ST Microelectronics – How to make a high-voltage, high-side current sensor with a low-voltage precision op amp

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Dedicated current-sense amplifiers which can handle high common-mode voltages are the designer's common choice when implementing a high-side current-sensing circuit. But dedicated devices have some limitations: in particular, they are unsuitable for use in applications in which the common-mode voltage exceeds 70V. So what is the best way to precisely measure a current in this circumstance?

On first consideration, a classic 5V, low-voltage operational amplifier might seem completely inappropriate for this kind of measurement. In fact, with the use of just a few external components it is possible for low-voltage amplifiers to sense a current accurately without any common-mode voltage limitation at all.

Example application: a motor-control system

The operation of this circuit may be illustrated through an example application, measuring via a shunt resistor the current of an industrial motor operating from a 150V power supply, as shown in Figure 1. In order to precisely measure the full range of currents, even down to very low values, a 5V precision op amp is to be used.

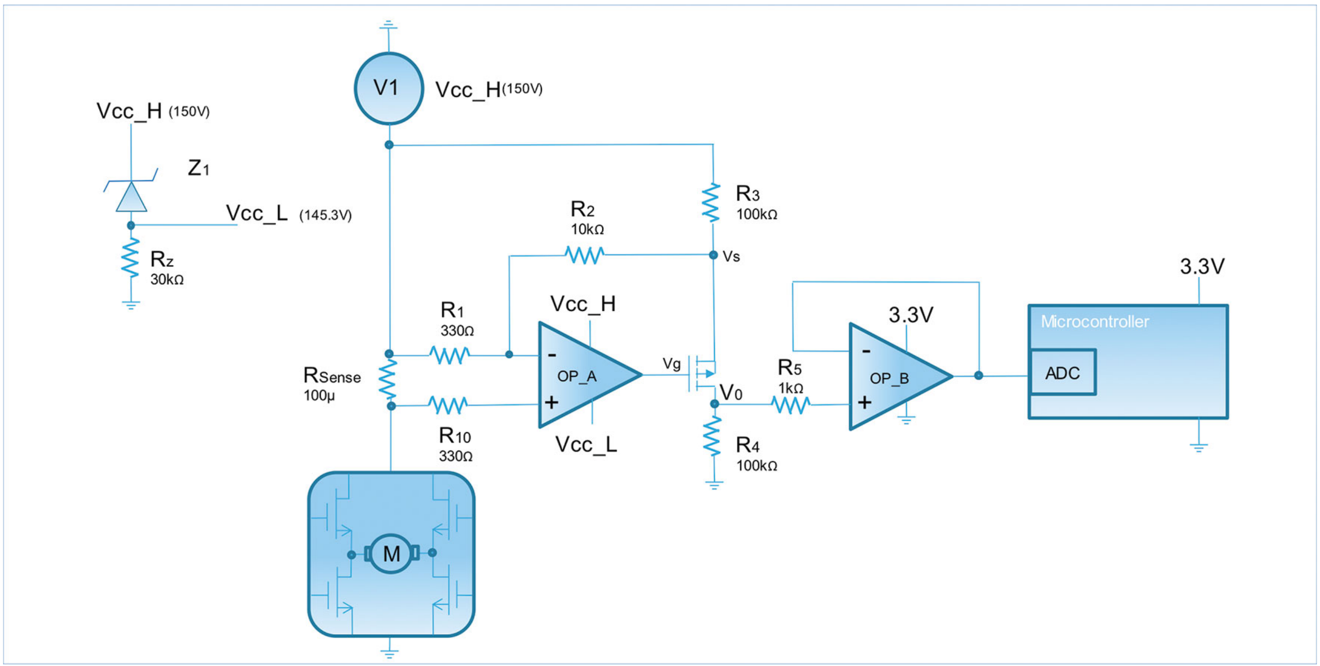

Fig. 1: Typical application circuit of a current sensor for an industrial motor

But will the 150V supply voltage burn up the op amp? Not if the V1 voltage is used to generate the positive power supply, VCC_H, for the first op amp, OP_A in Figure 1. This is possible because Z1, a BZT52C4V7S Zener diode from Diodes which has a 4.7V breakdown voltage, provides the negative power supply, VCC_L, for OP_A. This produces a 4.7V supply for OP_A, the difference between VCC_L at 145.3V and VCC_H at 150V.

