the sliding mode variable is approaching to zero, the second hyperbolic tangent function can ensure the sliding mode variable be infinitely close to zero slightly than cross the zero [9]. In this work, the sigmoid variable rate reaching law applied to the systems and its analysis with conventional reaching law, sigmoid reaching law is dynamic and superior to traditional reaching law [10]. In this work comparison between sigmoid and exponential reaching law applied DC-DC buck converter, chattering was minimized [11]. This work gives chattering minimization with SMC based reaching laws [12]. This work presents chattering alleviation using modified power rate reaching law for robotics, here varying the exponential term of power rate reaching law to minimize he chattering [13]. This work presents saturation function instead of signum function, so that it covers the entire sliding mode portion and chattering reduces [14]. This work presents an improved reaching law in SMC for chattering minimization, as compare to previous works [15]. This reaching law is an adaptive but it implemented to second-order nonlinear function [16]. This work presents new power exponential rate reaching law for second-order system to reduce the chattering in the system and control gains automatically adjusts the switching function [17]. In this work discrete sliding mode control and classical SMC with relative degree1 and relative degree2 for DC-DC buck converter discussed, no chattering issues in this work [18]. In this work reaching law based SMC for DC-DC buck converter has been done. Here d+ and d- method implemented, chattering is alleviated, but not measured and traditional reaching law implemented [19]. In this work newly exponential term added to the power reaching law. It implemented to PMSM system to achieve better performance, fast convergence and reduces the chattering in the PMSM [20].

All the above [14-17] new reaching law in their differential equations, these law are reduces the chattering to a certain extent and adapts the smooth variation of switching function. All these new reaching laws reduces the amplitude of the chattering in the system. The problems in the previous work [11, 18-20]. Sliding mode portion not covered, Chattering existence, more switching loss, more time to reach the steady state, ripple in the output voltage, less response to external disturbances and uncertainty of the systems. As many researchers are discussed about the new modified reaching laws, chattering mitigation and their consequences on the converter. As in this work considered a buck converter, this converter applied to many applications such as renewable energy sources, laptops, electronics industries, electronic gadgets, etc., using a sliding mode controller achieving a constant output voltage. But more switching loss occur due to chattering in system, in turn, high speed switching frequency operation in the switching devices. To the above mentioned problem to alleviate the chattering, a proposed tan hyperbolic reaching law, sigmoid reaching law and constant plus proportional pace reaching law are examined and applied to buck converter [21-23].

2. GENERAL IMPLEMENTATION OF SMOOTH SLIDING MODE CONTROL FOR BUCK CONVERTER USING REACHING LAW

The converter output voltage and its derivative both are selected as state variables for buck converter. Figure 1 shows the structure of SMC for buck converter [5].

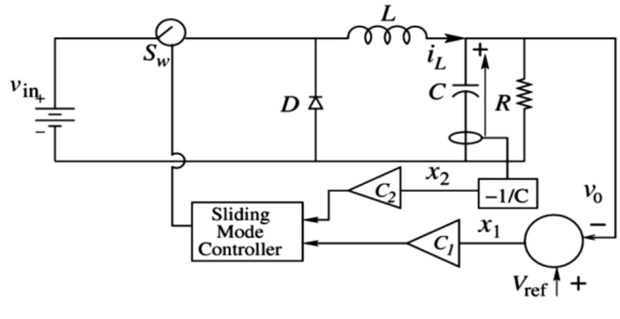

Figure 1. A Circuit diagram of SMC for buck converter

The mathematical equation,

$$X_{buck} = \begin{pmatrix} X_1 \\ X_2 \\ X_3 \end{pmatrix} = \begin{pmatrix} X_1 = Vref - \beta Vo \\ X_2 = \frac{\beta Vo}{RLC} + \int \frac{\beta Vo - \beta ViU}{LC} dt \\ X_3 = \int X1dt \end{pmatrix} \text{ [5]}$$

$$\dot{X} = AX + BU + D \tag{1}$$

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;

$$S = \alpha_1 X_1 + \alpha_2 X_2 + \alpha_3 X_3 \tag{2}$$

The derivative of the sliding surface and this equation equated with proposed reaching laws.

$$\dot{S} = \alpha_1 \dot{X}_1 + \alpha_2 \dot{X}_2 + \alpha_3 \dot{X}_3 = 0 \text{ [5]} \tag{3}$$

where α_1 α_2 & α_3 represent the sliding coefficients.

