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TUTORIAL 719

Understanding Voltage-Reference Topologies and Specifications

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Abstract: This document discusses the three most popular topologies of voltage references. These include bandgap and buried zener topologies in three-terminal series voltage references, and zener topologies in two-terminal shunt voltage references. Also demystified are the definitions of common voltage-reference parameters.

Introduction

The first considerations in choosing a voltage reference are output voltage and initial accuracy. Often overlooked, however, are the various other data sheet parameters that can assume major importance in specific applications. Also, be sure to take into account the error budget when evaluating a data converter (ADC or DAC) together with a voltage reference. (See application note 4300, "Calculating the Error Budget in Precision Digital-to-Analog Converter (DAC) Applications.")

The following discussion of voltage-reference basics will help you better understand the common types of voltage references and the performance parameters associated with the most common voltage-reference topologies: the two-terminal shunt and the three-terminal series designs. (For guidance in choosing between a series and a shunt voltage reference, see application note 4003, "Series or Shunt Voltage Reference?" and application note 2879, "Selecting the Optimum Voltage Reference.")

Common Types of Voltage References

There are three common types of voltage references: charged capacitor, zener, and bandgap. The charged capacitor is little used (particularly in safety applications) because of instability caused by ionizing radiation. Alpha, beta, gamma, and cosmic rays or common x-rays in airports, hospitals, and transport security all discharge the capacitor (typically a 7mV change to the capacitor at each discharge).

Zeners, the second type of common voltage reference, are used in and out of avalanche mode. Most avalanche mode zeners are used where they would be most stable (i.e., at a sharp knee), above approximately 5.5V depending on the semiconductor process. True zeners at lower voltages work because of quantum mechanical tunneling. The majority of zener noise issues are due to associated impurities on the die surface, which are overcome with buried zeners by burying the zener inside or below the die surface.

The most common voltage reference uses a bandgap. This is the clever use of two transistor junctions with different current densities and hence different temperature coefficients. Two voltages with opposing temperature coefficients are subtracted from one another to make a nearly flat temperature curve. (For a bandgap calculator (i.e., PC emulator) and a manual that outlines the design steps needed to understand the operating parameters, see application note 5062, “Bandgap Reference Calculator Tutorial.”)

Series and shunt references could use any of the above technologies. The **Appendix** compares the series and shunt configurations with these various technologies.

Two-Terminal Shunt Reference

As its name implies, the shunt reference operates in parallel with its load (**Figure 1**). It can be viewed as a voltage-controlled current sink in which the controlling voltage is applied to its input terminal. With no load applied, the shunt reference sinks just enough current so that the voltage drop across R1 produces the desired output voltage (V_{IN} - I_{REF}R1 = V_{REF}). If, for example, V_{IN} = 6.0V and the desired V_{REF} is 5.0V, the reference I_{REF} creates a 1.0V drop across R1. The reference then makes I_{REF} adjustments as necessary to maintain 5.0V across its input.

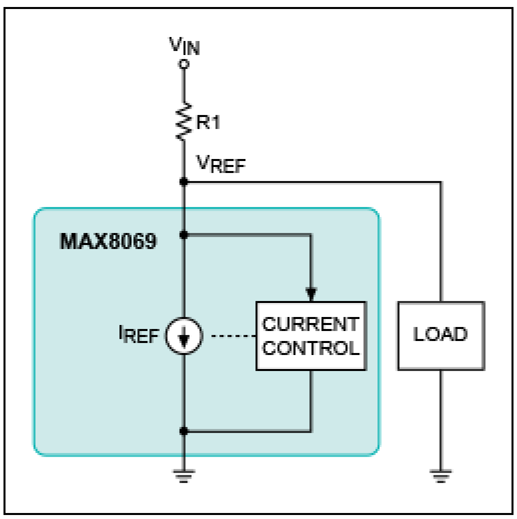

Figure 1. The shunt reference is connected in parallel with its load.

