Current-Sensing Techniques for DC-DC Converters

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ABSTRACT

Current sensing is one of the most important functions on a smart power chip. Conventional current-sensing methods insert a resistor in the path of the current to be sensed. This method incurs significant power losses, especially when the current to be sensed is high. Lossless current-sensing methods address this issue by sensing the current without dissipating the power that passive resistors do. Six available lossless current sensing techniques are reviewed. A new scheme for increasing the accuracy of current sensing when the discrete elements are not known is introduced. The new scheme measures the inductor value during the DC-DC controller startup.

1.INTRODUCTION

Regardless of the type of feedback control, almost all DC-DC converters and linear regulators sense the inductor current for over-current (over-load) protection. Additionally, the sensed current is used in current-mode control DC-DC converters for loop control [1]. Since instantaneous changes in the input voltage are immediately reflected in the inductor current, current-mode control provides excellent line transient response. Another application for current sensing in DC-DC converters is also reported [2,3], where the sensed current is used to determine when to switch between continuous-conduction mode (CCM) and discontinuous-conduction mode (DCM), which results in an overall increase of power efficiency in the DC-DC converters.

This paper gives an overview of current sensing techniques in DC-DC converters and their impacts on power losses. Section 2 discusses the traditional way of sensing current, which is not really lossless, as well as nontraditional lossless techniques. In section 3, the advantages and disadvantages of the different current sensing techniques are compared. Section 4 discusses the concerns of sensing current accurately when no information about the discrete elements is available, which is a reasonable assumption in integrated solutions, and introduces a new scheme for surviving in such an environment.

2. REVIEW

2.1 Series-Sense Resistor

This technique is the conventional way of sensing current. It simply inserts a sense resistor in series with the inductor (Fig. 1). If the value of the resistor is known, the current flowing through the inductor is determined by sensing the voltage across it.

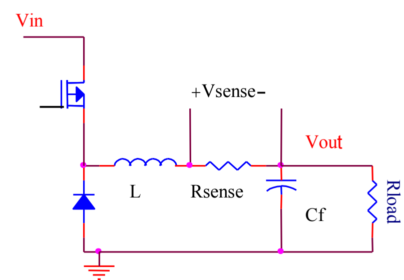

Figure 1. Series-Sense Resistor.

This method obviously incurs a power loss in R_{sense}, and therefore reduces the efficiency of the DC-DC converter. For accuracy, the voltage across the sense resistor should be roughly more than 100mV range at full load because of input-inferred offsets and other practical limitations. If full-load current is 1A, 0.1W is dissipated in the sense resistor. For an output voltage of 3.3V, the output power is 3.3W at full-load and hence the sense resistor reduces the system efficiency by 3.3%. In lower output voltages, the percentage of power lost in the sense resistor increases, which degrades efficiency further.

2.2 R_{DS} Sensing

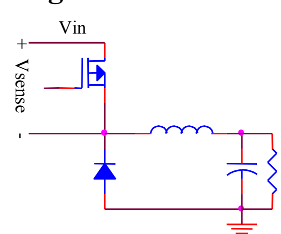

Figure 2. MOSFET R_{DS} Current-Sensing.

MOSFETs act as resistors when they are "on" and they are biased in the ohmic (non-saturated) region. Assuming small drain-source voltages, as is the case for MOSFETs when used as switches, the equivalent resistance of the device is

$$R_{DS} = \frac{L}{W\mu C_{ox}(V_{GS} - V_T)}, \tag{1}$$

where μ is the mobility, C_{ox} is the oxide capacitance per unit area, and V_T is the threshold voltage [4]. Consequently, the switch current is determined by sensing the voltage across the drain-source of the MOSFET, provided that R_{DS} of the MOSFET is known (Fig. 2). The main drawback of this technique is low accuracy. The R_{DS} of the MOSFET is inherently nonlinear. Additionally, The R_{DS} (for on-chip or discrete MOSFET) has significant process variation because of μC_{ox} and V_T, not to mention how it varies across temperature, which can yield a total variance of –50% to 100%. The R_{DS} depends on temperature exponentially (35% variation from 27°C to 100°C) [5]. In spite of low accuracy, this method enjoys commercial use because of its power efficiency (no additional resistor is added, lossless technique).

