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Design of integral sliding mode control for DC-DC converters

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Abstract

The development and implementation of an integral sliding mode control algorithm for closed loop control of a DC-DC buck converter is presented in this paper. Integral sliding mode controller (ISMC) is formulated to tackle the variable switching frequency problem faced during load and supply variations in conventional sliding mode controlled buck converters. Variable switching frequency is undesirable as it leads to complications while designing filters for the system. ISMC aims to alleviate this problem through appropriate transformation of the sliding mode control lawmaking use of pulse width modulation scheme. The control algorithm is validated through detailed simulation studies in MATLAB/Simulink environment. Comprehensive comparative assessment of the converter control system using ISMC is carried out with conventional sliding mode control (SMC) scheme which reveals the fixed frequency functioning of ISMC under diverse operating conditions.

1. Introduction

In recent years, DC-DC power converters have been used in several applications like switched mode power supplies, wind energy conversion systems, PV arrays for maximising the energy harvests as well as in integrating the energy storage systems with smart power grids.[1-4]. The control methodologies for DC-DC converter are designed for tight regulation of output voltage amidst varying input and loading conditions, keeping in mind the unpredictable nature of such diverse plants.

Traditional linear control schemes for power converters are designed based on their mathematical models. Mathematical modelling is an efficient tool to analyse the static and dynamic characteristics of any system. Several well-documented methods like the state space averaging method proposed by Middlebrook [5], PWM switch averaging method [6, 7] and the injected absorbed current method [8] are available in the literature to model any non-linear switched mode power converter. However, the mathematical model developed for controller design may typically have inconsistencies when compared with the actual plant. The controller should be well equipped to obtain

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optimized performance taking into account such mismatches in the modelled system. Non-linear control techniques are well suited to deal with such discrepancies in the system [9, 10].

A variable structure non-linear control scheme like the sliding mode control acts as a perfect fit for controlling a highly non-linear and time varying system like the DC-DC switched mode converter. A DC-DC converter controlled through sliding mode theory yields large signal stability as opposed to the linear conventional controllers which guarantee desired performance against only small perturbations in input voltage or load current [11, 12].

Conventional sliding mode controller for switched mode converter however suffers from the inherent disadvantage of variable switching frequency when subjected to parameter variations. The consequence of this variable switching are increased switching losses, losses in the inductor and transformer core and electromagnetic interference issues. Furthermore, the variable switching frequency makes it difficult to design the filters in the converter system [13]. Researchers down the years have proposed numerous techniques to overcome this shortcoming by incorporating artificial intelligence based algorithms along with sliding mode control [14, 15]. However, the main problem with the application of adaptive sliding mode schemes in DC-DC converters is that its industrial implementation is impractical since it typically involves the use of costly digital signal processors. In addition to the aforementioned drawback, conventional SMC exhibits non-zero steady state error due to its proportional derivative (PD)-type feedback. The PD feedback requires a small error to produce the necessary control signal for steady state operation [16]. Through addition of an integral term to the control law, such a problem can be eliminated [17].

In this paper, an integral sliding mode controlled DC-DC buck converter system with a PID-type feedback is proposed and comparison of the results with that of a conventional sliding mode controller is presented. The proposed control algorithm maintains the robustness of conventional SMC against parameter perturbations. In addition to this, the switching frequency deviations during load and supply voltage variations are eliminated through the use of pulse width modulation strategy.

Hereinafter, section 2 deals with the concept of the conventional sliding mode control methodology for DC-DC buck converter. Section 3 explains the structure of the integral SMC scheme while the following section presents the simulation results and brief discussion of the same. Finally the conclusions are drawn in section 5.

2. Conventional sliding mode control

Conventional SMC for DC-DC converter is based on hysteresis modulation (HM) scheme. The general description of the converter and its two switching states is shown in Fig. 1. In order to illustrate the control principle, state space description of the buck converter needs to be discussed. Reduced order conventional SMC has two control parameters in its state space description namely, load voltage error x_1 and rate of change of voltage error x_2 [17]. The buck converter in continuous conduction mode can be expressed as:

