Design of Fast-Response On-Chip Current Sensor for Current-Mode Controlled Buck Converters with MHz Switching Frequency

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Abstract – In this work, techniques to design fast-response on-chip current sensor for buck converter (BC) with MHz-range switching frequency is successfully developed. Unwanted voltage spike at the sensor output, which not only degrades the response time of sensor but also interrupts the operation of BC, is minimized by carefully controlling the activation and deactivation time of current sensor. Response time of sensor is also improved by specially designed error amplifier, which provides large slew-rate in both positive and negative direction during transient response and consumes only small quiescent current at steady-state operation. Sensing accuracy at small inductor current is also improved in the proposed design. It is shown that the proposed current sensor is able to respond to a BC with 10MHz switching frequency at only 8- μ A quiescent current consumption.

I. INTRODUCTION

Buck converters (BCs) are widely used in battery-powered mobile systems due to their superior power efficiency and also the increasing use of low-supply-voltage circuits, which are intended to lower power consumption of mobile systems. To enable BCs with fast dynamic response and also over-current protection, current-mode control is used. Inductor current is required to be acquired in current-mode controlled BCs. Among different inductor current sensing techniques, on-chip current sensor [1-3] based on the transistor-scaling technique [4] is often used in current-mode controlled BCs. However, requirements of BCs in nowadays mobile systems make the design of current sensor very challenging. The need of small off-chip inductor for printed circuit board (PCB) space reduction makes BCs to operate at several MHz [5-7] or even at tens to thousands MHz [8-10]. The continuously scaled supply voltage of circuits used in mobile systems, but not the battery voltage, reduces duty cycle of BCs and hence the conduction time of the main switch. Both the high switching frequency and the reduced main switch conduction time inevitably impose response-time constraint on the current sensor design. As a result, techniques to design fast-response on-chip current sensor is definitely required and worth to develop.

In this paper, techniques to design fast-response on-chip current sensor is successfully developed and thoroughly discussed. Section II first discusses the response-time limits

of existing designs. Then the proposed design and its advantages are introduced. Results and discussions are shown in Section III. Finally, conclusion is given in Section IV.

II. DESIGN OF FAST-RESPONSE ON-CHIP CURRENT SENSOR

A. Response-Time Limits

To successfully develop techniques to design fast-response on-chip current sensor, it is necessary to understand the response-time limits of existing designs. Fig. 1 shows the schematic of a generic current sensor used in a current-mode controlled BC. Switches S_1 and S_2 are used to activate and deactivate the current sensor by connecting the inverting input of error amplifier (V_M) to either the switching node (V_X) or the input (V_{IN}) of BC. When the main power transistor (M_{MAIN}) is on, the current sensor is activated by turning on switch S_1 and off switch S_2 . Negative feedback forces the non-inverting input of error amplifier (V_P) tracked with the V_M node. As size of the sensing transistor (M_{SEN}) and the M_{MAIN} is in ratio (e.g. 1:1000), inductor current is down scaled and reproduced by the M_{SEN} , and is converted to voltage by the sensing resistor (R_{SEN}). Once the M_{MAIN} is off, current sensor is deactivated by switching off S_1 and on S_2 so that the drain-to-source voltage of M_{SEN} is forced to zero by negative feedback of the error amplifier (EA). As negligible current flows through M_{MAIN} and hence M_{SEN} , voltage developed at the V_{SEN} node is therefore close to zero.

Fig. 1 Schematic of a generic current sensor used in current-mode controlled buck converter.

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Fig. 2 Impact of improper switching time of switch S_1 on the operation of current-mode controlled BC.

