Modeling and Analysis of a Novel Adaptive Hysteresis Band Controller for Boost and Buck Converter

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ABSTRACT

In this paper, a new topology of Adaptive Hysteresis Band controller for Boost & Buck converter has been proposed, modeled and analyzed. The difficulties caused in Hysteresis Band (HB) controlled dc-dc converter have been eliminated using Adaptive Hysteresis Band (AHB) controller. This novel control topology can be able to maintain the switching frequency constant unlike HB controller. Thus the filter design for the converters will become easier with this controller. Again this control methodology is a robust one as it depends upon the system parameters where there was no possibility with HB controller. The Mathematical modeling of the controller is shown in this paper, further this has been simulated using Matlab /SIMULINK to generate pulse. The steady state analysis to find the parameters and the stability condition of the converter using the dynamic behavior is also portrayed in this paper. The simulation for a Boost and a Buck converter is also shown separately using AHB controller.

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1. INTRODUCTION

Now-a-days, dc-dc converters are very much useful in all sorts of fields especially in the field of solar energy conversion as well as various industrial applications [1]. Even this is very much essential to convert solar energy to fulfill the power requirement as the global warming due to continuous combustion of fossil fuels occurs. So day by day the requirement of dc-dc converters should commensurately be increased to reduce the effect of global warming. Therefore the issues relating to dc-dc converter also have to be minutely analyzed and to be solved.

Basically any dc-dc converter is required to be operated in closed loop for responding to the dynamic behavior. In this context there are various control strategies available till now. Among these, voltage mode control is used to control the output voltage of the converters. But this cannot be always effective while the load is dramatically changed [2]. Here the boundary control also becomes failed in this condition as the general operation is totally independent of load, capacitor and inductor values [2]. But the actions like overshooting and switching frequency is totally depending upon the above said parameters. Among the various PWM technique and boundary control methods, Hysteresis Band control is very popularly used as it is easy to implement [3]. Again it plays a vital role in maintaining the output voltage but ripple cannot be affected, thus by making the system robust [2]. Hysteresis band control immediately responds to any system variation. Still there are few drawbacks of this control such as it cannot be able to be operated in all types of systems and it gives a variable switching frequency [2]. So the design of filter circuit becomes tough for this type of control. Even in the worst case condition i.e. lowest frequency, the size of the filter becomes very big [4]. Again, since the variation of PWM frequency is happening within a fixed band, it is very much required to control the peak to peak current ripple at all points of time. Due to this the harmonic quantity gets added to the load current and put more stress on the load circuit [3]. Further Peak Current control Mode (PCMC) and Average Current control mode (ACMC) can also be useful for closed loop control method. But, PCMC faces the presence of sub-harmonic oscillations at higher duty cycles and compensation ramp also prevails on that. Whereas, in ACMC, current error amplifier have to be additionally designed with compensation network [5].

The switching frequency can be made constant with the concept of hysteresis band if the bands can be varied in accordance to maintain the modulating frequency constant. This can be adopted by using Adaptive Hysteresis band control, first proposed by Bose [3] in 1990s in the field of PWM inverter for machine drive system. Later this concept has been utilized by Kale *et al.* [6] in 2005 in Shunt Active Power Filter. So this concept can also be utilized for controlling the dc-dc converter. Earlier this method was used to generate two pulses for the inverter, as the inverted and non-inverted signals. But since the dc-dc converters like Buck and Boost converters etc. require only one switch, so the non-inverted signal is considered for application.

Here, the steady state analysis of both the converters discussed in Section 2 whereas, the dynamic behavior is described in Section 3. The Mathematical modeling and control methodology is described in Section 4 and at last in Section 5 & 6, Simulation results and Conclusion is kept respectively.

