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Enhanced sliding mode controller performance in DC-DC buck converter using a tan hyperbolic reaching law and constant plus proportional reaching law

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ABSTRACT

This paper presents an enhanced sliding mode controller (SMC) operation, chattering analysis and loading conditions of the SMC DC-DC buck converter. Sliding mode portion, chattering attenuation are analyzed by using a conventional and proposed reaching law in buck converter. A proposed tan hyperbolic reaching law (THRL) is originated to be useful in terms of chattering mitigation and fast convergence. The major drawback of the conventional reaching law viz, it bypasses the main portion of the sliding mode portion to ensure fast reaching. It causes more chattering, more time to reach the steady state on the switching surface. The most significant improvement of SMC is that it guarantees strengthening the sliding mode phase. The proposed tan hyperbolic reaching law is being hit here during an exponential adjustment so that the attributes of it, covers complete sliding mode portion, chattering mitigation and fast reaching time. In turn, cause fewer switching loss in the buck converter. Even external disturbances and uncertainty of the system occurs. The loading conditions are applied to proposed tan hyperbolic reaching law and analyzed. Simulation analysis conducted by MATLAB/Simulink.

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1. INTRODUCTION

Sliding Mode Variable Structure Systems is an applied to nonlinear systems design technique, it evolved from the Variable Structure Control (VSC) and is established in the field of nonlinear control. SMC (sliding mode structure) is inherently suitable for fast switching operations in power electronic systems. In [1] control applications and drawbacks of the control methods of reaching sliding surfaces, various sliding surfaces that can be explained and implemented through sliding mode variable. In [2] to advance the dynamic characteristics of the reaching phase and to lessen chattering, the second approach called reaching law SMC is also existing, in this proposed scheme, chattering ismitigated [3]. In [4] Higher-Order Sliding Modes are accessible as an apparatus to take away discontinuity from the control action, to deal with upper relation degree systems and to recover the accuracy of the real sliding mode behavior when the discrete-time implementation. In [5] this research a novel reaching law (RL) is projected that use inverse hyperbolic function (IHF) as an alternative of the signum function for switching.

The attribute of this reaching law is that its switching gain is variable, during the reaching segment. In [6] the effectiveness of the reaching law approach for sliding mode control for SISO systemswith modified reaching law to reduce the chattering. In [7] this approach ensures that the control signal and all state variables of the system are limited by design parameters that do not depend on the initial state. In [8] this approach gives types of reaching laws for nonlinear systems and methods of reaching mode, sliding mode and various methods for switching surface. In [9] this approach gives general design issues to dc-dc buck converter with sliding mode controller. In [10] this approach gives enhanced performance of the SMC with the power rate reaching law for the robotic controller. This method exhibits the sliding mode motion property, against the traditional reaching law. In [11] this approach gives adaptive exponential reaching law, it adapts the variation of the parameters to a system and attributes to the applications. In [12] this approach the reaching law applied to dc-dc buck converter. D+ and D- method adopted using sliding mode motion, with this method chattering mitigated by traditional reaching law, but not measured the chattering amplitude. In [13] this approach a continuous approximation with sliding control by variable structure systems it is for SISO, MIMO systems. In [14] this approach double hyperbolic reaching law gives a fast convergence and fast attraction of states on a sliding manifold.It also reduces the chattering effectively in the sliding mode control. In [15] this approach only practical design aspects and sliding surface, and using the PWM method and not using the reaching law method. In [16] this approach reduced chattering by new reaching law in discrete systems.

The chattering is effectively reduced. In [17, 18] this approaches the reaching laws for MIMO systems for reduction of chattering. In [19-21] the gain of the reaching law are routinely synchronized by the control function and the exponential term that energetically adapts to the disparity of the switching function andtraditional sliding mode control intended with the continuous-time model and for the discrete-time with, comparative degree one (CD1) sliding surface and comparative degree two (CD2) on the sliding surface designs are compared. In [22-24] this reaching law gives less convergence speed and more chattering, a modified double reaching law, replace switching function by saturated function and add the exponential terms to the configuration. The proposed reaching law is a superior version than the conventional [1, 25] reaching law (Conventional Reaching Law) one [1]. This reaching law unable to cover the sliding mode portion.

