LINFINITY Application Note

AN-7

A Simple Current-Sense Technique Eliminating a Sense Resistor

LINFINITY
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Introduction

A sense resistor R_S, as shown in Figure 1, is often used for the purpose of over-current protection (OCP). R_S is usually a power device because it needs to handle the large current flowing through it. Therefore, it can be costly, bulky, and inefficient. Even though the $R_{DS(ON)}$ of the MOSFET or monitoring the output voltage are also used in OCP, those two techniques have very poor accuracy and are good only for output short-circuit protection. They can not protect the power supply when there is a weak short circuit at the output or the output is over current.

This application note introduces a simple current-sense technique that eliminates that sense resistor, resulting in system-cost reduction, PCB space saving, and power-efficiency improvement. Furthermore, the new current-sensing mechanism allows higher dynamic tripping current than the static one (built-in low-pass filtering) to improve current-sense noise immunity.

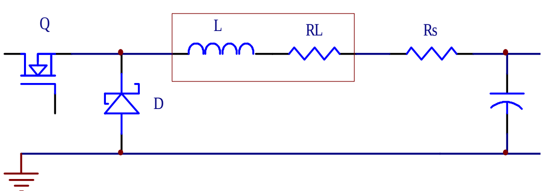

Figure 1 – A buck converter with a resistor Rs for sensing the inductor current. The resistor R_L is the parasitic resistance of the inductor.

The New Sensing Technique

This new sense technique utilizes the inductor parasitic resistance, R_L, to sense the inductor current. Figure 2 shows the new sensor circuitry with the original sensing resistor R_S eliminated. The new sensor consists of a resistor R and a small ceramic capacitor C_S, in parallel directly

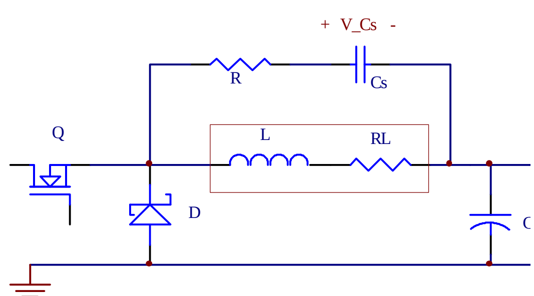

Figure 2 - The new current sense technique

with the inductor. The voltage V_{Cs} across C_S is the sensor's output.

The operation of the new sensor can be understood by examining the inductor current and the capacitor C_S voltage. When the buck converter is operating, the voltage on the left side of the inductor is a chopped voltage while the one on the right side is constant. The equivalent voltage across the inductor and the RC sensor is a square wave, as shown in Figure 3 (a) and (c).

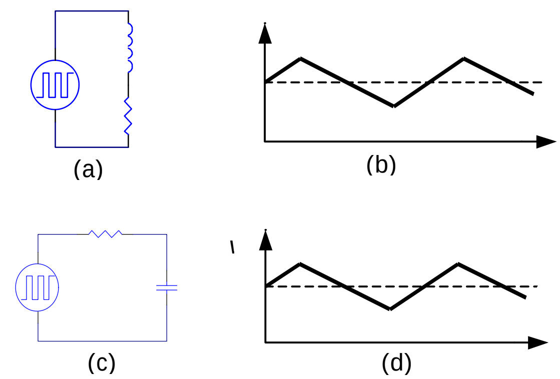

Figure 3 – The equivalent circuits and waveforms for the inductor and the sensing circuitry.

When L/R_L is much greater than the switching period T_S, i.e.

$$L / R_L >> Ts \ , \tag{1}$$

the inductor current is a triangular wave, as shown in Figure 3 (b). If values are selected such that

$$R \cdot Cs = L / R_L \ , \tag{2}$$

one can find that the capacitor voltage is directly proportional to the inductor current, as shown in Figure 3 (d). In fact,

$$V\_Cs = i_L R_L \tag{3}$$

where i_L is the inductor current. Therefore, one can use the capacitor voltage for OCP.

PERFORMANCE ANALYSIS

Equation (3) is valid under the condition that equation (1) and (2) are valid. Therefore, the performance of the new current-sense technique relies on whether or not (1) and (2) are valid and what the impact is if they are not valid.

