An Accurate Average Inductor Current Limit Method for Peak Current Mode Buck DC-DC Converters

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Abstract An accurate programmable average inductor current limit method for buck DC-DC converters with peak current mode (PCM) control is presented. A Gm-C filter is used to sense the voltage drop across a current sensing resistor in series with the inductor. Then, the voltage drop is converted into a current signal by a voltage-to-current (V2I) converter. The converted current signal is superposed on the output of the error amplifier to adjust the peak inductor current. The buck converter has been designed with 0.18 μm BCD process. The current limit value is designed 1 A/2 A for the sensing resistor of 50 mΩ/25 mΩ, respectively. When the the equivalent load resistance steps from 10 Ω to 2.5 Ω/1.67 Ω, the simulation results show that the average inductor current increases from 500 mA to 0.9 A/1.8 A for the sensing resistor of 50 mΩ/25 mΩ, respectively.

key words: current limit, average inductor current feedback, Gm-C filter

Classification: Integrated circuits (Analog)

1. Introduction

The buck DC-DC converters with PCM control is widely used in many areas, such as battery chargers, cellphones, electric vehicles, microprocessor units, and many other fields. The low output voltage, high output current converters are preferred nowadays, which makes the current limit function an important part in DC-DC converters. Then the current limit circuits can prevent the converters and subsequent load circuits from damage under overcurrent and output short circuit situations. The current limit function also plays an important part in the field of battery charging, because most of the batteries require battery chargers that not only output constant voltage but also output constant current. So far, many current limit methods for power converters have been proposed [1]-[6]. An adaptive reference is generated to adjust the peak and valley values of the inductor current, and the inductor current could be well controlled cycle by cycle [7]-[12]. Due to the slope compensation, the maximum inductor current is decreased with the increasing of the duty ratio for general PCM control [13]-[19]. The adjustable current limit method is proposed to increase the maximum value of the output of the error amplifier (EA) to compensate the affection of duty cycle variation [20, 21]. In this way, the peak inductor current is accurately adjusted. However, the maximum average inductor current which is equal to the load current is still varied with the duty cycle. The switching frequency fold-back technique is adopted to limit the peak inductor current [22]-[29] once an overcurrent or output short circuit event occurs. However, the inductor current could not be limited cycle-by-cycle and the fast response could not be guaranteed. A current-on-capacitor based clamped reference with a high-speed comparator is designed for smoothing the in-rush current for boost DC-DC converter [30, 31], in this way, the inrush current could be well controlled.

In this paper, an accurate average inductor current limit method is proposed. A Gm-C filter and a V2I converter are used to sense the average inductor current, and the sensed average inductor current is superposed on the output of the error amplifier to adjust the peak inductor current. This paper is organized as follows, Section 2 presents the principle of average inductor current limit, Section 3 shows the simulation results, and the conclusion is given in Sect. 4.

2. Average inductor current limit method

In typical PCM control, the pulse width modulation (PWM) comparator determines the duration of the on-time of the main power transistor. In this paper, an average inductor current limit method is proposed to accurately control the maximum load current. The average inductor current is sensed, and then superposed on the output of the error amplifier to adjust the on-time of the main power transistor. As shown in Fig. 1, the voltage drop across the current sensing resistor (\(R_S\)) is filtered and amplified by the Gm-C filter which constituted by the operational transconductance amplifier (OTA) Gm and the output capacitor \(C_C\). Then the amplified voltage drop is converted into the current signal \(I_{SEN\_AVG}\) by the V2I converter. The signals \(V_{SW}\) and \(V_{SEN}\) are the two input voltages of PWM comparator and their...
relationship could be expressed as

\[ V_{SW} = V_{IN} - R_{ON} I_L \]  

\[ V_{SEN} = V_{IN} - R_{SEN} \left[ \frac{V_C - V_{GS}}{R_3} - (I_{SLOPE} + I_{SEN\_AVG}) \right] \]