Now apply a load to the reference. I_{REF} no longer equals I_{R1}, because load current (I_L) produces part of the voltage drop across R1. The reference automatically reduces its sink current by the amount of I_L. Thus, the total current through R1 does not change (i.e., I_{REF} + I_L equals the original I_{R1}). I_{R1} is shunted between reference and load, hence the name "shunt reference." A shunt reference regulates the output voltage by adjusting its sink current to oppose changes in load current.

Three-Terminal Series Reference

The series reference operates in series with its load (**Figure 2**). It can be viewed as a voltage-controlled resistance in which V_{OUT} controls an internal resistance between the reference's input and output terminals. A series reference regulates by creating a voltage drop between its input and output; the voltage drop is equal to the product of the load current and the controlled internal resistance. With no load applied, the series reference draws a small amount of current (I_Q) through the internal resistance (R) to drop a voltage between the input and output necessary to produce the correct V_{OUT}.

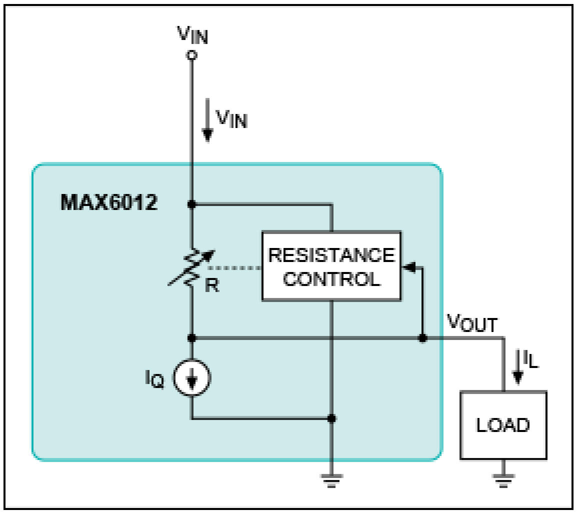

Figure 2. A series reference (its regulating part) is connected in series with its load.

As load current increases, the reference maintains the desired output voltage by changing R, as required, to produce the correct drop between input and output. Applying Ohm's Law, one notes that to maintain a constant drop between input and output, R must decrease as I_{OUT} increases.

Parameter-Measurement Units for References

The units that specify parameters such as accuracy differ among manufacturers. For specifying accuracy, the units in common usage include percentage of full scale (%), parts per million (ppm), decibels (dB), and voltage (V) or microvolts (µV). All are acceptable, but to make "apples-to-apples" comparisons you must be able to convert one unit to any other unit. These relationships are clarified below.

The accuracy calculator in **Figure 3** can aid in the design and analysis of voltage references and data-converter application circuits. It calculates the DC accuracy of an ideal data converter, covering both analog-to-digital converters (ADCs) and digital-to-analog converters (DACs). The DC accuracy of a data converter is the measure of the maximum deviation from the ideal linear transfer function. Although the HP® 50g handheld calculator is a convenient tool, there is also a free emulator that runs on many computers that use the Windows® operating system. For more information on the accuracy calculator, including the free emulator, see Steve's Analog Design Calculators.

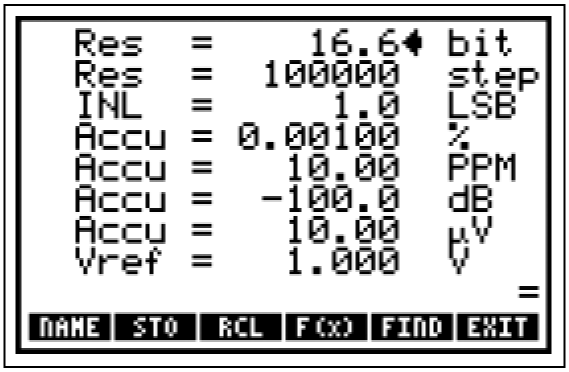

Figure 3. Accuracy in full scale (%), ppm, dB, V, and µV.

Accuracy Percentage of Full Scale

The most common means for stating reference accuracy is a percent of the nominal value, which is not even a unit. It probably follows the convention for expressing tolerance on resistors, capacitors, and inductors. Typical percent accuracy specifications for references are 1%, 1.5%, 2%, 5%, etc. Although percent accuracy is fine for comparing one reference with another, it does not provide specific information about how much the reference voltage fluctuates. What really matters is the variation in volts.