Equation (1) is generally valid. The switching period T_S is usually of the order of microseconds, given switching frequency of the order of a few hundred kHz. The ratio of the inductance and the parasitic resistance is typically in the order of a millisecond. For example, a 5µH, 15A inductor has typically 5mΩ parasitic resistance, therefore, L/R_L = 1ms.

Equation (2) usually is very difficult to satisfy due to the tolerances of all the variables. The tolerance of R can be 1%, 5%, or even higher. Cs has its initial tolerance and dependency on the temperature. The inductance, L, has initial tolerance as well as dependency on the dc biasing current, which makes the inductance vary over a large range.

Impact Of Parameter Uncertainty?

The impact depends on how the Cs voltage reacts to the inductor current. Analysis shows that the response of the Cs voltage to the inductor current is frequency dependent. The current sensor gain is

$$T(s) = \frac{V\_Cs(s)}{i_L(s)} = \frac{sL + R_L}{sRC_S + 1} = R_L \frac{sL/R_L + 1}{sRC_S + 1}. \qquad (4)$$

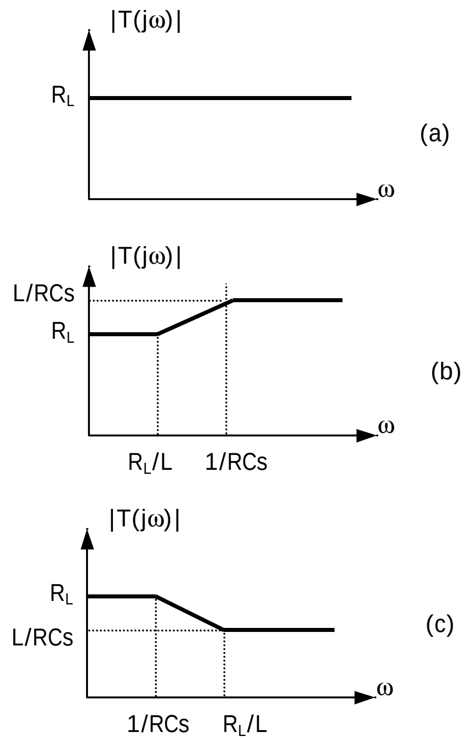

Figure 4 - The gain of the new current sensor. (a) L/R_L = RCs; (b) L/R_L > RCs; (c) L/R_L < RCs

If equation (2) holds, (4) can be simplified as R_L, as shown in Figure 4 (a); otherwise, the frequency-dependent gain has the asymptotes as shown in Figure 4 (b) and (c).

If the gain is the case shown in Figure 4(b), OCP may be tripped at a current level less than the desired value. An example of this case is shown in Figure 5. The current rise from 0A to 18A, but the sensor will output a signal indicating higher than 20A. If the current threshold is set at 20A, OCP will be tripped.

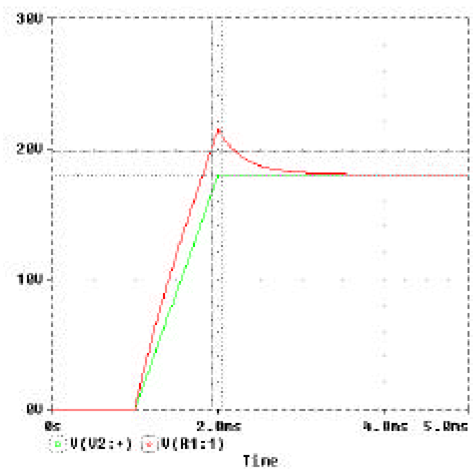

Figure 5 - The response of the current sensor to an 18A step current in the inductor when L/R_L > RCs

If the gain is similar to the case of Figure 4 (c), which has a lower high-frequency gain than the low-frequency gain, the response is in the opposite way. The response of the sensor to a 25A step current is shown in Figure 6 (a). The sensor exceeds the 20A threshold after 0.674ms delay.