2. PRINCIPLE OF OPERATION

2.1. Boost Converter

A Boost converter in Ideal condition is shown in Figure 1(a). It is operated in two different modes, i.e. ON Mode and OFF Mode as shown in Figure 1(b) and 1(c) respectively. The conduction path in each mode is shown with the maroon colored paths. The steady state parameters of the Boost converter can be found with reference to [7] as,

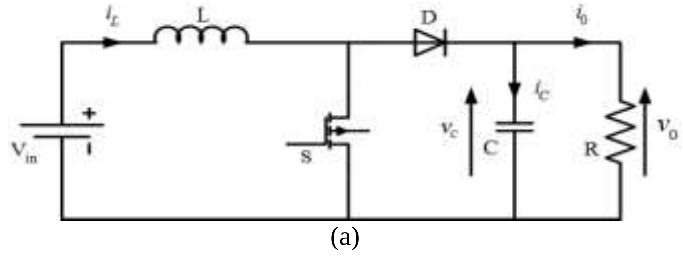
$$v_0(t) = \frac{v_{in}(t)}{1-d(t)} \tag{1}$$

$$i_L(t) = \frac{v_{in}(t)}{\left(1-d(t)\right)^2 R} \tag{2}$$

$$L = \frac{d(t)\left(1-d(t)\right)^2 R}{f_s \text{ x } per\ unit\ ripple} \tag{3}$$

$$C = \frac{d(t)}{f_s \text{ x } R \text{ x } per\ unit\ ripple} \tag{4}$$

where, *d(t)* is the duty ratio, f_s is the switching frequency, *per unit ripple* means $\frac{\Delta i_L(t)}{i_L(t)}$ and $\frac{\Delta v_C(t)}{v_C(t)}$ for inductor and capacitor respectively. Again the numerator terms signify the peak-peak ripple of inductor current and capacitor voltage respectively.



(a)

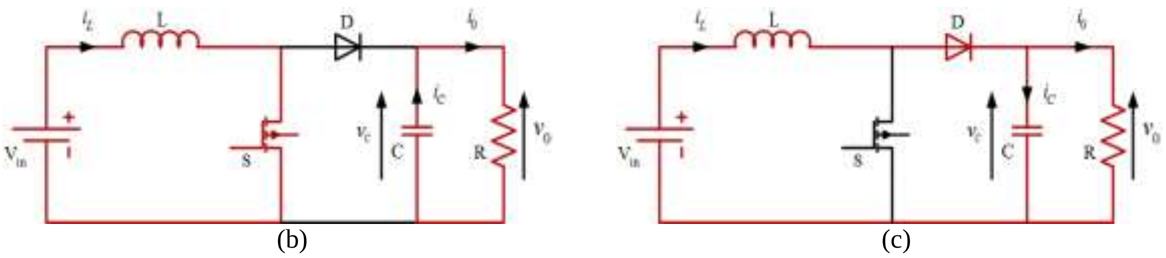


Figure 1. Circuit diagram of (a) Ideal Boost Converter, (b) ON Mode, (c) OFF Mode

2.2. Buck Converter

A Buck converter in Ideal condition is shown in Figure 2(a). It is operated in two different modes, i.e. ON Mode and OFF Mode as shown in Figure 2(b) and 2(c) respectively. The conduction path in each mode is shown with the maroon colored paths. The steady state parameters of the Boost converter can be found with reference to [7] as,