To determine the voltage deviation of a reference specified in percent accuracy, you multiply the reference's nominal output voltage by the percent accuracy and divide by 100. For example, a 2.5V reference accurate to ±1.5% has a deviation of:

$$\pm(2.5V \times 1.5)/100 = \pm0.0375V, \text{ or } \pm37.5mV$$

Because the reference error can be above or below nominal, the total deviation is twice this value, or 75mV. The total output voltage variation equals the nominal voltage plus or minus the error voltage:

$$2.5V \pm 0.0375V = 2.4625V \Leftrightarrow 2.5375V$$

Knowing these voltage limits for the reference gives you specific design boundaries for the circuitry supported by the reference.

Accuracy Parts per Million

Another reference accuracy unit found in data sheets is parts per million, or ppm. This unit is typically used to specify temperature coefficients and other parameters that change very little under varying conditions. For a 2.5V reference, 1ppm is one-millionth of 2.5V, or 2.5µV. If the reference is accurate to within 10ppm (extremely good for any reference), its output tolerance is:

$$2.5V \times 10/10^{-6} = 25\mu V$$

Converting this to voltage accuracy:

$$2.5V \pm 25\mu V = 2.499975V \Leftrightarrow 2.500025V$$

Converting to percent:

$$\pm(25E - 6V) \times 100/2.5V = \pm0.001\%$$

Accuracy in Bits

Use of the term "bits" as a unit, as in "16-bit reference," is somewhat confusing. Does it represent an actual measurement of accuracy, or does it mean that the reference is accurate enough for a 16-bit ADC? A 16-bit reference could be accurate to 1 LSB or 2 LSBs, so it cannot necessarily be considered sufficient for a 16-bit system. However, a reference "accurate to 16 bits" is specified with hard numbers.

If the unit is specified by an actual measurement, then "accurate to 16 bits" is simply the value of the parameter divided by the claimed bit accuracy expressed in decimal form. For example, a 2.5V reference, claimed to be 16-bit accurate (another extremely accurate tolerance for any reference), should deviate by no more than the decimal equivalent of 16 bits: 2^{16} = 65536. Therefore, 1 bit is 1/65536 of the total value. In this case, 2.5/65536 ≈ 8µV. If we assume 1-bit accuracy (±1 LSB), the output voltage can be 1 bit higher or lower than nominal, i.e., ±38µV.

Converting to voltage accuracy:

2.5V ±38µV = 2.499962V ⇔ 2.500038V

Converting to percent:

(±38E - 6V/2.5V) × 100 = ±0.0015%

Typical Parameters of Importance for References

Initial accuracy speaks for itself. It is the value set by any trimming. One can take a part off the shelf, connect it in a test circuit in automatic test equipment (ATE), and measure the output voltage. The measured value should be within the initial accuracy tolerance specified in the data sheet. This specification is usually for room temperature only, with a defined input voltage and load current. It provides a starting point for most of the other specifications. Initial accuracy tolerance can be affected by package stress, so proper control of the solder temperature profile is essential and twisting of the PCB must be kept to a minimum. Because package stress may start to change the unpowered part on the shelf, the initial accuracy tolerance may be subject to slight drifts; see the sections Temperature hysteresis and Long-term drift (stability) below. This is one reason why many industries, notable the military, require new products with date-coded parts to be less than a certain age.

Temperature coefficient (tempco) is the deviation of reference output voltage due to a change in the ambient or package temperature. Depending on the device structure and the way its output voltage is trimmed during the initial calibration, this output-voltage deviation can be positive (increasing with increasing temperature) or negative (decreasing with increasing temperature). It is almost never linear with temperature, which sometimes leads to confusion. For example, a temperature change from 25°C to 30°C is unlikely to lead to the same output voltage change as a temperature change from 65°C to 70°C, although the temperature increase is the same. For importance information on how references are specified over temperature, see application note 4419, "Understanding Voltage-Reference Temperature Drift."

