Understanding Ratiometric Conversions

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ABSTRACT

The primary factor that establishes the accuracy in most measurement systems is the reference. Ratiometric measurements change the reference from being a voltage or current to a component such as a resistor that has much tighter tolerances. This application note discusses the accuracy limits of both analog-to-digital conversions and different ratiometric configurations.

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1 Analog-to-Digital Conversion

An Analog-to-Digital converter (ADC) measures an analog voltage and converts that measurement into a digital representation of the analog voltage. Typically, this conversion follows a procedure similar to that described by Equation 1:

$$\text{ADC result} = \frac{V_{IN}}{kV_{REF}}\left(2^{N} - 1\right) \tag{1}$$

where *k* is generally a 1 or a 2.

The ADC determines which of the 2^N values most closely reflects the input voltage.

2 ADC Accuracy Limits

When making any electrical measurement, there are several factors that limit the absolute accuracy of that measurement. In particular, factors that affect the accuracy of an ADC measurement include the following: noise, offset error and drift, gain error and drift, reference voltage (V_{REF}) accuracy and drift, and integral non-linearity (INL). Some of these inaccuracies, such as offset error and gain error, can essentially be removed through device calibration. Noise can be reduced through averaging and other filtering techniques. Even INL can be compensated for by measuring several voltages across the input range and using that information to mathematically correct the ADC values. The remaining errors that cannot be compensated for or removed, and which are a major concern for high resolution systems, are the V_{REF} errors.

Any errors in the reference will directly affect the accuracy of the conversion results. For example, if a reference can maintain an accuracy of less than the voltage of ½ LSB, then the accuracy of the measurement is likely to be affected only by the other factors discussed previously. It is reasonable to accomplish this degree of performance with references for 8-bit ADCs. But as converters increase in resolution—from 12 to 16 or even 24 bits—the reference becomes more and more critical, compared with other factors, with regard to the overall accuracy of the system.

There are many variables that affect the accuracy of the reference voltage. Some of these variables include initial error, temperature coefficient, noise, thermal hysteresis, long term stability, settling time, line regulation and load regulation. Each of these elements influences the accuracy available from the reference. Table 1 shows the required accuracy for different ADC resolutions.

Table 1. Reference Accuracy Requirements

ADC Resolution (Bits)	Levels (2^N)	Reference Requirement (½ LSB)
8	256	1953ppm of FS
12	4,096	122ppm of FS
16	65,536	7.6ppm of FS
24	16,777,216	0.0298ppm of FS

The November, 1999 Analog Applications Journal includes an article on the performance of precision voltage references(1). This investigation demonstrates that a very good reference (specifically, the Thaler VRE3050) with a constant load will have an initial accuracy error of up to 100ppm. Over temperature, the error will approach 200ppm. A less accurate "precision" reference (such as the Maxim MAX6250) has initial accuracies of 400ppm, increasing to more than 750ppm when temperature variations are included. Therefore, it is only on 8- or 12-bit systems that it is possible to use a reference that has errors of less than ½ LSB.

3 Ratio Measurements

Quite often, the measurement of a voltage is actually being used to measure another quantity such as resistance. In such instances, the measurement can be set up to read the resistance more directly as a ratio to a reference resistor. By putting the same current through both the sensor resistance and the reference resistor, the ADC result will be a measure of the ratio of the two resistors. (See Equation 2.)

$$\text{ADC result} = \frac{i_{\text{EXCITE}} \bullet R_{\text{Sense}}}{i_{\text{EXCITE}} \bullet R_{\text{REF}}}\left(2^N - 1\right) = \frac{R_{\text{Sense}}}{R_{\text{REF}}}\left(2^N - 1\right) \qquad (2)$$

As one can see, the accuracy of the measurement is now set with the reference resistor. The current is no longer critical to the accuracy of the measurement. All that is required is that the current does not change during the conversion, or over-range either the reference or analog inputs of the ADC. Since it is much easier (and cheaper) to purchase high precision resistors than voltage references, the accuracy can be set to a higher level. Figure 1 shows an example ratiometric circuit using a resistance temperature detector (RTD).

