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Synchronous Buck Converter Modeling and Design of Hysteresis Band Based Sliding Mode Controller

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Abstract

The article deals with the design and mathematical model of the output voltage regulation of synchronous buck converter (SBC) with hysteresis band (HB) based sliding mode controller for drives the stable power supply. They are various applications such as, in battery operated portable devices, LED lightings, computer, industrial, LED lightings and robot interface device system etc. One of the DC-DC converter that converter fixed positive input voltage into variable negative output voltage. The performance is very poor and the switching features of SBC are non-linear. The output voltage of the converter with proportional integral (PI) controller is not controllable for load and line variations. Hysteresis band based sliding mode controller is designed for fine dynamic performance and to control the output voltage. By using state space averaging method, state space equations are derived and then HB based SMC are calculated. The designed controller performance characteristics can be known through the MATLAB/Simulink.Then this result is compare with the classical proportional integral controller.

Keywords: DC-DC power conversion, Hysteresis band, mathematical modeling, MATLAB/Simulink.

INTRODUCTION

The power electronics play a major role in present development technology for the conversion of voltage, frequency and current that can be utilized. For the several application such as mobile phones, laptop and electrical vehicles etc where DC-DC converter play a important role [1-2]. The major constraints of all the power electronics converters have high efficiency, high density, low switching losses, smaller size and robust to any variation in load and line. The efficiency must be greater for the converter with SMPS, power switch and efficiency is smaller for the converter without power supply [3].In this article control methodology of DC-DC synchronous buck converter is consider and two- phase synchronous buck converter with non linear controller have been discussed[4]. Moreover design parameters has not been discussed. The posicast controller and proportional integral (PI) controller for SBC has been reported [5]. Even for small duty ratio, they required large output current switching for modeling and implementation of SBC which operate in transient region [6]. SBC with impact of parasitic elements of storages components with spurious gating pulses is reported in [7]. By this method, they have long settling and large overshoot time and switching loss of load SBC has been discussed[8].

The achievement of non-linear controller deceit in doing superiorly nearby these problems in the variable structure systems (VSS) such as in DC-DC converter [9]. The controller of such system must control with their fundamental nonlinearity, good stability and huge line and load variation in all operating mode as providing quick transient and superior dynamic responses. Using large speed control law of the hysteresis band based sliding mode controller to drive non linear state trajectory in the state space is called switching surface,and sustain it on this surface throughout the entire process [10]. When compare to the linear controller, the HB based SMC have several benefits. It can easy implementation, good dynamic reaction and excellent stability for various load and line variations. The HB based SMC for Luo-converters has been considered and evaluated [11-13]. In all operating conditions, the output of HB based SMC in Luo-converter have produce better performance.DC-DC power converters modeling methods have been discussed in [14-16]. The main important modeling method of DC-DC converters are state space average model. To control the output voltage ,we need the healthy control the switching power supply for large change in the output voltage applications. A difficult task to the controller shows the VSS of the converter with the battery behavior. This difficulty can be rectified by synchronous buck converter HB based SMC.

This article deals the design and modeling of HB based SMC for SBC worked in current mode. First we derived the dynamic state space equation and then concentrate on HB based SMC. The dynamic state space equation of same converter is derived at initial and then HB based SMC is developed. The presentation of HB based SMC is established for different operating condition and compared with the classical linear PI controller.

The section 2 deals with the synchronous buck converter state space modeling and its operation. Section 3 shows the design of HB based SMC for SBC.Section 4 discussed the parameters of converter controller and its value of circuit elements. Section 5 shows the simulation of SBC using designed controllers. Finally, section 6 presents the conclusions.

SBC MODELING AND OPERATION

SBC Operation:

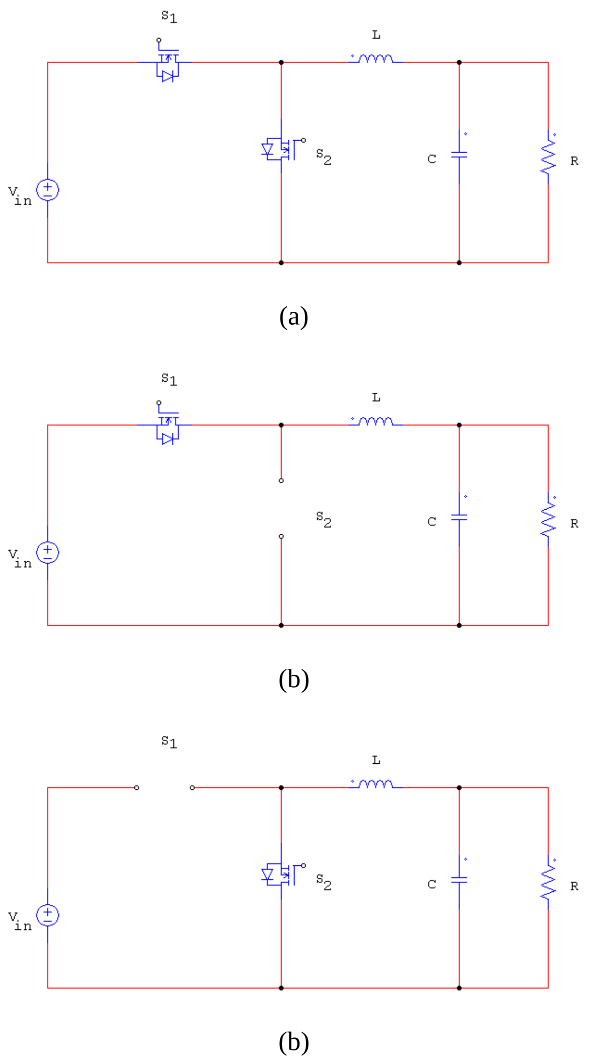


Figure 1. SBC power circuit, (a) topology, (b) operation of mode 1circuit, and (c) operation of mode 2 circuit.

The SBC power circuit is shows in Fig.1 (a) [30]. It consists of V_{in} - DC input supply voltage, L-output inductor, C_o-output capacitor, I_o-output current, R-load resistance, S_1 -main power MOSFET switch, and S_2 - synchronous rectifier power MOSFET switch. Using controlled synchronous converter rectifier swaps diodes and to maintain the excellent efficiency. Assume that SBC operate in CCM and all the components of SBC are best. Fig.1 (b) and Fig. 1 (c) show the working of SBC modes [2].

From mode 1, (see the Fig. 1(b)),the S_1 switch is closed and the S_2 switch is open, the input current passes through the passive elements such as C- the capacitor ,L-the inductor , and R - the resistance. From mode 2 (refer the Fig. 1(c)), the S_1 switch is open and the S_2 switch is closed. The current passes through the passive elements L- inductor- capacitor, R-resistance and the switch S_2. When the switch S_1 is closed, the inductor current decreases therefore the converter average output voltage is less than the input voltage.

The converter voltage transfer gain (by applying the voltage balance to mode 1 and mode 2 operation of the SBC) is expressed as follows.

$$G = \frac{V_O}{V_{in}} = d \tag{1}$$

SBC State space modeling L

The state variables of SBC, i_L the output inductor current, and V_C the output capacitor voltage are taken as x_1 and x_2 respectively. State space equations for mode 1 can be written as

$$\begin{cases} \dot{x}_1 = -\left(\frac{1}{L} - \frac{1}{LR}\right)V_C + \frac{V_{in}}{L} \\ \dot{x}_2 = \frac{i_L}{C} - \frac{V_C}{RC} \end{cases} \tag{2}$$

Similarly, the state space equation for mode 2 can be expressed as

$$\begin{cases} \dot{x}_1 = -\left(\frac{1}{L} - \frac{1}{LR}\right)V_C \\ \dot{x}_2 = \frac{i_L}{C} - \frac{V_C}{RC} \end{cases} \tag{3}$$

Using the equations (2) and (3), the complete SBC state-space modeling equations are expressed as

$$\begin{bmatrix} \frac{di_L}{dt} \\ \frac{dV_C}{dt} \end{bmatrix} = \begin{bmatrix} 0 & \frac{1}{LR} - \frac{1}{L} \\ \frac{1}{C} & -\frac{1}{RC} \end{bmatrix} \begin{bmatrix} i_L \\ V_C \end{bmatrix} + \begin{bmatrix} \frac{V_{in}}{L} \\ 0 \end{bmatrix} d + \begin{bmatrix} 0 \\ 0 \end{bmatrix} \tag{4}$$

$$\dot{x} = Ax + Bd + C \tag{5}$$

Where, d - the status of the switches, x and $\dot{x}$ - the vectors of the state variables (i_L, V_C) and their derivatives respectively.

$$d = \begin{cases} 1 \rightarrow \text{Switches} \rightarrow \text{ closed} \\ 0 \rightarrow \text{Switches} \rightarrow \text{open.} \end{cases} \tag{6}$$

SBC HB BASED SMC

Design of HB based SMC:

For better performance of the system, consider the HB based SMC. In SBC, the variations in circuit parameters and load/line SMC shows a fast and specific response.