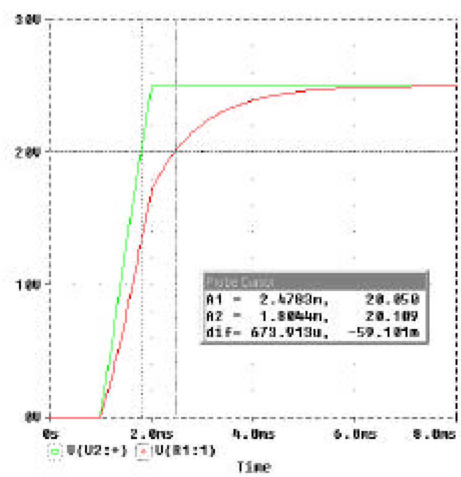

Figure 6(a) - Response to a 25A step current when L/R_L < RCs

This delay can, in fact, improve the noise immunity of the sensor and, furthermore, avoid unnecessary OCP tripping for a very short-duration over-current situation. An example is shown in Figure 6 (b), where the current exceeds the 20A threshold for a very short period. The output of the sensor, because of the delay, does not. Therefore, dissatisfaction of equation (2) does not hurt OCP performance. On the contrary, OCP behaves more desirably when the sensor gain is in the case shown in Figure 4 (c).

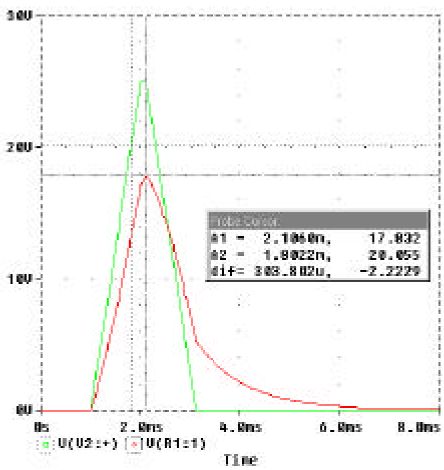

Figure 6(b) - Response to short duration transient

The important parameter in the new current sensor is the accuracy of R_L. When the inductor current changes from one level to another one, the sensor output will change to the new state, $i_L R_L$, within about 3 times of the time constant RCs. The OCP tripping current is

$$I_{TRIP} = V_{TRIP}/R_L, \qquad (5)$$

where V_{TRIP} is the tripping voltage of the current comparator. Therefore, the tripping current is directly related to R_L.

When using large gauge magnetic wire, R_L is can be controlled within reason. The diameter of the wire has a 1% tolerance, resulting in only 2% tolerance in the resistance per unit length. The length of the wire is in the order of 10cm so its error is negligible.

The copper wire resistance has a 0.39%/°C temperature coefficient. The positive temperature coefficient results in a higher resistance (lower OCP threshold) at higher temperature (which helps prevent thermal run away).

Figure 7 (a) shows the resistance variation from 20°C to 80°C, normalized at 80°C. The two dashed lines indicates the 2% tolerance. Figure 7(b) shows the OCP threshold vs. temperature, also normalized at 80°C. The temperature variation is due to the ambient and the temperature rise of the inductor in operation. The OCP threshold is 1.3 times higher at 20°C than at 80°C. In practice, this is not as bad as one might think. Because when the inductor temperature is low, so is the ambient, hence, the power MOSFETs in the power supply are allowed to operate at higher current without damage.

