Investment in voltage references pays big system dividends

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Unglamorous yet critical components, voltage references are increasingly showing up in high-volume applications. By choosing the right reference IC and applying it with care, you achieve superior system performance.

A voltage reference has a higher ratio of design-in subtlety to the number of active devices than any other linear component. For an IC with just two or three terminals, the voltage reference packs a lot of mystery into its design, packaging, and application. Yet, when you choose the right reference and apply it appropriately, you can achieve consistent performance and excellent accuracy and stability.

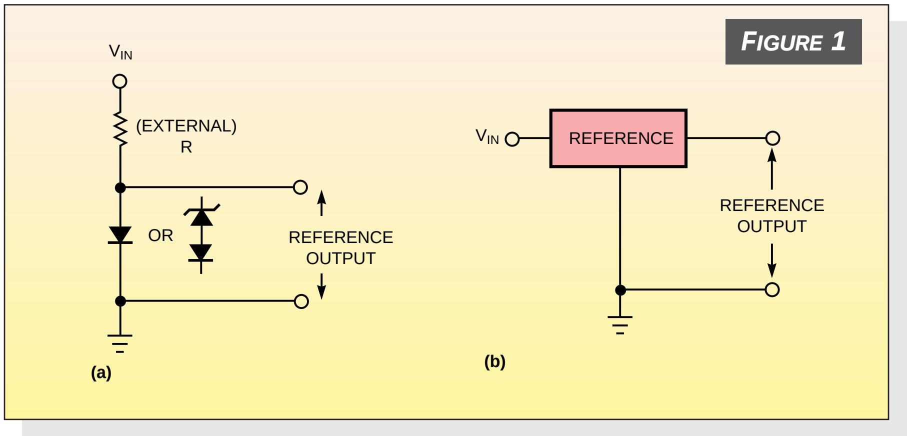
Although the designation "reference" suggests that the application of these devices is in just a few important niches, such as test instrumentation and transducer interfacing, engineers commonly use references, and this use is spreading. Communications and data-recovery systems, for example, use them to establish threshold levels in decoders. Even the commonplace battery charger now often needs a fairly precise reference for setting cutoff points when charging Lithium-ion cells.

To get the most benefit from a reference, you must not only choose a device with the appropriate specifications and trade-offs among these specs, but also use the device in a suitable circuit topology and physical installation. Otherwise, you risk seriously compromising the potential performance of your reference and thus your system.

Applications, convenience drive performance attributes

Since the beginning days of instrumentation in the 19th century, electrical systems have needed a compact source of well-defined potential difference—a voltage—that remains accurate, stable, repeatable, and inexpensive. Although labo-

FIGURE 1



The basic shunt reference is a two-terminal device that uses the voltage drop across a current-fed diode (a), and the series voltage reference is a three-terminal device that both sources and sinks current (b).

ratories have used carefully constructed, wet electrochemical cells, known as Weston cells, for primary references, these are hopelessly impractical for most systems. When solid-state technology developed through the 1950s and 1960s and as the physics of semiconductors became clearer, designers saw the opportunity for a more practical reference device based on diode characteristics.

Unfortunately, the temperature coefficients of diode junctions made them too inaccurate and variable for most system designs. As Dave Fullagar, vice president at Maxim Integrated Products, recalls, IC designers understood that a pn-diode's V_{be} has a negative temperature coefficient, and ΔV_{be} has a positive coefficient. At the 1970 International Solid-State Circuit Conference, though, the legendary, late Bob Widlar described a reference that simply and cleverly employed the two opposing temperature coefficients together in a mutually canceling way (**Reference 1**).

The resulting device was a bandgap voltage reference, which Fullagar notes was "one of the most elegant pieces of design work in our industry."

Although early stand-alone discrete references were commensurate with 8-bit system performance, they soon reached 10- and even 12-bit levels. Simultaneously, manufacturers of A/D and D/A converters started embedding references in the converters, because nearly every converter needs a reference to establish calibration for its transfer function. Many 10- and 12-bit converters today are called "complete" when they include an internal reference, eliminating the need for a separate, external reference device in some applications.