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -\frac{1}{LC} & -\frac{1}{RC} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 0 \\ -\frac{V_S}{LC} \end{bmatrix} u + \begin{bmatrix} 0 \\ \frac{V_{ref}}{LC} \end{bmatrix} \tag{1}$$

where L, C and R represent the inductance, capacitance and load resistance respectively; V_S and V_{ref} are the supply and reference voltages; u is a discrete set lying in the range $\{0,1\}$ and signifies the switching state of the DC-DC buck converter.
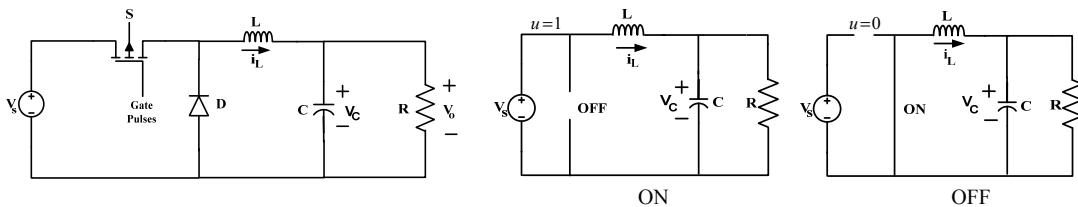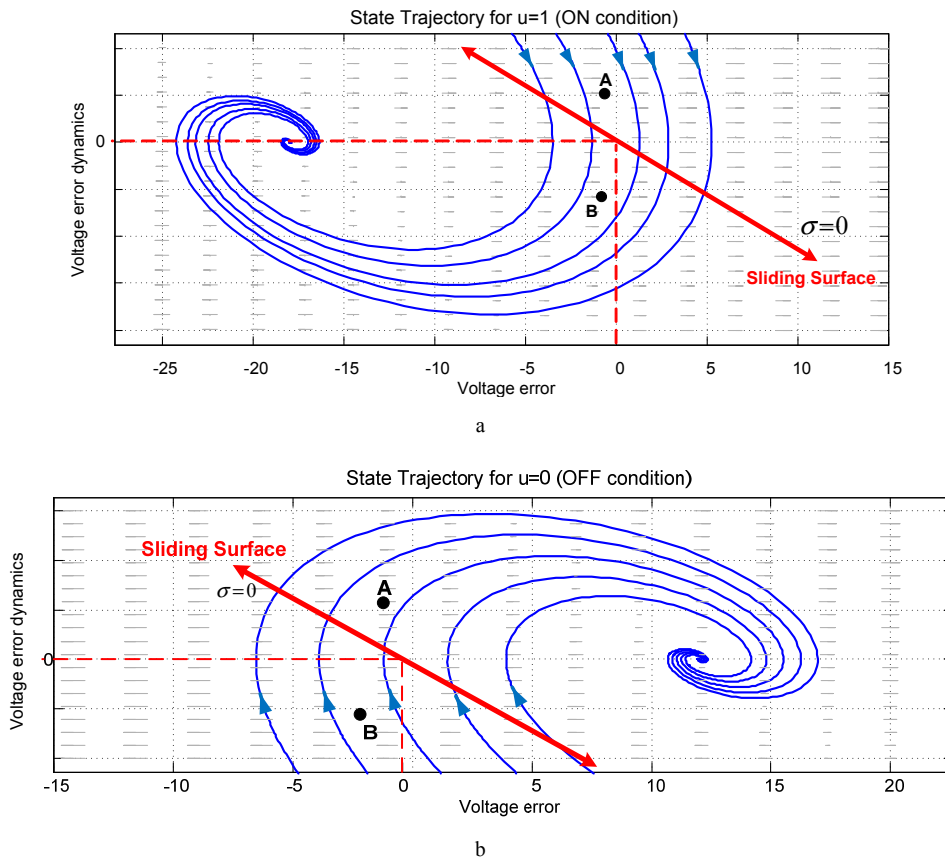

Fig. 1. DC-DC buck converter.

Fig. 2. DC-DC buck converter state trajectories for (a) $u = 1$; (b) $u = 0$.

To determine the switching function u the state trajectory σ is computed as:

$$\sigma = \lambda \left(V_{ref} - V_O \right) - i_C \tag{2}$$

where λ is a positive arbitrary constant called sliding coefficient; V_O and i_C are the instantaneous value of the output voltage and capacitor current respectively. The sliding surface $\sigma = 0$ divides the phase plane into two halves. A switching function must be employed such that the state trajectory of the system at any initial position should strike the sliding surface. The state trajectory at any arbitrary point 'A' (see Fig. 2 (a) and (b)) will converge towards the sliding surface only when the switching function becomes $u = 1$. Similarly, at any arbitrary point 'B' below the sliding surface, the switching function should be $u = 0$ for the trajectory to strike the surface [10]. This forms the basis of the control action and after consideration of a small hysteresis band 'k', the control law may be formulated as:

$$u = \begin{cases} 1, when\, \sigma > k \\ 0, when\, \sigma < -k \\ unchanged, otherwise \end{cases} \tag{3}$$
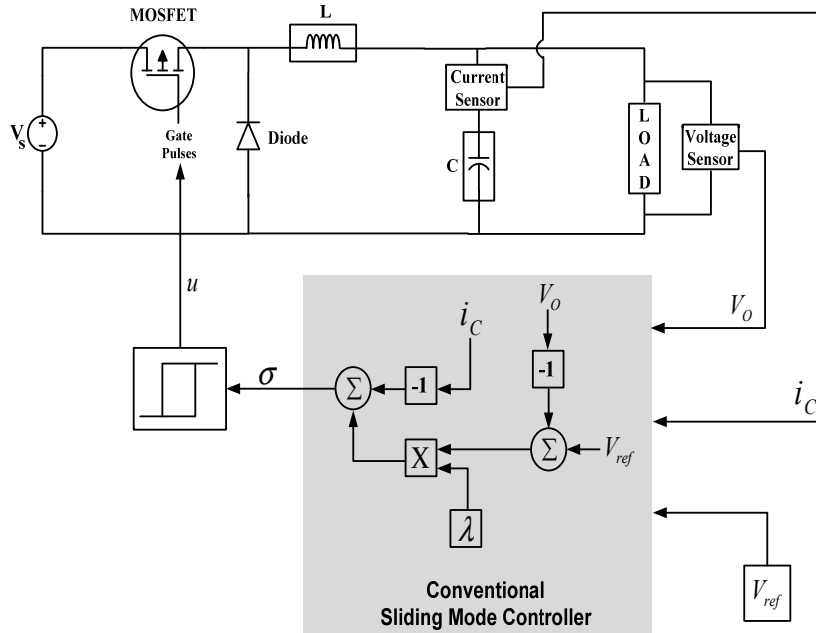
Fig. 3. Conventional hysteresis modulation-based sliding mode control of buck converter.

The value of hysteresis band 'k' is decided based on the required switching frequency for which the converter is designed. To ensure the sliding motion of the trajectory after it strikes the sliding surface, the existence condition based on the lyapunov's second method must be obeyed. Defining a positive definite candidate lyapunov function $V(s) = \sigma^2/2$. To guarantee asymptotic stability, the derivative of the lyapunov function must be negative definite [9] i.e. $\dot{V}(s) = \sigma\dot{\sigma} < 0$ which gives the existence condition of the sliding control as:

$$\dot{\sigma} = \begin{cases} \alpha_1 < 0, for\, 0 < \sigma < \varepsilon \\ \alpha_2 > 0, for -\varepsilon < \sigma < 0 \end{cases} \tag{4}$$

where ε is a small positive quantity and $\alpha_1 \,\& \, \alpha_2$ represent the voltage error dynamics at the aforementioned regions. Substituting values from Eq. (1) and Eq. (3) we get the inequality for ensuring existence of SMC as:

$$\alpha_1 = \left(\lambda - \frac{1}{RC}\right)x_2 - \frac{1}{LC}x_1 + \frac{V_{ref} - V_S}{LC} < 0$$
$$\alpha_2 = \left(\lambda - \frac{1}{RC}\right)x_2 - \frac{1}{LC}x_1 + \frac{V_{ref}}{LC} > 0 \tag{5}$$

Through detailed analysis of the inequalities and taking into consideration the fast dynamic response requirements of switched power converters, Siew-Chong Tan et al [11] proposed that the sliding mode control exists when $\lambda = 1/R$. The internal structure of the control circuit with conventional sliding mode control scheme is illustrated in Fig.3.

3. Integral sliding mode control

Integral sliding mode controller for DC-DC converter is based on pulse width modulation (PWM) scheme. In PWM switching mechanism, the control signal is compared with a saw-tooth waveform to generate gate pulses of

frequency equivalent to the desired switching frequency [5-7]. Unlike conventional SMC, ISMC has three control parameters namely, load voltage error x_1, rate of change of voltage error x_2 and integral of voltage error x_3 [17]. The state space description of the converter with three control parameters is:

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & -\dfrac{1}{RC} & 0 \\ 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} + \begin{bmatrix} 0 \\ -\dfrac{V_S}{LC} \\ 0 \end{bmatrix} u + \begin{bmatrix} 0 \\ \dfrac{V_O}{LC} \\ 0 \end{bmatrix} \tag{6}$$