The resistance, Rz, is used to bias the Zener diode with around 5mA, and to provide a return path for the op amp's bias current of around 40μA.

The sensor voltage, VSENSE, is determined by the current flowing through the shunt resistor, RSENSE; it is amplified by the R1, R2, R3 and R4 resistors.

A p-MOSFET sources an accurate output current proportional to the current flowing into the shunt resistor. With the R4 resistor, it generates an output voltage, Vo, with respect to ground which is proportional to the high-side current. This output voltage from the first stage of amplification can be given by the equation:

$$Vo = \frac{Vsense}{R1} \cdot \frac{R4}{R3} \cdot (R1 + R2 + R3)$$

The second op amp, OP_B, is required to buffer the output voltage. A resistor, R5, may be added in order to protect the integrated ESD diode of OP_B against any high current that might flow to the Input pins at start-up.

The maximum current drawn by the motor is 100A. So with a 100μΩ shunt resistor, the maximum sensor voltage is 10mV. The maximum output voltage is dependent on the sensor voltage, and the resulting output current across R4. As this voltage is to be digitised inside a microcontroller, this output voltage must not exceed 3.3V.

In order for this circuit to work properly, the values of the components must be carefully calculated. The main consideration is the requirement for a low gate-source voltage to the MOSFET, ensuring that the output of OP_A is not saturated.

This calls for a low drain-source current through the MOSFET: to achieve this, R4 needs a high resistance value. And in order to avoid any saturation of the output of the op amp, the gain relative to the op amp, OP_A, given by the ratio R2/R1 should not be too high.

Inevitably this results in some compromise over the choice of the various components' values, which must be calculated with this equation:

$$|Vgs\max| < Vzener - \frac{R3.(R1+R2)}{R4.(R1+R2+R3)}.Vo\_max$$

Where:

Vgs max = gate-source voltage needed to allow a current into the transistor of ID_max = (Vo_max)/R4

Vzener = VCC_H – VCC_L

The basic operation of the current-sensing circuit is clear from the above. The accuracy of its current measurements is limited mainly by the mismatch of the resistances as well as by the offset of the amplifiers, and the design therefore needs to take these error sources into account.

Impact of the mismatch of the resistances

The first equation above calculates the output voltage on the assumption that the resistances used are perfectly matched. Unfortunately, in practice they will not be, as all resistors show some variance from their nominal value.

The error in the gain attributable to the mismatch of the resistances is given by the following formula:

$$V0 = \frac{Isense*Rshunt}{R1}.\frac{R4}{R3}.(R1+R2+R3).[1+\left(\frac{2R1+4R2+2R3}{R1+R2+R3}\right).\,\varepsilon\alpha\ +\ \varepsilon Rshunt\ ]$$

Where:

ea = the precision of any of the resistances

eRSHUNT = the accuracy of the shunt resistor

From this equation, it is clear that the resistance R2 has a bigger impact on the error than the other resistances. Therefore its value should be as low as possible: 10kΩ. Note also that the sum of R1 and R3 should be high and unbalanced in order to achieve the required gain. Ideally R1 should be low to keep noise to a minimum.

Effect of input-offset voltage

Another error must be taken into consideration: the input-offset voltage. This application uses the

TSZ121, a chopper amplifier, because it features a very low input-offset voltage: 8µV over the full temperature range of -40°C to 125°C. Input-offset error has a marked effect on measurement accuracy, especially when a very small current has to be measured.

The transfer function may be used to compensate for the input-offset voltage, expressed as follows:

$$Vout = \frac{(Vsense \pm Vio1)}{R1} . \frac{R4}{R3} . (R1 + R2 + R3) \pm Vio2$$

Where:

Vio1 = the input offset of the first op amp (OP_A)

Vio2 = the input offset of the second op amp (OP1_ B).

As the TSZ121 has an extremely low input-offset voltage, Vio2 can in practice be ignored.

Total error

To estimate the total error of the output, the designer must add the mismatch of the resistances and the offset of the op amps. Then the output voltage can be calculated with this equation:

$$Vo = \frac{(Isense*Rshunt)}{R1} . \frac{R4}{R3} . (R1 + R2 + R3) . \left[1 + \left(\frac{2R1+4R2+2R3}{R1+R2+R3}\right) . \ \varepsilon\alpha \ + \ \varepsilon Rshunt \right] \pm \frac{Vio}{R1} . \frac{R4}{R3} . (R1 + R2 + R3)$$

The graphs in Figures 2 and 3 show the maximum error expected over the operating-temperature range, with reference to the accuracy of the shunt resistor.