The problems are in the previous work, sliding mode portion has not covered by the constant plus proportional pace reaching law, it cause extra chattering, more switching losses, added time to reach the steady state, less response to external disturbances and uncertainty of the systems. In Literature, the majority of researchers focused on hardware type and desired output voltage [14], and using reaching law method to provide a constant output voltage. In this work, an advanced reaching law is implemented as compare to [12], but more switching losses occur due to chattering in power converter system, in turn, high speed switching frequency operation in the switching devices. To solve the above-mentioned problem, a proposed reaching law technique is applied to the DC-DC power converter system. This work gives a modified switching function and enhances the performance of the proposed reaching law. The following functions are performed in the proposed reaching law technique to dc-dc buck converter as compared to Gao's traditional reaching law [1]. Sliding mode motion is ensured, inturn causes less switching losses, tan hyperbolic function smoothen the switching operation, it is designed for dynamic switching system.

2. RESEARCH METHOD

2.1. Analysis and designing of sliding mode controller variable structure of dc-dc buck converter using reaching laws

The Figure 1 shows the schematic diagram of the DC-DC buck converter model. The mathematical equation,

$$\dot{X}_1 = X_2 \tag{1}$$

$$\begin{aligned} \dot{X}_{n-1} &= X_n \\ \dot{X}_n &= \sum_{i=1}^{n} = -a_i + bu \end{aligned} \tag{2}$$

The switching surface is given by,

$$S = \alpha_1 X_1 + \alpha_2 X_2 + \alpha_3 X_3 \tag{3}$$

The derivative of the switching surface is given by,

$$\dot{S} = \alpha_1\dot{X}_1 + \alpha_2\dot{X}_2 + \alpha_3\dot{X}_3 = 0 \tag{4}$$

Where α1 α2 & α3 represent the sliding coefficients, and X_1, X_2, and $X_3$are state feedback variables.

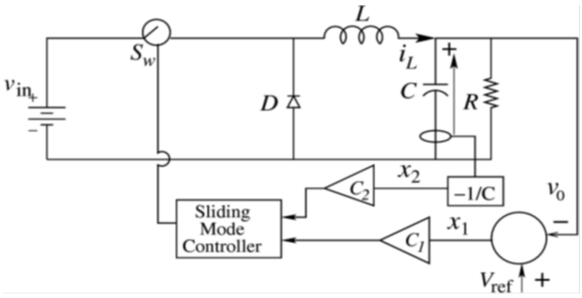

Figure 1. Schematic modeling of buck converter

2.1.1. Using a Conventional reaching law: designing of DC-DC Buck converter using constant plus proportional rate reaching law

The constant plus proportional rate reaching law by Gao's. It is given by,

$$\dot{S} = -Q\mathrm{sgn}(S) - kS \tag{5}$$

Q and K are constants and S is a sliding variable [23]. The mathematical equationquating the (4) with (5),

$$\dot{S} = -Q\mathrm{sgn}(S) - kS = \alpha_1\dot{X}_1 + \alpha_2\dot{X}_2 + \alpha_3\dot{X}_3 \tag{6}$$

$$-Q\mathrm{sgn}(S) - kS = \alpha_1\left(-\frac{\beta}{C}\right)ic + \alpha_2\frac{\beta ic}{RC^2} - \alpha_2\frac{UVin\beta}{LC} + \alpha_2\frac{\beta V0}{LC} + \alpha_3\left(Vref - \beta Vo\right)$$

The equivalent input with reaching law as follows
Ueq=d, d=Vc/Vramp, Vramp=β*Vin, β is a feedback ratio [18].

$$Ueq = \frac{LC}{\alpha_2 Vin\beta}\left[Q\mathrm{sgn}(S) + kS - \frac{\alpha 1ic\beta}{C} + \alpha_2\frac{\beta ic}{RC^2} + \alpha_2\frac{\beta Vo}{LC} + \alpha_3\left(Vref - \beta Vo\right)\right] \tag{7}$$

2.1.2. Using a proposed reaching law: designing of DC-DC Buck converter using tan hyperbolic reaching law

It is given by,

$$\dot{S} = -m1*|s|^{a}\tanh(s) - m2|s|^{b}\tanh(S) \tag{8}$$

$m_1>0$, $m_2>0$, $a>0$, $0<b<1$ [13]

