Precision voltage references

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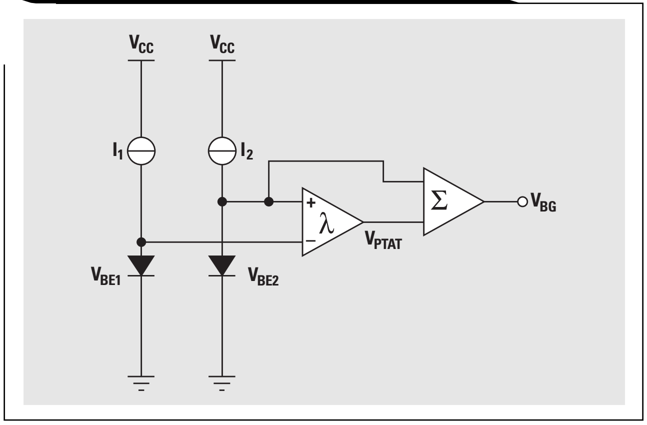
Introduction

One reason why designing a data conversion system is such a challenge is the fact that the system accuracy very much depends on the accuracy of the voltage established by the internal or external DC voltage reference. The voltage reference is used to produce a precise value of output voltage for setting the full-scale input of the data conversion system. In an analog-to-digital converter (ADC), the DC voltage reference together with the analog input signal is used to generate the digitized output signal. And in a digital-to-analog converter (DAC), the DAC selects and produces an analog output from the DC reference voltage according to the digital input signal presented at the input of the DAC. Any errors in the reference voltage over the operating temperature range will adversely affect the linearity and spurious free dynamic range (SFDR) of the ADC/DAC. Practically all voltage references vary with time or environmental factors such as humidity, pressure, and temperature. As a result most CMOS ADCs/DACs have internal references suitable only for applications demanding ≤12-bit resolution even though the converter may be capable of higher resolution. Modern CMOS converters operate from 3.3-V or 5-V supplies, which limits the on-chip voltage reference to a band-gap reference. By way of the external reference pins provided on the chip, an external precision reference can also be connected to a CMOS ADC or DAC. A precision external voltage reference has a much lower temperature coefficient, thermal hysteresis, and long-term drift than an on-chip band-gap voltage reference; therefore, in applications demanding high accuracy (14-bit or 16-bit ADCs/DACs), an external precision voltage reference is often required.

Precision voltage references are available with varying degrees of precision and initial accuracy over some operating temperature range. But often what is not obvious when reading a manufacturer's data sheet is how the initial accuracy of the device is affected by other key device parameters such as line regulation, load regulation, initial voltage error, output voltage temperature coefficient (TC), output voltage noise, turn-on settling time, thermal hysteresis, quiescent supply current, and long-term stability.

Figure 1. Band-gap reference circuit



The design origins

Modern voltage references are constructed using the energy-band-gap voltage of integrated transistors, buried zener diodes, and junction field-effect transistors. Each technology offers inherent performance characteristics that can be enhanced with compensation networks or additional active circuitry. The basis topologies for the band-gap, buried zener, and XFET references are shown in Figures 1, 2, and 3, respectively.

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Figure 2. Buried zener reference circuit