Conclusion

Dedicated amplifiers are commonly used to implement high-side current measurement. But in applications in which the common-mode voltage is higher than 70V, the measurement should be done with a conventional 5V op amp.

This Design Note shows that high-side current sensing can be implemented using the TSZ121 precision amplifier combined with a Zener diode, which enables it to operate in the 5V power-supply range, and with a level-shift transistor.

Errors due to the resistances and amplifiers may be compensated for by applying the equations shown in this note. The use of ±0.1% precision resistors is advisable in order to ensure the accuracy of the current measurements.

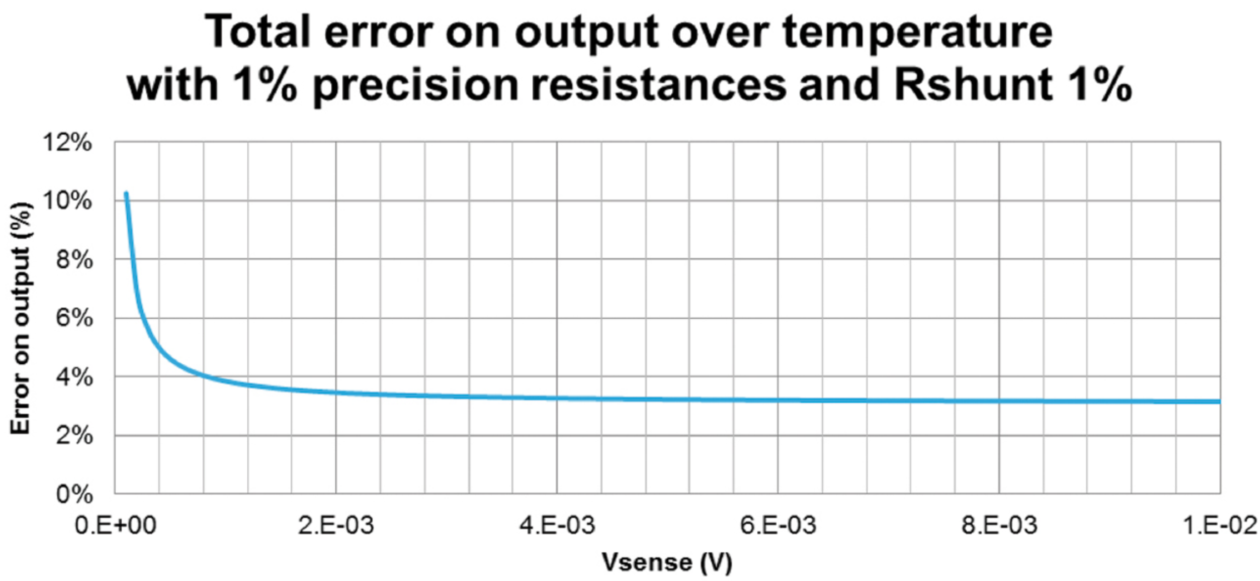

Fig. 2: Total error assuming 1% resistance mismatch with ±1% shunt resistor accuracy