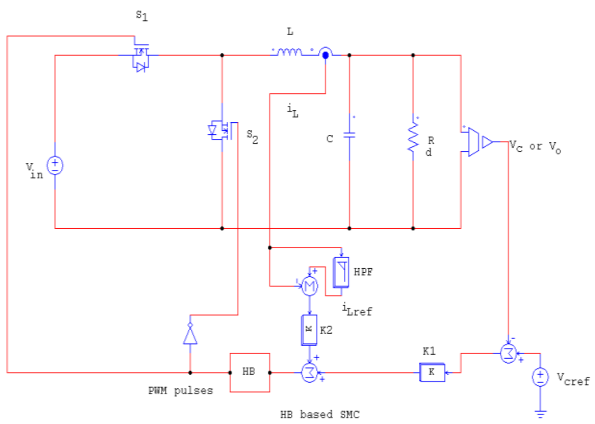


Figure 2. HB based SMC applied to the SBC.

Initially the HB based SMC design , choose a sliding surface (SS) that model the expected closed-loop performance in state variable space. According to the system phase trajectories make to forced closely to the sliding surface and keep on it control must designed. In the period of time phase trajectory before reaching the SS is called reaching phase. If phase trajectory of SBC reaches the SS, it stays on it and moves towards origin.

Basic needs of HB based SMC are measuring the state variables of converter and produce the correct references for each of them. On voltage and current loop , V_c and i_L are made follow the references that depends on load power requirement V_{in} and V_c. The value of i_L vary with respect to load ,so incoming at the i_{Lref} is create difficult whereas in voltage regulation V_{cref} should be constant by means of potentiometer. The above difficult can be rectified by passing the extract current i_{Lref} from the i_L through a high pass filter(HPF) based on the assumption that their low-frequency component is frequently modified as a purpose of load. For control high frequency component is required. This HPF can seriously influence the converter dynamics and increases the system order. Maintenance the cut-off frequency of the HPF as small as from the f_s can help in enhancing the dynamics to several levels [11-14]. To have a talented dynamic performance, a SS equation in the state space, that can be expressed as state-variable errors e_i (respective differences of reference current/voltage signals and feedback current/voltage signals)**,** must be choose optimally.

$$S=\left(i_L,V_C\right)=K_1e_1+K_2e_2 \tag{7}$$

Where,

K_1 and K_2 - co-efficients of SS, e_1 - the i_L error and e_2 - the V_c error. The errors e_1 and e_2 are give by

$$\begin{aligned} e_1&=i_L-i_{Lref} \\ e_2&=V_C-V_{Cref} \end{aligned} \tag{8}$$

By equation (8) in (7), SS becomes

$$S=\left(i_L,V_C\right)=K_1(i_L-i_{Lref})+K_2(V_C-V_{Cref}) \tag{9}$$

The circuit HB control means of real time realization of SS equation(9). The SBC MOSFET switches get the switching gate pulses by HB. From Fig.2 To minimize the error of the converter circuit variables i_L and V_C controlled the status of the switches (d) byHB. The SS coefficients K_1, K_2 and circuit parameters are calculated by system performance. The better control,stability andfine response will be achieved by proper choosing these coefficients.

Controller Parameters Selection

HB based SMC has theoretical difficulty and outstanding to the unavailability of straightforward procedure for the selection of controller parameters and these parameters are chosen to satisfy existence, hitting and stability conditions [26]. Once the SBC input /output specifications are chosen**,** inductance L and capacitance C are designed from specified output current and voltage ripples of large and fast load variations whereas from the SBC ratings and type of switch determine switching frequency. The coefficients K_1 and K2 are calculated from SBC performance, they must be chosen in an try to assembly existence, fast and stability response, even for large load and supply variations. The SBC equations must be written with respect to VSS theory as

$$\dot{x}=Ax+Bd+D \tag{10}$$

Where, x - the vector of state-variables errors and specified by

$$\dot{x}=x-X^* \tag{11}$$

Where, $X^*=\left[i_{Lref},\ V_{Cref}\right]^T$ - the vector of references.

Substitution of (11) in (2) results the equation (12) .

$$D=AX^*+C \tag{12}$$

$$D=\begin{bmatrix} 0 & \frac{1}{LR}-\frac{1}{L} \\ \frac{1}{C} & -\frac{1}{RC} \end{bmatrix}\begin{bmatrix} i_{Lref} \\ V_{Cref} \end{bmatrix}+\begin{bmatrix} \frac{V_{in}}{L} \\ o \end{bmatrix} \tag{13a}$$

$$D=\begin{bmatrix} \frac{V_{in}}{L}\frac{V_{Cref}}{LR}-\frac{V_{Cref}}{L} \\ \frac{i_{Lref}}{C}-\frac{V_{Cref}}{RC} \end{bmatrix} \tag{13b}$$

Substituting (11) in (9), the SS can be re-written in the following form as

$$S(x)=K_1x_1+K_2x_2=K^Tx \tag{14}$$

Where $K^T=\left\lfloor K_1, K_2\right\rfloor$ and $x=\left[x_1, x_2\right]^T$.

