Performance Estimation Of Tristate DC-DC Buck Converter With Fixed Frequency and Constant Switching Hysteresis Control

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ABSTRACT

The paper proposes the operation of the tristate dc-dc buck converter with hysteretic current-mode control scheme. The hysteretic controlled converters respond to disturbances and load change right after the transient takes place and they give excellent transient performance. It does not require the closed loop compensation network and results with a lesser component count and small size in implementation. Hence, hysteretic control is considered as the simplest and fastest control method. The dc-dc buck converter employing current hysteresis control scheme is given in thesis. The result shows that hysteresis control converters have inherently fast response and they are robust with simple design and implementation. A hysteretic current control technique for a tri-state buck converter operating in constant switching frequency is designed and its behavior is studied by making the use of essential tools of sliding mode control theory because dc-dc buck converter is a variable structure system due to the presence of switching actions. The principle of operation of tristate dc-dc buck converter is explained. The converter response is investigated in the steady-state region and in the dynamic region. The problem of variable switching frequency is eliminated without using any compensating ramp.

Keywords: Hysteresis control, Dc-dc buck converter, variable structure system.

1. INTRODUCTION:

The use of hysteretic controllers for low voltage regulators used in computer and communication systems has been gaining interest due to its various advantages. Advantages of this control approach includes fast response and robust with simple design and implementation. They do not require components for feedback loop compensation [6]-[8]. This reduces the number of components and size of theoretical analysis for implementation and also reduces the design effort for calculating the circuit component values (like inductor, capacitor, and input voltage). They respond to disturbances and load change right after the transient takes place. Hence they give excellent transient performances. While the elimination of the compensation network allows for fast responses to transient, the hysteretic controlled converter suffers from two major drawbacks: variable switching frequency and non-zero steady-state error. Non-zero steady-state error may be rectified by adding a PI block in series with the voltage feedback. Also, the output voltage ripple is higher than the fixed band of hysteresis comparator. That is because of delays and output filter parasitic element. The application of nonlinear control theory can be used for study and analysis of hysteretic controlled converters for alleviating the above mentioned problems. This way of analysis gives a better idea for proper design method [6]. The hysteretic controllers react immediately after the load transient takes place. Hence the advantages of hysteretic control over other control technique include simplicity, do not require feedback loop compensation, fast response to load transient. However, the main factors need to be considered in case of hysteresis control are variable switching frequency operation and stability analysis. The different types of hysteretic controllers are hysteretic voltage-mode controller, V2 controller, and hysteretic current-mode controllers. The current hysteretic control incorporates both the advantages of hysteretic control and current mode control. It can be implemented using two loop control method. The error between the actual output voltage and reference voltage gives the error voltage. A PI control block can use the voltage error signal to provide a reference current for hysteretic control. This is also called sliding mode control for dc-dc converter. Therefore, the current mode hysteretic controller can be considered as a sliding mode control system and the analysis of hysteretic controller can be done as per sliding mode control theory. The essential tools of this nonlinear control theory can be introduced for the study of the behavior of hysteretic controller. Therefore, the motivation of this thesis is to improve the performance of a dc-dc buck converter through controller improvements. Hence, this thesis focused on the design and analysis of a fixed frequency hysteretic current mode.
controller with improved performance for dc-dc buck converter circuit. The problem of switching frequency variation is alleviated with simplicity in controller design.

2. DC/DC Converters

The DC-DC converters can be divided into two main types: hard-switching pulse width modulated (PWM) converters and resonant and soft-switching converters. Advantages of PWM converters include low component count, high efficiency, constant frequency operation, relatively simple control and commercial availability of integrated circuit controllers, and ability to achieve high conversion ratios for both step-down and step-up applications. The circuit diagram of the DC/DC buck converter is shown in Figure 1. In this figure, the circuit schematic is depicted with the transistor-diode symbols. By sensing of the DC output and controlling of the switch duty cycle in a negative-feedback loop, the DC output voltage could be regulated against input line and output load changes.