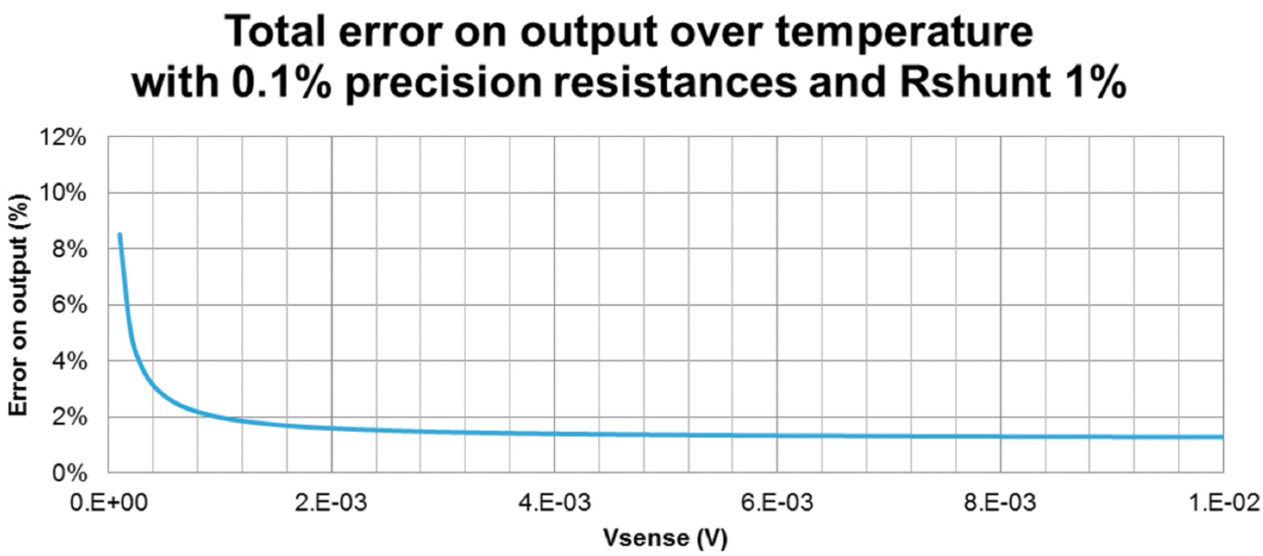

Fig. 3: Total error assuming 0.1% resistance mismatch with ±1% shunt resistor accuracy

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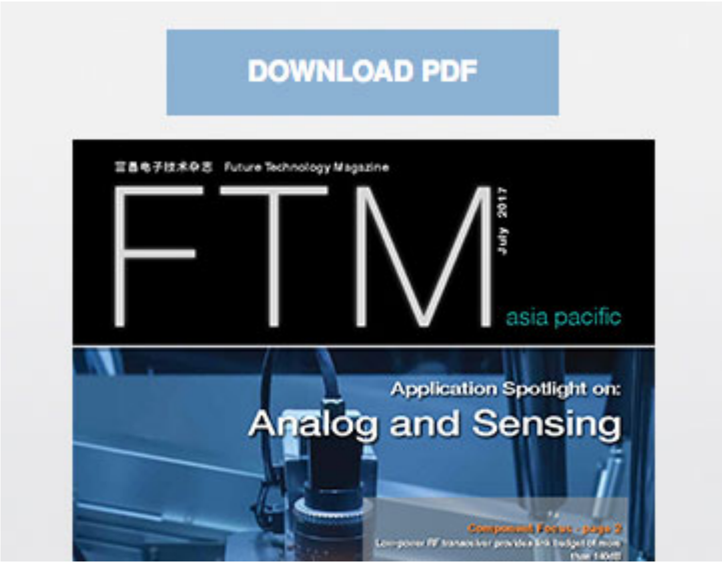

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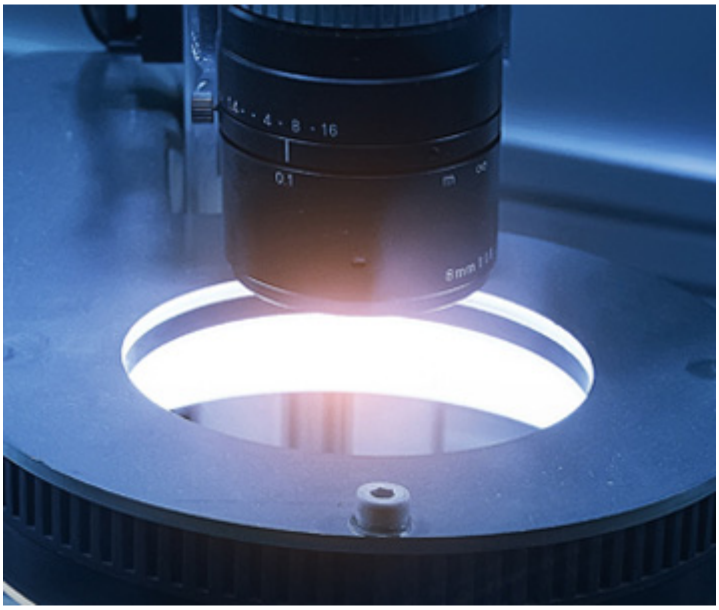
Site Pages 

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