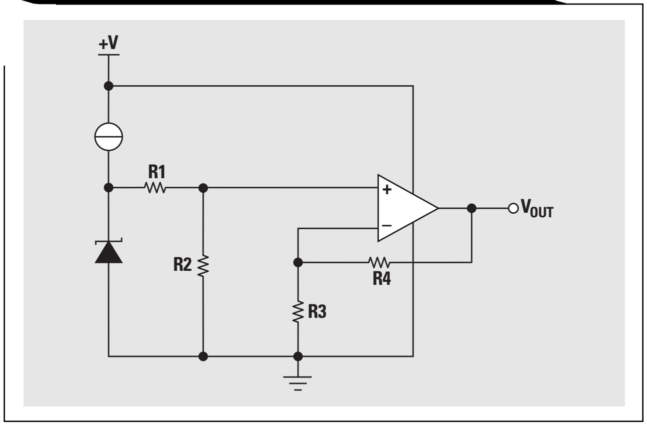
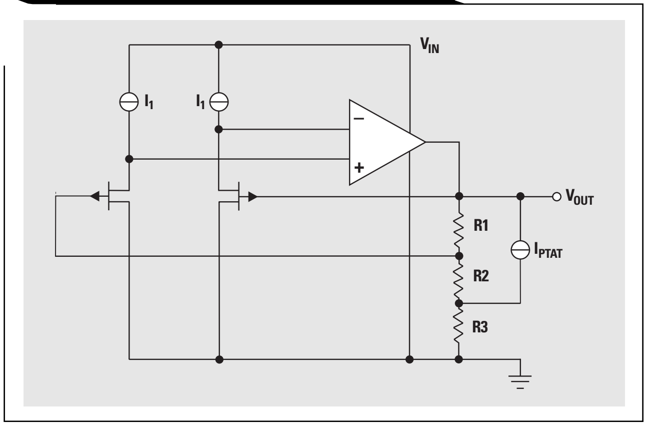


Figure 3. XFET reference circuit



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Band-gap reference

At its simplest, a band-gap reference is simply two transistors with different emitter areas used for generating a voltage proportional to absolute temperature. V_{BE1} and V_{BE2} have opposite temperature coefficients. The voltage V_{CC} is converted to a current I_1 and I_2 that are mirrored to the output branch. The output equation is

$$V_O = V_{BE1} + \lambda(V_{BE1} - V_{BE2}), \tag{1}$$

where λ is the scale factor, V_{BE1} is the base-emitter voltage of the larger of the two transistors, and V_{BE2} is the base-emitter voltage of the second transistor.

The band-gap references are widely used in ADC/DAC converters as well as for external reference source because they are fairly inexpensive. Generally, they are used in system designs where a maximum accuracy of 10 bits is required. Band-gap references typically have an initial error of 0.5–1.0% and a TC of 25–50 ppm/°C. The output voltage noise is typically 15–30 $\mu V_{p\text{-}p}$ (0.1–10 Hz) with a long-term stability of 20–30 ppm/1000 hrs.

Zener reference

The zener voltage reference and feedback amplifier shown in Figure 2 are used to provide a very stable output. A current source is used to bias a 6.3-V zener diode. The zener voltage is divided by the resistor network R1 and R2. This voltage is applied to the non-inverting input of the operational amplifier, which amplifies the voltage to the required output voltage. The amplifier gain is determined by the resistor networks R3 and R4, where G = 1 + R4/R3. A 6.3-V zener diode is used because it is the most stable zener diode over time and temperature.

The output equation is

$$V_O = \frac{R2}{R1+R2}\left(1+\frac{R4}{R3}\right). \tag{2}$$

Buried zener diode references are more expensive than band-gap references but provide a higher performance level. They typically have an initial error of 0.01–0.04%, a TC of 1–10 ppm/°C, and less than 10-$\mu V_{p\text{-}p}$ (0.1- to 10-Hz) noise. The long-term stability is typically 6–15 ppm/1000 hrs. Buried zener-based references are frequently used for 12-bit, 14-bit, and higher resolution systems because the performance of the buried zener-based references can be extended by incorporating nonlinear temperature compensation networks into the design. The compensation network is trimmed at several temperatures to optimize the electrical performance over the operating temperature range.

XFET reference

The XFET reference is a new reference technique that consists of two junction field-effect transistors, one of which has an extra channel implant to raise the pinch-off voltage. The two JFETs are run at the same drain current. The difference in pinch-off voltage is amplified and used to form a voltage reference. The general equation is

$$V_O = \Delta V_P\left(\frac{R1+R2+R3}{R1}\right) + (I_{PTAT})(R3), \tag{3}$$

where ΔV_P is the difference in pinch-off voltage between the two FETs and I_{PTAT} is the positive temperature coefficient correction current.

