

An Area Saving Inductor Current Sensor with Load Transient Enhancement in DC-DC Converter

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Abstract

Among the on-chip current sensing techniques, inductor current sensing method is the most feasible one for high switching frequency converter, which aids reduction of the filter inductor size. This paper presents a reduction of area design for the combined AC and DC inductor current sensor with load transient enhancement for the systems-on-chip applications. The proposed current sensor is simulated under several switching frequencies. Finally, the transient enhancement function of the proposed circuit is simulated in a buck converter at 4.5MHz switching frequency. When the load current changes by 500mA, by increasing time-constant delay for the sensed DC current ten times, the output voltage overshoot/undershoot reduces from 126mV/229mV to 76mV/74mV.

Keywords-DC-DC converter; current sensing; inductor current sensor; transient enhancer; system-on-chip (SoC)

Introduction

Reducing area is one of the key factor for on-chip DC-DC converter design. The simplest method is to increase switching frequency to reduce required filter inductance. A feasible combined AC and DC inductor current sensing design was implemented in [4], which solved the limitations in [1], [2], and [3]. However, by analysis, the design can be further simplified to reduce chip area. In addition, load transient enhancement can be employed by a small change in the component values in [4].

Proposed Current Sensor

A. Current Sensing Principle

Shown in Fig. 1 is the overall current mode buck converter (LEFT) with the proposed inductor current sensor (RIGHT). The proposed inductor sensing circuit has the working principle similar to the one in [4], which uses a capacitor $C_{AC,buf}$ to buffer AC inductor current information using C_F voltage, and a negative loop feedback NFB to sense DC inductor current information to V_{SEN} voltage. For sensing AC, $R_{AC}C_F = L_0$ (no unit). In addition, by the principle of capacitor-charge balance, $\overline{I_{R_{AC}C_F}}$ are zero; thus, $\overline{V_{R_{AC}}} = 0$. On the other hand, by the principle of inductor volt-second balance, $\overline{V_{L_0}} = 0$. Using Thevenin theorem, $\overline{V_L} + \overline{V_{DCR}} = \overline{V_{R_{AC}}} + \overline{V_{C_F}}$. Therefore,

$\overline{V_{DCR}} = DCR \cdot \overline{I_L} = \overline{V_{C_F}}$, i.e., C_F DC voltage does not depend on R_{AC} value. Therefore, in the proposed current sensor, DC inductor current information can be obtained using the AC sensing branch $R_{AC}C_F$.

B. DC Sensing Delay and Load Transient Enhancement

As shown in Fig. 2, when I_{LOAD} increases, if the DC component of inductor current is delayed, the slope of the sensed current reduces for some initial periods after the change. Therefore, the DUTY will be detected more slowly, which means the DUTY is larger compared to that used no DC inductor current delay. By this way, more high-side switch's current can charge more to the output. Similar explanation can be made for I_{LOAD} decreasing case, as shown in Fig. 3.

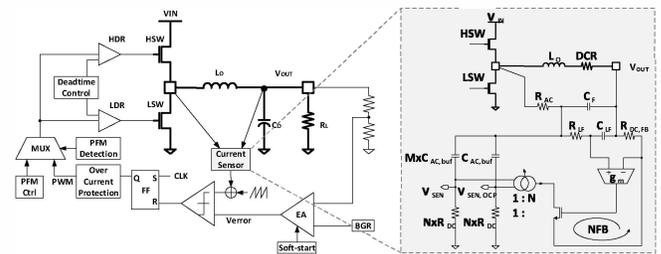


Fig. 1. Current Mode Buck Converter and the Proposed Combined AC and Delayed-DC Inductor Current Sensor.

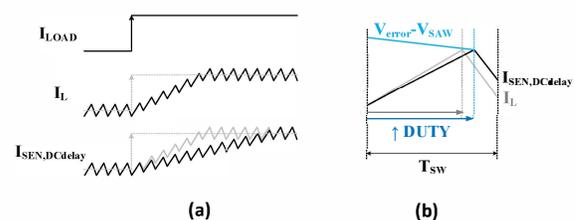


Fig. 2. (a) Sensing DC Current Delay at Rising Load Current; and (b) Its Influence to Loop Stability Explained in one period.

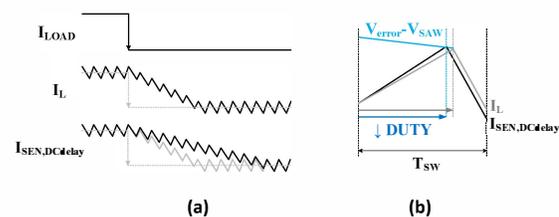


Fig. 3. (a) Sensing DC Current Delay at Falling Load Current; and (b) Its Influence to Loop Stability Explained in one period.