where \( V_{IN} \) is the supply voltage, \( I_L \) is the inductor current, \( R_{ON} \) is the on-resistance of the main power transistor (\( M_{HS} \)), \( R_{SEN} \) is the on-resistance of the sense-FET \( M_{SEN} \), \( V_C \) is the output of EA, \( V_{GS} \) is the gate-source voltage of \( M_1 \), \( I_{SLOPE} \) is the slope compensation current, and \( I_{SEN\_AVG} \) is the sensed average inductor current. The timing diagram of the PCM control is shown on the left of Fig. 1. When the rising edge of clock arrives, the main power transistor is turned on. Then, the inductor current is increased and the signal \( V_{SW} \) is decreased. When the signal \( V_{SW} \) and \( V_{SEN} \) intersect, the output of the PWM comparator flips from low-level to high-level to turn off the switch \( M_{HS} \). At the moment of turning off the main switch, the following equation is derived

\[ I_L = \frac{R_{SEN}}{R_{ON}} \left[ \frac{V_C - V_{GS}}{R_3} - (I_{SLOPE} + I_{SEN\_AVG}) \right] \]

According to Eq. (3), the maximum value of the inductor current \( I_L \) could be adjusted with the help of the average inductor current limit method. At steady state, the average inductor current is equal to the load current, so the load current can also be regarded as feedback to the PWM control.

If overcurrent or output short circuit event is not happened, \( I_{SEN\_AVG} \) is designed as insignificant and no current is injected to the resistor \( R_3 \), and the average inductor current limit circuit has no affection on the conventional PCM control. Once the average inductor current exceeds the predefined value, a large current injects to the resistor \( R_3 \), and the intersection point of PWM comparator rises then \( M_{HS} \) is turned off in advance. In addition, \( V_C \) will increase to the maximum clamp value when overcurrent occurs and PCM control is not work at this moment. Then, the sensed average inductor current \( I_{SEN\_AVG} \) control PWM comparator to determine the peak value of the inductor current \( I_L \). As a result, the maximum inductor current is limited to the predefined value according to Eq. (3).

2.1 Gm-C filter

In this paper, the average inductor current is sensed by adopt-
constitute the Gm-C filter and its gain is expressed as a constant voltage drop across resistor \( R \) shown in Fig. 2, the OTA Gm and the output capacitor \( C_C \) proportional to the voltage level of a constant current control to determine how long the switch \( M_{HS} \) turns on. As shown in Fig. 2, the OTA Gm and the output capacitor \( C_C \) constitute the Gm-C filter and its gain is expressed as

\[
A_V = g_m R_{out,eq}
\]

(4)

\[
R_{out,eq} = R_{OUT} \parallel \frac{1}{sC_C} \approx \frac{1}{sC_C}
\]

(5)

\[
A_V = g_m R_{out,eq} = \frac{g_m}{sC_C} = \frac{g_m}{2\pi f_{SW} C_C}
\]

(6)

where \( R_{OUT} \) is the output resistance of the OTA, \( R_{out,eq} \) is the equivalent output resistance of Gm-C filter, \( g_m \) is the transconductance of the OTA, and \( f_{SW} \) is the switching frequency. The Gm-C filter could filter the voltage drop across the sensing resistor and convert it into averaged current. In this way, the average inductor current information is obtained. However, the output of Gm-C filter can’t be directly connected to the source of transistor \( M_1 \), otherwise the output of Gm-C filter will be clamped by the voltage drop across the resistor \( R_3 \). Therefore, an extra converter in series with Gm-C filter which could convert the amplified voltage into current signal is required.

