# Selection of Three Locations of Current Sense Resistor in Buck Converter

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## Abstract

In current mode converters, current sense resistor can be placed in three locations: input loop, output loop and freewheeling loop. The pros and cons are discussed in details. The principles and features of peak current mode and valley current mode are also presented. The cautions and tips for using $R_{DS(ON)}$ of high-side MOSFET, low-side MOSFET and DCR of the inductor as the current sense resistor are also mentioned at the end.

## Introduction

Current mode converter is widely used, even though it requires a current sense resistor with a little bit higher cost and lower efficiency compared to voltage mode converter. Current mode has many advantages: (1) Inherent cycle-by-cycle peak current limit; (2) True soft-start of the inductor current; (3) Precise current detecting loop; (4) Output voltage independent of input voltage; (5) Simple feedback loop compensation for ceramic output capacitor; (6) Easy to be used in parallel/multi-phase for large current; (7) Allowance of high input ripple to reduce the value of input capacitor.

In current mode buck converter, the current sense resistor can be placed in three locations: (1) Input loop, i.e., in series with the high-side MOSFET; (2) Output loop, i.e., in series with the inductor; (3) Freewheeling loop, i.e., in series with catch diode or low-side synchronous MOSFET. For higher efficiency, $R_{DS(ON)}$ of high-side MOSFET, DCR of the inductor or $R_{DS(ON)}$ of low-side synchronous MOSFET can be used as the current sense element. This will be discussed in details below and the advantages and disadvantages of three structures will be listed to show design engineers how to select them based on their specific applications.

## 1. Current Sense Resistor in Input Loop

As shown in Figure 1, the current sense resistor is put in the input loop of the Buck converter. As for current mode control, there are 2 feedback loops: the voltage loop as the external loop and the current loop as internal loop. The voltage loop contains a voltage error amplifier, voltage feedback divider and feedback compensation network. The non-inverting terminal of the voltage error amplifier is connected to a reference voltage VREF and the inverse terminal VFB to voltage feedback divider. The feedback compensation network is connected between VFB and the output terminal VC of the voltage error amplifier. If the voltage error amplifier is a trans-conductance amplifier, the feedback network should be connected between the output terminal of the voltage error amplifier VITH and the ground. So far, the trans-conductance amplifier is more popular in high frequency DC-DC converter. The discussion below is based on this type of amplifier.

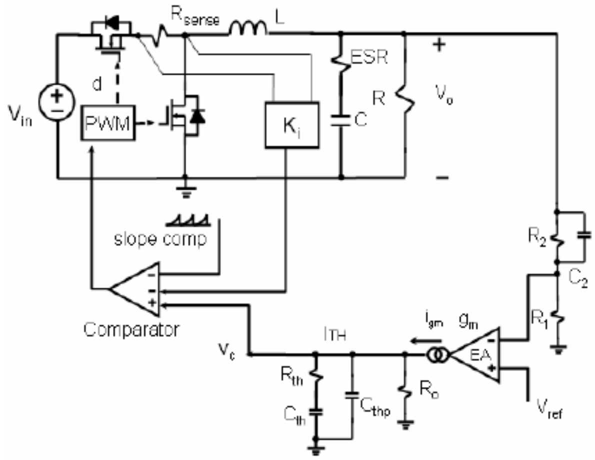


**Figure 1: Current sense resistor in input loop**

VFB is compared with VREF. The small error between VFB and VREF will be amplified by the voltage error amplifier. The output of the voltage error amplifier VITH is connected to the non-inverting terminal of the current comparator. The current sense signal VSENSE is connected to the inverting terminal of the current comparator. Therefore, the current signal of internal current loop is set by the voltage signal of external voltage loop.

The operation principle of peak current mode is: at the leading edge of the synchronous clock, the high-side MOSFET is switched on, the inductor is magnetized and its currents ramp up linearly, so does the current sense voltage. Because the output of voltage error amplifier is higher than VSENSE, the output of current comparator is at a high level. When VSENSE rises above the output of voltage error amplifier, the output of the current comparator flip-flops to low level, and then the high-side MOSFET is switched off. After that, the inductor is de-magnetized, and its current declines linearly until the next synchronous clock signal comes.