The simplified schematic for the XFET reference is shown in Figure 3.

The XFET references are relatively new and provide a performance level between band-gap and zener references. The initial error is typically 0.06%, a TC of 10 ppm/°C, and 15-$\mu V_{p\text{-}p}$ (0.1- to 10-Hz) noise. The long-term stability is 0.2 ppm/1000 hrs.

Reference selection for a 14-bit converter

Specified parameters for voltage references include line regulation, load regulation, initial voltage error, output voltage temperature coefficient (TC), output voltage noise, turn-on settling time, thermal hysterisis, quiescent supply current, and long term stability.

The most important parameters for data acquisition systems design are initial error, output voltage temperature coefficient (TC), thermal hysteresis, noise, and long-term stability of the voltage reference device.

Table 1 summarizes the major error sources for the three references that are compared in this application note. The data represents the highest grade for each

Table 1. Voltage reference major error sources

PARAMETER	THALER CORP. VRE3050 TEMPERATURE RANGE –40°C to +85°C	MAXIM MAX6250 TEMPERATURE RANGE –40°C to +85°C	ANALOG DEVICE ADR293 TEMPERATURE RANGE –40°C to +85°C
Output voltage	5.000 V	5.000 V	5.000 V
Initial error	0.01%	0.04%	0.06%
Temperature coefficient	0.6 ppm/°C	3.0 ppm/°C	8.00 ppm/°C
Noise (0.1–10 Hz)	3.0 $\mu V_{p\text{-}p}$	3.0 $\mu V_{p\text{-}p}$	15.0 $\mu V_{p\text{-}p}$
Thermal hysteresis 25°C→50°C→25°C	2 ppm	20 ppm	15 ppm
Long-term stability	6.0 ppm/1000 hrs.	20.0 ppm/1000 hrs.	0.2 ppm/1000 hrs.
Power supply	8.0 V–36 V	8.0 V–36 V	6.0 V–15 V
Turn-on settling time	10 µs	10 µs	<10 µs
Line regulation	15.00 ppm/V	35.00 ppm/V	100.00 ppm/V
Load regulation	3 ppm/mA	7 ppm/mA	100 ppm/mA
PSRR (10 Hz–900 Hz)	95 dB	90 dB	40 dB

respective model in the 8-pin plastic DIP package over the industrial temperature range (–40°C to +85°C). The poorest-performing references are band-gap type and are not included in this summary. Buried zener diodes have better overall performance than band-gap devices and the XFET references. The buried zener reference with a third-order temperature compensation network (VRE3050) is the best performer with respect to initial error, TC, and thermal hysteresis.

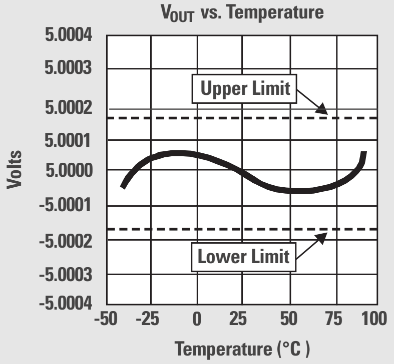
Explanation of parameters

Initial error—The output voltage tolerance of a reference after the device is turned on and warmed up. It is usually measured without a load applied. In many applications, initial error is the most important specification. Often instrument manufacturers will specify a reference with a tight initial error so they do not have to perform room-temperature systems calibration after assembly.