2.2 The principle of the average inductor current limit

As shown in Fig. 1, a current generator constituted with an amplifier AMP, transistor \( M_2 \) and resistor \( R_6 \) generates a constant current \( I_{DR} \) which is controlled by \( V_{CTRL} \). The constant current flows through the resistor \( R_3 \), and generates a constant voltage drop across resistor \( R_5 \), which is proportional to the voltage level of \( V_{CTRL} \). \( V_P \) and \( V_N \) are the non-inverting and inverting input of the OTA Gm, respectively. The relationship between \( V_P \) and \( V_N \) can be expressed as

\[
V_P - V_N = R_S I_{AVG} - R_5 I_{DR}
\]

(7)

where \( I_{AVG} \) is the average inductor current. The sensed average inductor current \( I_{SEN, AVG} \) can be expressed as

\[
I_{SEN, AVG} = A_C A_V (V_P - V_N)
\]

(8)

\[
I_{SEN, AVG} = \frac{A_C g_m}{2\pi f_{SW} C_C} (R_3 I_{AVG} - R_5 I_{DR})
\]

(9)

where \( A_C \) is the conversion ratio of the V2I converter. When the average inductor current is less than the predefined current limit value, the value of \( R_S I_{AVG} \) is smaller than \( R_5 I_{DR} \), which means that the \( V_P \) is smaller than \( V_N \). The value of \( I_{AVG} \) is almost zero and the inductor current sensing circuit has no influence on the conventional feedback loop. When the average inductor current is greater than the predefined current limit value, the value of \( R_S I_{AVG} \) is larger than \( R_5 I_{DR} \). According to Eq. (9), the value of \( I_{AVG} \) is very large and the conventional feedback loop is affected by the sensed average inductor signal. Under the condition of \( V_P = V_N \), the value of the average inductor current limit \( I_L_{AVG} \) is derived as

\[
I_{L, AVG} R_S = I_{DR} R_5
\]

(10)

\[
I_{DR} = \frac{V_{CTRL}}{R_6}
\]

(11)

Set \( R_4 = R_5 = R_6 = k R \), and \( I_{L, AVG} \) is derived as

\[
I_{L, AVG} = \frac{V_{CTRL}}{k R_S}
\]

(12)

where \( k \) is a positive number. According to Eq. (12), the value of \( I_{L, AVG} \) is actually the average inductor current limit level, which is determined by the values of \( V_{CTRL}, k \), and \( R_S \). Although the average current limit could be programmed by the values of \( V_{CTRL}, k \), and \( R_S \), their values must be carefully selected according to requirements. For example, the value of the sensing resistor \( R_S \) must be small enough for not degrading the power efficiency too much. Moreover, the current \( I_{DR} \) should also be small.

3. Simulation results

The proposed accurate average current limit buck DC-DC converter has been designed with 0.18 \( \mu \)m BCD process. The off-chip inductor is 4.7 \( \mu \)H and the output capacitor is 47 \( \mu \)F. The input voltage is 12 V, the output voltage is 5 V, the
maximum load current is 3 A, and the switching frequency is 700 kHz. In this paper, the control voltage $V_{CTRL}$ is equal to 1 V, and the parameter $k$ is equal to 20.

Fig. 3 shows the simulation results under the condition of $V_{IN}=12$ V, $V_{OUT}=5$ V, and $R_S=50$ mΩ. According to Eq. (12), the maximum value of average inductor current limit is set about 1 A. As shown in Fig. 3(a), the current limit function is triggered when the equivalent load resistance steps from 10 Ω to 2.5 Ω at 2 ms. The average inductor current $I_{L\_AVG}$ steps from 500 mA to 0.9 A, and output voltage $V_{OUT}$ decreases from 5 V to 2.27 V. Fig. 3(b) shows the details of the transient of the current limit. The sensed average inductor current signal $I_{SEN\_AVG}$ is delayed by about 60 μs after the overcurrent event occurs, and the average inductor current $I_{L\_AVG}$ continues to increase during this period. Then, as $I_{SEN\_AVG}$ increases from 0 to 148 μA, the average inductor current $I_{L\_AVG}$ gradually decreases to 1.8 A. It is not equal to the results of Eq. (12) because of $I_{SLOPE}$.

4. Conclusion

An accurate average inductor current limit method for peak current mode buck DC-DC converters has been proposed. The average inductor current is sensed by a Gm-C filter and feedback to adjust the peak inductor current. In this way, the maximum load current could be accurately controlled. The principle is analyzed, and the simulation results verify the validity of the proposed method. The proposed method is suitable for PCM controlled DC-DC converters.

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