$$v_0(t) = dv_{in}(t) \tag{5}$$

$$i_L(t) = i_0(t) = \frac{v_0(t)}{R} \tag{6}$$

$$L = \frac{R(1-d(t))}{f_s \text{ x } per\ unit\ ripple} \tag{7}$$

$$C = \frac{d(t)}{R \text{ x } f_s \text{ x } per\ unit\ ripple} \tag{8}$$

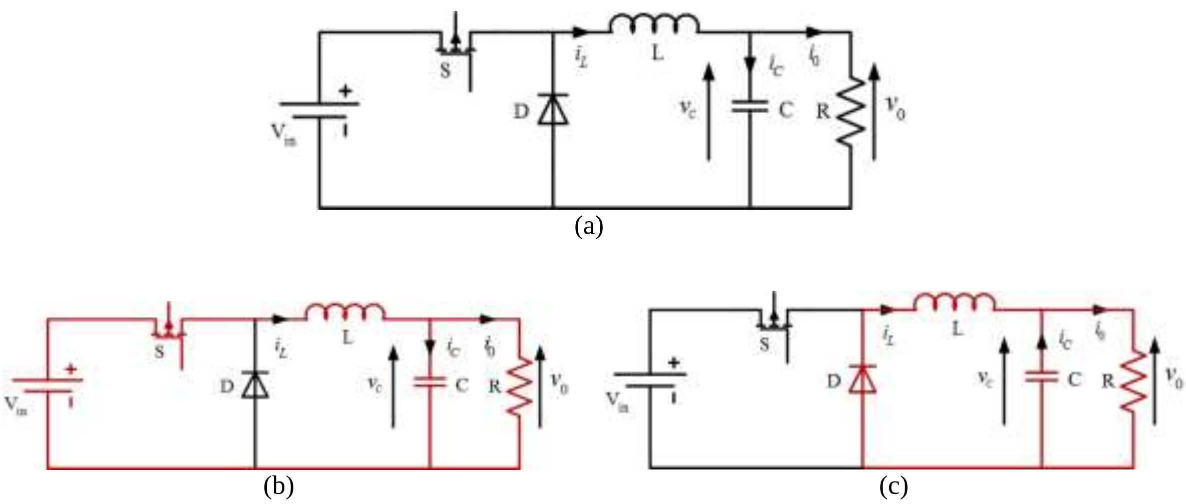


Figure 2. Circuit diagram of (a) Buck converter in ideal condition, (b) ON Mode, (c) OFF Mode

3. DYNAMIC BEHAVIOR OF CONVERTERS

The average modeling of various power electronic converters are described in [8]-[9]. Using this methodology, the average state space model of Boost converter and Buck converter is possible.

3.1. Boost Converter

The state space model of Boost converter is as follows:

$$\begin{bmatrix}\dot{i}_L(t)\\ \dot{v}_C(t)\end{bmatrix} = \begin{bmatrix}0 & -\frac{1-d(t)}{L}\\ \frac{1-d(t)}{C} & -\frac{1}{RC}\end{bmatrix}\begin{bmatrix}i_L(t)\\ v_C(t)\end{bmatrix} + \begin{bmatrix}\frac{1}{L}\\ 0\end{bmatrix} v_{in}(t) \tag{9}$$

This is a nonlinear model & it is used very commonly for the analysis and controlling of DC-DC converters. For the application of this method, this nonlinear model has to be converted into a linear model applying a perturbation into a nominal point. Now a small perturbation is applied to the signals for finding out linearization as:

$$d(t) = D + \tilde{d}(t) \quad \& \quad v_{in}(t) = V_{in} + \tilde{v}_{in}(t)$$

Here, the uppercase signifies the nominal point and the symbol ~ represents a perturbation applied. The above expressions are applied into (9) and the equation is formed as:

$$\begin{bmatrix}\dot{I}_L + \dot{\tilde{i}}_L(t)\\ \dot{V}_C + \dot{\tilde{v}}_C(t)\end{bmatrix} = \begin{bmatrix}0 & -\frac{1-D-\tilde{d}(t)}{L}\\ \frac{1-D-\tilde{d}(t)}{C} & -\frac{1}{RC}\end{bmatrix}\begin{bmatrix}I_L + \tilde{i}_L(t)\\ V_C + \tilde{v}_C(t)\end{bmatrix} + \begin{bmatrix}\frac{1}{L}\\ 0\end{bmatrix}\left(V_{in} + \tilde{v}_{in}(t)\right) \tag{10}$$

The linear average model of the Boost converter can be obtained by subtracting the averaged value of (9) from (10) and ignoring the higher order terms as:

$$\begin{bmatrix}\dot{\tilde{i}}_L(t)\\ \dot{\tilde{v}}_C(t)\end{bmatrix} = \begin{bmatrix}0 & -\frac{1-D}{L}\\ \frac{1-D}{C} & -\frac{1}{RC}\end{bmatrix}\begin{bmatrix}\tilde{i}_L(t)\\ \tilde{v}_C(t)\end{bmatrix} + \begin{bmatrix}\frac{V_{in}}{\{1-d(t)\}L} & \frac{1}{L}\\ \frac{V_{in}}{\{1-d(t)\}^2 RC} & 0\end{bmatrix}\begin{bmatrix}\tilde{d}(t)\\ \tilde{v}_{in}(t)\end{bmatrix} \tag{11}$$