By analogy, consider a simple resistive voltage-divider (**Figure 4A**). Voltage at the common point (V_{OUT}) is a fraction of the applied voltage (V_{IN}) equal to the ratio of the values of the two resistors. Both resistors change with temperature by the same percentage, maintaining a constant ratio, so V_{OUT} also remains constant.

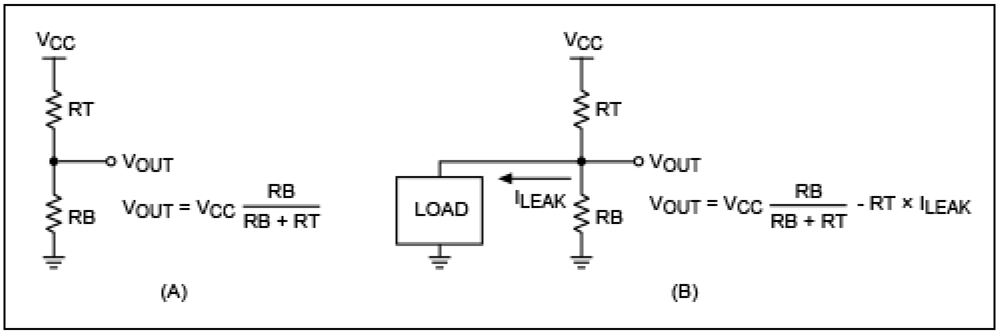

Figure 4. This simple resistor-divider analogy represents a voltage reference unloaded (A) and loaded (B).

Note that current flowing through the resistors varies with the temperature, and any leakage current from the common point of the divider (positive or negative) changes V_{OUT} (**Figure 4B**). At room temperature, this change is usually compensated for by trimming one of the resistors (changing its value). However, if this variation of leakage current with temperature differs from the variation in divider current due to changes in the resistor values with temperature, then the result is a change in V_{OUT} with temperature. The V_{OUT} change is called the temperature coefficient, or tempco. Although this analogy simplifies the more complex mechanism inside a reference circuit, it conveys the idea of a device tempco.

Temperature hysteresis is the change in output voltage with a cycle of temperature variation. To measure this, take a reference operating in a typical application, rated (as an example) for the extended operating temperature range of -40°C to +85°C. Record the output voltage at room temperature (+25°C). Cool the reference to -40°C and then heat it to +85°C before returning it to 25°C. Measure and record the output voltage again. The difference in these measurements, if any, is the temperature hysteresis. Note that it is also valid to heat it to 85°C, cool it to -40°C, and then heat it to 25°C. The deviation can be positive or negative. After many temperature cycles, one might deduce that the reference output voltage can be quite different. Because temperature hysteresis is both positive and negative, however, the deviations resulting from a series of temperature cycles tend to cancel out each other, producing a final average output voltage very close to the nominal value. This parameter is associated with stress on the die. Heat cycling tends to equalize the stress. Typically after five cycles, the stress has decayed to a minimum. However, stress can be reintroduced by soldering or twisting the package.

Line regulation is a measure of the change in output voltage due to a change in input voltage. This is important if the input voltage changes while the reference is operating, such as in a battery application. Typical units are ppm/V and %/V. Line regulation is a DC parameter and is typically specified at DC. Line regulation measures the change in output voltage for two (or more) different DC input voltages; it has little meaning if the input voltage varies rapidly, as for a voltage transient. In general, line regulation deteriorates inversely with the rate at which the line voltage changes. For applications likely to have line transients, reference input capacitors are recommended to minimize the resulting variations.

Load regulation is a measure of the change in output voltage due to a change in the reference load current. This parameter is important if the reference load current changes while the reference is operating, e.g., when a reference is driving a resistive ladder-type DAC with no reference buffer. The ladder impedance changes significantly with the DAC code. Again, load regulation is a DC parameter and is typically specified at DC. It measures the change in output voltage for two (or more) different DC load currents, and it has little meaning if the load current varies rapidly. In general, load regulation deteriorates inversely with the rate at which the load current changes. Output capacitors are recommended to stabilize the output voltage in applications subject to load-current transients. Typical units of measure are ppm/mA, %/mA, and percent change from no load to full load.