2.1. Implementation of smooth sliding mode control for buck converter with constant plus proportional pace reaching law (traditional reaching law)

Constant plus proportional pace reaching law (traditional reaching law) it is given by [1]

$$\dot{S} = -Qsgn(S) - kS \tag{4}$$

where Q and k are constants [1]. Equating the (3) and (4) (implementation of SMC with buck converter),

$$\dot{S} = -Qsgn(S) - kS = \alpha_1 \dot{X}_1 + \alpha_2 \dot{X}_2 + \alpha_3 \dot{X}_3 \tag{5}$$

$$-Qsgn(S)-kS = \alpha 1\left(-\frac{\beta}{C}\right)ic + \alpha 2\frac{\beta ic}{RC^2} - \alpha 2\frac{UVin\beta}{LC} + \alpha 2\frac{\beta V0}{LC} + \alpha 3\left(Vref - \beta Vo\right) \tag{6}$$

Simulation modelling eqution:
where U_{eq}=d; d=V_c/Vramp; Vramp=β V_{in}

$$\begin{aligned} Ueq &= \frac{LC}{\alpha 2 Vin\beta}\left[Qsgn(S)+kS-\frac{\alpha 1 ic\beta}{C}+\alpha 2\frac{\beta ic}{RC^2}+\alpha 2\frac{\beta Vo}{LC}+\alpha 3\left(Vref-\beta Vo\right)\right] \\ Vc &= \frac{LC}{\alpha 2}\left[Qsgn(S)+kS-\frac{\alpha 1 ic\beta}{C}+\alpha 2\frac{\beta ic}{RC^2}+\alpha 2\frac{\beta Vo}{LC}+\alpha 3\left(Vref-\beta Vo\right)\right] \end{aligned} \tag{7}$$

2.2. Implementation of smooth sliding mode control for buck converter with proposed method 1: Sigmoid reaching law

The proposed sigmoid reaching law is given by [10, 24, 25].

$$sig(X,\alpha,\theta) = (1+e^{-\alpha X+\theta})^{-1} \tag{8}$$

$$\text{if} \alpha = 1, \theta = 0$$

$$sig(X) = 2sig(X,1,0) - 1 = \frac{1-e^{-X}}{1+e^{-X}}$$

$$\text{if} \alpha = 2, \theta = 0$$

$$tanh(X) = sig(2X) = \frac{e^{X} - e^{-X}}{e^{X} + e^{-X}}$$

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

$$\dot{S} = -\varepsilon sig\left(\|X\|\right) sgn\, S(X) - K1S(X) \tag{9}$$

Equating the (3) and (9) (implementation of SMC with buck converter),
Simulation modeling equations:

$$-\varepsilon sig\left(\|X\|\right) sgn\, S(X) - K1S(X) = \alpha 1\left(-\frac{\beta}{C}\right) ic + \alpha 2 \frac{\beta ic}{RC^2} - \alpha 2 \frac{UVin\beta}{LC} + \alpha 2 \frac{\beta V0}{LC} + \alpha 3\left(Vref - \beta Vo\right) \tag{10}$$

$$Ueq = \frac{LC}{\alpha 2 Vin\beta}\left[\varepsilon sig\left(\|X\|\right) sgn\, S(X) + K1S(X) - \frac{\alpha 1 ic\beta}{C} + \alpha 2 \frac{\beta ic}{RC^2} + \alpha 2 \frac{\beta Vo}{LC} + \alpha 3\left(Vref - \beta Vo\right)\right] \tag{11}$$

where Ueq=d; d=V_c/Vramp; Vramp=β Vin where β is a feedback factor.

$$Vc = \frac{LC}{\alpha 2}\left[\varepsilon sig\left(\|X\|\right) sgn\, S(X) + K1S(X) - \frac{\alpha 1 ic\beta}{C} + \alpha 2 \frac{\beta ic}{RC^2} + \alpha 2 \frac{\beta Vo}{LC} + \alpha 3\left(Vref - \beta Vo\right)\right] \tag{12}$$

2.3. Implementation of smooth sliding mode control for buck converter with proposed method 2: Tan hyperbolic reaching law

Proposed a novel continuoustan hyperbolic reaching law is given by [9].
A proposed method 2 reaching law is given by;

$$\dot{S} = -\, m1 * |s|^{\alpha} \tanh(s) - m2|s|^{\lambda} \tanh(s) \tag{13}$$

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

The hyperbolic function range from (-1, +1),

$$\tanh(s) = \frac{e^{x} - e^{-x}}{e^{x} + e^{-x}}$$ [9].