Now the control to output voltage transfer function can be derived from equation (11) as,

$$\frac{\tilde{v}_C}{\tilde{d}}(s) = \frac{LRV_{in}\{sRC^2 + L(1-D)^2\}}{(1-D)^2\{s^2CLR + sL + R(1-D)^2\}} \tag{12}$$

The stability condition of the Boost converter has been analyzed using Bode diagram shown in Figure 3. The PI controller gains are also adjusted by considering the stability criterion using the optimization technique with RLTool in MATLAB. The gains for the controller has been found as $k_p = 1.82$ & $k_i = 63.29$.

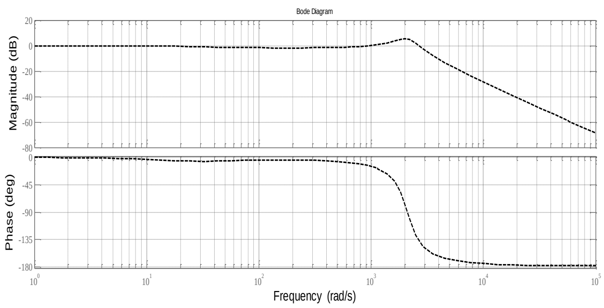


Figure 3. Closed Loop Bode diagram of control to output transfer function of Boost converter

3.2. Buck Converter

State space model of Buck converter in the same way can be obtained as:

$$\begin{bmatrix}\dot{i}_L(t)\\ \dot{v}_C(t)\end{bmatrix}=\begin{bmatrix}0 & -\frac{1}{L}\\ \frac{1}{C} & -\frac{1}{RC}\end{bmatrix}\begin{bmatrix}i_L(t)\\ v_C(t)\end{bmatrix}+\begin{bmatrix}\frac{d(t)}{L}\\ 0\end{bmatrix}v_{in}(t) \tag{13}$$

Again to get the linear equation, the same perturbation has to be added in the above equation by making it an averaged model.

$$\begin{bmatrix}\dot{I}_L+\dot{\tilde{i}}_L(t)\\ \dot{V}_C+\dot{\tilde{v}}_C(t)\end{bmatrix}=\begin{bmatrix}0 & -\frac{1}{L}\\ \frac{1}{C} & -\frac{1}{RC}\end{bmatrix}\begin{bmatrix}I_L+\tilde{i}_L(t)\\ V_C+\tilde{v}_C(t)\end{bmatrix}+\begin{bmatrix}\frac{D+\tilde{d}(t)}{L}\\ 0\end{bmatrix}\{V_{in}+\tilde{v}_{in}(t)\} \tag{14}$$

The linear averaged model of the Buck converter is obtained as:

$$\begin{bmatrix}\dot{\tilde{i}}_L(t)\\ \dot{\tilde{v}}_C(t)\end{bmatrix}=\begin{bmatrix}0 & -\frac{1}{L}\\ \frac{1}{C} & -\frac{1}{RC}\end{bmatrix}\begin{bmatrix}\tilde{i}_L(t)\\ \tilde{v}_C(t)\end{bmatrix}+\begin{bmatrix}\frac{V_{in}}{L} & \frac{D}{L}\\ 0 & 0\end{bmatrix}\begin{bmatrix}\tilde{d}(t)\\ \tilde{v}_{in}(t)\end{bmatrix} \tag{15}$$

The control to output transfer function for the Buck converter is,

$$\frac{\tilde{v}_C}{\tilde{d}}(s)=\frac{RV_{in}}{s^2CLR+sL+R} \tag{16}$$

Closed Loop Bode diagram of Buck converter has also been shown in Figure 4. The PI controller gains are also adjusted with RLTool in MATLAB in the same way as Boost converter. The gains for the controller has been found as $k_p=0.056$ & $k_i=4.698$.