Long-term drift (stability) is important if the reference must remain accurate for days, weeks, or years of continuous operation. It simply measures the variation in output voltage over a long period of time at some specified condition of steady-state operation. Long-term drift is a measure of the maximum and minimum output-voltage deviations over an extended time period, rather than a measure of deviation between "time A" and "time B." All other conditions (e.g., temperature, input voltage, load current) must be held constant if this measurement is to accurately reflect drift in the reference. Typical units are ppm per 1000 hours.

Supply current is self-descriptive, but consider these variations.

For a series reference, the term "no-load current" is usually specified in the data sheet and often used interchangeably with the term "quiescent current" (I_Q). Because it designates the actual current drawn by an unloaded reference, no-load current does not specify the current drawn by that reference when loaded.

Typical shunt references do not specify no-load current in the data sheet. Instead, they often list a minimum operating current (I_{MO}). This parameter specifies the minimum current that a reference must draw to maintain regulation. Note that a shunt reference must draw at least the minimum operating current under full-load conditions. Its series resistor (R1) must, therefore, accommodate the maximum load current plus the minimum operating current (**Figure 5**). In some applications, the minimum operating current (called "regulation current" in some data sheets) is disregarded because it is so much smaller than the load current.

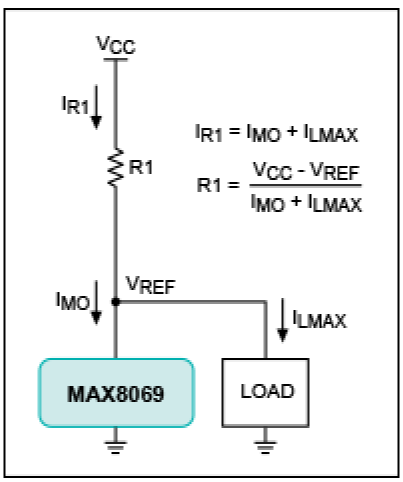

Figure 5. Current flow is the key for analyzing the operation of a shunt reference.

Ground current is often specified for a series reference. It measures the operating current at a given load. A series reference is in series with the load, so a measure of current flowing into the reference input yields the sum of load current and operating current. Ground current is often measured to determine the operating current for a series reference with load.

Dropout voltage (V_{DO}) is very important in low-voltage and battery-operated equipment and applies only to the series reference (in series references, this is the same as I_{MO} discussed above). The minimum difference between input and output voltage is what allows the reference to maintain its specified accuracy (V_{OUT} + V_{DO} = minimum input voltage). Battery voltage declines as the battery discharges. To maximize useful life in the battery, the reference must maintain an accurate output voltage while powered by the lowest possible battery voltage. Thus, a lower dropout voltage allows continued operation at a lower battery voltage. Pay close attention to the current at which the dropout voltage is specified. A dropout voltage at zero current gives an artificially low value. This is comparable to drawing a small current when a rail-to-rail output approaches the rail.

Load capacitance is the ability of a reference to drive capacitive loads, and it can be very important. Because typical references incorporate feedback control, their stability can be compromised by the zero introduced by a capacitive load. This can produce a large phase shift in the control loop that creates positive feedback at a particular frequency. Read the data sheet carefully for information on the range of load capacitance allowed. Some manufacturers refer to this limitation only in the text of the data sheet and not in the parameter tables.

Noise is apparent at a reference output, but it is, nonetheless, often overlooked. A reference's noise, which is a random signal generated by active and passive devices inside the IC, affects its accuracy. For example, a 1mV_{P-P} output noise voltage limits initial DC accuracy to no better than 1mV. For a 1.2V reference, this noise level alone limits initial accuracy to approximately 0.1%.