2.3 Filter-Sense the Inductor

This technique, reported in [5,6], uses a simple low-pass RC network to filter the voltage across the inductor and sense the current through the equivalent series resistance (ESR) of the inductor (Fig. 3).

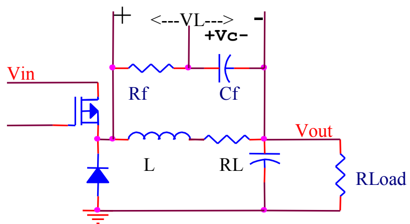

Figure 3.Filtering the voltage across inductor to sense the current.

The voltage across the inductor is

$$v_L=(R_L+sL)I_L\,, \tag{2}$$

where L is the inductor and R_L is its ESR. The voltage across capacitor C_f is

$$v_c=\frac{v_L}{1+sR_fC_f}=\frac{(R_L+sL)I_L}{1+sR_fC_f}$$
$$=R_L\left(\frac{1+s(L/R_L)}{1+sR_fC_f}\right)I_L=R_L\left(\frac{1+sT}{1+sT_1}\right)I_L, \tag{3}$$

where $T=L/R_L$ and $T_1=R_fC_f$. Forcing $T=T_1$ yields $v_c=R_L\,i_L$ and, hence, v_c would be directly proportional to i_L.

To use this technique, the values of L and R_L must be known (at least their ration), and then R and C are chosen accordingly. This technique is not appropriate for integrated circuits because of the tolerance of the components required. It is, however, a proper design for a discrete, custom solution where the type and value of the inductor is known.

2.4 Sensorless (Observer) Approach

This method is introduced by Midya [7]. It uses the inductor voltage to measure the inductor current (Fig. 4). Since the voltage-current relation of the inductor is $v=Ldi/dt$, the inductor current can be calculated by integrating the voltage over time. The value of L also must be known for this technique.

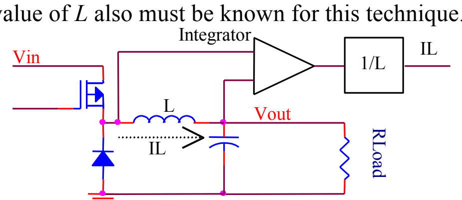

Figure 4. Observer current sensing technique.

2.5 Average Current

This current-sensing technique, referring to Fig. 5, uses an RC low-pass filter at the junction of the switches of the converter. Since the average current through resistor R is zero, the output averaged-current is derived as

$$I_o=\overline{I_L}=\frac{V_{out}-\overline{V_C}}{R_L}\,, \tag{4}$$

where $\overline{V_C}$ is the average capacitor voltage.

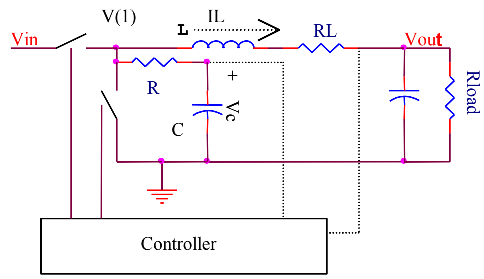

Figure 5. Average current-sensing technique.

If R_L is known, which is not the case for IC designers, the output current can be determined. Sensing the current in this method depends only on R_L, and not on the parasitic switch resistor or the values of R and C. This scheme is used mainly for load sharing in multiphase DC-DC converters [8].

2.6 Current transformers

The use of current-sensing transformers is common in high power systems. The idea is to sense a fraction of the high inductor current by using the mutual inductor properties of a transformer. The major drawbacks are increased cost and size, and non-integrablity. Furthermore, the transformer cannot transfer the DC portion of the current, which makes this method inappropriate for over-current protection.