In each cycle, the peak current is detected during the ramp-up period. The current waveform through the high-side MOSFET is a ramping up trapezoidal waveform while the current waveform through the low-side MOSFET or catch diode is a ramping down trapezoidal waveform. The current waveform through the inductor combines both parts above so it is a saw-tooth waveform. Intuitively, if the current sense resistor is placed in the input loop, the converter should operate in peak current mode.

It is noted that in Buck converter, the input voltage is higher than the output voltage. If the current sense resistor is placed in the input loop, the common mode input voltage of the current amplifier is equal to the input voltage of the converter. When the input is 12V or above, the cost of the current amplifier with high common mode input voltage will be high.

Note that non-overlap dead time is a must to avoid the shoot through between the low-side and high-side MOSFET. If the $R_{DS(ON)}$ of the high side MOSFET is adopted as the current sense resistor, the external current sense resistor can be removed. It will improve efficiency. Because of MOSFET $R_{DS(ON)}$ tolerance and temperature coefficient, the sensing accuracy is not very good. Furthermore, peak current mode is sensitive to leading edge current spike and needs leading edge blanking time to avoid false trigger of the current comparator. Slope compensation with duty cycle above 0.5 is needed to prevent sub-harmonic oscillation.

## 2. Current Sense Resistor in Freewheeling Loop

It is discussed above that the current waveform through catch diode or the low-side MOSFET is a ramping down trapezoidal waveform. This kind of current mode is also known as the valley current mode. Just like peak current mode, it also contains external voltage loop and internal current loop.

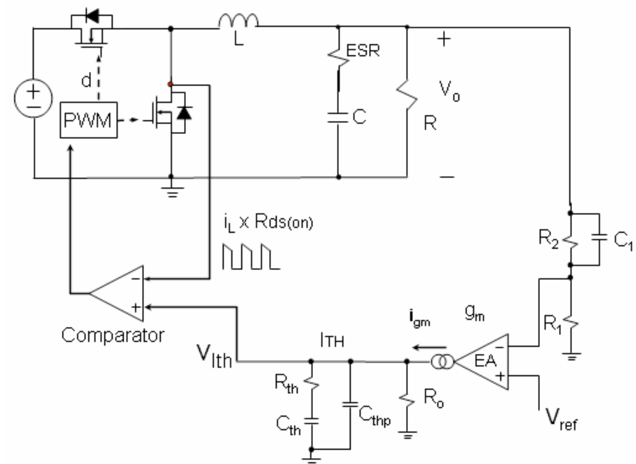


**Figure 2: Current sense resistor in freewheeling loop**

When the high-side MOSFET is switched on, the inductor is magnetized and its current ramp up linearly. The on duration of the high-side MOSFET is a constant time set by PWM controller. When the high-side MOSFET turns off, the low-side MOSFET turns on after small dead time and the inductor is de-magnetized. Its current ramps down linearly and so does the VSENSE voltage. While the output of the voltage error amplifier is lower than the voltage of the current sense resistor, the output of the current comparator is at low level.

The current comparator flip-flops to a high level when the output of the voltage error amplifier is higher than the voltage of the current sense resistor. As a result, the low-side MOSFET is turned off, and the high-side switch is turned on after short dead time. The next period will restart.

Valley current mode has the advantages of wide range input voltage, low duty cycle, easy current detection and fast response. Similarly, slope compensation is needed when the duty is lower than 50%. The response of the valley current mode to load transient is executed during current cycle while that of peak current mode is done in the next cycle.

When the input and output voltage change, if the high-side MOSFET turns on for a constant time, the system will work in PFM. It is not easy to design the inductor due to variable frequency. Usually a feed-forward circuit is needed to make the on time of the high-side MOSFET inversely proportional to the input voltage, which can keep the converter work approximately at constant frequency.