The controller can put into effect the system state to stay close to the sliding plane by suitable operation of the SBC switch. To variety the structure state to go close to the switching outer, it is important and sufficient that

$$\begin{cases}\dot{S}(x)<0, \text{if } S(x)>0 \\ \dot{S}(x)>0, \text{if } S(x)<0\end{cases} \tag{15}$$

HB based SMC is establish by means of the subsequent feedback control strategy, which relates to the d with the value of S(x):

$$d=\begin{cases}0, \text{for } S(x)>0 \\ 1, \text{for } S(x)<0\end{cases} \tag{16}$$

The existence condition (16) can also communicated as

$$\dot{S}(x)=K^TAx+K^TD<0, S(x)>0 \tag{17}$$

$$\dot{S}(x)=K^TAx+K^TB+K^TD>0, S(x)<0. \tag{18}$$

For the simulation, assuming that the error variables x_i are properly lesser than references X^*, then equations (17) and (18) can be rewritten as

$$K^TD<0, S(x)>0 \tag{19}$$

$$K^TB+K^TD>0, S(x)<0. \tag{20}$$

By substituting matrices B and D in (19) and (20), then it becomes,

$$\frac{K_1}{L}\left[V_{in}+\frac{V_{cref}}{R}-V_{cref}\right]+\frac{K_2}{CR}\left[Ri_{Lref}-V_{Cref}\right]<0 \tag{21}$$

$$\frac{K_1}{L}[2V_{in}+\frac{V_{cref}}{R}-V_{cref}]+\frac{K_2}{RC}[Ri_{Lref}-V_{cref}]>0 \tag{22}$$

The presence condition is satisfied if the variations (21) and (22) are truthfully. Lastly, it is necessary to protection that the designed sliding plane is absolute for all initial states. If the sliding mode exists, in the system defined by equation (10), it is a adequate condition that SS coefficients K_1 and K_2 be non-negative.

Switching Frequency

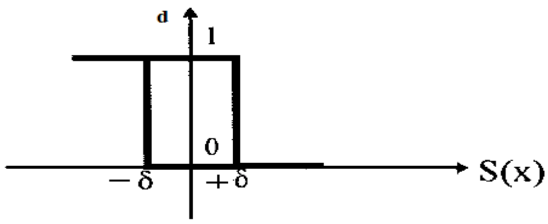


Figure 3. Switching function d.

In the ideal, sliding mode switch at f_s, phase trajectories are directed towards the direction of the SS and move closely along SS. A real-time system cannot switch at f_s. The average f_s working range of HB varies from 80 kHz to 130 kHz and its related band varies from 0.9 to 0.05. From the above working range, the best value of average f_s is 100 kHz and its related band is 0.5 [13]. Fig.3 indicated a practical relay with unique control circuit. A hysteresis model with real-time relay as given by .

$$d=\begin{cases}0, & \text{when } S>+\delta \text{ or} \\ & \text{when } \dot{S}<0 \text{ and } |S|<\delta \\ 1, & \text{when} S<-\delta \text{or} \\ & \text{when } \dot{S}>0 \text{ and } |S|<\delta\end{cases} \tag{23}$$

Where,

δ - an arbitrarily small positive quantity and 2δ - the amount of HB in S(x).

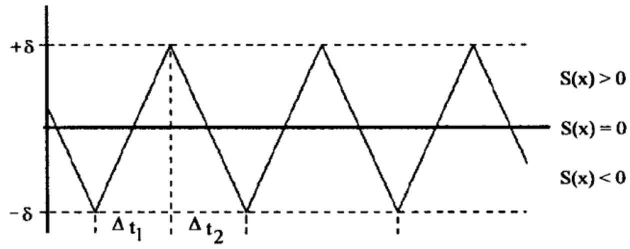


Figure 4. Phase trajectory slides around the surface with allowed HB

The hysteresis characteristic makes it not possible to control the switch on the SS, S(x) =0. As a effect switching occurs on the lines S =±δ, with a frequency depending on the slopes of i_L. This hysteresis causes 2δ-width of state space trajectory oscillations around the surface S(x) =0 as shown in Fig. 3. From Fig.4 In switch conduction time Δt_1, the function S(x) must increase from –δ to δ for Ś>0, whereas in switch off-time Δt_2, the function S (x) must decrease from +δ to δ for Ś<0. The switching frequency can be calculated as

$$f_s=\frac{1}{\Delta t_1+\Delta t_2} \tag{24}$$

Where, Δt_1- conduction time of the switches and Δt_2 -the off-time of the switches. The conduction time Δt_1 is derived from (22) and it is given by

$$\Delta t_1=\frac{2\delta}{\frac{K_1}{L}[2V_{in}+\frac{V_{cref}}{R}-V_{cref}]+\frac{K_2}{R_o}[Ri_{Lref}-V_{oref}]} \tag{25}$$

