# Application Bulletin AB-20

## Optimum Current Sensing Techniques in CPU Converters

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## Summary

Four different methods of sensing current in a buck converter are described, along with the Fairchild parts that incorporate them, and their accuracies, efficiencies and costs are contrasted. Two of the methods give the best efficiency, but have relatively low accuracy; the other two have good accuracy, but differ in efficiency and performance. Overall best performance is obtained using Fairchild's new third-generation controllers, the RC5052/RC5057.

### Method I: Output Current Sense Resistor

The traditional method of sensing current in a buck converter, as embodied in the industry standard Fairchild part RC5051, is an output current sense resistor, which is a low-value resistor in series with the buck's inductor, across which the voltage is sensed.

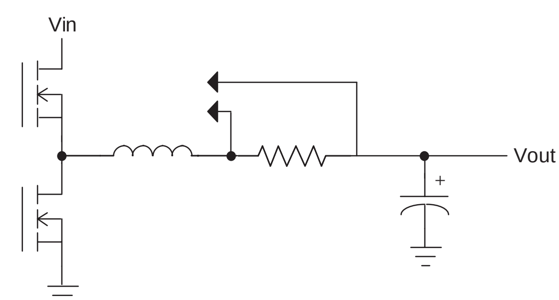


**Figure 1. Using an Output Current Sense Resistor**

The accuracy of this method depends on the type of resistor used. In the most common implementation, a discrete metallic resistor with zero temperature coefficient is used, either manganin or constantan. The accuracy is just determined by the initial tolerance of the part, typically ±10%; a discrete wirewound can be 5% or better.

The other implementation is to use a trace in the PCB as a resistor. Here, the initial tolerance is much wider, and there is also a temperature coefficient. As an example, consider using a 5.2mΩ trace resistor, as might be suitable for a Deschutes processor converter. Using 1oz. copper, and a width of 300 mils for power dissipation, a length of 3000 mils is required to get the correct resistance. The thickness of the copper is nominally 1.3 mils, and the tolerance is typically ±.1 mil. Thus error due to sheet resistivity is 0.1 mil/1.3 mil = ±8%; the tolerance on the length and width might be ±3/4 mil, and thus is negligible. Finally, the trace has copper's temperature coefficient, and so allowing for a 50°C ΔT, there is a 12% increase in resistance. Total error can thus be as high as 20%.

The power lost in this method is directly determined by the output current and the sensing level of the IC. As an example, the RC5051 hits current limit when the input across the sense resistor reaches a value of typically 120mV. Thus, maximum normal current might be set to generate say 80mV. With the Deschutes current level of 16A as maximum normal current, this implies a power loss of 80mV * 16A = 1.28W. Since Deschutes runs at 2.0V * 16A = 32W, this current sense has a loss in efficiency of 1.28W/(32W + 1.28W) = 3.8%.

The cost of a discrete resistor is about US $0.07; the cost of a PCB trace is 0.

### Method II: MOSFET Sensing

Since the MOSFETs used in the buck converter act like resistors when they are on, another method of sensing current is to measure the drain-source voltage of either the high-side- or low-side-MOSFET during the time when it is on. The RC5052, RC5053, RC5054, RC5055 and RC5056 use sensing of the high-side-MOSFET to determine current.

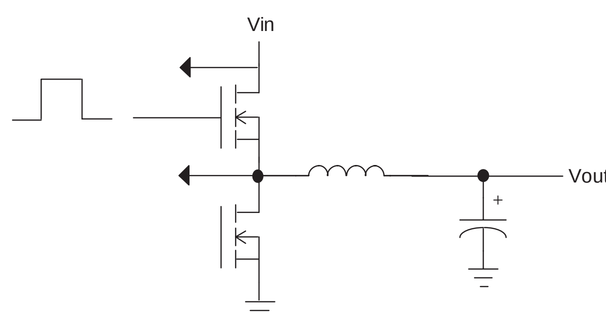


**Figure 2. Sensing the Current by Measuring the MOSFET's $V_{DS}$ Requires a Blanking Time**

Use of this sensing method is more complicated than the resistive method examined so far, because the voltage from drain to source alternates at the switching frequency, between being the small value of $I * R_{DS}$ to being approximately $V_{in}$. Clearly, there must be a way of ensuring that only the former value is measured, and that when the latter is present, not only is the value not measured, but the IC amplifier is not saturated either. To accomplish this, the IC "blanks" the input to its internal amplifier during the time that the gate drive signal is off. Actually, however, this is not enough, because even on carefully laid out designs, there will be some voltage ringing on the drain and source during the on-off and off-on transitions of the MOSFET, due to stray inductances and capacitances. Since this high frequency ringing will certainly be beyond the common-mode frequency rejection range of the amplifier, the blanking time is extended part way into the on-time of the MOSFET, and part way in to the other MOSFET being turned on. It is to be noted that higher input voltages and higher switching frequencies make this method increasingly difficult to implement on the IC, since both have the effect of reducing the MOSFET's on-time.