However, as converters have become more precise, offering 14- and 16-bit resolution and linearity, the discrete reference is increasingly vital (see **box** "When disintegration is a better choice"). By using a 16-bit system in the quest for greater dynamic range than 12-bit converters offer with a single range, designers avoid the need to use programmable-gain amplifiers, gain ranging, and switching, along with these devices' settling times and range-matching difficulties.

Even with a function as basic as a reference, you have four basic architectural choices. References are available based on either the buried-zener or the bandgap principle, and you can tailor each of these principles into a shunt or series reference configuration. Relative to the bandgap device, buried-zener references generally have lower noise, better long-term stability, and lower temperature drift. However, their lowest output voltage is approximately 6 to 7V, and they need a voltage about 1V higher than this output voltage to operate. So, they are unsuitable for low-voltage systems; furthermore, their dissipation is greater than that of bandgap devices. Bandgap devices can provide reference voltages as low as approximately 1V and are available with final device values such as 1.235, 1.25, 2.048, 2.5, 4.096, and 5V to match both the application need and the converter resolution.

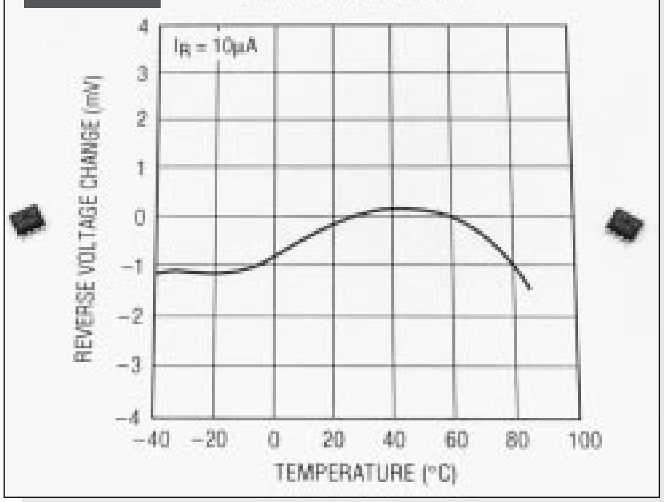
You must bias the two-terminal shunt-mode reference with a current value greater than the sum of the reference quiescent current and the maximum expected system load current (**Figure 1a**). You can operate the shunt reference from a wide span of supply voltages, because it is biased through a current-limiting resistor. However, the shunt reference wastes power through that resistor and can only source current. Note that some newer shunt references require very little quiescent current.

The three-terminal series-mode reference draws supply current equal to the quiescent current and the instantaneous load current, so this reference dissipates less power on average (**Figure 1b**). Series references can sink and source current without external components, as well. Current that this type of reference draws is independent of the current that the load draws.

@a glance

- For applications at 12-bit or better levels, a discrete reference is usually a better system choice than an embedded reference.
- Physical location, thermal conditions, and pc-board mounting are vital to optimal reference performance.
- Although absolute reference accuracy is important, reference stability and repeatability are increasingly important in calibrated systems.

FIGURE 2 Temperature Drift



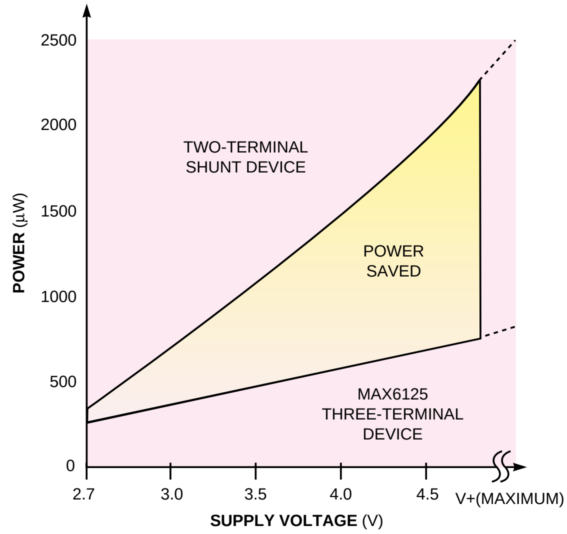
A temperature-drift curve for the LT1634 from Linear Technology shows the detail with which reference vendors must characterize their products.

