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Design Considerations For DCR Current Sensing In Boost Converters

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Higher efficiency and smaller solution size typically are the top priorities for designers of dc-dc converters. Using a current-sense resistor to detect overload conditions generates additional conduction loss and requires a large footprint for heat dissipation. Additionally, a current-sense resistor has a relatively high cost.

Inductor direct-current resistance (DCR) current sensing can be used to eliminate the current-sense resistor. This potentially can reduce the solution size while improving efficiency. Size and efficiency improvements could be significant in high-current, low-voltage applications. This article explains how to design a DCR current-sensing circuit and discusses practical design considerations to improve current-sensing accuracy and achieve higher efficiency in boost converter designs.

Designing A DCR Current-Sensing Circuit

Fig. 1 shows simplified schematics for boost converters with high-side current sensing. Each inductor is represented as a series combination of an ideal inductor and a lumped DCR.

A boost converter with resistor current sensing (Fig. 1a) has an additional current-sense resistor in the power path. The current-sense resistor (R_{SENSE}) generates additional power loss, which leads to lower efficiency. In contrast, a DCR-current-sensing boost converter (Fig. 1b) utilizes the inductor's inherent DCR to measure the inductor current, which eliminates the discrete current-sense resistor and the resistor power losses.

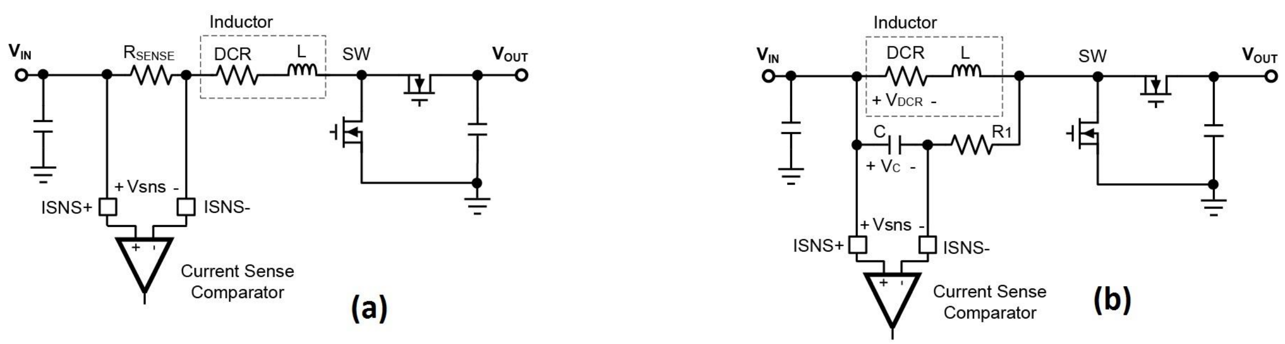


Fig. 1. Boost converters with high-side current sensing can use a low-value resistor as the current-sense element (a) or the DCR of the inductor (b).

The voltage across an inductor DCR is measured using a series RC network in parallel with the inductor. In a boost converter, the capacitor of the RC network is tied to the input side of the inductor while the resistor is tied to the switch-node side of the inductor. The s-domain equivalent voltage across the capacitor of the RC network can be calculated as

$$V_C = I_L \times DCR \times \left(s\frac{L}{DCR} + 1 \right) \times \frac{1}{sR_1C + 1} \quad . \qquad (1)$$

When the R_1C time constant matches the L/DCR time constant of the inductor

$$R_1 \times C = L / DCR \qquad (2)$$

then the capacitor voltage equals the voltage across the inductor's DCR,

$$V_C = I_L \times DCR = V_{DCR} . \qquad (3)$$

The equivalent current-sense resistance is thus equal to DCR,

$$R_{sns} = DCR \quad (4)$$

In applications where DCR is higher than the desired current-sense resistance, a resistor divider can be used to scale the sensed voltage signal. Fig. 2 shows DCR current sensing with a resistor divider, and in this circuit the s-domain equivalent capacitor voltage becomes

$$V_C = I_L \times DCR \times \frac{R_2}{R_1 + R_2} \times \left(s\frac{L}{DCR} + 1 \right) \times \frac{1}{s\frac{R_1 R_2}{R_1 + R_2} C + 1} \quad (5)$$