The accuracy of the MOSFET sensing method depends on the characteristics of the MOSFET, both its initial value of $R_{DS}$, and the temperature coefficient of this $R_{DS}$. A typical MOSFET datasheet will specify only the typical and maximum value of $R_{DS}$, not the minimum. However, it is a safe assumption that the minimum is very close to the typical: if it were any lower, the manufacturer would be touting this fact! Let's say, then, as a typical case, that the initial $R_{DS}$ of the MOSFET at 25°C is ±10%. Next we must consider the temperature coefficient of the resistance. Depending on the technology used, and the predominance or otherwise of the cell resistance over the package resistance, the temperature dependence of $R_{DS}$ of a MOSFET may be somewhere between $1.008^{\Delta T}$ and $1.004^{\Delta T}$, where ΔT is the change in temperature from 25°C. For low-$R_{DS}$ MOSFETs, the latter number will be approximately correct, and since this matches with the temperature coefficient of copper, we may say that a MOSFET that runs up to 100°C increases in $R_{DS}$ by approximately $1.004^{(100°C–25°C)} = 1.349$, that is, 35%. Taken together then, the uncertainty of the on-resistance of the MOSFET, and thus of the sensed current, may be approximately (1.10) * (1.35) = 1.49 or 49%.

Naturally this method has a great advantage, in that the MOSFET is already present in the circuit; therefore the power loss in this method may be said to be 0, and the additional cost is also 0.

## Method III: Inductor Sensing

Another method of sensing current is fundamentally similar to the first method using an output sense resistor: the winding resistance of the inductor itself is used as the sense resistor. This method is used in the Fairchild part RC5054.

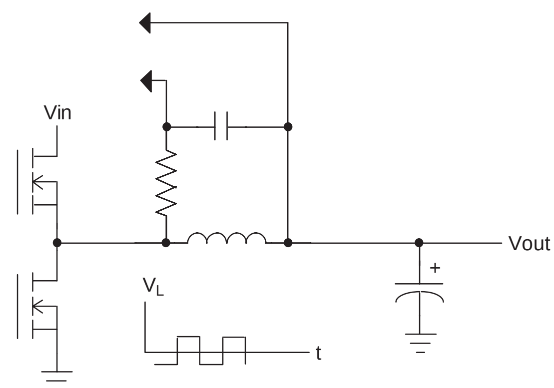


**Figure 3. Sensing the Current by Measuring the Voltage Across the Inductor Involves Filtering the Signal Because the Inductor has a Switching Waveform Applied**

This method is signficantly different than the others in one major respect, its bandwidth. Both the resistor sensing methods and the MOSFET sensing method sense current on a cycle-by-cycle basis. However, the inductor voltage has a large AC signal component riding on top of the desired I * R information, because the side of the inductor attached to the MOSFETs is being switched between $V_{in}$ and ground at the switching frequency. This AC signal must be filtered out to obtain the current signal.

We can easily estimate how much filtering is required using a single pole filter, such as the RC filter shown in Figure 3, or an internal rolloff in the IC's amplifier. Suppose that the input voltage is 5V and the output is 1.55V, so that the peak-to-peak voltage switching across the inductor is approximately 6.5V. If the desired signal level is 80mV, and we want a signal-to-noise ratio of 10:1 (to achieve ±10% accuracy) we need to suppress the AC signal by 6.5V * 10/ 80mV = 812. Supposing the switching frequency to be 300kHz, to achieve this filtering will require the pole to be at 300kHz/812 = 369Hz! And if the current needed to be sensed at lower than maximum current, the filtering would have to be even greater. Clearly, there is going to be a substantial tradeoff necessary here between accuracy and bandwidth; and if the bandwidth is too low, the signal will not be useful either for loop control nor for current limiting.

Having specified a SNR of 10:1, this is not yet the complete story on accuracy, because there is also initial tolerance of the winding resistance, as well as its temperature coefficient. Assuming the initial tolerance can be held to ±5%, the inductor has the same temperature coefficient as a PCB trace, and so allowing for a rise in temperature to 100°C, we again get a 35% increase in resistance. The total tolerance of this sensing method can then be as high as (1.10) * (1.05) * (1.35) = 1.56, or 56%.

Inductor sensing has the same zero cost and zero power loss as MOSFET sensing.