![FIG - 01 DC-DC BUCK CONVERTER](image1)

3. The State-Space Model of Buck Converter

To obtain the differential equations describing the buck converter, the ideal topology is used as shown in Figure-02. The differential equations describing the DC/DC buck converter dynamics are obtained through the direct application of Kirchhoff’s current and Kirchhoff’s voltage laws for each one of the possible circuit topologies arising from the assumed particular switch position function value. Thus, when the switch position function exhibits the value \( u = 1 \), we obtain the topology corresponding to the non-conducting mode for the diode obtained. Alternatively, when the switch position exhibits the value \( u = 0 \), the second possible circuit topology corresponding to the conducting mode for the diode is obtained.

![FIG - 02 Switching operation of DC-DC Buck converter](image2)

The system dynamics is described by the following differential equations.

For \( u = 1 \),

\[
\begin{align*}
L \frac{di}{dt} &= -v + E \\
C \frac{dv}{dt} &= i - \frac{v}{R}
\end{align*}
\]

For \( u = 0 \),

\[
\begin{align*}
L \frac{di}{dt} &= -v \\
C \frac{dv}{dt} &= i - \frac{v}{R}
\end{align*}
\]

By comparing the obtained particular dynamic systems descriptions, the following unified dynamic system model can be obtained:

\[
\begin{align*}
L \frac{di}{dt} &= -v + uE \\
C \frac{dv}{dt} &= i - \frac{v}{R}
\end{align*}
\]
4. Variable Frequency Hysteretic Controllers

The hysteretic controlled converters with variable switching frequency are segregated into two categories: voltage hysteretic controller and current hysteretic controller. The voltage hysteretic controller regulates the output voltage ripple within the hysteretic band. Similarly, a current hysteretic controller directly regulates the inductor current of the converter by regulating the inductor ripple or a scaled version of it within the hysteretic band.

4.1 Hysteretic Voltage-Mode Controller

Hysteretic voltage-mode control is the simplest control method available. The concept of operation is very simple. The switch is turned on, when the output voltage falls below minimum set point (i.e., lower boundary) and turns off when output voltage is higher than maximum set point (i.e., upper boundary). Since the controller does not use a compensation network, the converter is able to react quickly to a transient event making it seem like a perfect solution for voltage regulator modules. However, the drawback of the voltage-mode hysteretic controller is its reliance on the converter’s output capacitor parasitic. A block diagram of voltage hysteretic controlled converter is illustrated in Figure 3.

![Figure 3: voltage hysteresis control](image)

4.2 Hysteretic Current-Mode Controller

Hysteretic current-mode control functions by controlling both the peak inductor current and the valley inductor current. It does not require an external oscillator or sawtooth generator for operation and it has the ability to provide a fast response to a transient event. Figure 4 illustrates a block diagram of a current-mode hysteretic controlled dc-dc converter.

![Figure 4: Hysteretic CM controlled buck converter](image)

5. Constant Switching Frequency Current-Mode Hysteretic Controller

In this section, a new control topology, which includes the concept of SM control and peak current mode control is proposed. Therefore the essential tools of the nonlinear control theory can be introduced for the study of this hysteresis controller. The proposed control scheme is actually a fixed frequency hysteretic current mode controller for dc-dc buck converter that operates in pseudo-CCM (PCCM). In PCCM operation, the conventional buck converter circuit is modified by connecting an extra of switch across the inductor. This divides the total switching cycle into three subintervals which is termed as PCCM. The converter with this additional third interval is also known as tristate converter. Thus, the new control approach provides the advantages that are simple in implementation, fixed switching frequency operation, good transient performances and does not require a compensating ramp signal.

6. Basic Concept of Operation

The operation of the tristate dc-dc buck converter with hysteretic current-mode control scheme is discussed in this section. Figure 5 shows the tristate buck converter topology. It consists of two controlled switches $S_1$ and $S_2$, an uncontrolled switch $D$, an inductor $L$ and a capacitor $C$, a load resistance $R$. Switch $S_2$ is the additional switch which is connected across the inductor. The operation of the tristate converter includes three different configuration or
structures that are show in figure 6. At the start of the clock period, the switch $S_1$ is turned on and the switch $S_2$ is turned off. During this interval (mode 1), inductor current increases with a slope of $-\frac{v_o}{L}$. When $i_L$ reaches a peak value (upper bound), $S_1$ turns off. Then, $i_L$ starts falling with a slope of $\frac{v_o}{L}$ until it reaches some lower threshold. This interval is denoted as mode 2. During this interval, diode is forward biased and both switch $S_1$ and $S_2$ are turned off. When the inductor current reaches lower threshold, it stays constant at lower boundary, because the switch $S_2$ shorts the inductor $L$ and voltage across the inductor is thus equal to zero. During this interval $S_2$ is turned on while $S_1$ and diode are off. This is the additional interval, denoted as mode 3. The inductor current waveform showing the switch conditions for a tristate buck converter is shown in figure 7. All the circuit components are assumed to be ideal in the derivations.