This hyperbolic reaching laws gives smooth switching function by $-m1*|s|^{\alpha} \tanh(s)$,where α is a switching gain. $-m2|s|^{\lambda} \tanh(s)$ where λ is a linear gain for controlling the chattering in the sliding surface. By selecting propoer lear gain chatterin will be limited.

Simulation modeling equations $-m1*|s|^{\alpha} \tanh(s)$
Equating the (3) and (13) (Implementation of SMC with buck converter)

$$-m_1*|s|^{K_1} \tanh(s) - m_2|s|^{K_2} \tanh(s) = \dot{S} = \alpha_1\dot{X}_1 + \alpha_2\dot{X}_2 + \alpha_3\dot{X}_3$$

$$-m_1*|s|^{K_1} \tanh(s) - m_2|s|^{K_2} \tanh(s) = \alpha_1\left(-\frac{\beta}{C}\right) ic + \alpha_2 \frac{\beta ic}{RC^2} - \alpha_2 \frac{UVin\beta}{LC} + \alpha_2 \frac{\beta V0}{LC} + \alpha_3\left(Vref - \beta Vo\right) \tag{14}$$

where Ueq=d; d=V_c/Vramp; Vramp=β Vin

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

$$Vc = \frac{LC}{\alpha 2}\left[-m1*|s|^{\alpha} \tanh(s) - m2|s|^{\lambda} \tanh(s) - \frac{\alpha 1 ic\beta}{C} + \alpha 2 \frac{\beta ic}{RC^2} + \alpha 2 \frac{\beta Vo}{LC} + \alpha 3\left(Vref - \beta Vo\right)\right] \tag{15}$$

3. RESULTS AND DISCUSSION

Table 1 specification of sliding mode control buck converter with reaching laws. Figure 2 shows that proposed method 1 gives the ripple in the output voltage is 2mV, ouput voltage is 12.065V, whereas the proposed method 2 tan hyperbolic reaching law gives no ripple in the output voltage and it provides the output voltage of 12.01V. This is due to chattering exists in the sigmoid reaching law. Constant plus proportional pace reaching law not yet reached steady state because more chattering exist in the sliding manifold as shown in the Figure 2 and output voltage is 11.97V. (Simulation results of this Figure 2 from modelling (7), (12), (15)).

Figure 3 shows that the proposed method 2 has s overshoot voltage of 1.5V, ripple in the output voltage (2mV) and output voltage of 12.025V. Whereas the proposed method 1 gives no overshoot, no ripple in the output voltage and an output voltage is 12.02V.Constant plus proportional pace reaching law has taken more time to reach the steady state and output voltage is 11.97V. The more chattering occurs in the proposed method 2. It is observed that proposed method 2 is more sensitive for load component variations. (Simulation results of this Figure 3 from modelling (7), (12), (15)).

Table 1. Gives the specifications of the of sliding mode control buck converter with reaching laws

Sl.No.	Parameter	Symbol	Value
1	Input voltage	Vi	24Volts
2	Capacitance	C	220µF
3	Inductance	L	69µH
4	Switching Frequency	fs	250KHz
6	load resistance	R_L(max)	10 Ohm
7	Desired Output voltage	Vod	12V
8	Reference voltage	Vref	12V
9	Inductance	L_L	1mH
10	Capacitance	C_L	1microF
11	Feedback factor	β	0.98
12	Sliding coefficients,	$\alpha_1, \alpha_2, \alpha 3$	3,25,200
13	Duty cycle	α	0.5
14	Efficiency of the Converter	η	0.91
15	.λ α,K1,K2		0.5,1,0.95