Therefore, by increasing delay time constant of the DC current sensing voltage by M times using $Mx C_{AC,buf}$, the current compensation will be faster at the load transient response. The DC current delay should not be too much so that the different voltage of V_{error} and V_{SAW} crosses V_{SEN} within one period.

In reverse, the current sensing speed should be correct for the over current protection circuit, which limits the inductor current at an allowable level. Thus, a possible design may use different sensed DC current for different function, which can simply be accomplished by using a two-branch current mirror for each purpose as shown in Fig. 1.

Simulation Results

A. Sensed Inductor Current Response

Shown in Fig. 4 is the sensed inductor current simulated at 160MHz switching frequency: The sensed AC signal shows only maximum of 28mV error, with the mode of 7mV.

Shown in Fig. 5 (a) is the proof for the DC analysis tested at 1.2MHz switching frequency: The DC error of the voltage across V_{CF} by using the proposed structure is only 0.22% compared to the ideal $R_{AC,CF}$ time constant case ($R_{AC,CF} = L_o/DCR$). Fig. 5 (b) shows the ability of DC current tracking of the proposed current sensor tested at 5MHz switching frequency, when load current changes from 200mA to 400mA.

B. Load Transient Enhancer

Shown in Fig. 6 is the load transient response simulated with different $Mx C_{AC,buf}$ capacitance to verify the transient enhancing capability explained in Fig. 2 and 3. As in Fig. 6 (a), the load transient response results a large voltage output change when load current changes from 300mA to 800mA (500mA): For the increasing load current case, the maximum change is 126mV; and for the decreasing load current case, this change is 229mV. By increasing the sensing DC current time response by ten times (i.e. increasing the $Mx C_{AC,buf}$ by ten times), this maximum change reduces to 76mV for load current increasing case, and to 74mV for the decreasing case, as in Fig. 6 (b).

C. Other Recommendations

Practical implementation may consider eliminating DC OPAMP offset by using trimming bit or average sensing structure. Finally, a high switching frequency converter should also take switching loss into account.

Conclusion

An area saving current sensing inductor based on the architecture in [4] is presented and simulated under various switching frequencies. The simulation results show no difficulty in sensing current at high switching frequency. In addition, load transient can benefit from the delayed DC inductor current: By increasing the DC delay by ten times, the output voltage change reduces to maximum 3.1 times for load current change of 0.5A. Practical design may implement DC OPAMP offset cancellation. Finally, tradeoff between high switching frequency and switching loss should be considered.

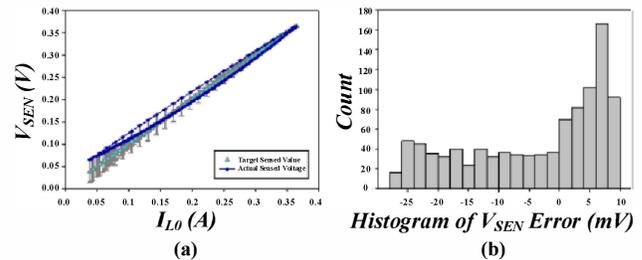


Fig. 4. Sensing AC Current: (a) Eye-Diagram of the Sensing AC Current comparing to the Ideal AC Inductor Current; (b) The Histogram of Sensing Current Error.

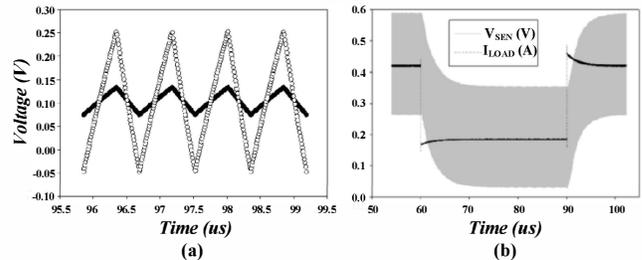


Fig. 5. Sensing DC Current: (a) V_{CF} under Different $R_{AC,CF}$ Time Constant; (b) Overall Sensing Current compared to the Load Current.

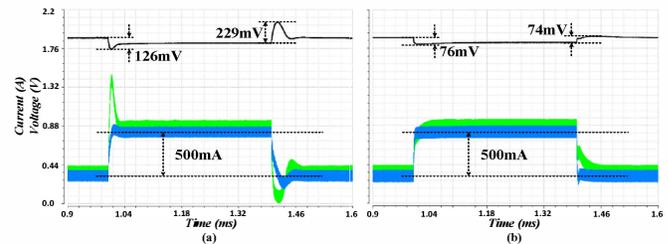


Fig. 6. Load Transient Enhancement: (a) $M = 1$; (b) $M = 10$.

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