2.7 SENSEFETs

This method is a practical technique for current sensing in many new power MOSFET applications [9,10,11,12]. The idea is to build a current sensing FET in parallel with the power MOSFET (Fig. 6) and use its "measuring" capabilities for sensing the current.

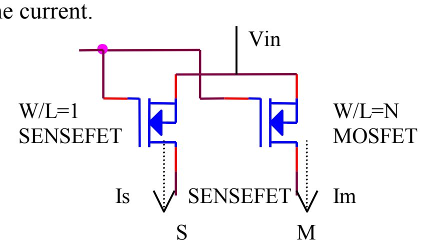

Figure 6. SENSEFET.

The effective width (W) of the sense MOSFET (SENSEFET) is significantly smaller than the power FET. The width of the power MOSFET should be at least 100 times the width of the

SENSEFET to guarantee that the consumed power in the SENSEFET is low and quasi-lossless. The voltages of nodes M and S should be equal to eliminate the current mirror non-idealities resulting from channel-length modulation. By using current conveyors [13] and other circuits, these effects can be mitigated. A complete current-sensing circuit using a SENSEFET is shown in Figure 7. M1 is the power MOSFET and M3 is the SENSEFET. The op-amp is used to force the drain voltages of M1 and M3 to be equal.

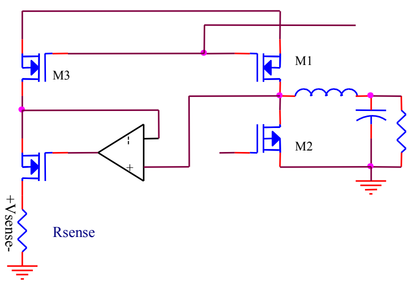

Figure 7. Sample circuit to increase the accuracy of the SENSEFET method.

As the width ratio of the main MOSFET and SENSEFET increases, the accuracy of the circuit decreases (matching accuracy of the FETs degrades). The bandwidth of this technique is reported unexpectedly low [14,15]. The low bandwidth cannot be estimated by RC pole analysis and is due to another phenomenon called transformer effect [14,15]. Since the current ratio in SENSEFET circuits is in the order of 100:1, even a low degree of coupling between the power MOSFET and the SENSEFET circuits can induce a significant error, and large spikes are injected in the sense signal during periods of high di/dt. Therefore, proper layout schemes should be chosen to minimize the mutual inductance between the SENSEFET and the power MOSFET.

3. COMPARITIVE OVERVIEW and CHALLENGES

Selecting a proper current-sensing method depends on the DC-DC converter control scheme. If voltage-mode control is used, current sensing is only needed for over-load current protection. Therefore, a simple, not very accurate but lossless method, like R_{DS} current sensing, is sufficient. If current-mode control or mode hopping (for high efficiency) is used, more accurate algorithms may be necessary. The traditional series resistor technique can be used when power dissipation is not critical, which is almost never the case for portable applications. For applications like desktop computers, decreasing the power efficiency by about 5% may not as critical. The majority of commercial current-mode controller solutions for desktop computers use a sense resistor. R_{DS} sensing is the other dominant technique, which is used even in current-mode controllers in commercial products, but its accuracy is poor. The other techniques are not appropriate for integrated solutions. Table 1 summarizes the advantages and disadvantages of the different current-sensing techniques explored.

Table 1. Comparative overview of current-sensing techniques.