Reference data sheets typically show noise in two frequency bands: low-frequency noise, ranging from 0.1Hz to 10Hz and specified in µV_{P-P}; and wideband noise, ranging from 10Hz to 1kHz and specified in µV_{RMS}. Designating noise in two bands allows circuit designers to distinguish between wideband noise, which they can filter with practical capacitor values, and low-frequency noise, which they cannot. Also, if a capacitor large enough to filter the low-frequency noise were used, the reference could be unstable with such a large capacitor placed at its output. For a thermal noise calculator (i.e., PC emulator) and a manual that outlines the design steps needed to understand the noise parameters, see application note 5059, "Thermal Noise Calculator Tutorial."

AC line regulation is not usually designated in a specification table, but it directly influences the performance of the voltage reference. In most applications, the supply voltage to the reference has voltage spikes present. These spikes tend to be spread over a wide frequency range. The accuracy of the voltage reference is inversely proportional to the frequency of the input voltage variation. Because the AC line regulation is typically not specified, the reference data sheet should at least contain a graph showing the typical AC line regulation versus frequency. This graph would indicate the sensitivity of the reference to input system noise, and could be used to determine the input filtering required. As the noise frequency increases, the input filtering must further reduce the input system noise so the reference can achieve its rated accuracy.

Power-supply rejection ratio (PSRR) is sometimes specified in a data sheet. PSRR is usually specified in dB. It is a measurement of how much noise is rejected by the part at the output from the input supply (PSRR = $\Delta V_{CC}/\Delta V_{OUT}$).

AC load regulation/output impedance is another important parameter often omitted in the specification table of a voltage reference. This parameter is important if the load current drawn from the reference is constantly changing. The accuracy of the reference is usually inversely proportional to the load variation frequency. A graph showing the AC load regulation or AC output impedance versus frequency should be contained in the reference data sheet. This graph should show what output filtering is required with the known output load variations to achieve the rated accuracy of the voltage reference.

Line transient response is typically shown as an oscilloscope screen shot displaying a step change in the input voltage and the resulting change and correction in the output voltage. This screen shot displays the recovery time of the reference returning to a specified accuracy after such an event. It is important to note the input and output capacitor values used. These capacitors have a tremendous effect on the performance of the reference.

Load transient response/output settling time is typically shown as an oscilloscope screen shot displaying a step change in the output current and the resulting change and correction in the output voltage. This screen shot displays the recovery time of the reference returning to a specified accuracy after such an event. It is important to note the input and output capacitor values used. These capacitors have a tremendous effect on the performance of the reference.

Turn-on/turn-off settling time. The turn-on settling time is a measure of how quickly the output voltage of the reference stabilizes after an initial power-up. The output only needs to be stable and may not necessarily have reached the specified accuracy of the reference. Typically, this parameter is specified with an output voltage error greater than the specified accuracy; it should always be given in the conditions of the parameter. This parameter is highly dependent on the input and output capacitor values used and the load applied to the reference. It is not uncommon for references to encounter their current limits at power-up, when they have to charge up all their load capacitance. Turn-off time is a simple measure of how long it takes for the output voltage of the reference to virtually reach zero volts. This parameter is also highly dependent on the input and output capacitor values used and the load applied to the reference.

OUTPUT short-circuit current is a protection feature that can be either a short to GND or a short to input. It is a measurement of the output current when the output pin is shorted to either GND or IN. Typically, this is a fault condition which the part will enter under maximum thermal stress. In the Absolute Maximum Ratings section of a data sheet, a time duration is shown to specify how long the part can operate in this condition.

Conclusion

Voltage references are often chosen in haste. Before making a decision, the designer will look at the price, the initial accuracy highlighted on the data sheet, and frequently nothing else. Make sure that you compare “apples to apples” when comparing references. When evaluating a specification listed on several data sheets, be sure that all are expressed in the same units. Determine what parameters are important for your application, and look beyond the initial accuracy specifications.

Appendix

Popular Voltage-Reference Types

Two-Terminal Shunt (Zener Reference)

A zener reference is based on the zener principle above approximately 5V, in which the current in a reverse-biased diode begins to flow at a certain voltage threshold and then increases (avalanches) dramatically with an increase in voltage. A resistor in series with the diode establishes a constant current, allowing the zener to achieve a stable reference voltage. The zener reference behaves like a typical shunt or two-terminal reference. It can also be used as a voltage clamp.