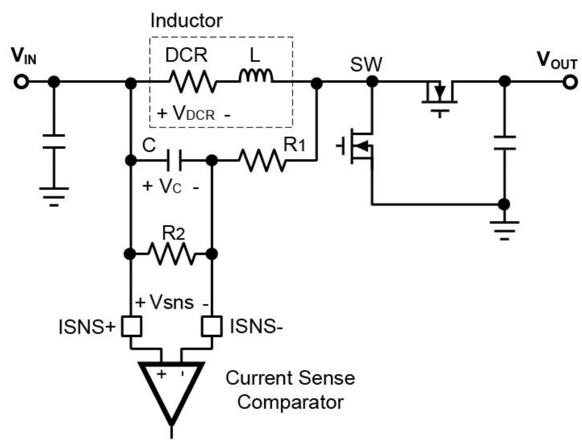


Fig. 2. DCR current sensing with a resistor divider.

As with the case where no resistor divider was present, by matching the equivalent RC time constant with the inductor L/DCR time constant in this case yields

$$\frac{R_1 R_2}{R_1 + R_2} \times C = L / DCR \quad (6)$$

where the capacitor voltage is proportional to the inductor current, inductor DCR, and resistor divider ratio,

$$V_C = I_L \times DCR \times \frac{R_2}{R_1 + R_2} \quad (7)$$

and the equivalent current-sense resistance is then equal to

$$R_{sns} = \frac{R_2}{R_1 + R_2} \times DCR . \quad (8)$$

Theoretically, by designing the RC network and resistor divider such that the RC time constant matches the inductor L/DCR time constant, the inductor current can be measured accurately. However, several practical factors should be taken into account to ensure current-sensing accuracy.

Improving Current-Sensing Accuracy

Parametric variations of the inductance L, DCR, and the RC time constant cause mismatching and affect current-sensing accuracy. Besides the time constant-mismatching, the current-sense comparator also has an impact on current-sensing accuracy.

A practical high-side current-sense comparator of a boost converter usually has bias currents (I_{BN} and I_{BP} in Fig. 3) flowing into the inputs. The bias current of the current-sense comparator's inverting input flows through resistor R_1, generating an offset voltage, which results in an error between V_C and V_{DCR} (Fig. 4), even if the RC time constant and inductor L/DCR time constant match. This error could be significant compared to a small current-sense signal, especially if the amplifier bias current and R_1 are relatively large.

For example, TI's TPS43061 synchronous boost controller has a typical sense-comparator bias current of 70 µA. For a 1-kΩ resistor, R_1, the sense error is