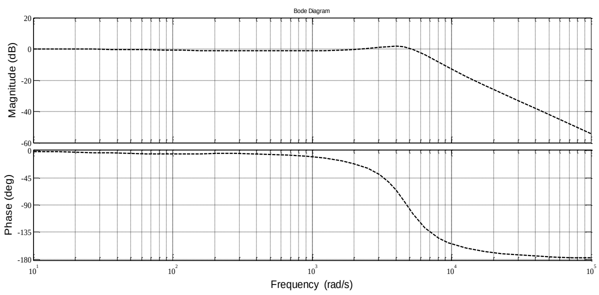


Figure 4 Closed Loop Bode diagram of control to output transfer function of Buck Converter

4. MODELING OF ADAPTIVE HYSTERESIS BAND CONTROLLER

The hysteresis band current controller has shown its usefulness in applications of current controlled power electronic devices such as dc-dc converters, active power filters etc. It has some advantages like independent stability, dynamic response and better accuracy [6],[10],[11]. But the conventional hysteresis technique faces some unwanted characteristics like variable switching frequency which causes acoustic noise and filter design problems [12].

The conventional hysteresis band current controller method is shown in Figure 5. The error between the reference inductor current and the feedback inductor current signal is passed through a defined hysteresis band controller. Here the switching pulse is generated as follows:

if, $i_L(t) < (i_L^*(t) - HB)$, pulse = HIGH;

if, $i_L(t) > (i_L^*(t) + HB)$; pulse = LOW;

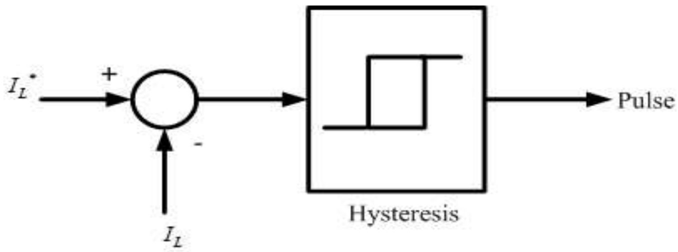


Figure 5. Conventional hysteresis band current controller

The width of the band is unchangeable. So the switching frequency of such method is always variable. The method described above is depending upon how rapidly the inductor current changes from the upper limit to lower limit of the hysteresis band and vice versa. However, by controlling the bandwidth, it is possible to control the average switching frequency.

The above said problems can be minimized by considering a change in the bandwidth as per requirement for maintaining switching frequency of the converter as constant. In this regard, Bose [3] put the first light on Adaptive Hysteresis Band Current Controller in the field of PWM inverter. This idea can also be utilized for the controlling and operation of dc-dc converter. In this control technique, the bandwidth is continuously changing with respect to the reference signals to maintain frequency constant.

The PWM technique for the hysteresis band controller is shown in Figure 6. When inductor current ($i_L(t)^+$) rises from lower band to upper band, the switch of the dc converter has to be turned ON. Again when the current ($i_L(t)^-$) starts to fall from the upper band level, the switch gets turned OFF as the pulse becomes lower. The equations required to find the Adaptive Hysteresis Band for Buck and Boost converter are discussed in the following part.

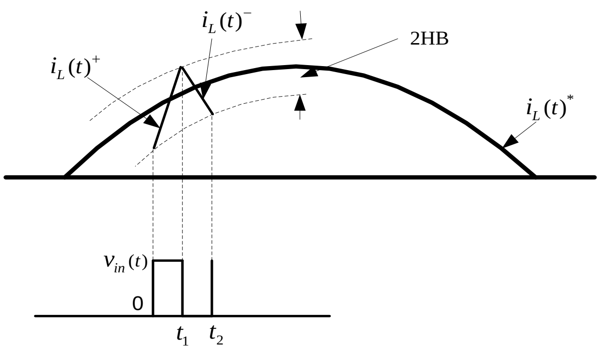


Figure 6. Current and voltage waveforms of Hysteresis Band current controller for dc-dc converters

4.1. Boost Converter

The equations for the Boost converter can be written in the respective switching intervals t_1 and t_2 from Figure 6.