The revised sliding surface for ISMC is formulated as:

$$\sigma : \lambda_1 x_1 + \lambda_2 x_2 + \lambda_3 x_3 = 0$$

$$\sigma : \frac{\lambda_1}{\lambda_2} x_1 + x_2 + \frac{\lambda_3}{\lambda_2} x = 0 \tag{7}$$

where λ_1, λ_2 and λ_3 are sliding coefficients. The existence condition is ensured through the inequality $\sigma\dot{\sigma} < 0$ after defining a positive definite lyapunov function $V(s) = \sigma^2/2$ [9]. Based on this, to ensure existence of the sliding mode, the following inequality should be met.

$$\dot{\sigma} = \begin{cases} \alpha_1 < 0, \, for \, \sigma \to 0^+ \\ \alpha_2 > 0, \, for \, \sigma \to 0^- \end{cases} \tag{8}$$

Substituting the values from Eq. (6) and Eq. (7) we get the condition for existence [13] as:

$$0 < \left(\frac{1}{RC} - \frac{\lambda_1}{\lambda_2} \right) Li_C + \frac{\lambda_3}{\lambda_2} \left(V_{ref} - V_O \right) LC + V_O < V_S \tag{9}$$

The reaching phase of the control action is minimised in ISMC and anyhow it does not participate in deciding the degree of robustness of the control system. Robustness is evaluated only in the sliding phase which can be assumed to be made up of two distinct waveforms as shown in Fig.4; a high frequency waveform which oscillates in a zig-zag manner about the sliding surface and a slow moving waveform which moves along the surface. While designing of the control action for ISMC, the high frequency zig-zag component of the sliding motion may be neglected since it appears as undesirable chattering in the system and the low frequency control action can be realised as equivalent to the control action of the ideal ISMC. This low frequency control action commonly called equivalent control can be found through invariance condition by equating the derivative of sliding surface to zero $(\dot{\sigma} = 0)$ [10]. Substituting from Eq. (6) & Eq. (7) and replacing control action u with equivalent control action u_{eq} we get:

$$u_{eq} = \frac{\left(\dfrac{1}{RC} - \dfrac{\lambda_1}{\lambda_2} \right) Li_C + \dfrac{\lambda_3}{\lambda_2} \left(V_{ref} - V_O \right) LC + V_O}{V_S} \tag{10}$$
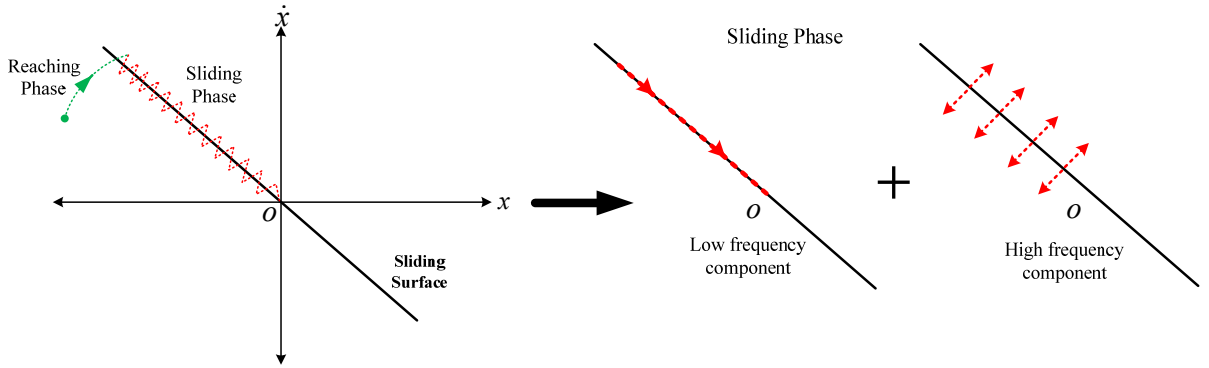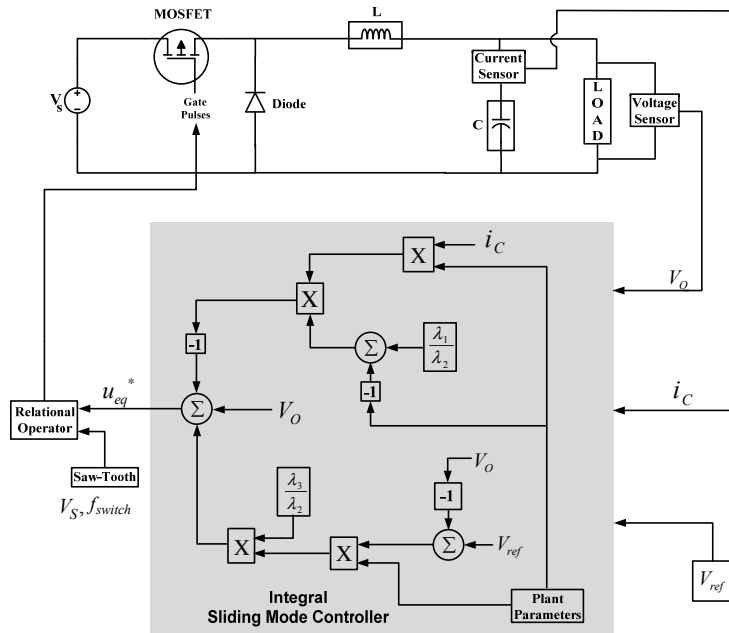
Fig. 4. Equivalent control principle.