## Method IV: Input Current Sense Resistor

A final method that requires an additional IC pin is to move the current sense resistor to the input side of the converter. This method can be implemented using the new Fairchild parts RC5052 and RC5057.

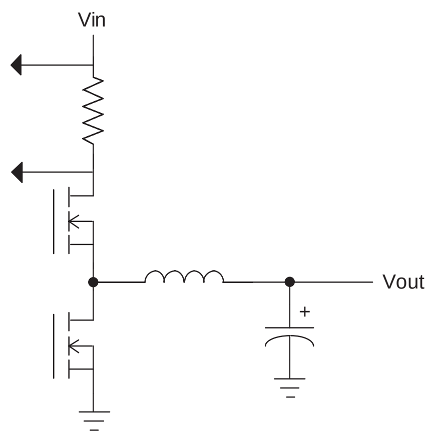


**Figure 4. Using an Input Current Sense Resistor (Conceptual)**

The accuracy of this method of current sense is clearly exactly the same as that for the output current sensor, with the same two options of using either a discrete resistor or a PCB trace.

The power lost in this method, though, may be substantially less than that in the output current sense method, because the input current is lower than the output current. Consider again the Deschutes processor: With an input voltage of 5V, the input current is approximately equal to the output power divided by the input voltage, $I_{in} \approx 32W/5V = 6.4A$ (ignoring efficiency). Using the same level of 80mV sensing for the IC, the power loss is only 6.4A * 80mV = 512mW; the loss in efficiency is only 0.512W / (32W + 0.512W) = 1.6%, a factor of 2 improvement; clearly, running from an input voltage of 12V increases the efficiency of this method even further.

Again, the cost of a discrete resistor is US $0.07; the PCB trace is 0. Actual implementation of the input current sense resistor technique is shown in Figure 5.

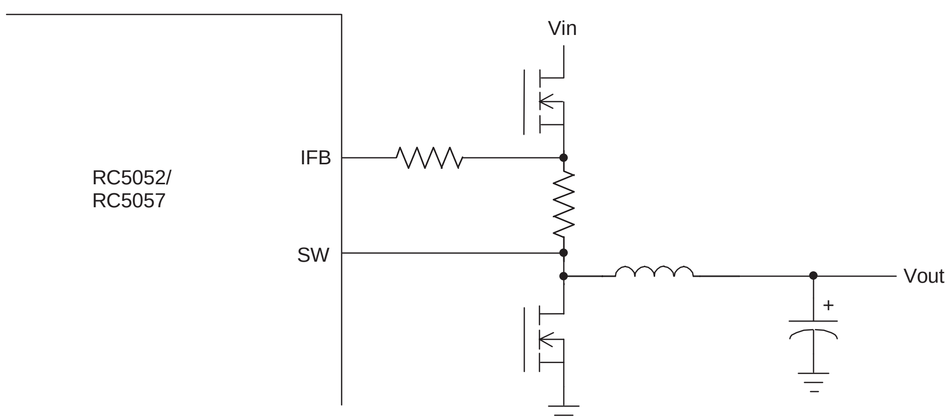


**Figure 5. Implementation of an Input Current Sensing Resistor using Fairchild's RC5052/RC5057**

## Conclusions

The results of these calculation are summarized in Table 1.

### Table 1. Efficiency, Accuracy and Cost of Various Current Sensing Methods

| | Accuracy | ΔEfficiency | Cost |
|---|---|---|---|
| Discrete Output R Sensing | 5-10% | 4% | 0.07 |
| PCB Output R Sensing | 20% | 4% | 0 |
| Discrete Input R Sensing | 5-10% | 2% | 0.07 |
| PCB Input R Sensing | 20% | 2% | 0 |
| MOSFET Sensing | 49% | 0 | 0 |
| Inductor Sensing | 56% | 0 | 0 |

**Note:** No attempt has been made in this table to estimate differences in IC cost.

The tradeoffs between cost, efficiency and accuracy are clear: The best accuracy can be obtained with a discrete resistor, but there is a penalty in both efficiency and cost; the input sense resistor is less inefficient than the output sense resistor, but requires additional pins on the IC, which may also translate into cost. To minimize the hit on efficiency, either MOSFET or inductor sensing could be used, and this also minimizes cost impact (ignoring IC cost differentials), but the accuracy of these methods is poor.

The best overall performance, efficiency and cost is achieved by discrete input resistor sensing, as can be implemented using the RC5057/RC5052. If no efficiency or cost penalty is allowed, the best performance is with MOSFET sensing, as can be obtained with the RC5057/RC5052, or with a variety of other parts from Fairchild.





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