This new current sense technique is more accurate than

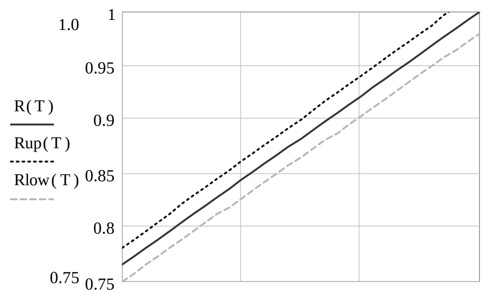

Figure 7(a) - R_L versus temperature

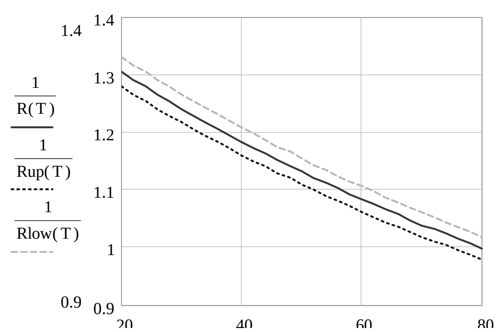

Figure 7(b) - Itrip versus temperature

using PCB trace. Using PCB trace has a poor tolerance due to the copper foil thickness. For example, the 1-oz copper PCB's thickness is 34 ± 5µm (0.0014 inch ± 0.0002 inch). The percentage error is 14%! The errors due to width and length of the trace are negligible compared to the thickness error. Moreover, the current density in the copper is usually higher than that in the inductor, hence the temperature rise is higher.

USING THE NEW CURRENT SENSE TECHNIQUE

When using the new current sense technique, one should consider the possible range of the parameters and make sure the sensor gain is in the case shown in Figure 4 (a) or (c). For example, assume R has 5% accuracy, L has a value with possible maximum 2.5µH at low current and a minimum1.1µH at high current, Cs has 10% tolerance, and R_L is 3mΩ at 20°C. The minimum dc sensor gain is 3mΩ, and then the maximum ac gain should be selected to be below the dc gain, i.e.

$$L_{max}/R_{min}Cs_{min} = 3\ m\Omega. \quad (6)$$

Therefore,

$$R_{min}Cs_{min} = 3m\Omega/2.5\mu H = 1.2\ ms. \quad (7)$$

Considering the tolerances of R and Cs, select RCs 15% larger than 1.2ms, i.e. 1.4ms. One can select R = 3kΩ and Cs = 0.47µF.

In most case, R_L is larger than the desired value. The desired value can be found from

$$Rs = V_{TRIP}/I_{TRIP}, \quad (8)$$

where V_{TRIP} is the tripping voltage in the current comparator, as shown in Figure 8, and I_{TRIP} is the tripping current. The typical V_{TRIP} of the LX166xA and LX1668 devices is 60mV. If the parasitic resistance is larger than the desired value, one can put a resistor in parallel with Cs, as shown in Figure 8 (a) that is equivalent to Figure 8 (b). Notice that the equivalent R_L changes to R_L*R2/(R1+R2) and the equivalent R is R1//R2, compared to those parameters in Figure 2.

TEST VERIFICATION

Two tests were carried out to verify the new current sense technique. The first one was to measure the dc Cs voltage when a dc current is flowing in the inductor. The second was a short-circuit load test of a Pentium® II processor power supply using LX1664 control IC.

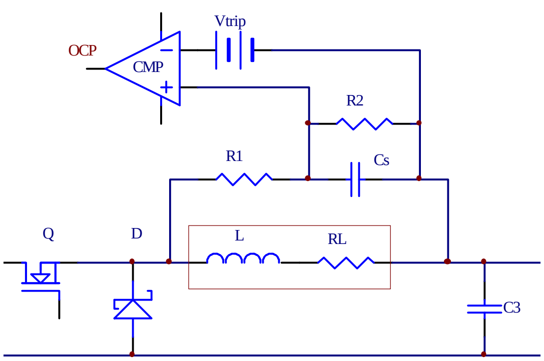

Figure 8(a) - Complete Sense Circuit

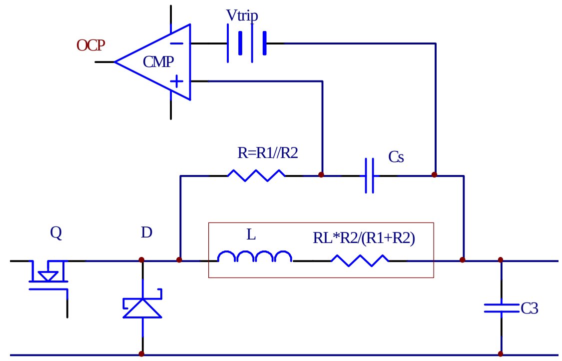

Figure 8(b) - Equivalent Circuit

The first test was on a 2.5µH inductor. The inductor used a Micrometals' material 52 iron powder core and 8 turns of AWG 18 wire. The measured results are shown in Figure 9. The slope of the curve indicates the resistance. At low current, the resistance is estimated to be 3mΩ. Notice that the slope increases slightly at higher currents, due to the higher temperatures.