Temperature coefficient (TC)—A change in output voltage due to change in temperature usually expressed in ppm/°C. It is the second most important specification after initial accuracy. For many instrument manufacturers, a voltage reference with a temperature coefficient less than 1 ppm/°C makes it possible not to have to perform a system temperature calibration, a slow and costly process. Of the three TC specification methods (slope, butterfly, and box), the box method is most commonly used. A box is formed by the min/max limits for the nominal output voltage over the operating temperature range. The equation follows.

$$\mathrm{TC} = \left[\frac{\mathrm{V_{MAX}} - \mathrm{V_{MIN}}}{\mathrm{V_{nominal}} \times (\mathrm{T_{MAX}} - \mathrm{T_{MIN}})} \right] \times 10^6 \qquad \textbf{(4)}$$

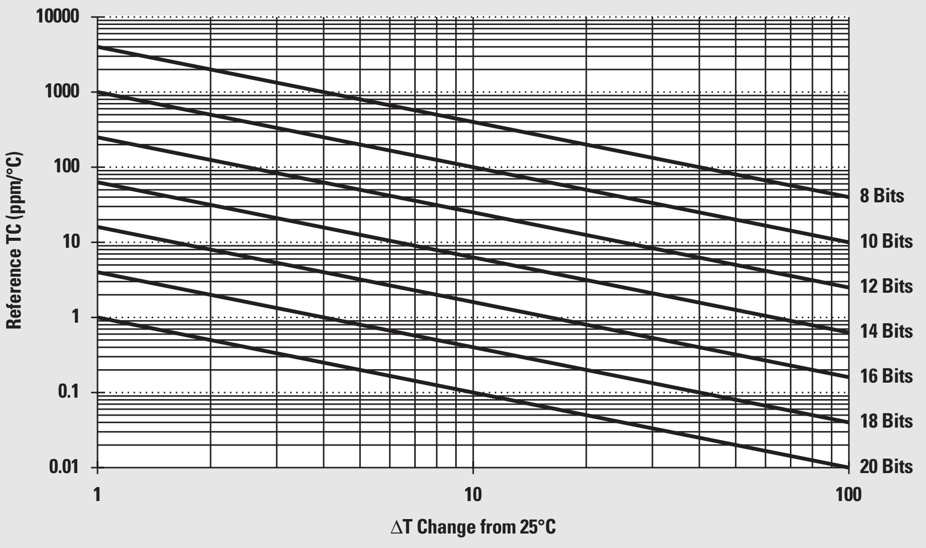
Figure 4. V_{OUT} vs. temperature



This method corresponds more accurately to the method of test and provides a closer estimate of actual error than the other methods. The box method guarantees limits for the temperature error but does not specify the exact shape and slope of the device under test. Assuming a 5-V reference with a 0.6-ppm/°C TC over the industrial temperature range, a plot of the box calculation method would appear as in Figure 4.

A designer who needs a 14-bit accurate data acquisition system over the industrial temperature range (–40°C to +85°C) will need a voltage reference with a TC of 1.0 ppm/°C if the reference is allowed to contribute an error equivalent to 1 LSB. For ½ LSB equivalent error from the reference, a voltage reference with a temperature coefficient of 0.5 ppm/°C would be needed. Figure 5 shows the required reference TC vs. ΔT change from 25°C for resolution ranging from 8 bits to 20 bits.

Figure 5. System performance vs. reference TC



Reference TC vs. ΔT change from 25°C for 1 LSB change

Thermal hysteresis—A change in output voltage as a result of a temperature change. When references experience a temperature change and return to the initial temperature, they do not always have the same initial output voltage. Thermal hysteresis is difficult to correct and is a major error source in systems that experience temperature changes of 25°C or more. Voltage reference manufacturers are starting to include this important specification in their datasheets.

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Noise (1/f and broadband)— Electrical noise on the output of a voltage reference. It can include wideband thermal noise and narrowband 1/*f* noise. Wideband noise can be effectively filtered with a simple RC network. 1/*f* noise is inherent in the reference and cannot be filtered. It is specified in the 0.1- to 10-Hz range. Low 1/*f* noise references are important in precision designs.

