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HOW-TO

Accurate and Lossless Current-Sensing Techniques for Power Applications -- A Practical Myth?

By Gabriel A. Rincón-Mora, Senior Member, IEEE, and H. Pooya Forghani-zadeh, Student Member, IEEE

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The power supply is the backbone of any electronic device, and its performance is especially critical in the growing mobile consumer market, where not only accuracy but also power efficiency is crucial, which explains why switching supply circuits have enjoyed such popularity. For the safety, performance, and feedback control of these switching supplies, it is often necessary for the circuit to better understand its loading environment, especially load current. Protecting the supply circuits, for instance, against overloading and short-circuit conditions requires the system to self-monitor its current delivery. Additionally, in current-mode DC-DC converters, the inductor current is regulated and must therefore be sensed and processed. Monitoring current is perhaps even more critical in smart power supply circuits for portable applications, where several load-dependent regions of operation exist for the sole purpose of increasing power efficiency and therefore extending battery life, which is why lossless current-sensing techniques are so important.

The most basic form of a current-sensing circuit is through the use of a series sense resistor in the current-flowing path (R_{sense} in Figure 1), where the voltage across it is linearly proportional to the current. The problem with this scheme is the power loss incurred by the resistor, which is the cost of simplicity. The use of a simple sense resistor is therefore not an acceptable solution for high-performance DC-DC converters with efficiencies exceeding 85-90%. Consequently, several lossless current-sensing techniques have been developed, and lossless implies less than 1% of degraded power efficiency. The basic idea in all of these lossless schemes is to extrapolate current information from already existing series devices, circumventing the need to add a series resistor. The following discussion is an overview of these techniques.

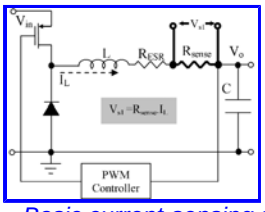

Figure 1 - Basic current-sensing scheme

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RDS Sensing:
All power supply circuits have switches (usually MOSFETs) that carry the load current from the input source to the load, and they have a characteristic series resistance; in other words, they are series sense resistors when they conduct current [1]. The current can therefore be inferred by sensing the voltage across the switch and knowing its characteristics impedance (that is, $I_D = V_{Switch}/R_{DS}$), as shown in Figure 2 ($i_L = V_{s2}/R_{DS}$). When the switch is conducting and the voltage across it is therefore small (that is, $V_{DS} < V_{DS\_sat} = V_{GS}$ " V_T), the MOSFET is in its triode region and acts like a linear resistor, and its resistance is therefore given by:

$$R_{DS} = \frac{1}{\beta(V_{in} - V_T)}$$

(1)

where β is the effective transconductance parameter of the MOSFET, V_{in} is the input supply voltage, and V_T is the threshold voltage. The problem with this technique is the tolerance of R_{DS}, which is not only a strong function of temperature (that is, mobility and threshold voltage V_T) and input supply voltage (that is, gate drive - V_{GS}) but also process. In fact, its total tolerance can range from 50 to 200%, which implies the accuracy of the R_{DS} current-sensing technique is equally poor. This is complicated, of course, by the fact that the current only flows through the switch when it is conducting so sample-and-hold circuits are required, significantly complicating the circuit solution and plaguing it with noise.

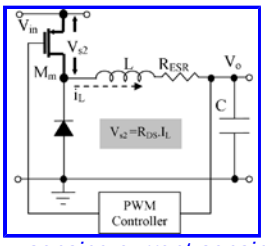

Figure 2 - R_{DS} sensing current-sensing technique

Sense FET:
If the power switch is on-chip, the tolerance of sensing the current through the MOSFET is improved by using a smaller and matched sense FET in a current-mirror configuration, as shown by M_M and M_s in Figure 3 [2-5]. Amplifier A_1 forces the drain-source voltages of both power FET M_M and sense FET M_s to be equal, and since their gate-source voltages are already equal (i.e., shorted together), their corresponding current densities are also equal (I_D is a function of V_{GS} and V_{DS}). Therefore, if the sense FET is a smaller but matched device, its current is linearly proportional to the current flowing through the power device, and in the case of Figure 3, the sense current is N times smaller than the current flowing through power FET M_M " in practice, N can be any where from 1000 to 10,000.

