AN4835
Application note

High-side current sensing for applications using high common-mode voltage

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Introduction

This application note explains how to extend the common input voltage range of a standard operational amplifier (op amp) to realize a high-side current sensing.

When a high-side current measurement is needed, we generally use specific amplifiers from the TSC10x family. These high-side current sensing amplifiers can amplify input differential signals at a common-mode voltage well beyond their power supply rail.

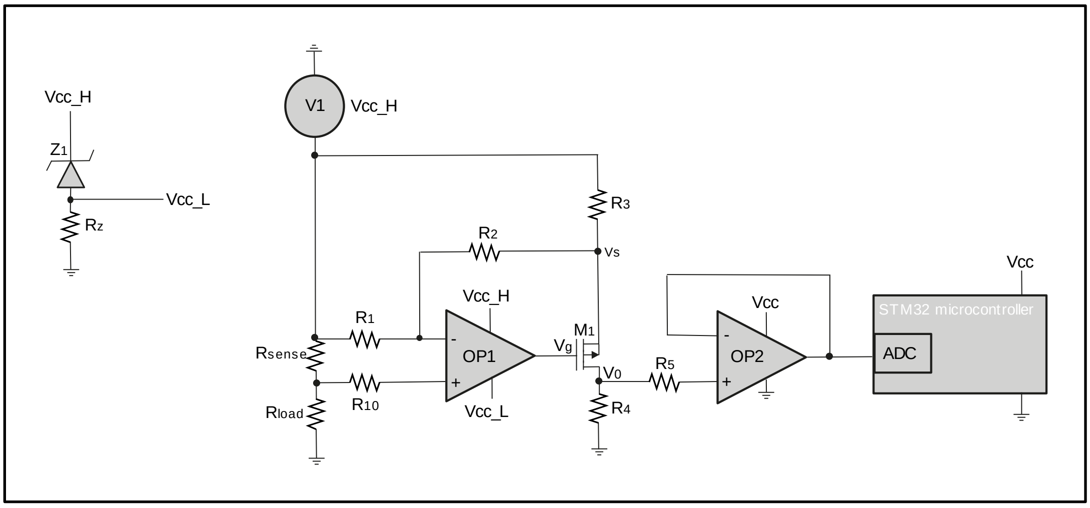
Even if the TSC10x can work with a common-mode voltage largely above its power supply, it is limited to 70 V when using the TSC103.

In this application note, we will see how to overcome this limitation to realize a high-side current sensing simply by using a standard op amp and some external components.

Contents

1 Schematic and description

Figure 1: General system overview



In this application, the power source, V1, works at 150 V. The main goal is to measure the current delivered by V1 thanks to a shunt resistor. To limit power dissipation in the shunt, it's value should be chosen as low as possible. If we follow this procedure, the Vsense (Isense * Rsense) generated through the shunt will also be small. To get a precise measurement for low current, a precision op amp such as the TSZ121 is used. The TSZ121 is a chopper op amp with an extremely low input offset voltage of 8 µV max. over temperature. It is also biased with a very low current of 40 µA.

The measured current value is then treated with a STM32 microcontroller which works with a power supply of 3.3 V. But, the TSZ121 is a 5 V op amp, and in this application the common voltage is up to 150 V.

To use the TSZ121 in its operating condition, i.e. without burning it by applying 150 V on its input, the V1 voltage is used to generate a positive power supply (Vcc_H) for the first op amp (OP1). Thanks to a Zener diode, with a 4.7 V breakdown voltage, the negative power supply (Vcc_L) of the TSZ121 is generated. In this way the TSZ121 is powered with 4.7 V (in this example, Vcc_H = 150 V and Vcc_L = 145.3 V).

The resistor, Rz, is used to bias the Zener diode (~5 mA) and provides a return path for the bias current of the TSZ121 (~40 µA).

The voltage, Vsense, is the result of the current flowing through Rsense, and it is amplified thanks to the resistors R1, R2, R3, and R4.

The P-MOSFET, M1, sources an accurate output current proportional to the current flowing into Rsense. Then, thanks to the R4 resistor, M1 generates a voltage, Vo, with respect to ground which is proportional to the high-side current. The voltage output of the first stage, can be given by *Equation 1*.