$$V_{error} = R_1 \times I_{BN} = 70mV \quad . \qquad (9)$$

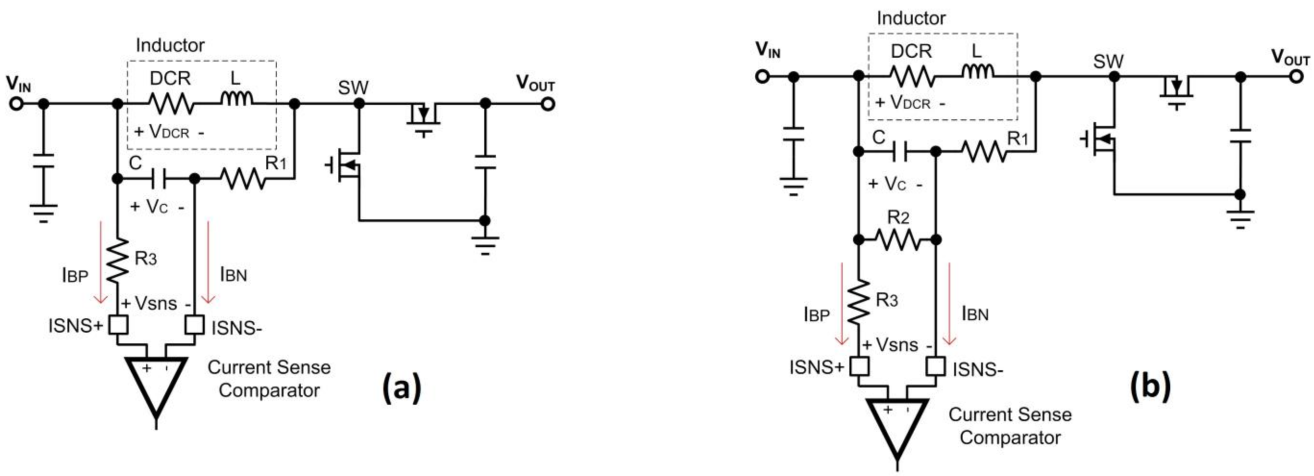


Fig. 3. DCR current sensing with offset voltage cancellation without a resistor divider (a) or with a resistor divider (b).

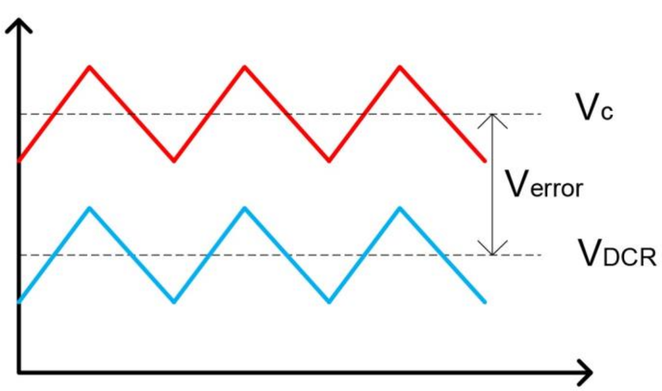


Fig. 4. Current-sense error caused by the bias current.

This error is of the same order as the current-limit threshold (73 mV), and is therefore unacceptable. This error can be reduced by choosing a smaller R1. However, a small R1 consumes more power and reduces efficiency, especially under light-load conditions.

The bias currents to the two inputs of the current-sense comparator are typically almost equal. A resistor (R_3 in Fig. 3) can be placed between the RC network and non-inverting input of the current-sense comparator to correct the input bias current error. Assuming identical bias currents, R_3 should be chosen to be equal to R_1 for DCR current sensing without a resistor divider (Fig. 3a).

For DCR current sensing with a resistor divider (Fig. 3b), R_3 should be designed to be equal to the equivalent resistance of R_1 and R_2 connected in parallel. By cancelling the offset voltage caused by the bias current, current-sensing accuracy is improved. With balanced resistance at the comparator inputs, relatively high-value resistors can be used to minimize power loss and improve efficiency.

Power Loss And Efficiency Analysis

Both resistor current sensing and DCR current sensing generate power loss, however their power loss mechanisms are different. In a resistor sensing scheme, the inductor current flows through a current sense resistor generating additional power loss in the current-sense resistor. This power loss is related to the inductor current and current-sense resistance, and is calculated by

$$P_{R_{SENSE}} = I_{L\_rms}{}^2 \times R_{SENSE} \quad (10)$$

Given the inductor current (I_{L_rms}), the power loss dissipated in the current-sense resistor can be reduced by lowering its resistance. However, a current sense-resistance that is too low results in low signal-to-noise ratio (SNR) and reduced noise immunity. Furthermore, the current-sense resistance must be chosen to set the desired current-limit threshold.

In a DCR sensing configuration, the inductor voltage is applied to the RC network, producing power loss in the resistor (R_1). The voltage across the resistor is approximately equal to the inductor voltage since the voltage across the capacitor is small and usually negligible. Fig. 5 (parts a and b) show ideal waveforms for the voltage across R_1 for the converter operating in continuous-conduction mode (CCM) and discontinuous-conduction mode (DCM), respectively.