$$\frac{di_L(t)^+}{dt} = -\frac{v_{in}(t)}{L} \tag{17}$$

$$\frac{di_L(t)^-}{dt} = -\frac{v_{in}(t) - v_0(t)}{L} \tag{18}$$

From the geometry of Figure 4 can be written as,

$$\frac{di_L(t)^+}{dt} t_1 + \frac{di_L(t)^*}{dt} t_1 = 2HB \tag{19}$$

$$\frac{di_L(t)^-}{dt} t_2 + \frac{di_L(t)^*}{dt} t_2 = -2HB \tag{20}$$

$$t_1 + t_2 = \frac{1}{f_c} \tag{21}$$

where, t_1 and t_2 are the respective switching intervals, f_c is the switching frequency. Adding (19) and (20) and substituting the value of (21) on it becomes as,

$$\frac{di_L(t)^+}{dt} t_1 + \frac{di_L(t)^-}{dt} t_2 - \frac{1}{f_C}\frac{di_L(t)^*}{dt} = 0 \tag{22}$$

Subtracting (20) from (19), we get

$$\frac{di_L(t)^+}{dt} t_1 - \frac{di_L(t)^-}{dt} t_2 - (t_1 - t_2)\frac{di_L(t)^*}{dt} = 4HB \tag{23}$$

Substituting the values of (17), (18) into (22), we get

$$t_2 = \frac{L}{v_0(t) f_C}\left(\frac{v_{in}(t)}{L} - \frac{di_L(t)^*}{dt}\right) \tag{24}$$

Replacing the value of t_2 into equation (21), it is found that,

$$t_1 = \frac{1}{f_C}\left\{1 - \frac{L}{v_0(t)}\left(\frac{v_{in}(t)}{L} - \frac{di_L(t)^*}{dt}\right)\right\} \tag{25}$$

Now the solution of equation (23) gives,

$$HB = \frac{1}{2f_c}\left[\left(\frac{v_{in}(t)}{L} - \frac{di_L(t)^*}{dt}\right) - \frac{L}{v_0(t)}\left(\frac{v_{in}(t)}{L} - \frac{di_L(t)^*}{dt}\right)^2\right] \tag{26}$$

The adaptive hysteresis band current controller changes its bandwidth to maintain constant frequency with respect to the variation of inductor current $i_L(t)$ change [6]. The adaptive hysteresis band control application method is described with the help of block diagram in Figure 7. Here the generated HB has to be applied which is a variable parameter i.e. adaptive in nature that depends upon system parameters.

Now, this band is compared with the inductor current, $i_L(t)$ and the reference inductor current, $i_L(t)^*$ generated by the PI controller. The comparator, by following the condition stated above, generates the pulse and this is applied to the switch. The function of the PI controller is to compensate the error between the voltage command and the output voltage feedback. The same process is applied to the Buck converter also.

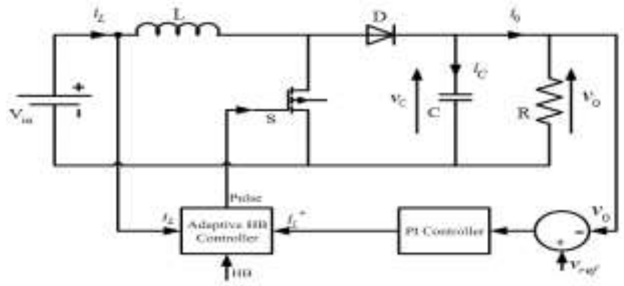


Figure 7. Block diagram of Adaptive Hysteresis Band controller in Boost converter

4.2. Buck Converter

Similarly the equations for the Buck converter can be derived as,

$$\frac{di_L(t)^+}{dt} = \frac{1}{L}\{v_{in}(t) - v_0(t)\} \tag{27}$$

$$\frac{di_L(t)^-}{dt} = -\frac{1}{L}v_0(t) \tag{28}$$

Substituting the values of (27) & (28) into (22), we get

$$t_1 = \frac{L}{v_{in}(t) f_C}\left(\frac{v_0(t)}{L} + \frac{di_L(t)^*}{dt}\right) \tag{29}$$