The off-time Δt_2 is derived from (21), and it is given by

$$\Delta t_2 = \frac{-2\delta}{\frac{K_1}{L}\left[V_{in} + \frac{V_{cref}}{R} - V_{cref}\right] + \frac{K_2}{CR}\left[Ri_{Lref} - V_{Cref}\right]} \quad (26)$$

The value of switching frequency is achieved exchanging (25) and (26) in (24) with the converter is working in no load (i_{Lref} = 0 and 1/R=0) and the output voltage reference ($V_{Coref(max)}$). The full switching frequency is obtained as

$$f_{s(max)} = \frac{K_1 V_{in}}{2\delta L}\left(1 - \frac{V_{in}}{V_{cref(max)}}\right) \quad (27)$$

Duty Cycle

$$d = \frac{\Delta t_1}{\Delta t_1 + \Delta t_2} \quad (28)$$

At any operating condition HB based SMC an instantaneous control, the ratio between the output and the input voltages must satisfy the fundamental relation (1).

Inductor Current

The maximum ripple inductor current is obtained from Fig. 2 and given by [1]

$$\Delta_{iL} = \frac{V_O - V_{in}}{L}\Delta_{t1} \quad (29)$$

Capacitor Voltage

The capacitor voltage is given by

$$\Delta Vc = \frac{V_C}{RC}\Delta t_1. \quad (30)$$

It is interesting to note that the switching frequency, capacitor voltage ripple and inductor current ripple depend on circuit parameters, control parameters, reference voltage, output capacitor voltage V_{Co} and inductor current i_L.

It is significant to control the circuit at any operating condition bounds and constants K_1 and K_2 that choose a required value of maximum capacitor voltage ripple, maximum inductor current ripple, stability, optimum switching frequency ripple and fast response.

DETERMINATION OF CONTROLLER PARAMETERS AND CIRCUIT COMPONENTS

The main aim of this section is to determine exact values of various SBC elements and controller parameters .

Voltage (V_C) Calculation

For the V_{in} of 12V and the corresponding duty cycle of 0.571 is considered. Hence the V_{Cmax} = 20.79V.The capable variation of the duty cycle is between the d_{min}= 0.1 and d_{max} = 0.99.

Ratio (K_1 / L) Calculation

In equation (27) substituting V_{in}, $V_{Cref\ (max)}$ and δ = 0.571) the ratio K_1 / L is obtained as 14583.33.

Ratio (K_2 /C_O) Calculation

From (21) and (22), i_{Lref}=$i_{L(max)}$=6A (middling value), the circumstance 1408 < K_2 / C < 225433 is reached. There are some degrees of choice in choosing the ratio K_2/C. In this controller, the ratio K_2 / C is a modification parameter.

It is recommendable to select the ratio K_2/C to agree with essential levels of stability and response speed. The percentage K_2/C is selected by iterative method (i.e. the ratio is adjusted pending the temporary response is fitting), and it is established by simulation. The final adopted value is K_2/C=10100.

Inductance (L) Calculation Chose Chose 25% of maximum inductor current from maximum inductor current ripples [25], and for this value the L= 85.5μH is determined from (29) .

Values of Coefficients (K_1 and K_2) and (Co) calculation

Chose 25% of maximum capacitor voltage from maximum capacitor voltage ripples ΔV_{Cmax} [26], and the value C= 107μF is calculated by using [30]. Consider the values of the ratio K_1/L and inductor, the value of K_1 is reliably obtained (K_1 0.1258).Similarly the K_2 = 10 is evaluated using the ratio K_2 / C and the C.

SIMULATION RESULTS

A simulation study of SBC using both HB based SMC and PI controller in MATLAB/Simulink software platform (7.9 Version) and the specification are listed in Table 1. First obtain the designed HB based SMC then compared with the classical PI controller.

A PI controller with K_p = 0.012 and T_i = 0.013s, which are obtained by the Ziegler-Nichols tuning technique is used [10]. For different operating states SBC using controller's performance confirmation is made .via. Load disturbance, line disturbance, steady state region, Start-up transient and also circuit basics changes.