Equation 1

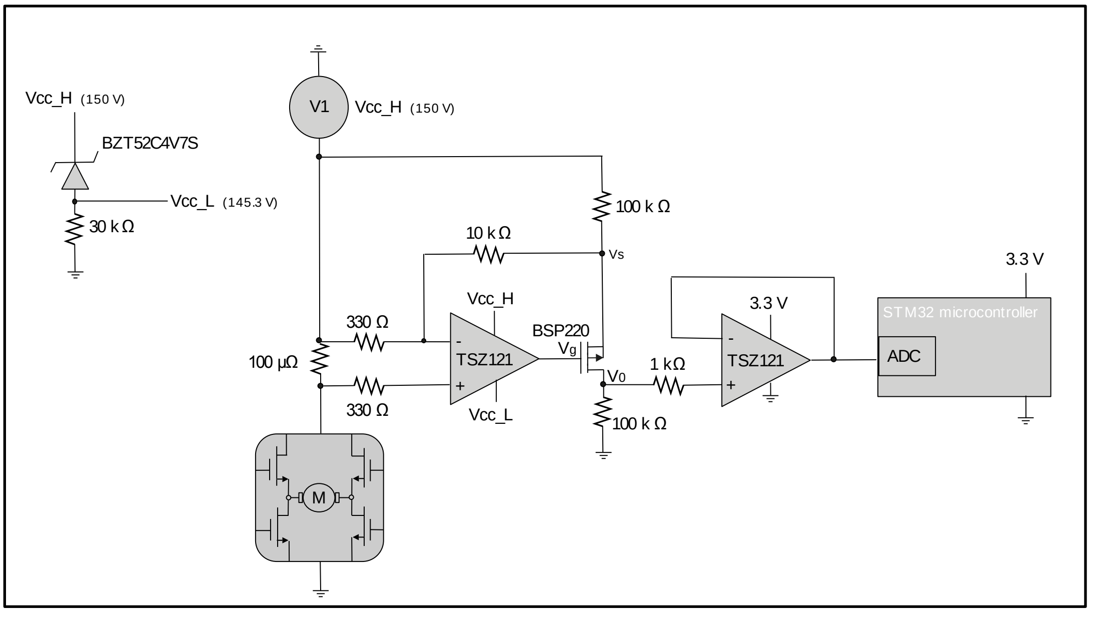
$$Vo = \frac{Vsense}{R1}\frac{R4}{R3}.(R1 + R2 + R3)$$

The second op amp, OP2, is necessary to buffer the Vo voltage. An R5 resistor may be added to protect the intrinsic protection diode of the OP2 in case a high current flows into the input pins at startup.

2 Application

In this section, we will consider a typical application used to measure the current of an industrial motor control powered with 150 V, as illustrated in *Figure 2*.

Figure 2: Typical application



The maximum current drawn by the motor control is 100 A. So, for a 0.1 mΩ shunt resistor, the maximum Vsense is 10 mV. The maximum output voltage is dependent on the Vsense voltage, and the resulting output current flowing across R4. As this current is treated by the ADC of the STM32 microcontroller, the maximum output voltage, Vo, must not exceed 3.3 V.

The gain of the whole system is given by *Equation 2*.

Equation 2

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

The values of the components must be carefully chosen for the system to work properly.

The main goal is to work with a low |Vgs| so as not to saturate the output of OP1.When the current |Ids| increases, |Vds| decreases, so |Vgs| must increase while Vs is decreasing. Therefore the gate voltage is limited by the low saturation of OP1 (Vcc_L) for a high Ids (see *Equation 3*).

Equation 3

$$|Vgs\ \max| < Vs - Vcc\_L$$

$$|Vgs\ \max| < Vzener - \left(1 + \frac{R2}{R1}\right).Vsense$$

As keeping Ids low helps the situation, it is better to choose a high value for R4.

To avoid any saturation of the op amp output, the gain, relative to OP1 and given by the ratio R2/R1 (*Equation 3*), should not be too big.

Consequently, there is a compromise to be made regarding the choice of component values (see *Equation 4)*.

Equation 4

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

Where Vgmax is the Vgs needed to allow a current into the transistor of Id_max = Vo_max/R4 and Vzener = Vcc_H - Vcc_L.

The P MOSFET transistor (BSP2220) is choosen with a breakdown voltage of -200 V to sustain the maximum voltage of the system.

In *Figure 2: "Typical application"* the voltage gain is set at 334.

3 Error analysis

We will now have a look at the precision of the "typical application" described in *Section 2: "Application"*. Some inaccuracy exists and it is mainly due to the mismatch of the resistors and the offset of the amplifiers.

3.1 Impact of resistor mismatches

Equation 1 gives a result of the output voltage by considering that the resistors are perfectly matched. Unfortunately, this is not the case, as the resistors have their own precision.

The error on the gain, due to the mismatch of the resistors, is given by *Equation 5*.