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

Here tan hyperbolic function is used instead of sign and saturation function, it adapts smooth switching function as compared to saturation function. The reaching phase and convergence speed of the hyperbolic function is quick and keep the system state at the phase plane $-m_1*|s|^{\alpha}\tanh(s)$. As α varies, the system brings on to a phase plane and hits the sliding line at high speed. $m_2|s|^{\lambda}\tanh(S)$ term keep the system steady on the phase plane and selecting a controller gain value λ such that chattering will be attenuated at an assured point. The convergence pace varies with the sliding mode variable for a tan hyperbolic function, which can pace up the reaching phase when the sliding mode variable is far away from the switching surface. The least chattering property is obtained with the tan hyperbolic reaching law in sliding mode control scheme. The complete analysis of the convergence and the steady-state error of proposed reaching law provided in the next section. Where s is the sliding mode, a, b denotepositive controller gain parameters. It's derivative in the range of [-1, 1].

Mathematical modeling:

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

$$-m_1 * |s|^a \tanh(s) - m_2 |s|^b \tanh(s) = \alpha_1 \left(-\frac{\beta}{C}\right) ic + \alpha_2 \frac{\beta ic}{RC^2} - \alpha_2 \frac{UVin\beta}{LC} + \alpha_2 \frac{\beta V0}{LC} + \alpha_3 (Vref - \beta Vo) \tag{9}$$

The control equation given by after equating with proposed reaching law

$$Ueq = \frac{LC}{\alpha_2 Vin\beta} \left[-m_1 * |s|^a \tanh(s) - m_2 |s|^b \tanh(s) - \frac{\alpha_1 ic\beta}{C} + \alpha_2 \frac{\beta ic}{RC} + \alpha_2 \frac{\beta Vo}{LC} + \alpha_3 \left(Vref - \beta Vo \right) \right] \tag{10}$$

Ueq=d, d=Vc/Vramp, Vramp=β*Vin, β is a feedback ratio [18]. From [12] in this work, the chattering is not measured.

3. RESULTS AND DISCUSSION

3.1. Comparison results of the proposed method with constant plus proportional pace reaching law

Table 1 shows the controller parameters and specifications of the buck & reaching law parameters to carry out the work. Table 2 shows the Proposed Reaching Law with constant plus proportional rate reaching law. From the Tables 1 and 2. The Proposed Reaching Law gives better results than constant plus proportional rate reaching law Inturns of reaching time, sliding mode portion and sliding mode variable. It is experiential that the proposed method (Tan Hyperbolic reaching law) gives better results than the constant plus proportional rate reaching law Figure 2. Shows that derivative of error v/s error of proposed reaching law and constant plus proportionla reaching law.

From Figure 2 it is observed, the following 1. The proposed reaching law covers an entire sliding mode portion, whereas the constant plus proportional rate reaching law has not covered the entire portion of the sliding mode 2. The constant plus proportional rate reaching law has reached the steady state by delay, without covering the sliding line path 3. The proposed reaching law covers the entire sliding mode portion, As compare to [12]. Constant plus proportional reaching law has not covered sliding mode portions, in turn, cause chattering and fails to satisfy the robustness of SMC.

Figure 3 it is observed that the sliding mode variable‘s' v/s time. From Figure3 it is observed that 1. The proposed reaching law's sliding mode variable is $-2.6*10^6$ (low), because it covers the complete sliding mode portion, whereas the constant plus proportional rate reaching law is $-0.28*10^6$ (high) 2. The constant plus proportional rate reaching law has not covered sliding mode portion, it causes more chattering, in turn, more switching losses.