Table 1. SBC Specifications

Parameters	**Symbol**	**Value**
Input Voltage	V_{in}	21V
Output Voltage	V_o	12V
Inductor	L	85.5µH
Capacitors	C	107 µF
Nominal switching frequency	f_s	100kHz
Load resistance	R	2Ω
Input Power	P_{in}	75.6W
Output Power	P_o	72W
Input Current	I_{in}	3.6A
Output Current	I_o	6A
Adopted Value of Duty Ratio	d	0.571
Efficiency		95.23%

Start-up Region

Fig.5 shows the SBC dynamic response of the output voltage using HB based SMC and PI controller at the start-up for input voltage 12V.

From these outcome, it can be found that output voltage of SBC with HB based SMC/PI controller has a insignificant overshoot (M_P) and settling time (T_s) of 0.04s (HB based SMC)/0.038s (PI controller).

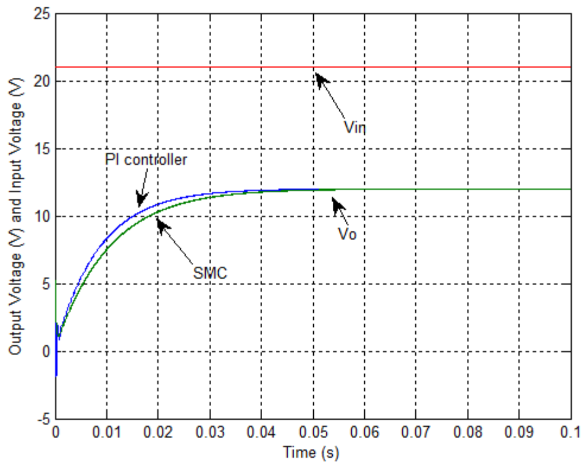
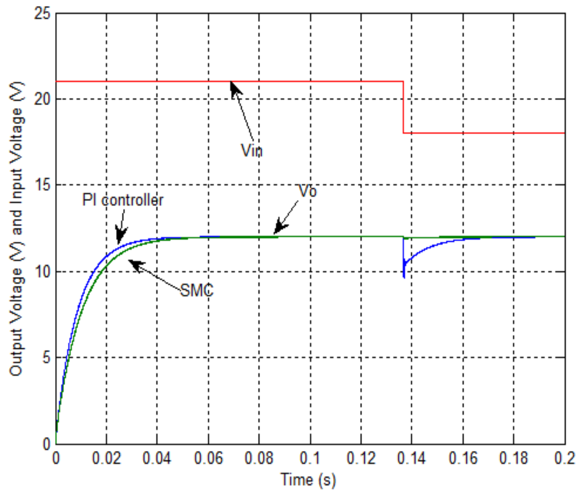
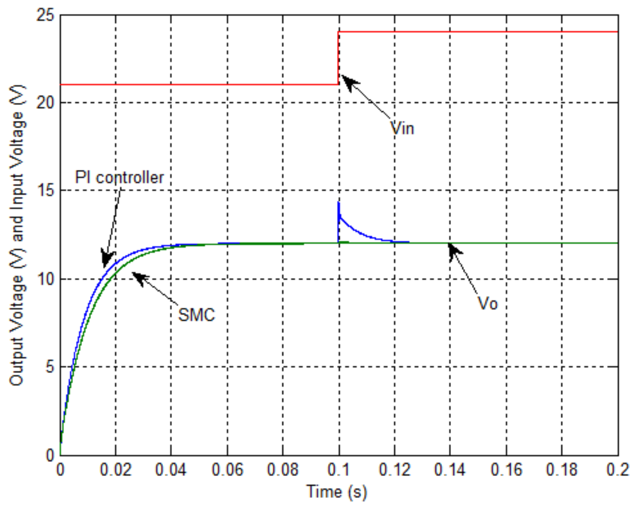


Figure 5. SBC Simulated output voltage reponses using HB based SMC and PI controller in start-up transient region for V_{in} = 21V.

Line Variations



(a)

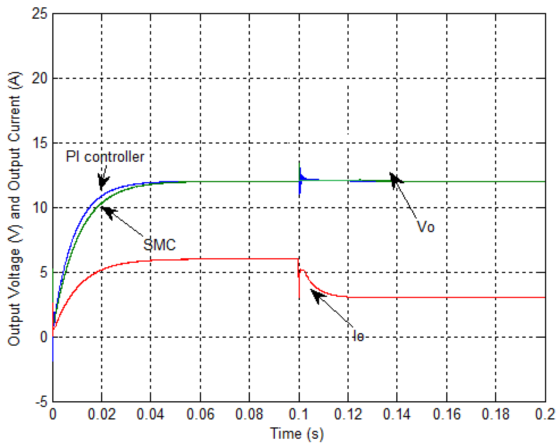


(b)

