High-Voltage Bidirectional Current Sensor

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Abstract
A high-voltage (HV) bidirectional current sensor using fully-differential amplifier (FDA) is designed and analyzed in this investigation. The FDA balances bidirectional input voltages of the HV current sensor by a feedback loop. Thus, the proposed design can detect the direction and magnitude of the current by the difference between the output voltage and a reference voltage. Detailed analysis, including the method of the HV current sensor, is reported. All-corner post-layout simulations of the proposed HV current sensor justify the maximum error $\leq$ 1.43 % in the range of $\pm 8 \sim \pm 20$ V.

1. Introduction

The current sensor has been recognized as an important circuit for battery management systems (BMS) [1], where the current sensor is used to ensure the safety by detecting over-current and enabling an emergency stop. Moreover, the current estimation also plays a key role in SOC assessment. That is, the accuracy of SOC is significantly affected by the accuracy of the current sensor. Nevertheless, Hall-effect current sensor is the most popular device for current sensing [2]. It has two advantages, which are low cost and good reliability. However, the accuracy of the Hall-effect current sensor is lower than that of many other current sensors. Therefore, a compensator is usually used with Hall-effect current sensor for accuracy. Insulated-gate bipolar transistor (IGBT)-based approaches are also quite popular for current sensing in high-voltage systems, because IGBT can convey a large current. Motto and Donlon proposed an IGBT-based current mirror structure to sense large currents [3]. However, since IGBT is mainly power devices good for discretes or drivers, it is not a good option to be integrated with other signal processing control circuit on the same die. A HV current sensor is then proposed in this work to resolve the mentioned problems.

2. Architecture of HV current sensor

Referring to Fig. 1, a HV current sensor is shown, including a current sensing resistance (R_{sense}), a capacitor, four resistors, an FDA, two HV PMOS, a current mirror, and an output resistor (ROUT). First, a very small sensing voltage (V_{sense}) is generated by I_{sense} via R_{sense}. Furthermore, the RC filter consisting of the 4R and C filters unwanted high-frequency noise. Because the FDA has a negative feedback, a virtual short exists across the FDA's input terminals ($V_{ip} \cong V_{in}$). Therefore, the current of the M1 and M2 is proportional to $(V_{sp} - V_{ip})/2R$ and $(V_{sn} - V_{ip})/2R$. A current difference between I_{M1} and I_{M2} will be obtained. Then, the difference is converted into an output voltage (VOUT) by ROUT. VOUT is written as Eqn. (1).

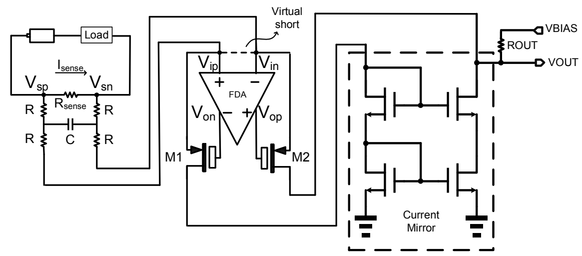

Figure 1. The proposed HV current sensor

$$VOUT = V_{sense} \cdot A_v + VBIAS \tag{1}$$

where A_v is the total system gain of the proposed design, V_{sense} equals to $V_{sp} - V_{sn}$. A_v can be written as follows.

$$A_v = ROUT/2R \tag{2}$$

Based upon Eqn. (1) and (2), VOUT is re-organized as follows.

$$VOUT = \frac{V_{sense} \cdot ROUT}{2R} + VBIAS \tag{3}$$

Therefore, I_{sense} can be indirectly estimated by VOUT as follows.

$$I_{sense} = V_{sense}/R_{sense} = \frac{(VOUT\text{-}VBIAS) \cdot 2R}{ROUT \cdot R_{sense}} \tag{4}$$

Assume the left side of current mirror is a reference current. When V_{sp} is higher than V_{sn}, VOUT is lower than VBIAS to inject current into current mirror. It means that the battery is in discharge mode. By contrast, when V_{sp} is lower than V_{sn}, VOUT is higher than VBIAS to drain current from current mirror. It means that the battery is in charge mode. Hence, not only can this work sense the current, but also detect the direction thereof.

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3. Implementation and Simulation

The proposed HV current sensor is carried out using TSMC 0.5 μm CMOS high voltage mixed signal based LDMOS USGAL 2P3M polycide (T50UHV). Fig. 2 shows the layout of the proposed HV current sensor. The core area is 420.9 × 569.3 μm^2.

The all-corner post-layout simulation of the proposed HV current sensor is shown in Fig. 3. When the sensing voltage range is -200 ~ 200 mV, the output voltage range, VOUT, is 2.6 ~ 5.4 V. The proposed HV current sensor has the worst-case 1.43 % sensing error when V_{sense} equals to 50 mV as shown in Fig. 4. The average error is +0.33 % and -0.77 % in two directions, respectively, with maximum error range 0.7 ~ -1.5 % (≤3σ).

The performance comparison of the proposed design and several recent works is tabulated in Table 1. Notably, the proposed design is the only solution to detect the direction of the current. In addition, the Input voltage works in the range of ±8 ~ ±20 V, with the maximum error 1.43 %.

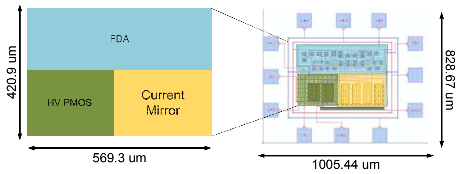

Figure 2. Layout of the proposed HV current sensor

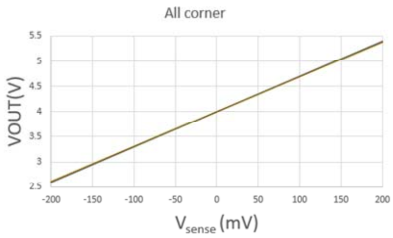

Figure 3. All-corner post-layout simulation results

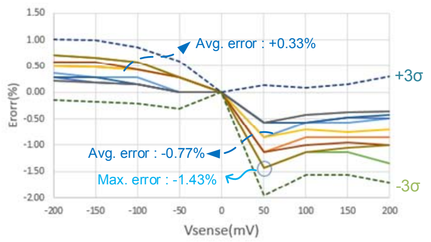

Figure 4. The sensing voltage error distribution

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Table 1. Performance comparison of HV current sensors

	[4] TPE	[5] TENCON	[6] INTELEC	This work
Year	2014	2015	2015	2017
Process	0.5 μm CMOS	0.25 μm BCD	PCB	0.5 μm CMOS
Input Voltage Range (V)	2.7 ~ 4.5	36 ~ 55	1 ~ 12	±8 ~ ±20
Core Area (mm^2)	2.25	1.58	N/A	0.24
Power (mW)	N/A	N/A	N/A	37
Avg. Error (%)	N/A	N/A	N/A	+0.33 & -0.77
Max. Error (%)	4	2.5	3.3	1.43
Direction detection	NO	NO	NO	YES

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