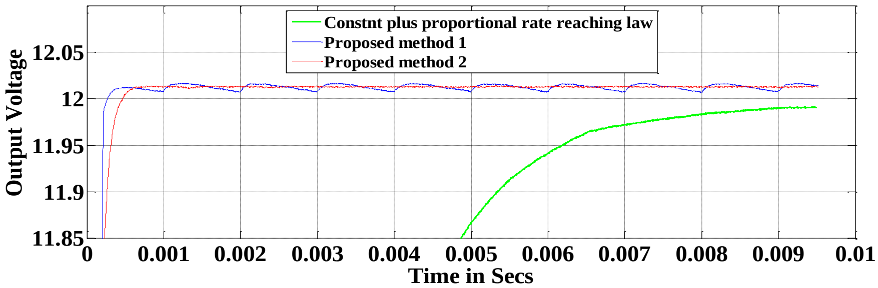

Figure 2. Shows the output voltage v/s time in secs of buck converter,
Proposed method 1 (sigmoid reaching law), Proposed method 2 (tan hyperbolic reaching law),
and Constant plus proportional pace reaching law **(R-Load)**

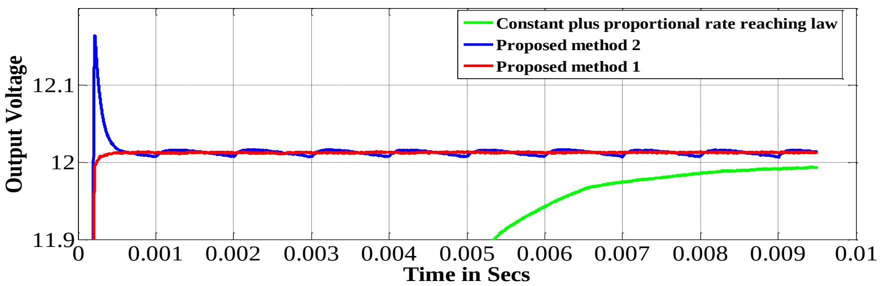

Figure 3. Shows the output voltage v/s time in secs of buck converter,
Proposed method 1 (tanhyperbolic reaching law), Proposed method 2 (sigmoid reaching law),
and Constant plus proportional pace reaching law **(R-L Load)**

Figure 4 shows that the proposed method 1 gives a deviated from the desired output voltage is 0.38V, whereas the proposed method 2 has 0.28V, deviated from the desired output voltage respectively. The output voltage of proposed method 1 is 12.32V and output voltage of proposed method 2 is 12.36V. Constant plus proportional pace reaching law reaches the steady state at 6msecs and output voltage is 12.01V, but not stable in output voltage. Proposed method 1 has a more sensitive to change in load components and exhibits the change in output voltage. (Simulation results of this Figure 4 from modelling (7), (12), (15))

Figure 5 shows that proposed method 1 has deviated the output voltage 0.43V, whereas the proposed method 2 has 0.29V.The output voltage of proposed method 1 is 12.44V and the output voltage of proposed method 2 is 12.29V. Constant plus proportional pace reaching law reaches the steady state at 6msecs and output voltage is 11.99V, but not stable in output voltage. In R-L-C load, the proposed method 2 has less deviated from the desired output voltage and more stable. Proposed method 1 has more deviated from the output voltage.

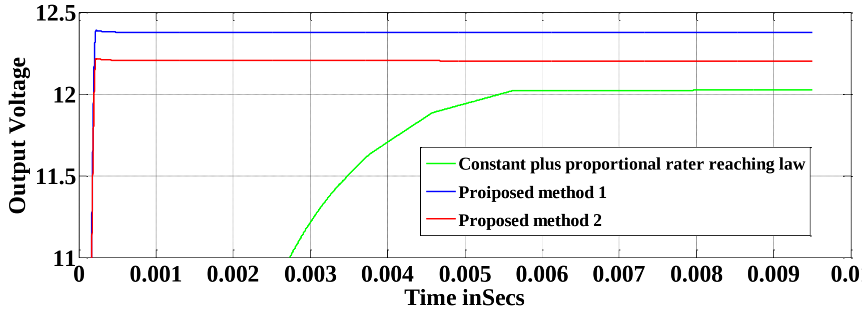

Figure 4. Shows output voltage v/s time in secs of buck converter,
Proposed method 1 (sigmoid reaching law), Proposed method 2 (tanhyperbolic reaching law),
and constant plus proportional rate reaching law **(R-C Load)**