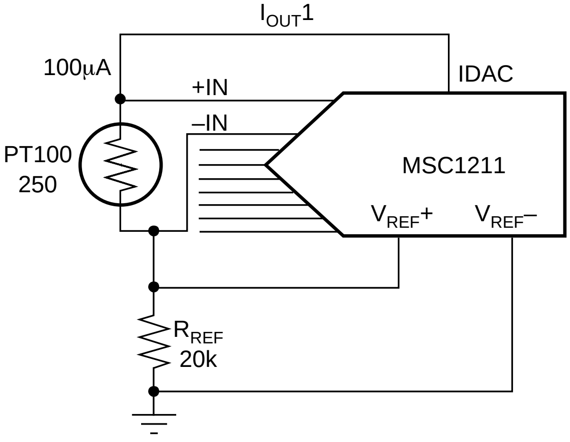

Figure 1. Ratiometric RTD Measurement

Because of the differential reference inputs on the MSC1211 ADC, the voltages on the reference resistor can be either more positive or negative than the sensor. The only limitation is to assure that the voltages for the reference inputs meet the input requirements as specified in the product data sheet. The IDAC output is also limited, in order for the output voltage to be less than 1.5V below the supply voltage. Using 100μA as the excitation current, the maximum voltage for the reference input would be slightly more than 2V, depending on the temperature of the thermistor or RTD. Figure 2 shows the same circuit as Figure 1, except that the sensor is now grounded, and the current flows through R_{REF} before it reaches the sensor.

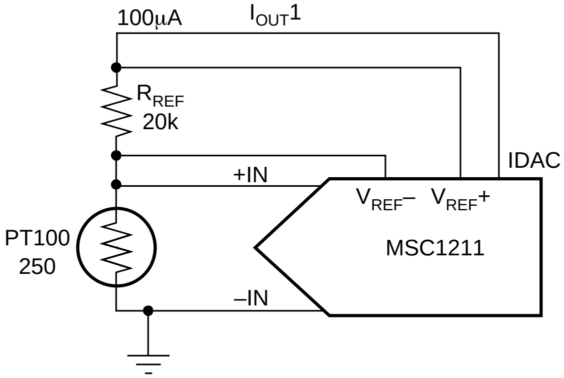

Figure 2. Grounded Sensor

Another possibility is to use a bridge excitation voltage as the reference voltage, as shown in Figure 3. In this case, any changes in the excitation voltage will be seen in both the bridge output voltage and the reference voltage.

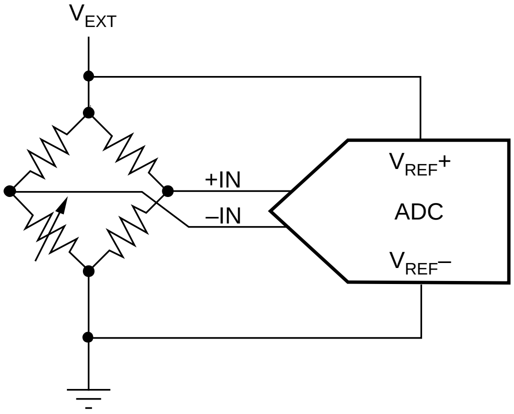

Figure 3. Bridge Circuit Ratiometric Measurement

The measurement voltage (V_{IN} = IN+ – IN-) is directly related as a measured ratio (MR) of the measurement parameter and the excitation voltage, as seen in Equations 3 and 4.

$$\text{ADC result} = \frac{V_{IN}}{V_{REF}}\left(2^{N} - 1\right) \tag{3}$$

$$\text{ADC result} = \frac{V_{\text{EXT}} \bullet R}{V_{\text{EXT}}}\left(2^{N} - 1\right) = MR\left(2^{N} - 1\right) \tag{4}$$

