Ask The Applications Engineer—11
by James Bryant

All analog-to-digital converters (ADCs) and digital-to-analog converters (DACs) require a reference signal, usually a voltage. The digital output of the ADC represents the ratio of the input to the reference, the digital input to a DAC defines the ratio of its analog output to its reference. Some converters have their references built-in, some require an external reference, but all must have a voltage (or current) reference of some sort.

Most early applications of data converters were in "dc" measurements of slowly varying signals, where the exact timing of the measurement was unimportant. Today most data-converter applications are in sampled data systems, where large numbers of equally spaced analog samples must be processed and spectral information is as important as amplitude information. Here the quality of the frequency or time reference (the "sampling clock" or "reconstruction clock") is comparable in importance to that of the voltage reference.

VOLTAGE REFERENCES

Q. How good must a voltage reference be?

A. It depends on the system. Where absolute measurements are required, accuracy is limited by the accuracy with which the reference value is known. In many systems, however, stability or repetatability are more important than absolute accuracy; and in some sampled-data systems the long-term accuracy of the voltage reference is scarcely important at all—but errors can be introduced by deriving reference from a noisy system supply.

Monolithic buried-Zener references (for example the AD588 and AD688) can have initial accuracy of 1 mV in 10 V (0.01% or 100 ppm) and a temperature coefficient of 1.5 ppm/°C. They are accurate enough to use untrimmed in 12-bit systems (1 LSB = 244 ppm) but not in 14- or 16-bit systems. With the initial error trimmed to zero, they can be used in 14- and 16-bit systems over a limited temperature range. (1 LSB = 61 ppm, a 40°C temperature change in an AD588 or AD688).

For higher absolute accuracy, the temperature of the reference may need to be stabilized in a thermostatically controlled oven and calibrated against a standard. In many systems, while 12-bit absolute accuracy is unnecessary, 12-bit or higher resolution may be required; here, less accurate (and less costly) bandgap references may be used.

Q. What do you mean by "buried Zener" and "bandgap"?

A. These are the two commonest types of precision references used in integrated circuits.

The "buried" or subsurface Zener is the more stable and accurate. It consists of a diode with the correct value of reverse-breakdown voltage, formed below the surface level of the integrated-circuit chip, then covered by a protective diffusion to keep the breakdown below the surface.

-- Diagram of a simplified Zener generator --

At the surface of a silicon chip there are more impurities, mechanical stresses and crystal-lattice dislocations than within the chip. Since these contribute to noise and long-term instability, the buried breakdown diode is less noisy and much more stable than surface Zeners—it is the preferred on-chip reference source for accurate IC devices.

However, its breakdown voltage is normally about 5 V or more and it must draw several hundred microamperes for optimum operation, so the technique is not suitable for references which must run from low voltage and have low power consumption. For such applications, the "bandgap" reference is preferred. It develops a voltage with a positive temperature coefficient to compensate for the negative temperature coefficient of a transistor's $V_{BE}$, maintaining a constant "bandgap" voltage. In the circuit shown,* Q2 has 8 times the emitter area of Q1; the pair produces a current proportional to their absolute temperature (PTAT) in R1, developing a PTAT voltage in series with the $V_{BE}$ of Q1, resulting in a voltage, $V_{z}$, which does not vary with temperature and can be amplified, as shown. It is equal to the silicon bandgap voltage (extrapolated to absolute zero).

Bandgap references are somewhat less accurate and stable than the best buried-Zener references, but temperature variation of better than 3 ppm/°C may be achieved.

---

loop around the sources of error, these connections avoid the
effects of voltage drops; they also correct gain and offset errors
when current-buffer amplifiers are used to drive substantial
loads or sink currents flowing in the wrong direction. The
sense terminal should be connected to the output side of the
buffer amplifier, preferably at the load.

Q. What do you mean by “flow in the wrong direction”?

A. Consider a +5-V reference operated from a +10-V supply. If
its 5-volt output terminal is loaded by a resistor to ground,
current will flow out of the terminal. If the resistor is instead
connected to the +10-V supply, current will flow into the
terminal. Most references will allow net current flow in either
direction; but some will source current but not sink it—or will
sink much less than can be sourced. Such devices, identifiable
by the way their output current is specified on the data sheet,
may not be used in applications where substantial net current
must flow into the reference terminal. A common example is
the use of a positive reference as a negative reference.

Q. Why not just buy a negative reference?

A. Because most single voltage-output references are positive
references. Two-pin active references, of course, can be used for
either polarity; they are used in the same way as Zener diodes
(and they are usually bandgap devices).

For a three-terminal positive reference to be used as a negative
reference, it must be able to sink current. Its output terminal
is connected to ground and its ground terminal (which be-
comes the negative-reference terminal) is connected to the
negative supply via a resistor (or a constant current source).
The positive supply pin must generally be connected to a
positive supply at least a few volts above ground. But some
devices can provide negative reference in the two-terminal
mode: the positive and output terminals are connected to-
gether to ground.

Q. What about capacitive loads?

A. Many references have output amplifiers that become unstable
and may oscillate when operated with large capacitive loads; so
it is inadvisable to connect high capacitance (several μF or more)
to the output of a reference to reduce noise, but 1-10 nF
capacitors are often recommended—and some references (e.g.,
ADS88) have noise-reduction terminals to which capacitance
can be safely connected. If force-sense terminals are available,
it may be possible to tailor loop dynamics under capacitive
load. Consult data sheets and manufacturers’ Application Engi-
neers to be sure. Even if the circuit is stable, it may not be
advisable to use large capacitive loads since they increase the
turn-on time of the reference.

Q. Don’t references turn on as soon as power is applied?

A. By no means. In many references the current that drives the
reference element (Zener or bandgap) is derived from the
stabilized output. This positive feedback increases its stability
but leads to a stable “off” state that resists startup. On-chip
circuitry to deal with this and facilitate startup is normally
designed to draw minimal current, so many references come
up somewhat slowly (1-10 ms is typical). Some devices are
indeed specified for faster turn-on; but some are even slower.

If the designer needs reference voltage very quickly after
power is applied to the circuit, the reference chosen must have
a sufficiently fast turn-on specification; and noise reduction
capacitance should be minimized. Reference turn-on delay
may limit the opportunities for strobing the supplies of data
conversion systems in order to conserve system power. The
problem must still be considered even if the reference is built
into the converter chip; it is also important in systems of this
type to consider the power-up characteristics of the converter
as well [discussed in “Ask the Applications Engineer—1,”

High-precision references may require an additional period of
thermal stabilization after turn-on before the chip reaches
thermal stability and thermally induced offsets arrive at their
final values. Such effects will be mentioned on the data sheet
and are unlikely to exceed a few seconds.

Q. Does using these high precision references instead of its internal
reference make a converter more accurate?

A. Not necessarily. For example, the AD674B, a high-speed
descendant of the classical AD574, has a factory-trimmed
 calibration error of 0.25% (±10 LSB) max, with an internal
reference guaranteed accurate to within ±100 mV (1%). Since
0.25% of 10 V = 25 mV, full scale is 10,000 V ± 25 mV.
Suppose that an AD674B with a 1%—high internal reference
(10.1 V) had been factory-trimmed for 10.000 V full scale, by
a 1% gain increase. If an accurate 10.00-V ADS88 system
reference were to be connected to the device’s reference input,
full scale would become 10.100 V, at 4 times the specified max
error.

Q. Please discuss the role of the clock as a system reference.

A. Oops, we’re out of space! This question introduces a topic
that merits thoughtful discussion. We’ll do it in a future issue.