"Pro" (i.e., Arguments in Favor of) Zener Reference	"Con" (i.e., Arguments vs.) Zener Reference
External bias resistor and load capacitors filter power-supply noise	I_Q varies with changes in power-supply voltage
Low power-supply voltages	High power dissipation
	Requires a careful choice of bias resistor, based on the supply and load requirements
Smaller package size	External bias resistor requires additional board space
Stable over a wide range of C_{LOAD}	Requires accurate supply voltage to improve line regulation
Can be used as a voltage clamp	Low efficiency
Can be referenced to either supply rail	Low initial accuracy (design dependent)
Low cost	Poor temperature stability (design dependent)

Three-Terminal Series and Buried (Subsurface) Zener References

"Pro" (i.e., Arguments in Favor of) Buried Zener Reference	"CON" (i.e., Arguments vs.) Buried Zener Reference
Eliminates surface noise	Requires supply voltages well above 5V
Lower temperature drift vs. zener and bandgap types	High power consumption
Excellent long-term stability	Expensive design
High accuracy	

Two and Three-Terminal Series (Bandgap) References

For applications below approximately 5V that require a compromise between cost and outstanding performance (low-noise operation and accuracy), the bandgap reference has become one of the most popular voltage references available. It compensates for the effect of temperature by subtracting the negative-tempco voltage of a forward-biased base-emitter junction from a positive-tempco PTAT (proportional to absolute temperature) voltage. The PTAT voltage is generated by measuring and amplifying the voltage difference between two forward-biased diode junctions.

"PRO" (i.e., Arguments in Favor of) Bandgap Reference	"Con" (i.e., Arguments vs.) Bandgap Reference
Lower power consumption	Moderate noise characterization
Accuracy is generally sufficient; can be improved with trimming	Limited temperature drift
Guaranteed operation down to 1V supply voltage (ideal for portable applications)	Larger package

Related Parts

Part	Initial Accuracy (±%, max)	Noise (0.1Hz to 10Hz, μV_{P-P})	Tempco (ppm/°C, max)	Quiescent Current (µA, max)	Features	Request Samples
DS4303	0.03	200	30	1,600	EE program	o
LM4040	0.1	35	50	60	AEC-Q100 shunt	o
LM4041	0.1	20	100	65	Shunt	o
LM4050	0.1	35	50	60	AEC-Q100 shunt	o
MAX6006	0.2	60	30	1	Shunt	o
MAX6012	0.3	12	20	35		o
MAX6018	0.2	36	60	5		o
MAX6023	0.2	25	30	35		o
MAX6029	0.15	80	30	5		o
MAX6033	0.04	16	7	75		o
MAX6034	0.2	45	30	115		o
MAX6035	0.2	21	25	95		o
MAX6037	0.2	6	25	275	Adjustable	o
MAX6043	0.05	4	15	490		o
MAX6061	0.4	13	20	125		o
MAX6070	0.04	6	7	150	Enable, NR	o
MAX6100	0.4	18	75	150		o
MAX6101	0.4	13	75	150		o
MAX6125	1	15	50	100	Adjustable	o
MAX6126	0.02	1.45	3	550	Trim	o
MAX6129	0.4	30	40	5		o
MAX6133	0.04	16	3	80		o
MAX6138	0.1	35	25	65	Shunt	o

MAX6143	0.1	4	3	490	Trim, temp	o
MAX6160	1	15	100	100	Adjustable	o
MAX6173	0.06	3.8	3	450	Trim, temp	o
MAX6190	0.1	40	5	35		o
MAX6220	0.1	1.5	20	3,300	Trim	o
MAX6225	0.04	1.5	2	2,700	Trim	o
MAX6325	0.02	2.5	1	2,900	Trim	o

For more information on available solutions, see Maxim's voltage references.

More Information
For Technical Support: http://www.maximintegrated.com/support
For Samples: http://www.maximintegrated.com/samples
Other Questions and Comments: http://www.maximintegrated.com/contact

Application Note 719: http://www.maximintegrated.com/an719
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