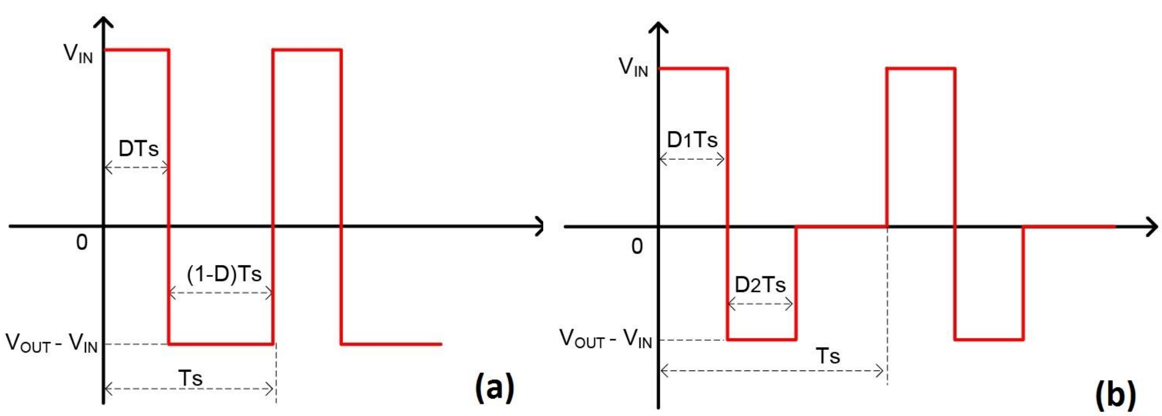


Fig. 5 The voltage across R_1 with the boost converter operating in continuous conduction mode (a) and discontinuous conduction mode (b).

In CCM, the power loss dissipated in R_1 is expressed as

$$P_{R_1} = \frac{V_{IN}{}^2}{R_1} \times D + \frac{(V_{OUT} - V_{IN})^2}{R_1} \times (1 - D) \quad (11)$$

where D is the duty cycle of the boost converter.

This power loss is determined by the inductor voltage (input voltage, output voltage and duty cycle) and the resistance of R_1. Lower voltage generates reduced current-sensing power loss in the DCR sensing circuit. This power loss also can be reduced by increasing R_1. In CCM, this power loss is independent of inductor current. In DCM, the load current has an effect on duty cycle, and therefore on power loss. The smaller the load current in DCM, the lower the power loss.

Fig. 6 shows an analytical comparison of the current-sensing power loss using resistor sensing and DCR sensing in CCM. DCR sensing usually reduces current-sensing power loss and improves efficiency under heavy load conditions, while resistor sensing has higher efficiency at very light load conditions. DCR sensing also provides substantial benefits in low-voltage high-current applications.