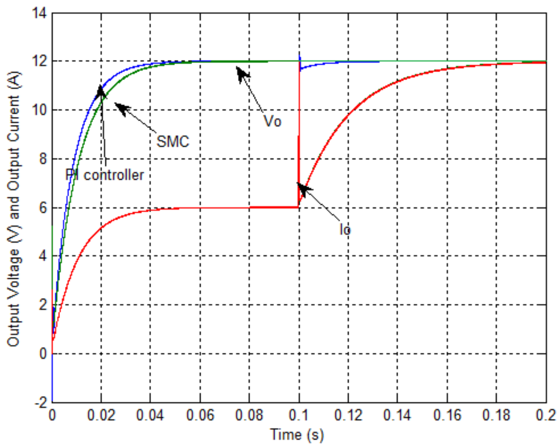
Figure 6. SBC Simulated output voltage responses using controllers for load R=2Ω, (a) for input step change from 21V to 18 V, (b) for input step change from 21V to 24 V.

Figs. 6(a) and 6(b) display the SBC simulated output voltage responses of with both the PI controller and HB based SMC for input voltage step change from 21V to 18V and 21V to 24V at corresponding times of 0.138s and 0.1s respectively. This figure, shows that the output voltage of SBC using HB based SMC has overshoot of 0.1V and settling time of 0.0001 s, at the similar time as PI controller has generates the overshoot as 2.1V and settling time of 0.02s in the line variations.

Load Variations



(a)



(b)

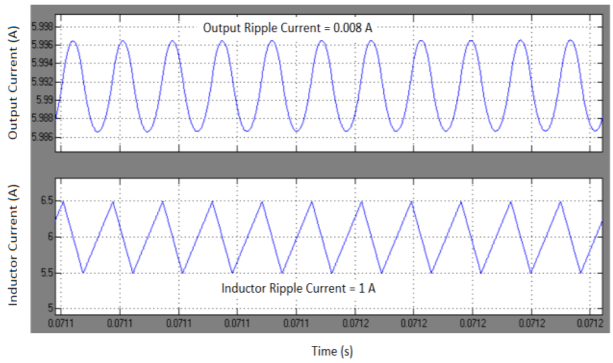
Figure 7. SBC Simulated output voltage and current responses using controller with V_{in} = 21V (a). when load value takes a step changes from 2Ω to 4Ω and (b). when load value takes a step changes from 2Ω to 1Ω.

Figs. 7 (a) and 7 (b) show the SBC simulated output voltage responses with both PI controller and HB based SMC for load step change from 2 Ω to 4 Ω and 2 Ω to 1 Ω at time of 0.1s. It can be seen that the output voltage of SBC using HB based SMC has a insignificant overshoot with settling time and insignificant steady state error, simultaneously same converter using PI controller has created settling time of 0.0001s, peak overshoots of 0.01V and steady state error of 0.01V.

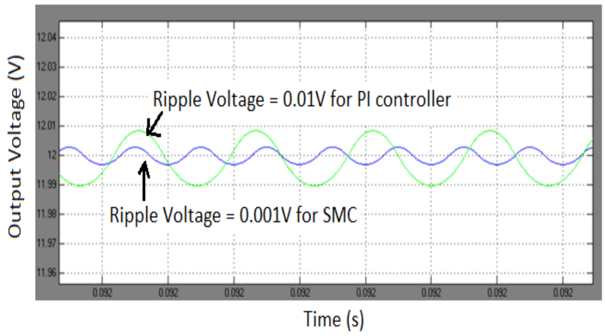
Steady State Region

Figs. 8(a) and 8(b) show the instantaneous output current, output voltage and the inductor current of SBC in the steady state region using both the HB based SMC and the PI controller.

It is marked from the figure that the output voltage ripple is very small about 0.001 V (HB based SMC) /0.01 V (PI controller) and the peak to peak inductor/output current ripple current is 1A/0.008A (HB based SMC) for the average switching frequency of 100 kHz closer to theoretical designed value (refer the Table 1).



(a)



(b)

Figure 8. SBC Simulated output voltage and inductor current i_L responses in steady state region using controllers.