Technique	Advantages	Disadvantage
A. R_{SENSE}	Good accuracy	High power dissipation
B. R_{DS}	Lossless	Low accuracy
C. L_{Filter}	Lossless	Knowledge of L High number of discrete elements
D. Observer	Lossless	Knowledge of L
E. $I_{Average}$	Lossless	Known inductor ESR Average inductor current only
F. Transformer	Lossless	Cost Size Not integrable No I_{DC} information Not practical
G. SENSEFET	Lossless Integrable Practical Moderate accuracy	Special MOSFETs Matching issues Low bandwidth

4. PROPOSED SCHEME

All of the discussed current-sensing methods, except for the SENSEFET technique, depend on knowing the value of discrete elements, such as the inductor, sense resistor, or MOSFET's R_{DS}. In a lossless current-sensing technique, only node voltages are sensed and the value of the current in a branch is estimated using the values of passive elements (i.e., $v=Ri$, $i=Cdv/dt$ and $v=(\int idt)/L$).

In a custom discrete design, the values of external components are known and the current-sensing technique can be adjusted before mass production. On the other hand, if a current sensing scheme is designed for a general-purpose controller, where the end-user can select the inductor, capacitor, and switches from a specified range, the IC designer is incognizant of the values of the external components. Hence, current-sensing techniques are best designed if they are independent of external component values. To solve this problem, the circuit shown in Figure 8 is proposed, where the value of the inductor is measured and stored during startup and the voltages are sensed during normal operation to determine the current. Just before startup, the power MOSFETs are forced off and switches S1 and S2 are "on".

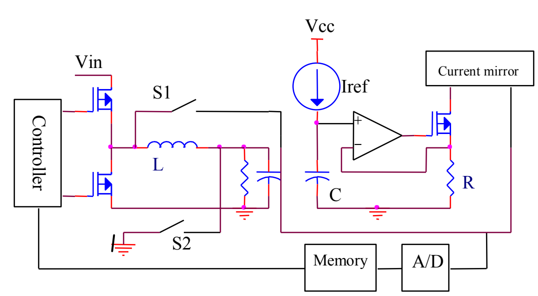

Figure 8. Inductor measuring circuit

Constant current source I_{ref} charges capacitor C during that time, creating a linear voltage ramp, which is turned into a linear current ramp by the op-amp.

The voltage at the positive port of the op-amp is

$$V_c(t) = \frac{1}{C}\int I_{ref}\,dt = \frac{I_{ref}\,t}{C}, \qquad (5)$$

where t is time. The op-amp, along with the negative feedback, forces the negative port of the op-amp to be equal to the positive port; thus, the current forced is a ramp ($I_L(t)=V_c/R=I_{ref}t/(RC)$) . Therefore, the voltage across the inductor is

$$V_L(t) = L\frac{dI_L}{dt} = L\frac{I_{ref}}{RC}, \qquad (6)$$

where I_{ref} is a function of a constant reference voltage and another integrated resistor. The voltage given by (6) is a constant voltage inductor across a 1uH inductor. Fig. 9 shows the simulation results for the voltage across the inductor. Capacitor C, resistor R and current source I_{ref} are 1pF, 100Ω, and 10uA, respectively. This measurement technique boosts the observer technique accuracy, especially when the value of the inductor is not known.

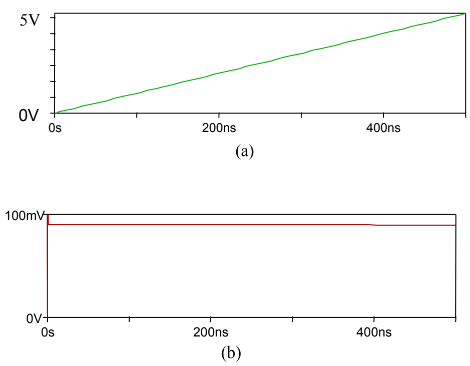

Figure 9. Simulation of transient voltage across (a.) Capacitor C and (b.) Inductor L.

5. CONCLUSION

Six lossless current-sensing techniques were reviewed. Among these techniques, only the SENSEFET method is independent of external component values. A novel approach for sensing current, when values of external components are not known, is proposed and simulation results were presented. The new approach enjoys the benefits of being integratable, accurate, and lossless (low power loss during startup).

6. ACKNOWLEDGEMENTS

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