Table 1. The parameters of the DC-DC buck converter and controller parameters of reaching laws

Sl.No.	Parameter	Symbol	Value
1	Supply voltage	Vi	24Volts
2	Capacitance	C	220μF
3	Inductance	L	69μH
4	Switching Frequency	fs	200KHz
5	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	α1, α2, α3	3, 25, 2000
11	Duty cycle	α	0.5
12	Efficiency of the Converter	η	0.91
13	a,b		1, 0.5

Table 2. Evaluation of proposed method with constant plus proportional reaching law

Parameters	Proposed (THRL)reaching law	Constant plus proportional reaching law [12]
Sliding mode portion	Covered	Not covered
Sliding mode variable	$-2.6*10^6$	$-0.28*10^6$
Reaching time To steady state	0.027mSecs	8mSecs
Switching losses	0.29W	0.55W

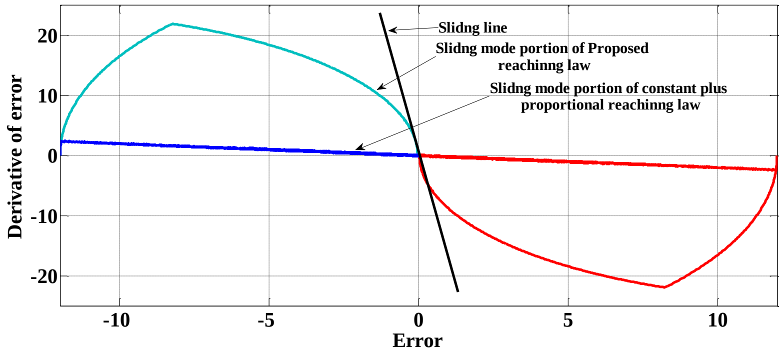

Figure 2. The derivative of error v/s error. Sliding mode portion of the proposed and constant plus proportional rate reaching law

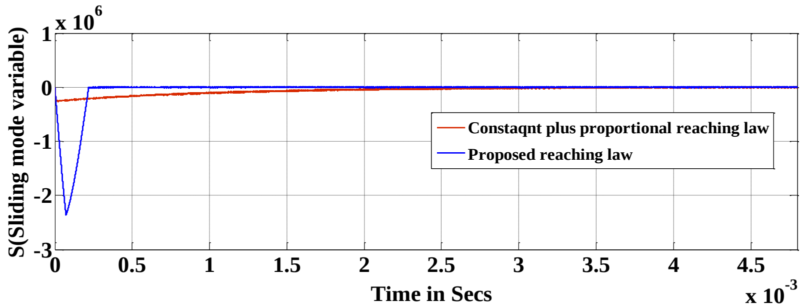

Figure 3. Sliding mode variable of proposed and constant plus proportional rate reaching law

Figure 4 shows the comparison between chattering of proposed and constant plus proportional rate reaching law, from Figure 4 it is observed that 1.The proposed reaching law technique gives less chattering amplitude is 0.0143, 2. Whereas the constant plus proportional rate reaching law gives more chattering amplitude is 0.5. Inturn less switching loss by proposed reaching law method. As compared to [12], this proposed work gives minimum chattering nearby the origin.

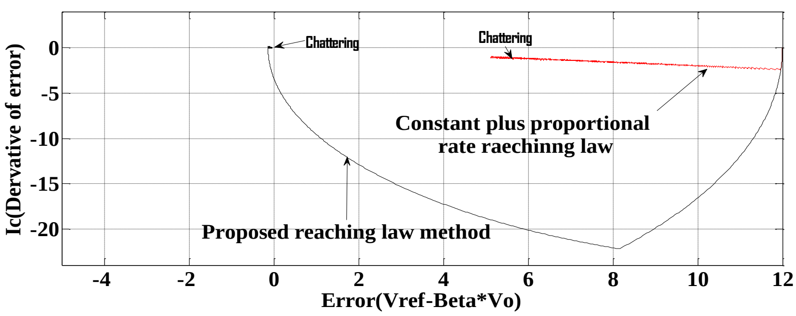

Figure 4. The chattering of proposed tan hyperbolic reaching law and constant plus proportional pace reaching law

The proposed technique provides steady output voltage, it arrives the steady state with quick convergence. It attenuates the chattering and coat the complete sliding mode portion of the switching plane trajectory as compared to constant plus proportional rate reaching law. As a result of this chattering attenuates and takes less time to arrive in the steady state. In turn, fewer switching loss in the buck converter. This exhibits the robustness and dynamic properties of the tan hyperbolic reaching law. It adapts the smooth switching performance as compared to saturation and sign functions.