Equation 5

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

Where εα is the precision of any of the resistors and εRshunt is the accuracy of the shunt resistor. We can see that the R2 resistor has a bigger impact on the error than the other resistors. Consequently, its value must be as low as possible e.g. 10 kΩ is a good value for the TSZ121.

Considering *Figure 2: "Typical application"*, if the resistors are chosen with a precision of 1 %, the gain error due to the mismatch will be 2.2 %. For better accuracy, resistors with a precision of 0.1 % should be chosen. In this case, the gain error will be 0.22 %.

Note that the error due to the shunt accuracy should be added (1 % on the shunt means 1 % more on the total error).

We need to keep the following points in mind:

- Choose R4 as high as possible to have a low Ids current (*Equation 4*)
- Choose R2 as low as possible to limit total error (*Equation 5*)
- The sum of R1 and R3 should be high and unbalanced to achieve the gain required (*Equation 5*). Ideally, R1 should be low to limit the noise.

3.2 Impact of input voltage offset (Vio)

The second error that must be taken into account is the input voltage offset (Vio). The TSZ121 is a chopper amplifier with a very low Vio, 8 µV over temperature. This error becomes important especially when a very small current has to be measured.

The transfer function, taking the Vio into account, can be written as shown below in *Equation 6*.

Equation 6

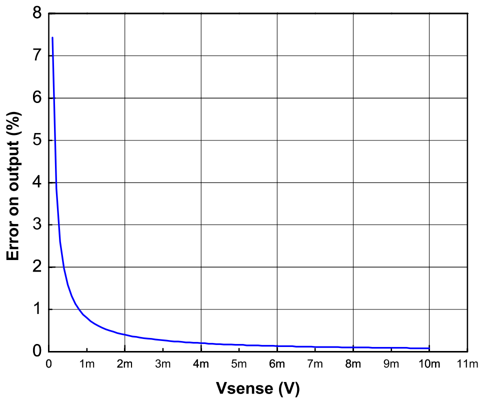
$$Vout = \frac{(Vsense \pm Vio1)}{R1} \cdot \frac{R4}{R3} \cdot (R1 + R2 + R3) \pm Vio2$$

Where Vio1 is the input offset voltage of the first op amp (OP1) and Vio2 is the input offset voltage of the second op amp (OP2).

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

Figure 3 below shows the accuracy over temperature for a different Vsense voltage using the value shown in *Figure 2: "Typical application"*.

Figure 3: Error on the output, with a different Vsense voltage, due to the Vio



3.3 Total error

To get some idea of the total error on the output, we must add the error due to the mismatch of the resistors and the error due to the input voltage offset of the op amp. The output voltage can be written as shown in *Equation 7*.

Equation 7

$$V0 = \frac{Isense*Rshunt}{R1}.\frac{R4}{R3}.(R1+R2+R3).[1+(\frac{2R1+4R2+2R3}{R1+R2+R3}).\varepsilon a + \varepsilon Rshunt] \pm \frac{Vio}{R1}.\frac{R4}{R3}.(R1+R2+R3)$$

In the figures below, we see the percentage error on the output depending on the current flowing through the shunt resistor when we use resistors with a precision of 1 % or 0.1 % respectively.

Figure 4 and *Figure 5* represent the maximum error expected over temperature without taking the shunt accuracy into account.

Figure 4: Total error on the output over temperature assuming a resistance of 1 %

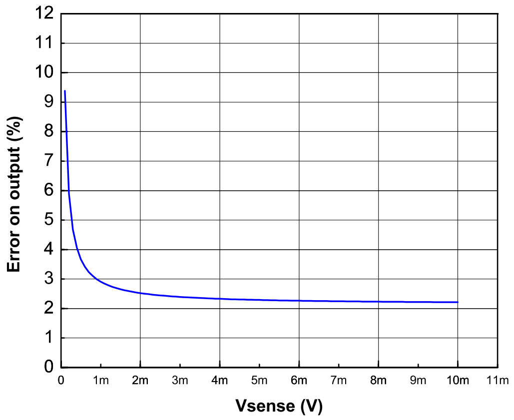


Figure 5: Total error on the output over temperature assuming a resistance of 0.1 %

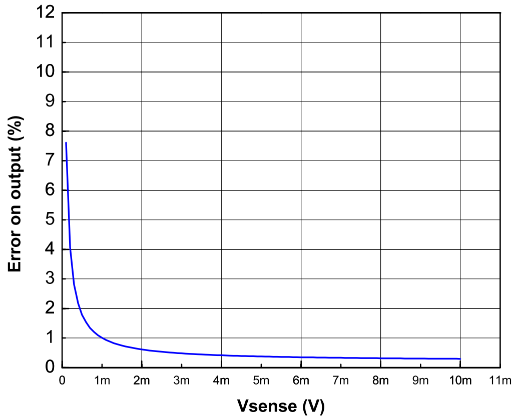


Figure 6 and *Figure 7* represent the maximum error expected over temperature when we take the shunt accuracy into account.