If the low-side MOSFET $R_{DS(ON)}$ is used as the current sense resistor, it can also improve the efficiency a little. Because of the MOSFET $R_{DS(ON)}$ tolerance and temperature coefficient, the sensing accuracy is not so good.

This mode is adopted widely in high input voltage, low output voltage and high current output application.

## 3- Current Sense Resistor in Output Loop

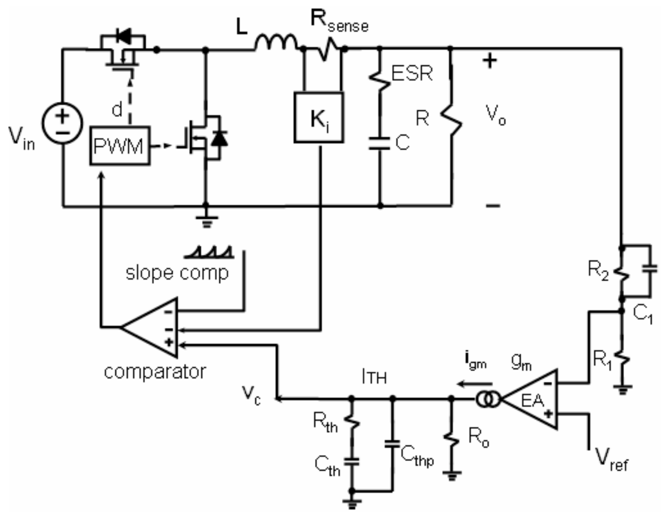


**Figure 3: Current sense resistor in output loop**

The current through the inductor in the output loop contains both ramping up and down current. If the current sense resistor is placed in the output loop, the converter can work in valley current mode or peak current mode.

Because the output voltage is usually low, the common mode input voltage of the current amplifier is also low. Its cost is relatively low and the accuracy of sensing current is high and the noise is low. Another advantage is that DCR of the inductor can also be used as the current sense resistor. Care must be taken that DCR must meet the output current requirement for the range of the input voltage and output load current. At the same time the saturation current of the inductor should also meet the requirement of the system. As a result, the inductor must be customized for the applications.

Another thing to consider is that the current amplifier must have enough high input impedance and small offset current between two input pins for high current sense accuracy. The filter for current sense is shown in Figure 4.

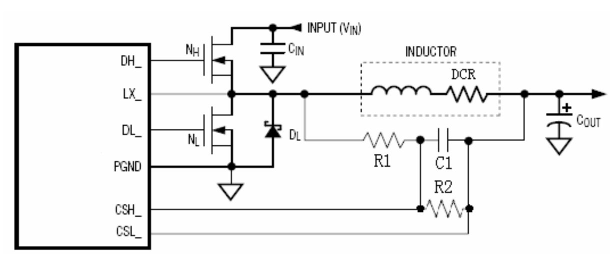


**Figure 4: DCR as current sense resistor filter**

Usually the value of DCR is higher than the required value of the current sense resistor so a resistor divider is needed to get suitable current sense voltage.

$$V_{C1} = \frac{R2}{R1 + R2} \bullet V_{DCR}$$

The condition in below equation is used to meet the filter time request

$$\frac{R1 \bullet R2}{R1 + R2} \bullet C1 = \frac{L}{DCR}$$

Actually the current sense accuracy is affected by the variations of DCR based on the temperature. In some controllers, the reference of the current amplifier can be programmed to meet more applications for general inductor even though its DCR cannot meet the requirements above.

## Conclusion

1) Current sense resistor in the input loop is adopted for the peak current mode. $R_{DS(ON)}$ of the high-side MOSFET can be used as the current sense resistor, which can improve the efficiency while the sensing accuracy may be worse.

2) Current sense resistor in the freewheeling loop is adopted for a fast response valley current mode. $R_{DS(ON)}$ of the low-side MSOFET can be used as the current sense resistor, which can improve the efficiency while the sensing accuracy may be worse.

3) Current sense resistor in the output loop is adopted for peak current mode or valley current mode. DCR of the inductor can be used as the current sense resistor, which can improve the efficiency while the design becomes complicated and the accuracy of sensing is also worse.