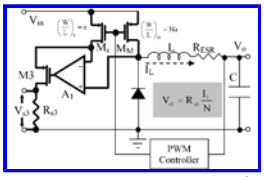

Figure 3 - Sense FET current-sensing technique

This technique is more accurate than its predecessor, but still not ideal. Like R_{DS} sensing, the current through the power FET is not continuous and it therefore

requires a sample-and-hold circuit, which may be a simple capacitor across R_{s3} - it holds sensed current V during off times ($V_{s3} = IR_{s3}$). Since the sense current is relatively small, the capacitor need not be large, although transient spikes will continue to occur, introducing noise into the system. Moreover, the accuracy of this method is limited by the matching performance of the sense and power FETs and by the input-offset voltage of the amplifier. The fact is that matching performance degrades with increasing spreads, in other words, with increasing values of N, and since the power FET is used in its triode region, the current is also a strong function of its drain-source voltage, which is why an amplifier is needed and its offset performance determines, in part, the accuracy of the circuit (for example, a 10mV offset in a 50mV source-drain voltage causes up to 20% error). In spite of all this, the accuracy improvement of this technique over R_{DS} sensing is vast.

Matched Filter:
The inductor (L) and its equivalent-series resistor (ESR) are nothing more than a filter of two series impedances with a large tolerance, and the current through it is therefore proportional to the voltage across them and inversely proportional to the total impedance (that is, $I_L = V_{L+R_{ESR}} / [LS + R_{ESR}]$). Consequently, if a parallel impedance network comprised of a capacitor-resistor combination is connected and designed to be proportional to the total impedance of the inductor (that is, k $[LS + R_{ESR}]$), the voltage across the capacitor (V_{s4} in Figure 4) is therefore linearly proportional to the inductor current [6],

$$V_{s4} = \frac{I_L(LS + R_{ESR})}{(R_f + 1/sC_f)}(1/sC_f) = \left[\frac{R_{ESR}(LS/R_{ESR} + 1)}{(sC_f R_f + 1)}\right] I_L \quad \textbf{(2)}$$

where Rf and Cf is the parallel impedance network designed to satisfy the following condition:

$R_f + 1/sC_f = k\ (LS + R_{ESR})$ or -- $R_fC_f = L/R_{ESR}$, **(3)**

and therefore
$V_{s4} = R_{ESR}I_L$,**(4)**

at all frequencies (k is a gain factor). The main advantage of this technique is that the current is sensed continuously through all switching phases, without the complexities and noise implications of a sample-and-hold circuit. The drawback, however, is the design of the parallel filter network, and how it must match the inductor-ESR combination, which ultimately determines its accuracy performance.

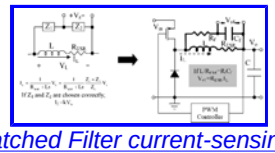

Figure 4. Matched Filter current-sensing technique

Average Current:
The average or DC voltage across the inductor is only the voltage across its ESR, since the impedance of the inductor is negligible, and the average current is therefore $V_{L+R_{ESR}}$ R_{ESR}. So, measuring the average voltage across the inductor amounts to measuring the DC current flowing through it, which is the basic idea behind the circuit shown in Fig. 5 [7]. Resistor-capacitor combination R_A-C_A average out switching voltage V_{phase}, which is then used in combination with V_o to measure the inductor current (that is, $V_{s5} = R_{ESR}I_{L\_DC}$). The requirement for this circuit to work is that R_AC_A be much greater than L/R_{ESR}, which is really a special

case of the matched-filter technique previously described (Eq. (3)), arising because the current measured is only valid for very low frequencies. The design requirements for the R_A-C_A combination are therefore relaxed, but at the cost of ac and transient current information, which is important in current-mode control schemes and protection circuits. The technique, however, may be useful to balance the average load current of various channels in multi-phase converter applications.

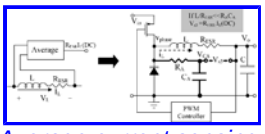

Figure 5 - Average current sensing technique

Electromagnetic Techniques:
Replacing the inductor with the primary winding of a transformer and using the secondary winding as a sense inductor is the easiest way to measure current [8]. And Hall-effect sensors, which rely on the electromagnetic principle of the Hall-effect, are another means through which current can be measured [9]. The main drawbacks with these techniques are cost and PCB real-estate, which is why they do not enjoy popularity in portable electronics.