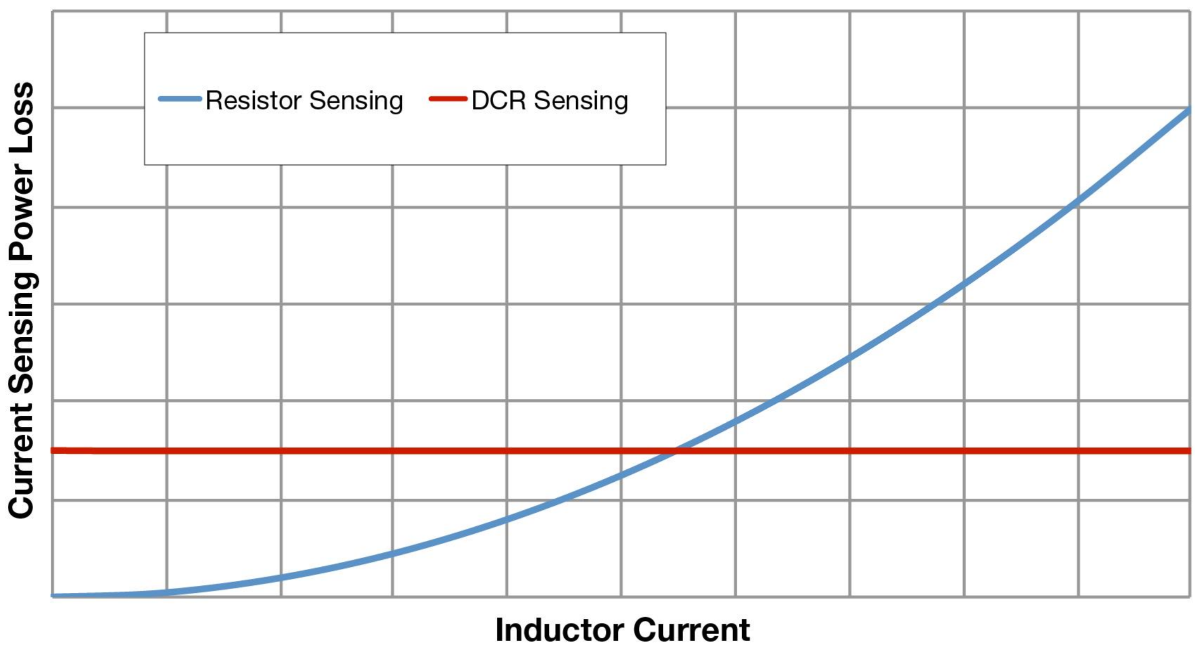


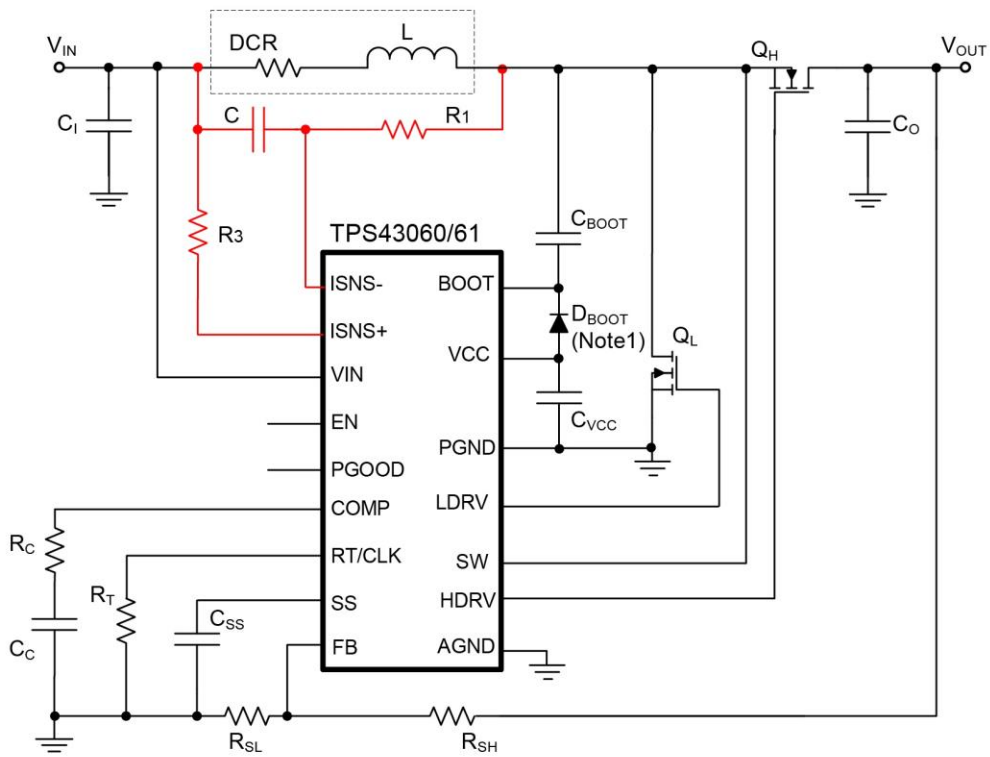
Fig. 6. A comparison of current-sensing power loss for resistor versus inductor DCR sensing.

In Fig. 7, one boost converter using DCR sensing is built and tested to compare with another using resistor sensing. Key parameters of the two boost converters are shown in the table. Both converters use TI's TPS43061 synchronous boost controller and a 3.3-µH inductor with 9.42-mΩ DCR.