Although function of those switches is very simple, the time to switch them on and off not only has a great impact on the response time of current sensor but also the control of BC. When the M_{MAIN} is on, the V_X -node voltage is pulled from approximately zero volt to almost V_{IN} . It is necessary to ensure the S_1 is on and S_2 is off at the time where V_X is settled. Otherwise, any intermediate V_X -node voltage (e.g. $V_{IN}/2$) is possible to be sampled and misinterpreted by the current sensor as very-large inductor current. Response time of current sensor is hence degraded as extra period of time is required by the sensor to settle from a misinterpreted large value to the actual value. More seriously, this misinterpreted large value is possible to trigger the current-mode controller to turn off the M_{MAIN} early than what supposing to be. This is illustrated in Fig. 2. In similar manner, switch S_1 should be off and S_2 should be on before the M_{MAIN} is ordered to fully turn off by the controller. Otherwise, the current sensor is possible to misinterpret a large inductor current again.

Another response-time limit is caused by the slew-rate of the EA. When every cycle the V_M node is routed from the V_X node to the V_{IN} node and vice versa, a voltage step is appeared at the V_M node. The EA is forced to either charge or discharge the gate of M_N by negative feedback until the V_P -node voltage is tracked with the V_M -node voltage. This delay time depends on the slew rate (SR) of EA that is expressed in equation (1)

$$SR = \frac{I_{EAMAX}}{C_{GMN}} \quad (1),$$

where I_{EAMAX} is the maximum output current of EA, and C_{GMN} is the gate capacitance of the transistor M_N .

However, conventional EA with tail-current bias has a very strong tradeoff between its slew-rate and its quiescent-current consumption. This is because I_{EAMAX} of such EA is limited by its tail current. As a result of it, current sensor in [1] and [3] with tail-current-biased EA is not suitable for BC with MHz-range switching frequency.

In [2] and [4], voltage mirror instead of conventional EA is used in the current sensor to force the V_P -node voltage tracking with the V_M -node voltage. The corresponding schematic is shown in Fig. 3. It is observed that drain current of M_1 to charge the gate of M_N can be much larger than the value of biasing current (I_B) when the V_M node is just routed from the V_{IN} node to the V_X node. However, the current to discharge the gate of M_N is fixed and defined by the I_B . It means that such current sensor can only have fast response on a sudden increase but not a sudden decrease inductor current.

Fig. 3 Schematic of current sensor with voltage mirror having asymmetrical response time.

B. Proposed Design

To enable a fast-response current sensor without the aforementioned limits, it is necessary to control the time to switch S_1 and S_2 and to develop an error amplifier with high slew-rate and low quiescent current consumption. Fig. 4 shows the proposed current sensor. Both the switches S_1 and S_2 are implemented by PMOS transistors. To achieve the on an off time of switch S_1 mentioned before, the gate of switch S_1 is connected to the gate of M_{MAIN} . For the switch S_2 , its gate is connected to the intermediate stage of the buffer used to drive the M_{MAIN} as shown in Fig. 4. This connection makes S_2 tuned off before the S_1 turned on, from which the V_M node is much easier to be pulled down when S_1 is on.

Fig. 4 Schematic of proposed current sensor.

As S_2 is on before the S_1 turned off, it is guaranteed that the V_M -node voltage can be quickly pulled up to the level of V_{IN} when S_1 is off. This prevents unwanted voltage spikes at the current sensor output when the M_{MAIN} is off.

The error amplifier used in the proposed current sensor is constructed by two constant current sources (I_B), two current mirrors with matched PMOS transistors in cross-coupled connection, and one current mirror with matched NMOS transistors. When the V_M node is routed from the V_{IN} node to the V_X node, transistor M_{P22} can provide larger current, which is much larger than the value of I_B , to quickly charge the gate of M_N . Once the V_M node is routed from the V_X node to the V_{IN} node, a current larger than I_B can be provided by transistor M_{P12} . With the current mirror constructed by two matched NMOS transistors (M_{N1} and M_{N2}), this large drain current of M_{P12} is redirected to quickly discharge the gate of M_N . When the V_P -node voltage is tracked with the V_X -node voltage, current of both the M_{P12} and the M_{P22} is defined by the constant current source I_B . As a result of it, the proposed design is able to have large slew-rate at transient response and low quiescent current consumption at steady-state operation. Moreover, large slew-rate in both positive and negative direction is achieved. Therefore, symmetrical response time is successfully achieved in the proposed current sensor.

