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APPLICATION NOTE 3998

Calculating Temperature Coefficient (Tempco) and Initial Accuracy for Voltage References

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Abstract: The primary purpose of a voltage reference (V_{REF}) is to establish system accuracy. An analog-to-digital converter (ADC), for example, uses a reference voltage to set its full-scale input level. The following discussion explains how a tradeoff between initial accuracy and temperature coefficient (tempco) can broaden your selection of voltage references while meeting a given requirement for system accuracy. The calculations presented determine precisely the tempco needed for a given value of initial accuracy, and vice versa.

Any typical ADC application specifies a range of analog voltages to be digitized by the ADC. To fit a standard input-voltage range, these analog signals must generally be anti-alias filtered, buffered, and perhaps scaled in amplitude. Among the typical full-scale values specified for an ADC input, 2.048V and 4.096V are obviously useful in a digital system because they provide an integral number of millivolts for the bit value. A 12-bit ADC with 4.096V full-scale input, for example, gives bit values of $4.096 / (2^{12} = 4096) = 1\text{mV}$. An 8-bit ADC in the same system has a "granularity" of $4.096 / (2^8 = 256) = 16\text{mV/bit}$.

We assume that a digital system requires full resolution from the ADC—the output is reasonably correct and responsive to even a 1 LSB input change. As a consequence, we state that the total allowable conversion error is 0.5 LSB. To simplify the discussion, we assume it is a perfect ADC with errors contributed only by the reference. The worst-case error allowed from the V_{REF} is therefore 0.5 LSB (8mV for an 8-bit ADC).

Initial Accuracy

To lock the boundary conditions, we separate variables and temporarily assume the possibility of a V_{REF} having a tempco of zero, thereby assuming that all of its error comes from its initial accuracy. Note that 0.5 LSB (8mV for an 8-bit ADC) of error in a 4.096V output represents an error of 0.195%, and that a zero-tempco reference of that accuracy can have a potential error of 0.195% at any temperature.

Tempco

To again consider boundary conditions, assume for the moment that we have a V_{REF} with zero initial error at +25°C (where most voltage references are calibrated). All of its error must therefore come from its tempco, which can cause an error of no more than 0.5 LSB above or below 4.096V at the operating-temperature extremes. In other words, the tempco of V_{REF} for an 8-bit ADC must cause no more than 8mV of error at the operating-temperature extreme furthest from +25°C, whether hot or cold.

An actual V_{REF} exhibits both initial-accuracy and tempco errors, so we take the following approach:

- Determine the V_{REF} operating temperature range.
- Note the temperature extreme that is furthest from +25°C.
- Base all calculations on that extreme.
- Determine the reference output voltage (V_{REF}).
- Calculate 0.5 LSB as a percentage of full scale, which is the total accuracy for a zero-tempco part. An 8mV error in a 4.096V reference, for instance, is 0.195% of full scale.
- Calculate the worst-case tempco allowed in ppm/°C, assuming a perfectly accurate, zero-tolerance part at +25°C.
- Find suitable solutions using the technique illustrated below.

As an example, we assume an operating-temperature range of 0°C to +70°C and a 10°C rise inside the enclosure, giving a maximum V_{REF} temperature of +80°C. (The minimum V_{REF} temperature is the minimum operating temperature of 0°C.) A V_{REF} temperature of +80°C is 55°C hotter than +25°C and 0°C is only 25°C colder than +25°C, so we are concerned in this example with the hot extreme. For the maximum allowed error (0.195%), the tempco (assuming zero errors at 25°C) is $0.195\% / 55 = 0.00355\% = 35.5\text{ppm}/^\circ\text{C}$. (See discussion below for a reminder on why we convert from percentage to ppm.)

Figure 1 depicts this situation graphically. An actual voltage reference that just meets the requirements mentioned above is represented by any one of the multiple lines converging at the worst-case point in the upper right corner.