Fig. 5. Integral pulse width modulation-based sliding mode control of buck converter.

The duty ratio d of a closed loop controlled DC-DC buck converter based on pulse width modulation is the ratio of the control signal $v_{control}$ to the amplitude of the saw-tooth carrier waveform $v_{saw-tooth}$ [5]. Translating the equivalent control action in terms of duty ratio control and rearranging Eq. (9) we have:

$$0 < d = \frac{v_{control}}{v_{saw-tooth}} = \frac{u_{eq}{}^*}{V_S} < 1$$

$$where, u_{eq}{}^* = \left(\frac{1}{RC} - \frac{\lambda_1}{\lambda_2}\right)Li_C + \frac{\lambda_3}{\lambda_2}\left(V_{ref} - V_O\right)LC + V_O$$

(11)

The sliding coefficients are designed based on the desired response of the converter system [11].The detailed schematic of integral sliding mode control scheme for DC-DC buck converter is depicted in Fig. 5.

Table 1. Buck converter parameters.

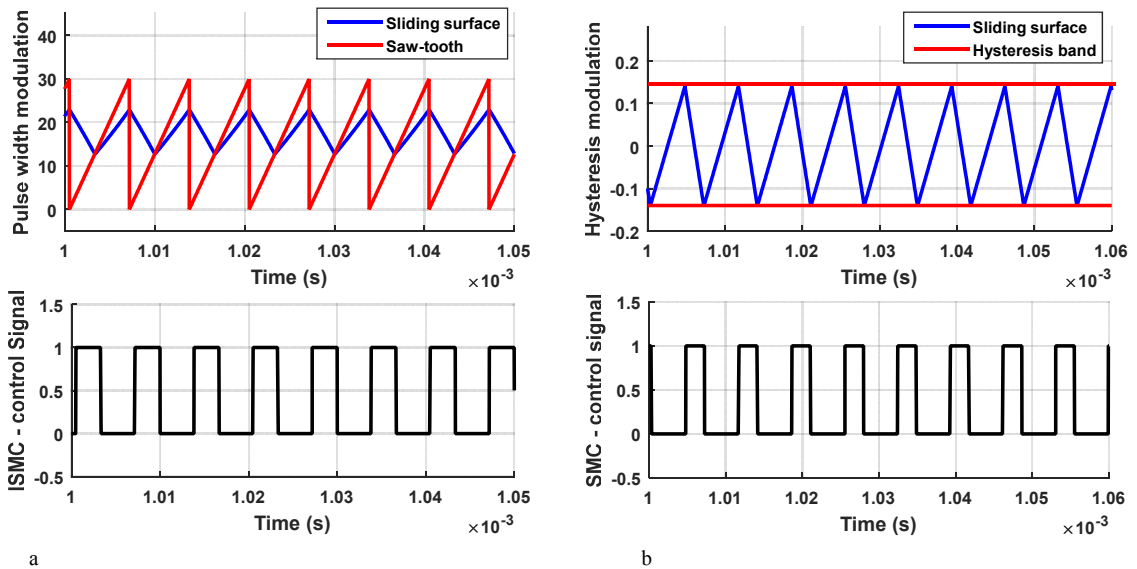| Parameter	Value
V_s	30 Volts
V_{ref}	12 Volts
L	171.428 μH
C	100 μF
Load	24 Watt
f_S	150 kHz