Circuit Components Variations

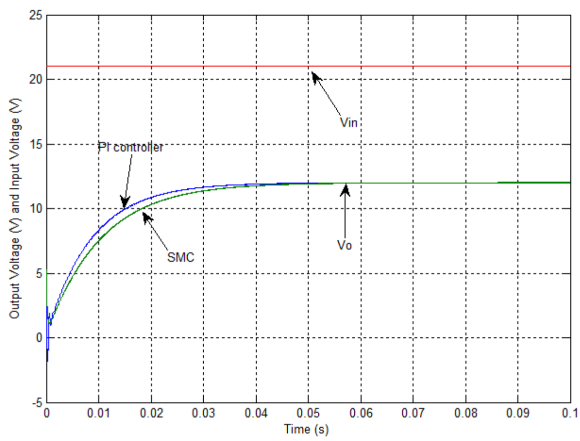


Figure 9. SBC Simulated output voltage responses with HB based SMC and PI controller when inductor variation from 85.5 µH to 100 µH.

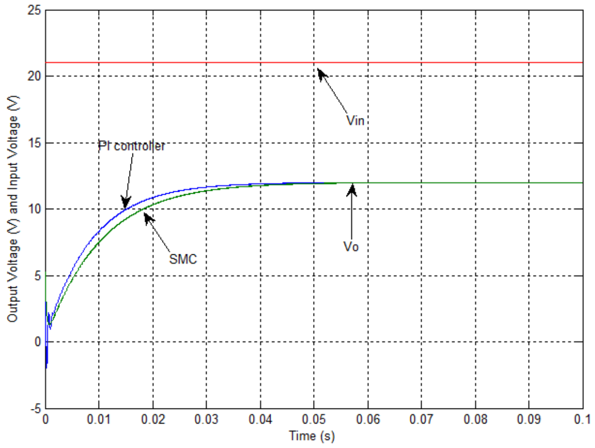


Figure 10. SBC Simulated output voltage responses with HB based SMC and PI controller when capacitor variation from 107μF to 150μF.

Fig. 9 show SBC simulated output voltage responses using both controllers for inductor L change from 85.5μH to 100μH. It might be found that the change does not influence the SBC performance owing to dexterous HB based SMC than PI controller. A attractive result is show in Fig. 10. It explains the SBC simulation response of output voltage with controllers for the change in capacitors values from 107μF to 150μF. It could be found that the designed HB based SMC is very successful in eliminating effect of capacitance difference. From the Fig.11, it is clearly establish that the average input/output currents of the SBC with HB based SMC is 3.6A (I_{in})/6A (I_o), which are same with the theoretical designed value listed in Table 1. Time domain specifications of SBC using both the HB based SMC and PI controller are listed in Table 2.

Table 2. Time domain specification analysis of SBC using controllers

Start up-Region			**Line Variations**				**Load Variations**			
	M_p	**T_s (s)**	**V_{in}=21Vto 18V**		**V_{in}=21Vto 24V**		**R=2Ω to 4Ω**		**R=2Ω to 1Ω**	
			M_p	**T_s (s)**	**M_p**	**T_s (s)**	**M_p**	**T_s (s)**	**M_p**	**T_s (s)**
SMC	nil	0.04	0.1V	0.0001	0.1V	0.0001	nil	nil	nil	nil
PI	nil	0.038	2.1V	0.02	2.1V	0.02	0.01V	0.0001	0.01V	0.0001

From this table, it is evident that the SBC using HB based SMC is superior in comparison with PI controller.

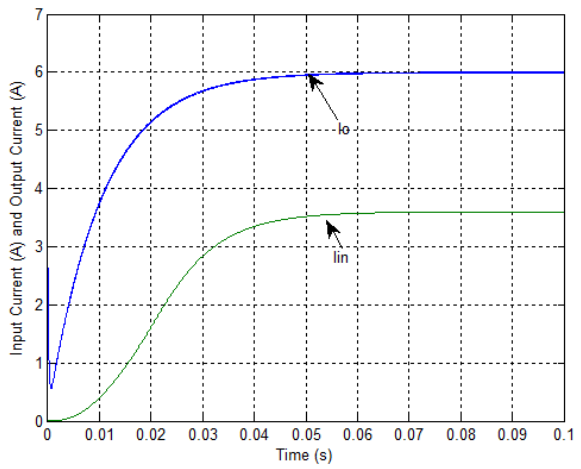


Figure 11. SBC Simulated response of average input and output currents with HB based SMC.

CONCLUSIONS

The article deals with design, analysis, and output voltage regulation of SBC worked in CCM with HB based SMC has been successfully investigated in MATLAB/Simulink. The results of design HB based SMC has produced capable output voltage , brilliant dynamic performance, fine time domain specifications and minimized ripple in inductor/capacitor over the classical linear PI controller. It also frequently designed for any unchanging power source real-world commercial applications such as medical physiotherapy instrument, power supply in battery operated portable devices, mobile phones, personal digital assistant (PDA), MP3 players, lap-tops, blue tooth devices, LED TV and industrial applications etc.

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