Another advantage of the proposed current sensor is its improved accuracy on sensing small inductor current. As shown in Fig. 4, part of the current of M_{SEN} is used by the error amplifier. If the current of M_{SEN} is very small, it is possible that the current injected into the R_{SEN} is much smaller than that of M_{SEN} . Large error is occurred. To minimize this error, part of the current used by the error amplifier is reused and injected into the R_{SEN} . This can be easily understood by steady-state analysis. In steady-state operation, the V_P -node voltage is well tracked with the V_M -node voltage. It means that current of all transistors inside the error amplifier is very close to the value defined by the current source I_B . As the error amplifier consumes $2xI_B$ current from the M_{SEN} , source terminal of transistors M_{N1} and M_{N2} are connected to the R_{SEN} such that $2xI_B$ current is injected into the R_{SEN} . Therefore, current of R_{SEN} becomes very close to that of M_{SEN} . Accuracy on sensing small inductor current is hence improved.

III. RESULTS AND DISCUSSIONS

The proposed current sensor is designed in a 0.35- μm CMOS process. To minimize the power consumption, size of M_{SEN} is designed to be one thousand times smaller than that of M_{MAIN} . The R_{SEN} is designed to be 500 Ω so that 0.5V at the V_{SEN} node represents 1A of inductor current flowing through the M_{MAIN} . The current source I_B is designed to be 2 μA . To reduce quiescent current consumption, size of M_{P12} and M_{P22} is set to be the same as that of M_{P11} and M_{P21} . Total quiescent current consumed by the error amplifier is only 8 μA . Table I summarize the size ratio of transistors inside the proposed current sensor.

To exam the response time of the proposed current sensor, extensive simulations are done. Fig. 5 shows the simulated result where the current sensor is in a BC with 2.7-V V_{IN} (e.g. minimum voltage of lithium battery), 0.9-V output, and 4-MHz switching frequency. It is shown that the output of current sensor is quickly jumped from zero volt to $\sim 0.22\text{V}$ that represents the $\sim 440\text{-mA}$ minimum inductor current. The output of current sensor is able to track with the increasing inductor current and quickly jump from $\sim 0.31\text{V}$, which represents the $\sim 620\text{-mA}$ peak inductor current, to zero volt. It is observed that unwanted voltage spike is greatly minimized. To further exam the response time of current sensor, the switching frequency is increased from 4MHz to 10MHz. As shown in Fig. 6, the current sensor still responds quickly at only 8- μA quiescent current.

TABLE I
SIZE RATIO OF TRANSISTORS OF PROPOSED CURRENT SENSOR

Transistors	Ratios
$M_{MAIN} : M_{SEN} : S_1 : S_2$	1000 : 1 : 1 : 1
$M_{P11} : M_{P12}, M_{P21} : M_{P22},$ & $M_{N1} : M_{N2}$	1 : 1

Fig. 5 Simulated response of proposed current sensor in a buck converter operating at 4MHz.

Fig. 6 Simulated response of proposed current sensor in a buck converter operating at 10MHz.

IV. CONCLUSION

Techniques to design fast-response on-chip current sensor applied in MHz-switching BC are successfully developed. The first technique minimizes the voltage spike, which occurs at the sensor output when it is started or disabled, by carefully control both its activation and deactivation time. This voltage-spike minimization helps to prevent regulation error. Another technique enables the error amplifier used in the sensor with large slew-rate in both pull-up and down direction with very low quiescent current consumption. Response time of current sensor is greatly improved without huge power consumption. The reuse of part of error amplifier quiescent current also helps to improve the sensor accuracy, especially when the inductor current is small. As a result of them, the proposed current sensor is very applicable to switching converters with very high switching frequency or to an application where accurate current waveform is required for control purpose or information acquisition.

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