Realizing potential

Unlike with most digital and some analog components, making sure you actually get the maximum performance and minimum difficulty from your reference requires consideration of numerous electrical *and* mechanical details. Start with the power supply for the reference. Although an independent supply isolated from the rest of your system supplies is often unfeasible, you should make sure that the reference is tied to a supply rail with local bypassing, because the power-supply rejection ratio of references is often too small to maintain their stated performance with a less-than-perfect supply. You may want to use a separate regulator for the reference in extreme cases.

When you choose a reference, look at its specifications for both line and load regulation, just as you would with a power supply. Load stability is especially important when your load has transients. For example, many A/D architectures inherently have transient glitches at their reference inputs during various stages in their conversion cycle. You may need to buffer the reference output using a low-drift op amp if your analysis reveals potential problems here. Alternatively, you can add a filter capacitor on the reference output to provide some reserve capacity. However, many references are unstable with capacitive loads, so this tactic can backfire on your system performance.

FIGURE 3



Compared with a shunt regulator, a three-terminal series reference, such as the Maxim MAX6125, provides increased power savings with increased load and supply voltage.

Although all vendors specify load and line regulation, they may not do so at extremes. In other words, vendors may specify line regulation with a minimum, resistive-only load or load regulation at nominal line value. Depending on your application, you may need to see the load-regulation specifications at the minimum operating voltage as well, for example.

If you use the reference to supply operating current to other parts of the circuit, it's unlikely you'll find a reference that has the necessary output capability, because most references can provide only as high as about 10 mA. If you need more current, you need to buffer the reference output with a higher current output op amp, but these devices tend to have large drift, and it may negate the virtues of the reference performance.

Consider whether a trimmed, low-dropout regulator may be a better choice when you need to supply current. After all, a regulator is *conceptually* like a reference, providing a fixed, stable voltage. Compared with a reference, a regulator can generally source currents greater than 10 mA, has stability worse than 10 ppm, and has accuracy inferior to 0.5 to 1%; a reference supplies less current but with better stability and accuracy.

When your reference drives physi-

WHEN DISINTEGRATION IS A BETTER CHOICE

Although integration of additional functions onto one semiconductor die is generally a good strategy to reduce costs, increase performance, reduce power, and save space, this common trend falls apart in the region of 14- to 16-bit converters.

There are several reasons for this failure. First, the underlying processes used to make high-performance converters are different from those used to make high-performance references. Instead of a good converter and a separate good reference, you can end up with many performance compromises and a mediocre final component. A good embedded reference can provide initial-accuracy performance no better than 0.5 to 1%, along with temperature coefficients no better than 50 ppm/°C. To keep some perspective, for maintaining ½ LSB performance over a 100°C temperature range, you need drift of less than 1.22 ppm/°C in a 12-bit system, 0.31 ppm/°C in a 14-bit system, and 0.08 ppm/°C in a 16-bit system.

Second, a reference is just a small part of a converter's size but a large factor in the converter's pass/fail determination at the vendor's final test. When vendors establish appropriate performance standards and guardbands for the reference embedded within the converter, they will have to scrap many of the otherwise acceptable converter die. This yield loss leads to relatively costly remaining devices.

There's an even more important reason, though, to consider a separate reference. In many systems, many components at various locations in the circuit need the reference voltage. Even if these disparate components each have their own sufficiently good reference, you soon have the different references drifting with respect to each other. Alternatively, you could buffer and use the reference from one converter to support your system's reference needs. However, it's much better to invest in one good reference and then properly use it in the system as a single point of accuracy to which all other ICs can refer. Your overall error-budget calculations are much simpler, your system performance is better and more consistent, and your system performance is better, if needed, because you concentrate on that single reference. Your system is also less expensive because you can use lower cost converters that need no embedded reference or that have mediocre references you can bypass.