Putting the value of t_1 in equation (21), the solution comes as,

$$t_2 = \left[1 - \frac{L}{v_{in}(t)}\left(\frac{v_0(t)}{L} + \frac{di_L(t)^*}{dt}\right)\right] \tag{30}$$

Considering all the parameters found, the solution of equation (23) can be given as,

$$HB = \left|\frac{L}{2 f_C v_{in}(t)}\left(\frac{v_0(t)}{L} + \frac{di_L(t)^*}{dt}\right)^2\right| \tag{31}$$

Here, equation (26) reflects about the variable Hysteresis Band for Boost converter and equation (31) describes for the Buck converter as suggested by Bose in [3] for PWM inverter and Kale *et al.* in [6] for shunt APF.

The equations for the Hysteresis band are the functions of input voltage, switching frequency, output voltage and slope of reference inductor current ($di_L(t)^*/dt$). Hysteresis band is controlled as a function of input voltage and the reference inductor current slope to make the frequency f_c constant [6]. This will be reducing the filter design easier and will reduce the EMI problem of the converters.

The adaptive hysteresis bandwidth calculation block diagrams are shown in Figure 8 and Figure 9 respectively for Boost and Buck converter. As the equations for both the converters are different, the calculation blocks will also be different.

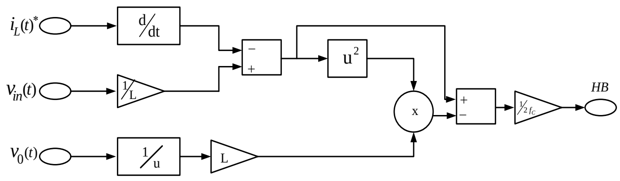


Figure 8. Adaptive Hysteresis Band calculation block diagram for Boost converter in continuous time domain

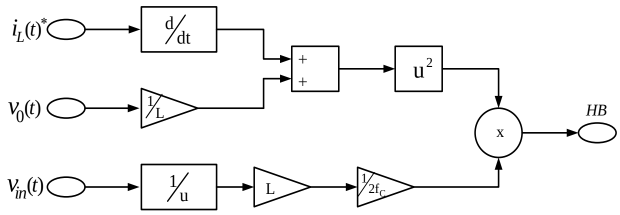
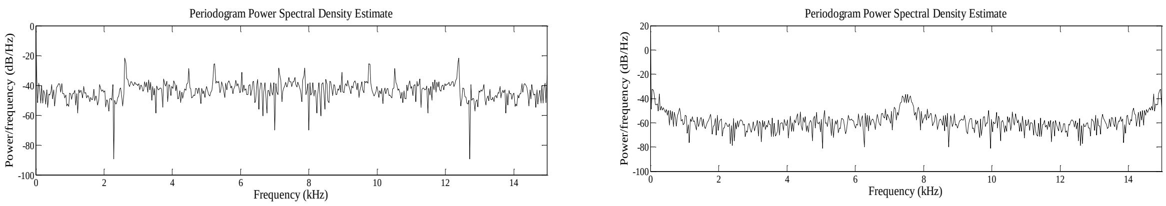


Figure 9. Adaptive Hysteresis Band calculation block diagram for Buck converter in continuous time domain

5. SIMULATION RESULTS

The Power Spectral Density (PSD) analysis of the switching frequency is shown in Figure 10. Here the spectral density analysis being done for the Hysteresis Band controller and the Adaptive Hysteresis Band controller. Basically PSD is used to find out the dominant frequency level present in any signal. In this process, the dominant frequency level shows more Gain i.e. it approaches towards the positive direction. So in Figure 10(a) PSD result displays about the presence of various frequency levels i.e. the frequency is variable. While in Figure 10(b) the dominant frequency is showing maximum gain at 7.5 kHz and the other frequency orders are almost attenuated.