For a strain gauge, the MR is a measure of the applied force to the full-scale force.

$$\begin{gathered} MR = \frac{kF_{\text{STRAIN}}}{F_{\text{MAX}}} \\ \text{ADC result} = \frac{kF_{\text{STRAIN}}}{F_{\text{MAX}}}\left(2^{N} - 1\right) \end{gathered} \tag{5}$$

If the actual voltage from the bridge sensor is small compared with the excitation voltage, then gain can be applied to the input signal before it is converted using the PGA of the ADC.

4 Single-Ended Ratiometric Measurements

Of course, ratiometric measurements can also be made with single-ended measurements, as shown in Figure 4.

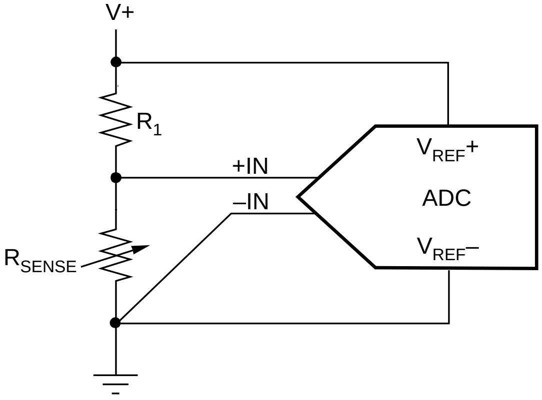

Figure 4. Single-Ended Measurement

As we examine Figure 4, though, we see that it looks very much like Figure 2. R_{SENSE} represents the variations in resistance in response to sensor stimulus. The ADC measures the voltage at IN+ and then determines what the resistance value is. Once the resistance is known (such as a thermistor), then the measured quantity can be determined (that is, temperature). To determine the resistance, the ADC result has to be used in combination with the value of V_{REF}, which means that this method does not produce an exact ratiometric measurement. This circuit could be changed, however, so that the resistance is measured directly. R_1 would then become the reference resistor (as shown in Figure 5), thus making the ADC result the ratio of R_{SENSE} to R_1. This means that for a single-ended measurement to actually be ratiometric, the sensor output must be between 0V and full-range. The ADC result will provide that ratio, and will not be dependent on the actual excitation voltage. This effect also means that many single-ended measurements will not be ratiometric.

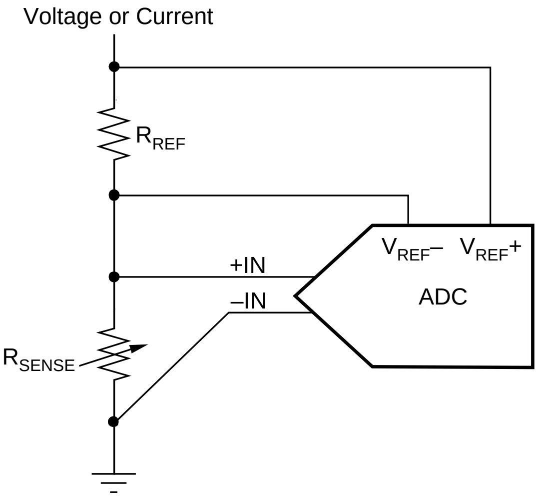

Figure 5. Single-Ended Converted to Ratiometric Resistance

5 Additional Circuits

There are some additional circuit configurations that can be useful when setting up a ratiometric measurement system. One convenient way to create a current source is with an op amp driving a transistor. The resistor connected to the emitter of the transistor sets the current by the voltage set across that resistor. That same resistor could be used for the reference or voltage for a ratiometric measurement, as shown in Figure 6.