Note that for some common reference applications in which you use the reference with other analog building blocks, some vendors offer a small-scale analog IC combining just these few functions. For example, Maxim's MAX951 puts a 125-kHz gain-bandwidth product op amp, comparator, and 1.2V/±2% reference in an eight-pin package; SGS-Thomson Microelectronics offers a 1.24V/±1% reference, two 1-MHz op amps, and a current source in its TSM101A, an eight-pin IC targeting switching-supply PWM-controller as well as battery-charger designs. Linear Technology Corp, as well, has its LTC1541, a micropower op amp with rail-to-rail outputs, a comparator, and a 1.2V reference in an SO-8 package.

cally long lines and remote loads, regardless of load current, be prepared for IR drops. The voltage drop from even a few milliamps of load current to a few milliohms of track resistance can severely compromise your reference accuracy and perceived stability, especially if the load varies over a wide range. You have to resort to a buffer with a force/sense (Kelvin) four-terminal configuration to compensate, and you have to decide which of your various load points controls the output value. Some reference ICs have built-in force/sense terminals, allowing you to access their buffer inputs and so eliminating the need for an external buffer.

Be especially concerned about where you mount the reference, for both thermal and stress reasons (see **box** "Can cans really be better?"). References perform best when their ambient temperature is stable. It's almost always better to put the reference in a warmer location but at a nearly constant temperature than it is to put it where there are wide temperature fluctuations yet with a lower average temperature value. You can even get references with built-in heaters that maintain a more stable temperature. There are two disadvantages to this option, however. First, the reference consumes more power, and, second, you limit the number of vendors and models from which to select.

Some vendors specify the hysteresis

CAN CANS REALLY BE BETTER?

You normally don't need to give much consideration to performance limitations that the physical package of an IC imposes, except for some thermal and RF issues at the extremes. Although early ICs came in metal TO-5 and TO-46 cans, the ceramic and plastic DIP largely made these packages obsolete; these ceramic and plastic DIPs in turn gave way to tiny surface-mount packages for analog functions.

But for references, as with extremely low bias-current op amps, the package itself is a large part of the performance equation. This relationship is partially because of the fact that smaller packages have less thermal mass and are therefore more susceptible to ambient-temperature fluctuations.

A larger detrimental factor is die stress that the package itself induces via the piezoelectric effect on crystalline structures. The encapsulation of the plastic IC stresses the silicon die, and residual stress remains after the plastic cools. This stress causes both an initial error in the reference output and the harder-to-predict drifts when temperature changes and the strain changes with it. Vendors know this subtlety and use special techniques, such as using either an additional underlying layer of silicon in the package to stiffen the die or a coating on the die, to reduce these effects. Vendors also employ special plastic molding compounds and techniques. None of these steps come easy.

The Seebeck effect in the package also affects reference performance. Minute temperature differentials across the disparate materials used for the IC's lead frame, leads, and connections act as miniature thermocouples, adding or subtracting microvolts between the reference die and the outside world.

Furthermore, when the IC is attached to the pc board, any flexing of the board stresses the IC package. Even though the stress may be small, it's still enough to affect the low-value ppm specifications of the reference. Vendors offer guidelines about how to place the reference IC to minimize the impact of such flexing, but you still have to consider pc-board stiffness, support rails, and even board stiffeners for the highest performance.

Ironically, the nearly obsolete metal-can package minimizes many of these problems, and many reference vendors still offer it as a packaging option. The metal can puts almost no stress on the die during packaging, isolates the die from the pc board because of the flexible wire leads, and has the least stress interaction with the die after packaging. It also has the best thermal performance and the fewest temperature differentials. Another viable, attractive alternative to the surface-mount-technology package is the plastic TO-92 standup transistor housing.