Self-Matched Filter:
The key parameters of any current-sensing technique are accuracy, power efficiency, and cost, and, of the schemes presented, the matched-filter method is the most promising because it is lossless, relatively simple to implement, and potentially accurate for both ac and DC current information. The key challenge is designing the resistor-capacitor combination, which is what we are currently working on in our lab. Our approach is to have the circuit determine it "itself" during start-up. We propose to use a variable resistor and tune its value, matching the filter performance of the inductor-ESR combination with the variable resistor-capacitor network by superimposing a sinusoid signal and using a phase-locked loop to match its phase response, thereby guaranteeing the condition specified in Eq. (3) [11]. In this configuration, the designer is not required to know the specific values of the inductor or its ESR, since the circuit is self-learning. We implemented a PCB-level solution and the results were promising. We are currently developing an integrated circuit (IC) solution for a full evaluation.

Table 1 summarizes the performance tradeoffs among the most pertinent current-sensing techniques presented here. The simple sense resistor is the most accurate, but lossy, unfortunately. The sense FET has good accuracy, but it is noisy and only senses part of the current - it is discontinuous. A complementary sense FET may be added, but at the cost of complexity and noise. The filter techniques are relatively simple, but with poor accuracies, given the difficulty of matching the filters. R_{DS} sensing is simple but also the least accurate. The scheme we propose has the potential of improving the accuracy performance of the filter techniques to the level of the sense FET, perhaps slightly better (for example, our scheme promises to be better than 10% accurate whereas the sense FET is roughly 20%, which is basically the matching performance of a sense FET [10].

	Continuous	Lossless	Accuracy	Switching noise	On-chip/off-chip switches	DC/AC current accuracy
R_{sense}	Yes	No	Best	No	Both	Both
R_{DS}Sense	No	Yes	Worst	Yes	Both	Both
Sense FET	No	Yes	Good	Yes	On-chip	Both
Matched Filter	Yes	Yes	Poor	No	Both	Both

Average-I	No	Yes	Poor	No	Both	DC
Self-matched Filter	Yes	Yes	Good	No	Both	Both

Table 1. Current-Sensing Summary

For additional details, questions, and/or comments on this article, please contact us, the Georgia Tech Analog and Power IC Design Lab, at gtap@ece.gatech.edu.

More information about our research can be found at www.rincon-mora.com/research.

References

[1] R. Lenk, "Application bulletin AB-20 optimum current-sensing techniques in CPU converters," Fairchild Semiconductor Application Notes, 1999.
[2] S. Yuvarajan, "Performance analysis and signal processing in a current sensing current MOSFET (SENSEFET)," in Proc. Industry Applications Society Annual Meeting, pp. 1445"1450, 1990.
[3] P. Givelin, M. Bafleur, "On-chip over-current and open-load detection for a power MOS high-side switch: a CMOS current-source approach," in Proc. Fifth European Conference on Power Electronics and Applications, pp. 197 "200, 1993.
[4] S. Yuvarajan and L. Wang, "Power conversion and control using a current-sensing MOSEFET," in Proc. 34th Midwest Symposium on Circuits and Systems, pp.166 "169, 1992.
[5] C. Lee and P. Mok, "A monolithic current-mode CMOS DC-DC converter with on-chip current-sensing technique," IEEE Journal of Solid States Circuits, pp. 3-14, Jan. 2004.
[6] E. Dallago, M. Passoni and G. Sassone, "Lossless current sensing in low voltage high current dc/dc modular supplies," IEEE Trans. Industrial Electronics, vol. 47, pp. 1249-1252, Dec. 2000.
[7] X. Zho and P. Xu, "A novel current-sharing control technique for low-voltage high-current voltage regulator module applications," IEEE Trans. Power Electronics, vol. 15, pp. 1153-1162, Nov. 2000.
[8] C. Xiao, L. Zhao, T. Asda, W. Odendaal, and J. van Wyk, "An overview of Integratable Current Sensor Technologies," in Proc. 38th Industry Applications Conference, pp. 1251-1258, 2003.
[9] Z. Randjelovic, M. Kayal, R. Popovic, and H. Blanchard, "Highly sensitive hall magnetic sensor microsystem in CMOS technology," IEEE Journal of Solid States, pp. 151-159, Feb. 2002.
[10] P. Drennan and C. McAndrew, "Understanding MOSFET mismatch for analog design," IEEE Journal of Solid States, pp. 450-459, March 2003.
[11] H.P. Forghani-zadeh, and G. Rincon-mora, "Current-sensing techniques for DC-DC converters," in Proc. 45th Midwest Symposium on Circuits and Systems, pp. 577-580, 2002.