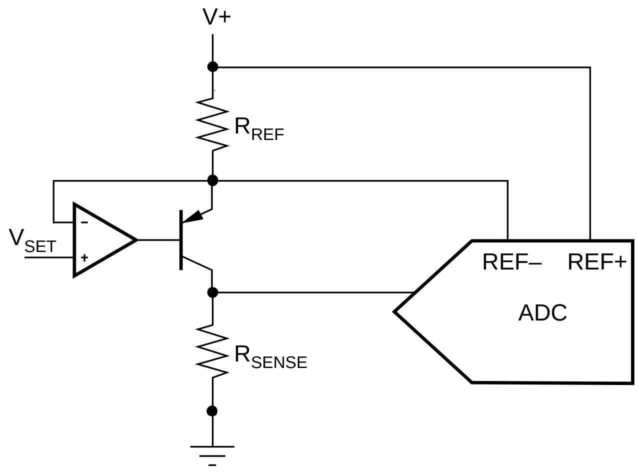

Figure 6. Current Set Resistor for Reference

If the current in R_{REF} is not the same as the current in R_{SENSE}, there will be a gain error in the measurement. To reduce this error, a hi-beta or darlington transistor should be used.

The configuration of the input channels with the MSC12xx products further allows the inputs to be both the low and high inputs of differential measurements. This feature means that eight differential measurements can be set up, as shown in Figure 7.

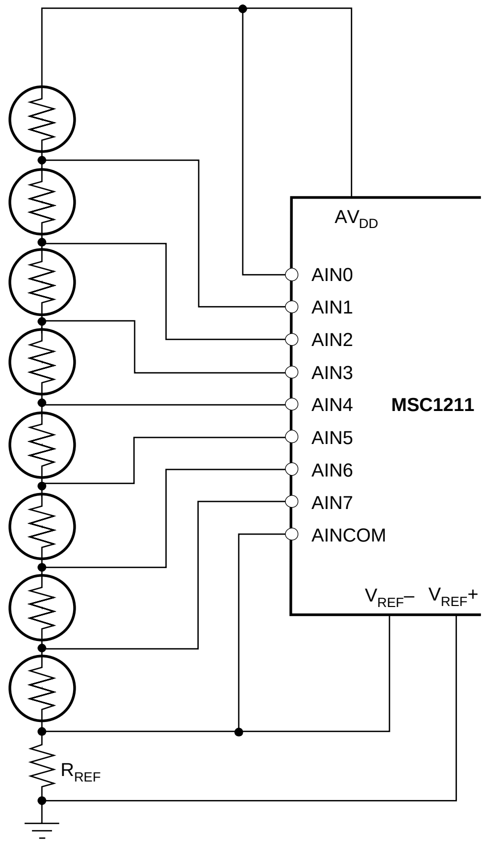

Figure 7. Eight Differential Measurements

6 Reference Resistance Accuracy

Any changes in the value of the reference resistor over time or temperature will have an effect on the accuracy of the measurement. With a calibrated source, the reference resistance errors can be corrected. This source will be in the units of what is being measured. For example, if temperature is being measured, then a calibrated temperature can be applied and the ADC result examined. This result and the correct ADC result can be used as a ratio to multiply future measurements and compensate for the shift in the reference resistor value.

Conclusion

A voltage reference has a direct influence on the accuracy of output that is possible with an ADC. If the measurement can be arranged such that the ADC result is a ratio of the input and a precision element such as a resistor, then much higher precision results can be obtained. A circuit that has the appearance of being ratiometric does not assure the user that the benefits of ratiometric measurement will be obtained. Stray capacitance, inductance and resistance in the reference connections can degrade the expected performance. Anything that limits the correct voltage on the reference or ADC inputs will also be a limiting factor for the overall accuracy.

References

1. Miller, P. and Moore, D. (1999.) Precision Voltage References. Analog Applications Journal, 11/99. http://www.ti.com/sc/docs/apps/msp/journal/1999_nov.htm (Also available as slyt010b.pdf at www.ti.com; keyword search.)

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