Fig. 6. Generation of control signal in (a) ISMC through PWM; (b) Conventional SMC through HM.
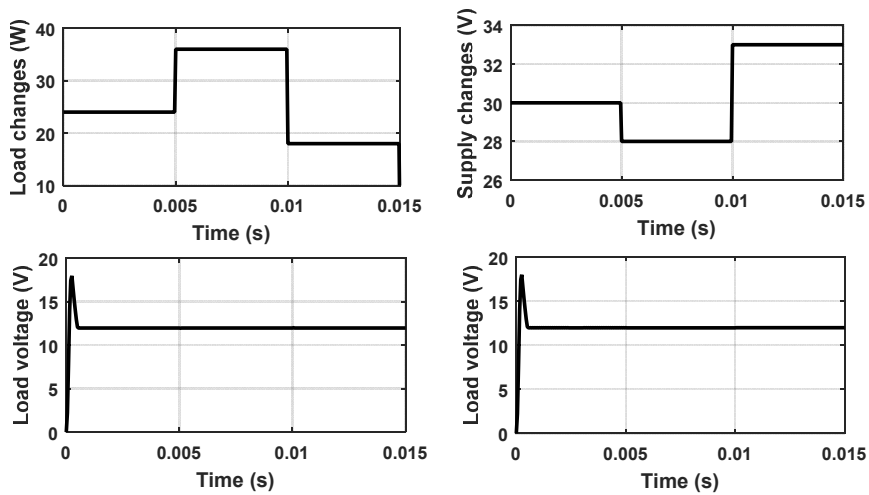

Fig. 7. Robustness of ISMC buck converter system to load and supply variations.

Table 2. Effect of parameter variation on average switching frequency.

Parameter variations	Average switching frequency (kHz) Nominal value-150kHz	
Supply Voltage (volts)	*with ISMC*	*with SMC*
26	147.8	134
28	147.1	142.7
30 (nominal value)	148.6	150.3
32	146.5	156.8
34	146	162.5
Load Resistance (ohms)	*with ISMC*	*with SMC*
4	152.8	149.7
5	151.2	149.6
6 (nominal value)	149.7	149.7
7	144.9	149.7
8	141.6	149.7

4. Results and discussion

The analysis and comparison of the control methodologies have been performed based on simulation studies done in Matlab/Simulink environment. The system parameters considered for simulation are mentioned in Table 1.

The converter is designed for output voltage ripple less than 0.5%. A hysteresis band of ±0.14 is considered while simulating the conventional SMC whereas the ISMC is designed for critically damped response considering a bandwidth equalling one-tenth of the switching frequency. Fig. 6 depicts the generation of control pulses in ISMC and conventional SMC through pulse width and hysteresis modulation schemes respectively. Both the controllers provide satisfactory output voltage regulation amidst step variations in supply voltage and load resistance. Fig.7 shows the waveforms for ISMC. Overshoot in the output voltage waveform of ISMC is more than that in conventional SMC. No other major differences could be found between the voltage responses of the two controllers.

4.1. Average switching frequency

The disadvantages of variable switching frequencies with changing load and supply voltage conditions were briefly discussed in section 1. When the two converter control systems were subjected to a ±13.33% change in supply voltage ranging from 26 volts to 34 volts, a variation of around 19% was found in the average switching frequency of conventional sliding mode controlled converter whereas the ISMC showed a minute variation of 1.2% as shown in Table 2. When subjected to wide variations of ±33% in load resistance, the deviations in average switching frequency for both the controllers were found to bewithin permissible limits.As clearly observed from Table 2, the average switching frequency in conventional sliding mode controlled buck converter system is greatly affected by changes in supply voltage. This problem is greatly rectified through integral SMC.

5. Conclusion

An integral sliding mode control of a DC-DC buck converter feeding a resistive electronic load has been presented in this paper which proficiently achieves the aim of containing the switching frequency variations caused in conventional SMC system due to load and supply variations.The system under consideration was simulated under varying load and supply voltage operating conditions.Detailed comparative analysis of the ISMC was performed alongside a conventional SMC. The output voltage regulation under such operating conditions was found to be satisfactory with ISMC exhibiting slightly greater overshoot in voltage response during start-up than in conventional

SMC. However, the average switching frequency variation with ±13.33% changes in supply voltage is greatly reduced from 19% in conventional SMC buck converter system to 1.2 %in ISMC. Thus, ISMC exhibits almost fixed frequency operation and provides an efficient means of implementing sliding mode control for DC-DC buck converter.

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