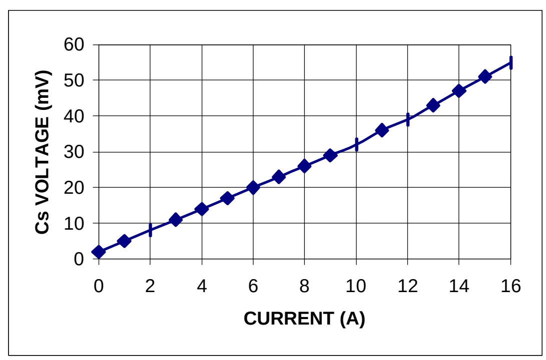

Figure 9 - The measured Cs voltage versus inductor current

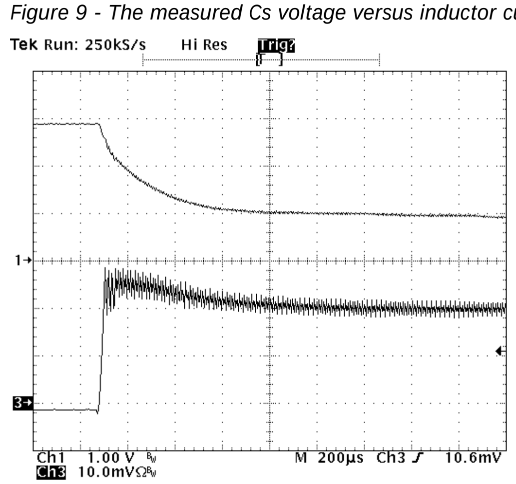

Figure 10 - OCP Action. The top trace is output voltage (1V/div) and the bottom is inductor current (10A/div)

The second test replaced the sense resistor in the LX1664 evaluation board with the new current sense. Since V_{TRIP} = 100 mV in LX1664, we used a 5µH inductor that has an R_L of 5mΩ. The R and Cs were 10kΩ and 0.1µF ceramic capacitor respectively. The output was short-circuited when the circuit was running and the transient waveforms are shown in Figure 10. Notice that the current limit was at a higher level at the beginning of the transient but drops to 20A after about 0.5ms because the sensor gain was in the case of Figure 4 (c).

The new sensor does not affect the voltage-positioning feature of LX166x family ICs. Figure 11 shows the output voltage and a 15A step-current load. The voltage positioning is clearly shown.

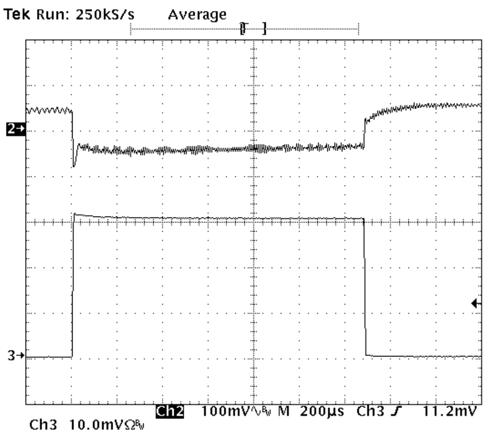

Figure 11 - Step load response. Top trace is output voltage (100mV/div) and bottom is load current (5A/div)

Design Procedures For Using The New Sensor

1. Calculate the desired sense resistance R_S with equation (8).
2. Select an inductor with $R_L \geq R_S$.
3. Find the maximum value of $L_{max}/R_{L,min}$ possible. Usually the maximum L is at zero current and minimum R_L is at room temperature. Take the tolerance of L and R_L into account as well.
4. Decide R and Cs so that the time constant $R_{min}*Cs_{,min} > L_{max}/R_{L,min}$.
5. If R_L > Rs, Select R1 and R2 so that R2/(R1+R2) = Rs/R_L and R1//R2 = R.