For your design, at least consider using a larger package than the smallest one available from the vendor or even using a can if you can accept its handling and insertion difficulties. Because the reference itself is usually a small fraction of your overall system size and cost, the incremental price may be very low and the return, quite high.

TABLE 1—REPRESENTATIVE VOLTAGE REFERENCES

Company	Model/ family	Type	Initial accuracy	Maximum drift (ppm/°C)	Supply current	V_{OUT}	Package styles	Price (1000)	Additional features
Analog Devices Circle No. 322	AD158x	Bandgap series	0.10%	50	65 µA	2.5, 3, 4.096 5,	SOT-23	$0.75	5-mA source/sink
	ADR292	Combination	2 mV	8	12 µA	2.48, 2.5, 4.096, 5	TSSOP, TO-92, SOIC	$1.95	Very low noise and power
Burr-Brown Circle No. 323	REF102	Buried-zener series	2.5 mV	2.5	1.4 mA	10	TO-99, PDIP, SOIC	$2.25	Also available in die
Linear Technology Circle No. 324	LT1634	Buried-zener shunt	0.05%	25	10 µA	1.2, 2.5, 4.096, 5	SOIC, TO-92	$2.35	Less than 1Ω dynamic impedance
	LT1460	Bandgap series	0.20%	20	100 µA	2.5, 5	SOT-23, PDIP, SOIC, MSOP, TO-92	$1.35	20-mA output
Maxim Circle No. 325	MAX6325	Buried-zener series	0.02%	1	2 mA	2.5, 4.096, 5	PDIP, SOIC	$6.70	15-mA source/ sink, 1.5-µV noise
	MAX61xx	Bandgap series	1.00%	50	80 µA	2.5, 4.096, 4.5, 5	SOT-23, SOIC	$1.25	Adjustable versions available
National Semiconductor Circle No. 327	LM4041	Bandgap shunt	0.10%	100	60 µA	1.2	TO-92, SOT-23, SOIC	$1.56	Adjustable versions available

for their parts, which indicates how closely the device retraces its output-value variation path as its temperature moves away from an initial value and then returns. Low hysteresis is critical in applications with temperature cycling. High hysteresis values can negate any initial precision or tight temperature-coefficient specs, so check this factor if your reference is in a fluctuating environment.

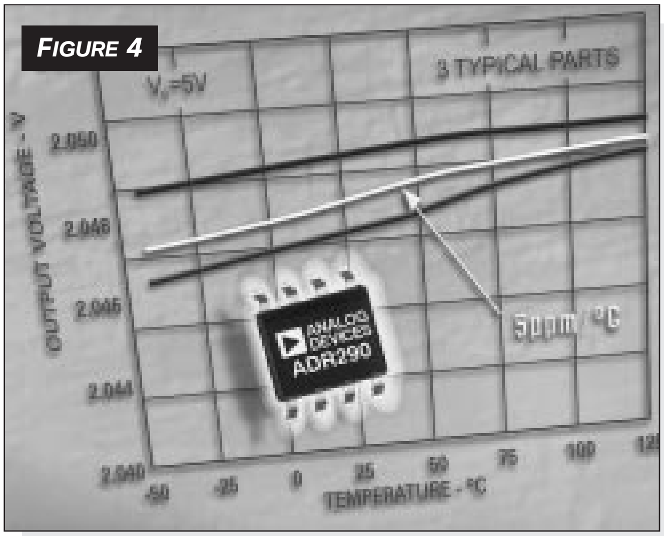
Resist the urge to save power by shutting down a reference when you don't need it; the thermal cycling from power-up/power-down cycles necessitates that you wait a relatively long time before getting an accurate reading. Instead, look for a low-power device that meets your other requirements. If you must conserve every microamp of power, look for a reference that settles and stabilizes relatively quickly to specified output.