![Figure 5: A tristate buck converter configuration](image)

![Figure 6: A tristate buck converter in three modes](image)

These three modes of operation can be described as follows:

Mode 1: when $S_1$ is on and, $S_2$ is off, the state space equation of buck converter is derived as

$$\frac{dx}{dt} = \begin{bmatrix} \frac{1}{RC} & -\frac{1}{L} \\ -\frac{1}{L} & \frac{1}{C} \end{bmatrix} x + \begin{bmatrix} 0 \\ \frac{1}{L} \end{bmatrix} v_o$$

where $x = [v_o \ i_L]^T$, $v_o$ is the output voltage, $i_L$ is the inductor current.

Mode 2: when $S_1$ and $S_2$ both are off, the equation is derived as,

$$\frac{dx}{dt} = \begin{bmatrix} -\frac{1}{RC} & -\frac{1}{C} \\ -\frac{1}{L} & \frac{1}{C} \end{bmatrix} x + \begin{bmatrix} 0 \\ 0 \end{bmatrix} v_o$$

Mode 3: when $S_1$ is off, and $S_2$ is on, the state-space equation is

$$\frac{dx}{dt} = \begin{bmatrix} -\frac{1}{RC} & -\frac{1}{C} \\ 0 & 0 \end{bmatrix} x + \begin{bmatrix} 0 \\ 0 \end{bmatrix} v_o$$
Mathematical Analysis of Proposed Controller

The operation of a hysteretic current-mode controller for tristate dc-dc buck converter is proposed and the schematic diagram of proposed controller is shown figure 8.

$$\begin{align*}
    x_1 &= v_{ref} - v_{ref} \\
    x_2 &= i_L
\end{align*}$$

where $i_L$ represent the inductor current, $v_0$ and $v_{ref}$ represent the output voltage and reference voltage respectively. Here the switching state of the switch is either 1 or 0.

Then by taking the derivative of (7) with respect to time,

$$\begin{align*}
    \dot{x}_1 &= \frac{dv_0}{dt} \\
    \dot{x}_2 &= \frac{di_l}{dt}
\end{align*}$$

Considering the buck converter when the switch $S_1$ is on, $S_2$ off
\[
L \frac{di}{dt} = v_o - v_i \quad \cdots \quad 9
\]
\[
i_L = C \frac{dv_i}{dt} + \frac{v_0}{R} \quad \cdots \quad 10
\]

Substituting equation (8)
\[
\begin{align*}
\dot{x}_1 &= -\frac{1}{RC} x_1 - \frac{1}{C} x_2 + \frac{v_{ref}}{RC} \quad \cdots \quad 11 \\
\dot{x}_2 &= \frac{1}{L} x_1 - \frac{v_{ref}}{L}
\end{align*}
\]

The dynamics of the converter circuit in mode 3, when \( S_2 \) is on, \( S_1 \) is off, can be expressed as,
\[
L \frac{di}{dt} = 0 \quad \cdots \quad 12
\]
\[
i_L = C \frac{dv_i}{dt} + \frac{v_0}{R} \quad \cdots \quad 13
\]
Since in this mode of operation, inductor current stays at a constant value, so we get the derivative of a constant value is zero. By substituting equation (8) into equation (12) and (13) results in,
\[
\begin{align*}
\dot{x}_1 &= -\frac{1}{RC} x_1 \quad \cdots \quad 14 \\
\dot{x}_2 &= 0 \quad \cdots \quad 15
\end{align*}
\]
As studied from the previous discussion that the basic principles of a hysteresis control is based on the two hysteresis bands (upper and lower bands), whereby the controller turns the switch on when the output current falls below the lower band and turns the switch off when output is beyond the upper bound. The switching action can be determined in the following way,
1. If \( i_L < \text{lower bound} \), \( u = 1 \) (ON)
2. If \( i_L > \text{upper bound} \), \( u = 0 \) (OFF), where \( u \) is the control input.