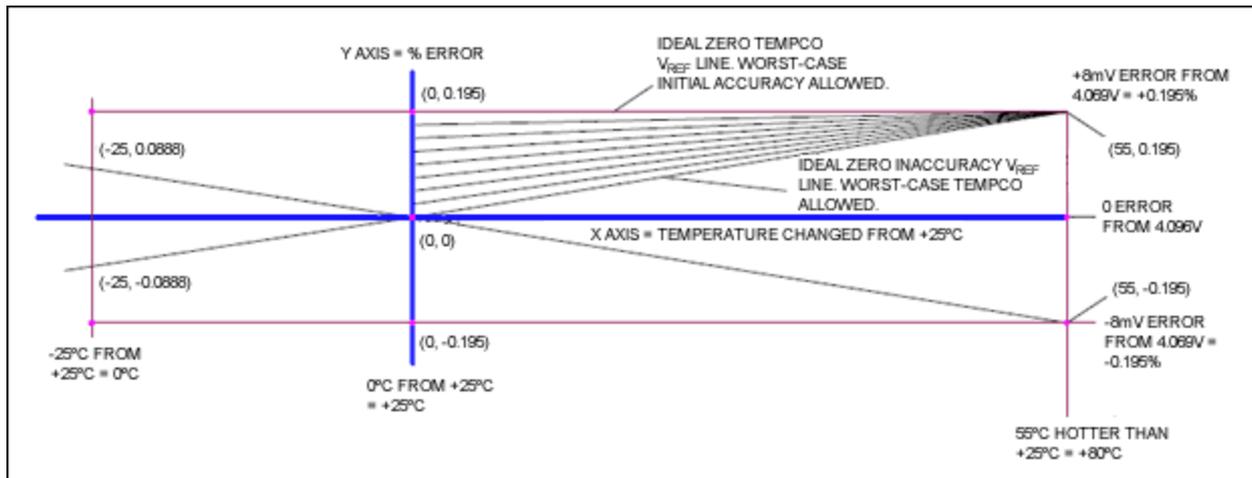


Figure 1. This graph shows allowable temperature coefficients for 1 LSB variation of reference voltage per degree of difference from room temperature.

The worst-case performance over temperature for the given V_{REF} can be represented by a line that passes through the point +80°C, 8mV (with respect to 4.096V). Use the formula for a line ($y = mx+b$), with variables defined as follows:

- $y = \text{error } (\%)$
- $m = \text{tempco } (\%/^\circ\text{C})$
- $x = \text{temperature difference from } +25^\circ\text{C}$
- $b = \text{initial accuracy at } +25^\circ\text{C}$

Notice that the temperature coefficient in these formulas is in terms of %/°C. This format provides units

that are consistent with error (e), which we express in %. Often, temperature coefficients are so small that they are more easily expressed as parts per million (ppm). The measurement unit "ppm" is 10,000 times smaller than the unit "%"—"%" means "parts per 100"—and the ratio of 100 to 1,000,000 is 10,000. For convenience, we can rename the variables as follows:

y becomes e
m becomes T_C
x becomes ΔT
b becomes A

Thus,

$$e = T_C(\Delta T) + A$$

Solving for the initial accuracy (A) makes this equation more useful:

$$A = e - T_C(\Delta T)$$

as does the solution for tempco (T_C):

$$T_C = (e - A) / \Delta T$$

For the V_{REF} in our example, all lines defining the various combinations of A and T_C must pass through the maximum-error point of (55°C, 0.195%):

$$0.195 = T_C(55) + A$$

Solving for A: Solving for T_C :

$$A = 0.195 - 55T_C \quad T_C = (0.195 - A) / 55$$

You can now evaluate a V_{REF} by plugging in its tempco (expressed as %/°C) and calculating its required accuracy. Alternatively, you can pick a given accuracy and use the second formula to calculate the maximum allowed tempco.

For example, the initial accuracy of a MAX6043BAUT41 reference is 0.1%, which is about half of 0.195%. Its tempco is 25ppm/°C. To determine whether this tempco is acceptable, substitute this accuracy in the second formula to give the allowable tempco:

$$\begin{aligned} T_C &= (0.195 - A) / 55 \\ &= (0.195 - 0.1) / 55 \\ &= 0.00173\%/^{\circ}\text{C} \\ &= 17.3\text{ppm}/^{\circ}\text{C} \end{aligned}$$

Thus, the 25ppm tempco of this part is not acceptable, because 17.3ppm or better is needed. Fortunately, the A-grade version (MAX6043AAUT41) has a tempco of only 15ppm/°C, and its initial accuracy is also better (0.06%). Manufacturers, such as Maxim, offer a wide range of voltage references with initial accuracies ranging from 2% down to 0.02%, as well as temperature coefficients ranging from 150ppm down to 1ppm.

Conclusion

Many factors have an effect on voltage-reference accuracy, including load regulation, line regulation, temperature hysteresis, and long-term drift (also known as stability). These effects are usually secondary, but they should be considered when a reference selected by the basic method (described above) is only marginally acceptable. To see several excellent application notes that cover not only these effects but also the pros and cons of available voltage reference technologies, go to [Voltage References](#).

A similar article appeared on the [Planet Analog](#) website in March of 2006.

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