Figure 6: Total error on the output over temperature assuming a resistance of 1 % with Rshunt of 1 %

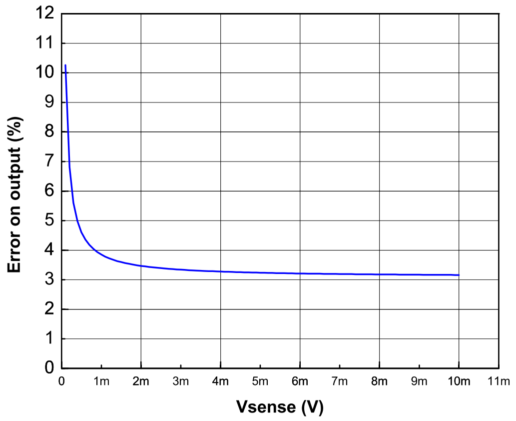
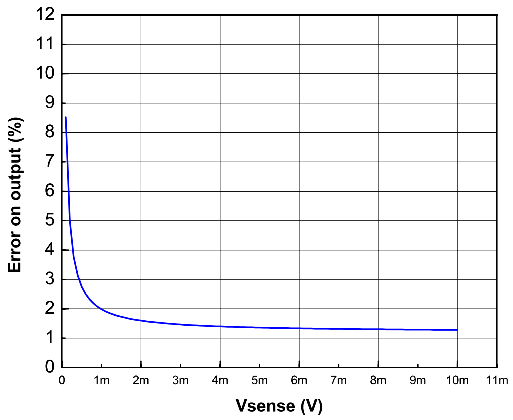


Figure 7: Total error on the output over temperature assuming a resistance of 0.1 % with Rshunt of 1 %

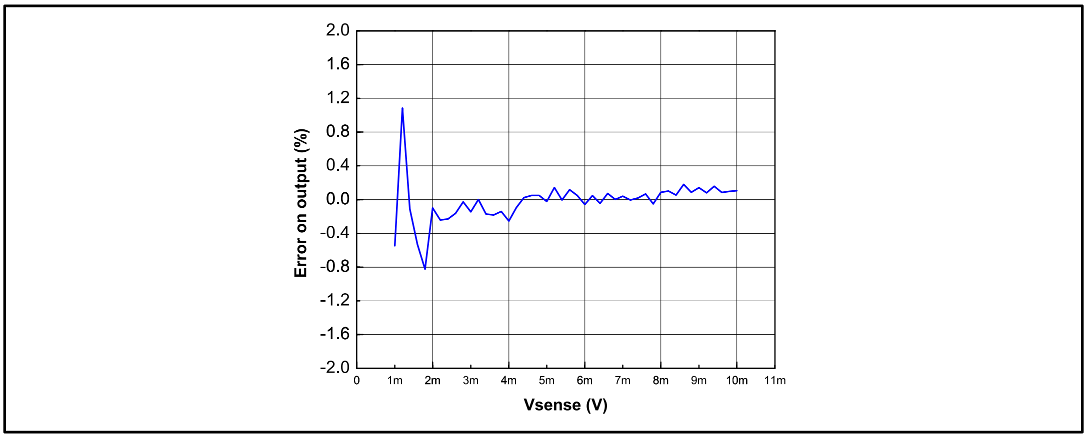


4 Application measurement

Figure 8 below shows the results of application board measurements made with the respect to the schematics of *Figure 2: "Typical application"*. Resistances of 1 % precision were used. Vsense varies from 1 mV to 10 mV.

This measurement does not take into account the shunt accuracy.

Figure 8: Error on the output vs. Vsense at 25 °C



5 Conclusion

To realize high-side current sensing measurements, some dedicated circuits of the TSC10x family amplifier are commonly used. But, in applications where the common-mode voltage is higher than 70 V this kind of measurement should be done with a conventional 5 V op amp.

Effectively high-side current sensing can be achieved using a TSZ121 which is a low-voltage, precision amplifier. It is combined with a zener diode to work in a 5 V range and a level shift transistor.

Errors due to the resistors and amplifiers used must be taken into account. To obtain good accuracy for the current measurement it is advised to use 0.1 % precision resistors.

6 Revision history

Table 1: Document revision history

Date	Revision	Changes
21-Nov-2016	1	Initial release

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