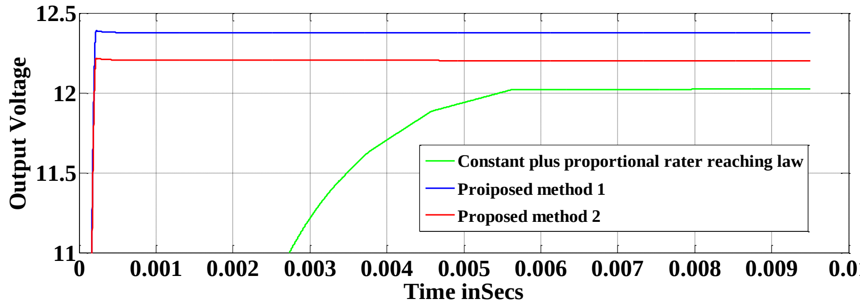

Figure 5. Shows output voltage v/s time in secs of Buck converter,
Proposed method 1 (sigmoid reaching law), Proposed method 2 (tan hyperbolic reaching law),
and Constant plus proportional rate reaching law **(R-L-C Load)**

Figure 6 shows the derivative of error and error. The chattering has occurred on nearby the origin of both methods. Whereas the constant plus proportional pace reaching law is far away from the origin, due to chattering in the sliding manifold. Proposed method 1 is just away from the origin when compared to proposed method 2 and constant plus proportional reaching law. This is due to sign switching function gives discontinuous in the sliding mode, proposed method 2 gives a smoother switching function and avoid the discontinuity in the sliding mode, whereas the proposed method 1 gives less discontinuity in the sliding mode. Hence proposed method 2 exhibits superior continuous approximation than other methods. The chattering of proposed method 1 is 0.156, the proposed method 2 chattering is 0.143 and constant plus proportional pace reaching law chattering is 0.5. In turn, switching loss is more in constant plus proportional pace reaching law than proposed method 2. Results are tabulated in Table 2. (Simulation results of this Figure 6 and Table 2 are obtained from modellin (7), (12), (15)).

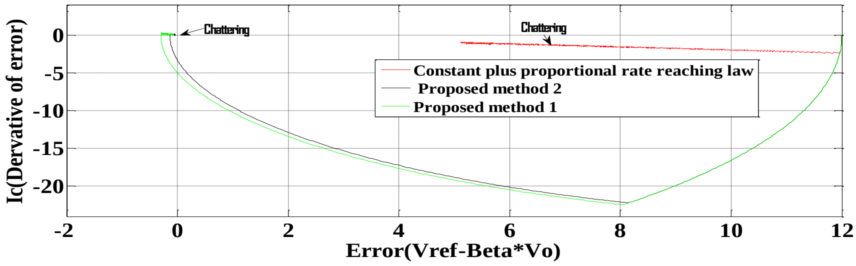

Figure 6. Shows derivative of error v/s error of buck converter, Proposed method 1 (sigmoid reaching law), Proposed method 2 (tan hyperbolic reaching law), and Constant plus proportional rate reaching law (chattering)

Table 2. Comparison of proposed method 1, proposed method 2 and constant plus proportional pace reaching law (buck converter)

Parameters	A proposed method1 sigmoid reaching law	A proposed method2 tan hyperbolicreaching law	Constant plus proportional pace reaching law
Chattering amplitude from x and y-axis	0. 156	0.143	0.5
Output Voltage(R load)	12.065V	12.01V	11.97V
Output Voltage(R-L load)	12.025V	12.012V	11.97V
Output Voltage(R-C load)	12.32V	12.36V	12.01V
Output Voltage(R-L-C load)	12.44V	12.29V	11.99V
Switching loss	0.31W	0.29W	0.55W

4. CONCLUSION

The proposed method 2 (tan hyperbolic reaching law) gives constant output voltage, reaches steady state with fast convergence time and it mitigates chattering, it covers the entire sliding mode portion of the phase plane trajectory as compared to method 1 (sigmoid reaching law). The different loading is applied to converter, among these two methods the tan hyperbolic reaching law gives better controlling the output voltage and fewer ripples in the output voltage than the sigmoid reaching law and constant plus proportional pace reaching law. Tanhyperbolic reaching law gives less chattering and takes less time to reach a steady-state. In turn, less switching loss in the buck converter.

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