8. Model including parasitic elements
The influence of parasitic elements on the converter behavior is not yet discussed. Therefore the circuit including the parasitic elements is given below. The tristate buck converter circuit consists of parasitic elements in the switches \((r_1 \text{ and } r_2)\), the capacitor \((c_r)\), the inductor \((L_r)\) and the diode \((d_r)\) are shown in figure 10.

![Model of tristate buck converter with all parasitic elements](image)

The three modes of operation can be described as follows:
Mode 1: when \( S_1 \) is on and \( S_2 \) is off, the state space equation of buck converter is derived as
\[
\frac{dx}{dt} = \begin{bmatrix}
-\frac{1}{C(R + r_1)} & \frac{R}{C(R + r_1)} \\
-\frac{R}{L(R + r_1)} & -\frac{1}{L} \left( \frac{r_1}{R + r_1} + \frac{R}{R + r_1} \right)
\end{bmatrix} x + \begin{bmatrix}
0 \\
\frac{1}{L}
\end{bmatrix} v_o \quad \cdots \quad 16
\]
Where \( x = [v_c \ i_L]^T \), \( i_L \) is the inductor current, \( v_c \) is the output voltage.
Mode 2: when \( S_1 \) and, \( S_2 \) both are off, the equation is derived as,
\[ \frac{dx}{dt} = \begin{bmatrix} \frac{1}{C(R+r_c)} & \frac{R}{C(R+r_c)} \\ - \frac{R}{L(R+r_c)} & - \frac{1}{L} (r_f + r_c) + \frac{R_c}{(R+r_c)} \end{bmatrix} x + \begin{bmatrix} 0 \\ 0 \end{bmatrix} v_i \quad .............17 \]

Mode 3: when \( S_1 \) is off, and \( S_2 \) is on, the state-space equation is

\[ \frac{dx}{dt} = \begin{bmatrix} \frac{1}{C(R+r_c)} & 0 \\ 0 & - \frac{r_f + r_c}{L} \end{bmatrix} x + \begin{bmatrix} 0 \\ 0 \end{bmatrix} v_i \quad .............18 \]

9. Simulation Results

In this subsection, based on the above proposed hysteretic current control method, the simulation studies have been performed on a dc-dc buck converter under steady-state and also under dynamic conditions of line and load variations. The buck converter parameters chosen for the simulation studies are input voltage \( v_i = 20 \) V, desired output voltage \( v_o = 5 \) V, inductance \( L = 3mH \), capacitance \( C = 69 \mu F \), minimum load resistance \( R_{min} = 10\Omega \), maximum load resistance \( R_{max} = 15\Omega \), voltage reduction factor \( k_1 = 0.8 \), proportional gain \( k_p = 2 \), delta \( \Delta = 0.003 \) and current sensing gain \( k = 3\Omega \). The switching frequency \( f_s \) is set to 100 kHz. A simple proportional controller is considered here. The simulations are done using MATLAB/SIMULINK.

![Figure 11](image1.png)  
**Figure 11**: Start-up transient performance of the converter with the proposed controller

![Figure 12](image2.png)  
**Figure 12**: The proposed current hysteretic controller operating principle
Figure 13: Transient response for change in load from 15Ω to 10Ω and back to 15Ω

Figure 14: Output voltage response from load transient 10Ω to 15Ω

Figure 15: Load transient response from 15Ω to 10Ω

Figure 16: Load transient response from 15Ω to 10Ω for conventional current hysteretic control method

From figure 15 and 16, it is seen that in case conventional current hysteretic control method the switching frequency is not constant ($T_1 \neq T_2$) when load is varied. But for the proposed control technique we are getting a fixed switching frequency ($T_1 = T_2$) when load varies.

Figure 17: phase plane diagram
10. Conclusion

In this chapter, the principle and operation of different types of hysteresis controllers are discussed. The effectiveness of hysteresis controller for faster transient response is described through the simulation results. The main problem associated with these conventional hysteretic controlled converters is variable switching frequency operation. Thus a constant switching frequency hysteretic controller is proposed. The controller is of current-mode operation. The proposed controller is simple in design and implementation without the use of compensating ramp circuit. The steady state and transient responses are presented. The result shows good performances.

References


**BIOGRAPHY**

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