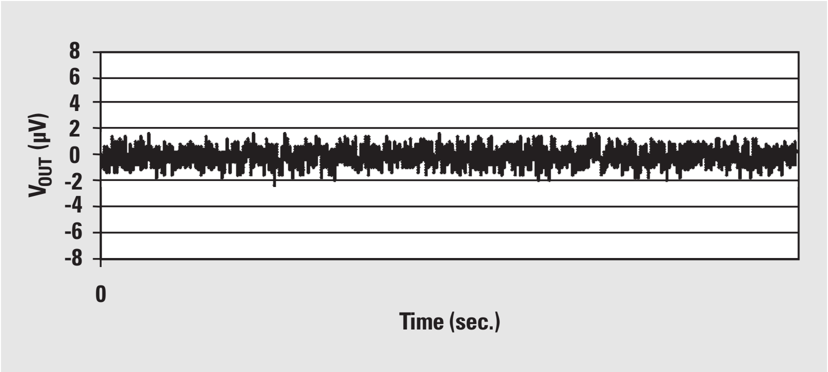
***Long-term drift*—**A slow change in output voltage that occurs over months of operation. Long-term drift is usually expressed in ppm/1000 hrs. In zener references, the long-term drift is typically 6 ppm/1000 hrs. and decreases at an exponential rate over time. Additional temperature burn-in of the reference can accelerate the stability of a zener reference. The XFET reference has excellent long-term stability—0.2 ppm/1000 hrs.

***Turn-on settling time*—**A change in voltage over a specified time interval after the power is applied. Most references settle to 0.1% in less than 10 µs. Turn-on settling time is important for portable battery systems that conserve energy by powering the circuitry only for short periods of time.

***Line regulation*—**An error produced by a change in the input voltage. This dc specification does not include the effects of ripple voltage or line transients.

***Load regulation*—**An error produced by a change in load current. Like line regulation, this dc specification does not include the effects of load transients.

Figure 6. 0.1-Hz to 10-Hz noise

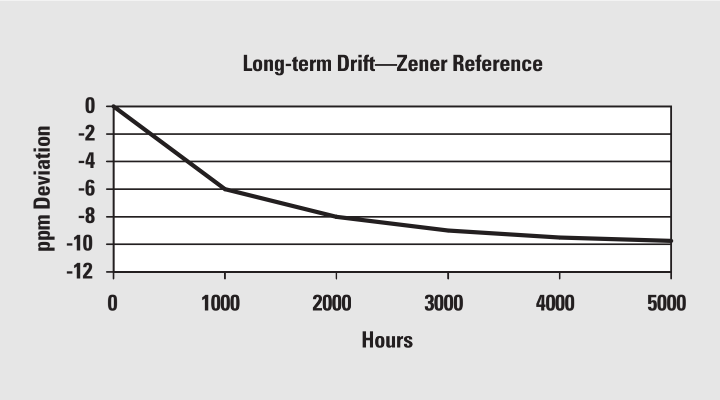


***PCB layout*—**Poor printed circuit board layout can adversely affect the performance of the reference. Poor layout can affect the output voltage, noise, and thermal performance of the device. Inherent stress in the PCB can also be transferred to the reference and can shift the output voltage.

Conclusion

It has been shown that a number of key parameters must be evaluated before selecting an external reference for a high-resolution data acquisition system. The XFET reference is suitable for systems that will be held at a constant temperature and where good long-term stability of the reference is important. In 14-bit conversion systems that are designed for the industrial operating temperature range, the VRE3050 is the preferred device over the MAX6250 because of its better initial error, TC, and thermal hysteresis performance.

Figure 7. VRE3050 long-term drift vs. hours



References

1. Analog Device Inc., Low Noise, Micropower, Precision Reference ADR293 Datasheet.
2. Paul R. Gray and Robert G. Meyer, *Analysis and Design of Analog Integrated Circuits*, 3rd ed. (John Wiley & Sons, Inc., 1992).
3. Maxim Corp., MAX6250, Low Noise Precision, +2.5 V +4.096 V +5 V Voltage Reference Datasheet.
4. Texas Instruments, THS1265, 12-bit, 65 MSPS, IF Sampling Communications A/D converter.
5. Texas Instruments, THS1470, 14-bit, 70 MSPS, IF Sampling Communications A/D converter.
6. Thaler Corp., Precision Reference VRE3050 Datasheet.