(a) (b)

Figure 10. Periodogram Power Spectral Density analysis of switching frequency for (a) Hysteresis band, (b) Adaptive HB Controller

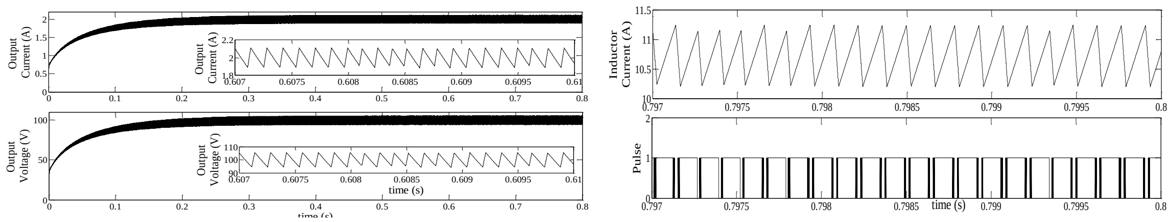
The mathematical formulations evolved in the previous section have been simulated using MATLAB/Simulink toolbox. The parameters considered for the simulation for both the converters are shown in Table 1.

5.1. Boost Converter

The output voltage and current waveforms of the Boost converter is shown in Figure 11(a). The average output current is 2 A whereas the average output voltage is 100 V. The switching frequency can be observed from the waveforms that it is 7.5 kHz. The average output voltage comes equal to the reference voltage provided. Here output voltage and current waveforms are shown with a zoomed view in the corresponding windows as well.

Table 1. Converter Parameters

Parameters	Buck Converter	Boost Converter
Input Voltage (V)	100	20
Output Voltage (V)	20	100
Switching Frequency (kHz)	7.5	7.5
Inductor (mH)	10.7	2.1
Capacitor (μF)	26.7	21.3
Resistor (Ω)	10	50



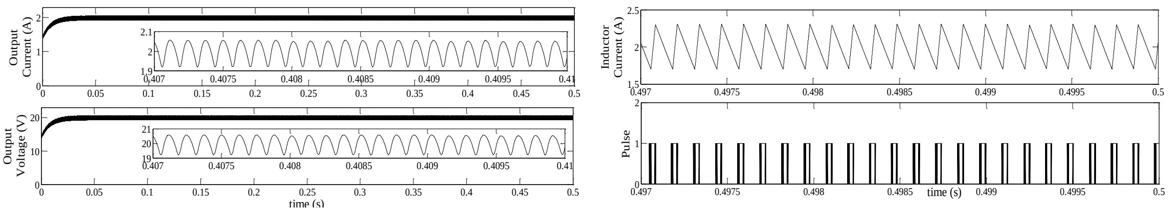
(a) (b)

Figure 11. (a) Output Current and Voltage waveforms, (b) Inductor Current and Pulse of Boost Converter

Figure 11(b) shows the inductor current conduction with a relation with the pulses generated by the controller. The pulses with duty cycle 0.8 shown here are also can be seen as the approximately constant and the switching frequency comes as 7.5 kHz. Here the inductor current ripple depends upon the value of the inductor.

5.2. Buck Converter

The output voltage and current waveforms of the Buck converter are shown in Figure 12(a). Here also the average output voltage becomes equal to the reference voltage provided as 20 V. The output voltage ripple depends upon the value of the capacitor connected at the output side. Here also the output voltage and current waveforms are shown with a zoomed view. Again Figure 12(b) describes the inductor current transition with the change in the input pulses to the switch. Here also it can be seen that the pulses are coming as constant. The duty cycle is coming as 0.2.



(a) (b)

Figure 12. (a) Output Current and Voltage waveforms, (b) Inductor Current and Pulse of Buck Converter

6. CONCLUSION

This paper represents about a new control strategy for the Boost and Buck converter keeping the switching frequency constant. Basically the main disadvantage of Hysteresis Band controller is being eliminated with this control topology. HB controlled converters face a difficulty of filter designing as the switching frequency becomes inconsistent. So with the help of Adaptive HB controller, this filter design will become easier for the designers for this kind of converters. Further this controller depends upon the system parameter which was also a disadvantage with the HB controller. So overall study gives an outcome such that, this controller can be a better replacement for the HB controller.

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