3.2. Proposed reaching law analysis for variation of exponential parameter and load Inductance

Table 3 shows the analysis of proposed reaching law. The exponential parameter of proposed reaching law is varied 1 the 'b' value is 0.5, the chattering of the buck converter is lower 2. The value of 'b' is 0.7 the chattering increase as the previous chosen value of 'b'. 3. The value of 'b' is 0.9, the chattering increases more than two values chosen of 'b'. In Table 3 variation of Inductance in proposed reaching law, as a result, 1. The peak overshoot voltage is more at L=2mH, and lessen at L=1mH and chattering occurred is more at L=2mH, and lessen at L=1mH. The overall performance of the proposed reaching law technique gives a better and dynamic response on the DC-DC buck converter than the constant plus proportional pace reaching law. Figure 5 it is observed that Ic v/s Vref-beta*Vo (Derivative of error v/s Error):
- This case inductance value is varied and analyzed in proposed reaching law.
- When L=2mH more chattering has occurred
- When L=1mH, the chattering is less. It is observed that low chattering occurs at L=1mH

From Figure 6 it is observed that 1) The high peak overshoot voltage occurred at L=2mH (12.26V) as refer to desired 12V and less at L=1mH (12.16V) as refer to desired 12V.

Table 3. Analysis of proposed reaching law method (tan hyperbolic reaching law)

	Parameters					
	Exponential parameter			Variation of Load Inductance		
Chattering	b=0.5 Exists on x-axis 0 to 0.34 Amplitude is 0.143	b=0.7 Exists on x-axis 0 to 0.5 Amplitude is 0.170	b=0.9 Exists on x-axis 0 to 0.9 Amplitude is 0.1970	Peak overshoot voltage Chattering with R-L load	L=1mH 12.16V on x-axis - 0.17 to 0 Amplitude of chattering is 0.1463	L=2mH 12.26V on x-axis - 0.30 to 0 Amplitude of chattering is 0.153

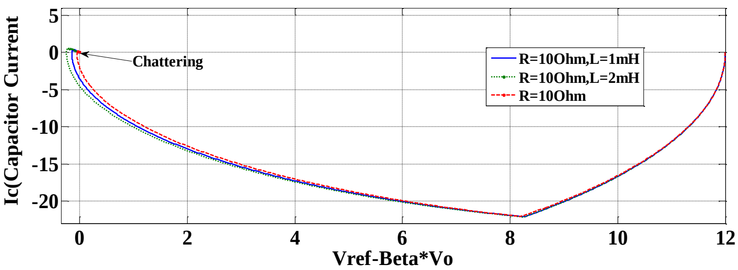

Figure 5. Chattering of proposed reaching law with L=1mH, L=2mH and R=100

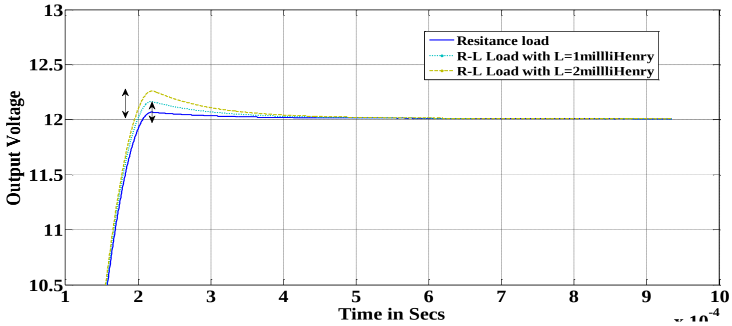

Figure 6. The output voltage of the proposed reaching law with L=1mH and L=2mH

4. CONCLUSION

The Gao's reaching law fails to satisfy the attribute of close to chattering free operation, sliding mode portion and reaching time to steady state. Thus the proposed tan hyperbolic reaching law covers the sliding mode portion and improves the performance of SMC. It adapts smooth switching function as compared to traditional switching functions. The reaching time and convergence pace of the tan hyperbolic function is kept speedy and keep the system state remains on the sliding surface. Analysis of the proposed reaching law done through variation of exponential parameter and load inductance. This exhibits the effectiveness and robustness of tan hyperbolic reaching law and more smoothness in the output voltage of buck converter. Simulation studies conducted on a DC-DC Buck converter.

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