Look at vendors' suggested guidelines for pc-board placement and routing around the reference. According to **Reference 2**, in a test using a surface-mount reference on a 7×9-in. pc board with deflection of 18 mils/in., the reference output had a 60-ppm p-p shift, compared with 4 ppm for an unflexed reference mounting. You can minimize the effect of board flex by routing the board area around the reference to decouple it from the rest of the board, using a thicker pc board, using flexible standoffs for mounting the pc board, and looking at the location and orientation of the reference package vs the location of the pc-board mounts and restraints.

In critical applications, you may need to consider burn-in of the assembled board. Powered burn-in helps age the reference and accelerate its trajectory to more stable performance. Even if your reference is sufficiently stable when you receive it from the vendor, you can use unpowered burn-in for 168 hours (one week) at 100°C to relieve latent stresses that can adversely affect reference performance in the final pc-board assembly.

When you look for a reference, the primary technical attributes to consid-

FIGURE 4



The ADR290 family of series devices combines low supply current with a temperature coefficient of just a few parts per million.

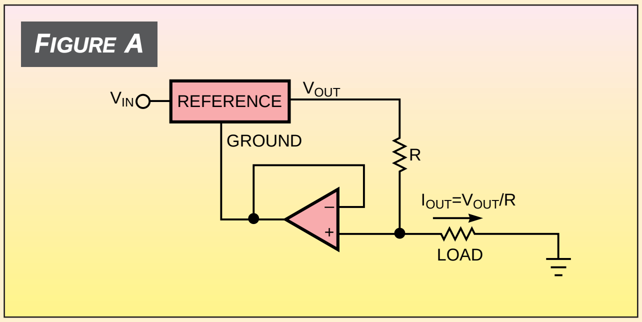
WHAT ABOUT CURRENT AFFAIRS?

There's a small but significant class of applications that prefers a current reference to a voltage reference. Transducers, such as resistance temperature detectors (RTDs), need a current source to drive them; the measured voltage across the RTD is proportional to the sensed temperature. Often, the transducer resides at a significant distance from its excitation, so you need to use four-wire Kelvin connections to minimize IR drop and uneven lead-length effects. To complicate matters, a system often has more than one RTD, so the number of excitation and sense leads quickly adds up. By using a current source, you can supply multiple sensors with one current loop, still sensing with one pair of leads per RTD.

You can construct a current-source reference using a voltage reference, op amp, and current-scaling resistor (Figure A). However, the performance of this source depends on the accuracy, temperature coefficient, and stability of this single resistor. As an alternative, Burr-Brown offers the REF200, a current source/sink based on its REF102 bandgap reference, which provides two fixed 100-μA outputs and a current mirror (although with stability that is less than a high-end voltage reference). You can pinstrap this current-reference IC for currents of 50, 100, 200, 300, or 400 μA as well. National Semiconductor also offers current sources such as the LM134, which you can use to construct extremely low-power voltage references (Reference A).

For an adjustable current source, you use the REF200 with an op amp and a pair of scaling resistors. The precision and stability of the adjustable current value depend on the ratio accuracy of the two resistors, which is easier to maintain than the absolute performance of the single-resistor voltage/current converter. Ironically, using a current source is an easy way for you to get a programmable voltage value as low as even the millivolt level, by forcing the current through one resistor.

FIGURE A



In concept, it's easy to build a current reference based on a voltage reference, but to achieve high performance, you may prefer a specifically designed current-reference device.

Reference

A. "Precision Reference Uses Only Ten Microamperes," National Semiconductor Corp, Linear Brief 41, June 1978.

er are initial absolute accuracy, temperature coefficient, long-term stability and drift, and noise (**Table 1**). In addition, you may need to consider operating-voltage span and power consumption. This factor is now often less critical because the power that a single reasonably good, low-power reference needs is a small fraction of most overall system-power budgets. Note that vendor specs are often package-dependent: Vendor A's SOT-23 reference may be better than vendor B's in the same package but inferior to vendor B's reference when housed in an SO-8. Make sure the vendor provides all the specs you need or can run special tests if you require them, because the precise and temperature-related nature of many reference specs makes it difficult to ascertain results yourself.