Table 1. A comparison of key parameters for boost converters using resistor versus DCR sensing.

	R_{SENSE} (mΩ)	R_1 (kΩ)	C (µF)	R_3 (kΩ)	DCR (mΩ)	L (µH)
Resistor sensing	10	N/A	N/A	N/A	9.42	3.3
DCR sensing	N/A	1.18	0.33	1.18		

Fig. 7 shows the boost converter with DCR current sensing wherein a 1.18-kΩ resistor is used for both R_1 and R_3, and a 0.33-µF capacitor is used for the capacitor in the RC network. In the version of this boost converter with resistor sensing, a 10-mΩ discrete resistor is inserted into the circuit (just before the inductor) as the sense element.



Note 1: D_{BOOT} is required for TPS43060, but optional for TPS43061.

Fig. 7. Boost converter using a synchronous boost controller with DCR current sensing.

These two boost converters are evaluated while boosting the 6-V input voltage to 15-V output with 2-A rated output current. Fig. 8 shows the measured efficiency. DCR sensing improves efficiency under high output-current conditions, but does not outperform resistor sensing at low current levels.

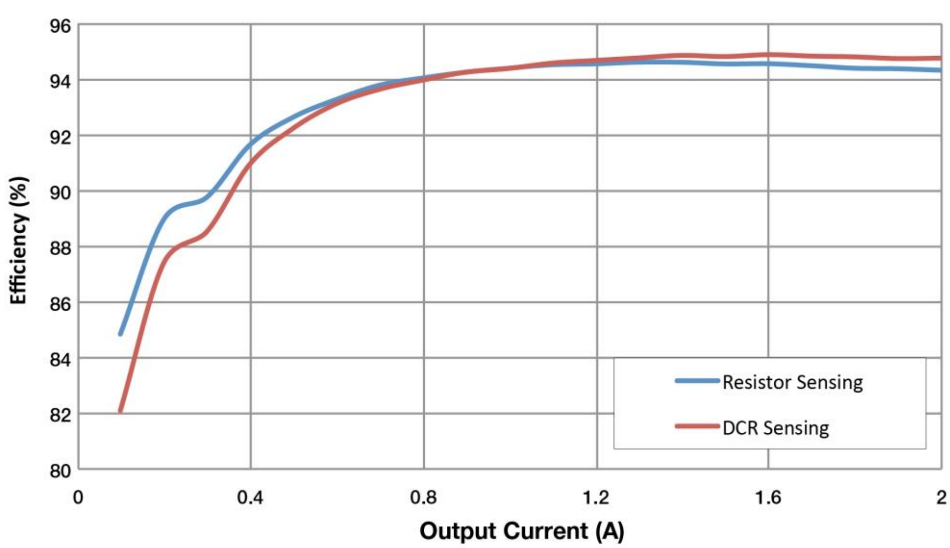


Fig. 8. Efficiency comparison between DCR sensing and resistor sensing.

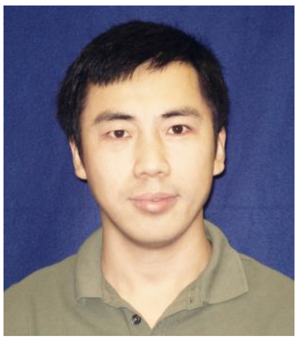
Conclusion

Inductor DCR current sensing eliminates the relatively high cost and large footprint of discrete current-sense resistors. In addition to matching the RC time constant with the L/DCR time constant of the inductor, the offset voltage introduced by input bias currents of a practical current-sense comparator should be addressed to ensure accurate current sensing. DCR sensing can provide substantial efficiency improvement in low-voltage high-current applications.

Reference

"Low Quiescent Current Synchronous Boost DC/DC Controller with Wide VIN Range," TPS43060/61 Datasheet (SLVSBP4), Texas Instruments, September 2013.

About The Author



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For further reading on the design of current sensing circuitry, see the How2Power Design Guide, select the Advanced Search option, go to Search by Design Guide Category and select "Test and Measurement" in the Design Area category.