For micropower applications with precision performance, Linear Technology offers the LT1634 family, with 1.25, 2.5, 4.096, and 5V members. These shunt devices require just 10 μA and guarantee initial accuracy to 0.05% and maximum drift of less than 25 ppm/°C (**Figure 2**). The company's LT1460 series reference family strives for high performance in an SOT-23 package with 0.2% initial accuracy and a 20-ppm/°C temperature coefficient. The family operates with an input-to-output-voltage differential as low as 0.9V or as high as 20V, and the vendor also specifies this family as having a typical pc-board solder shift of 0.02%.

If you want low noise, the Maxim MAX6325 buried-zener series reference features 1.5/2.4 μVp-p (typical/maximum) noise over the 0.1- to 10-Hz span and suits 16-bit applications. This 0.02%-accurate, 1-ppm/°C temperature-coefficient device operates from 8 to 30V and includes an optional noise-reduction pin to which you can connect a 2.2-μF capacitor to reduce the noise by a factor of two. The long-term stability of this reference is 20 ppm/1000 hours, and its temperature hysteresis for a 25° shift is also 20 ppm. For applications that need the lower power of a bandgap device, the MAX61XX family operates from an 80-μA supply current and provides initial accuracy of ±1% and maximum drift of 50 ppm/°C; typical drift is half that figure (**Figure 3**).

Also for power-constrained applications, Analog Devices' AD158X family of series bandgap references has quiescent current of 65 μA maximum and operates from a supply that ranges from 200 mV to 12V above the nominal output. Worst-case initial inaccuracy is less than ±0.1%, and the reference can sink or source as much as 5 mA. Analog Devices further pushes the low-power envelope with minimal performance compromise with its ADR29x family. This family employs a new internal architecture with performance that minimizes the compromises of both zener and bandgap designs (**Figure 4**). The family specifications include 6-μVp-p noise from 0.1 to 10 Hz, 12-μA supply current, initial accuracy of ±2 mV, and 8-ppm/°C maximum temperature coefficient (5 ppm typical).

If you prefer a bandgap shunt device, National Semiconductor has the LM4041 1.2V device, which is stable with any capacitive load. Minimum operating current is 60 μA, and maximum current is 12 mA. Output-voltage error is ±0.1%, and output noise is less than 20 μV rms. This reference also has a maximum drift of 100 ppm/°C.

Some references are available from several sources, and thus vendors have carefully characterized them over years of experience. Burr-Brown's REF102, for example, provides 10V ±0.0025V output with drift of less than 2.5 ppm/°C. Long-term stability for this part is better than 5 ppm/1000 hours, and noise is typically 5 μVp-p. This reference operates from 11.4 to 36V dc, requiring quiescent current of 1.4 mA.

It seems almost contradictory, but sometimes you need a reference that is not only stable but also adjustable. For this reason, many vendors offer some of their references with an adjustment pin brought out to the IC package to connect to a trimming potentiometer. This pin gives you the adjustment you need, but it also shifts the burden of stability from the reference IC to you and your adjustment. If possible, avoid the need for an adjustable reference by using a different calibration algorithm or by looking at alternatives to hardware reference variation. Once you add an external trim device to your reference, you have to worry about the trim device's thermal stability and settability. You also have trouble isolating the cause of system-performance drift if it exceeds your limits.

If your application demands a current source rather than a voltage source, you can use many of the voltage references supplemented by additional components or seek a current-reference IC (see **box** "What about current affairs?").

References differ from most components in another practical consideration. Because they are basic building blocks, many devices are pin- and function-compatible. These alternative sources mean that in your quest for the best system performance at the lowest cost, you can substitute other devices from the same vendor or try devices from another vendor without board redesign or software changes.

Invest in a good reference, and treat it with care, consideration, and respect, and you'll get the system performance you need. Treat a reference IC just as you would any other IC, and you'll probably be disappointed and frustrated. Be sure to study vendor application notes and specifics—their reference reference designs—for general guidelines as well as device-specific advice. EDN

Acknowledgments

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