Considerations In Designing Low-Power, Single-Supply Systems

Part I : Designs using ac line power

By Steve Guinta

We consider here the implications and performance tradeoffs of converting a system design using active devices (e.g., op amps, A/D and D/A converters, etc.), conventionally characterized for dual supplies, to single-supply operation. (Conventional active devices designed for optimum performance with bipolar power supplies have inherently less-than-optimum performance in single-supply operation, especially at the lower voltages.) We go on to observe the advantages in speed and dynamic performance of several new product families built on processes specifically designed and characterized for single-supply operation.

One can't help noticing that single-supply designs are becoming very popular within the design community, because they reduce costs and take advantage of the widely available power sources commonly used in computer systems and digital/mixed-signal equipment. Many classical high-performance circuits were developed using op amps with ±15-volt supplies, but now single-supply operation at lower voltage is necessary in (for example) high-speed video circuits. In order to minimize power consumption in the handling of video signals, typically of the order of only 1-2 volts p-p, a 5-V single supply is used. But a conventional high speed op amp, originally designed to operate normally with ±15-volt supplies, would have to be operated at a considerably reduced voltage and biased at mid-supply. Reducing the supply voltage, however, reduces quiescent current, which adversely affects bandwidth and slew rate, as we will see, and may introduce "headroom" problems.

Another example in which single-supply operation is not only desirable, but essential, is in portable, battery-operated equipment. Where a battery is the primary supply voltage, minimal quiescent current is critical to extended operation. Battery-powered systems will be discussed in detail in part II of this article, which will appear in the next issue of *Analog Dialogue*.

A prime example of a battery-powered application in which low-power, single-supply devices are advantageous and essential is the "laptop" or "notebook" PC. Ten years ago, who would have thought you could carry around a system with up to 10× the computing power and memory capability of the older benchtop PCs (at 1/10th the size and weight!)—and sporting such increased functionality as VGA Color Graphics monitors, FAX/modem and CD-ROM, yet capable of running off a battery for 2-3 hours without recharging!

Another motive for designing (or converting to) a single-supply system may be simply to reduce the *cost, complexity and power consumption* of an existing multi-supply design. A conventional multi-supply design, with both analog and digital circuitry, generally needs ±12-V or ±15-V supplies to power op amps, +5 V or +12 V to drive TTL or CMOS logic circuits—and perhaps both to power A/D or D/A converters. The use of an existing on-board single supply voltage (typically +5 V) to power all the components can eliminate the need for costly dc-dc converters—which can consume considerable pc board space. For example, a +5 V to ±15-volt dc-dc converter, providing up to 200 mA of output current, might require a 2" × 2" space on the board; a similar converter with 400-mA output might require as much as 2" × 3.5" of real estate!

Increasing the reliability of the system is yet another—and not-so-obvious—advantage of single supply operation. Components operating at voltage levels much lower than their maximum rating inherently last longer. In reliability calculations, stress factor (the ratio of the device's operating voltage to its maximum rating) is included in the mean-time-to-failure (MTTF) calculations: an amplifier with a maximum rating of ±18 volts and operating from ±15 volts has a stress factor of 5/6, or 0.833; when operated at +5 V, the stress factor drops to 5/36 (= 0.139).

Having touched upon some of the areas where single supply operation can be beneficial or essential, let's examine in more detail some of the potential design limitations and possible tradeoffs in designing or converting to single supply operation. We will then then consider products, processes, and practices to overcome the speed and dynamic limitations inherent when conventional devices are used within a single-supply design. Although an operational amplifier is used as our model in many of the examples, the design issues and performance tradeoffs generally apply to other devices as well.

PERFORMANCE TRADEOFFS

Dynamic Range: Dynamic range is perhaps the most significant tradeoff in using conventional op amps in a single-supply design. Decreased dynamic range reduces signal-to-noise ratio, which ultimately limits usable system resolution. For example, a conventional bipolar op amp operating from ±15-volt supplies (Figure 1 left) usually requires a fixed "headroom" of from 1.5 V to 3 V between its maximum input/output swing and the supply

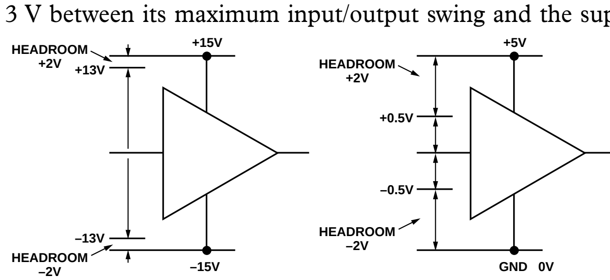


Figure 1. Illustration of headroom in relation to supply voltage.

*For technical data on devices mentioned here, use AnalogFax™. Phone 1(800) 446-6212, and use Faxcode numbers.

IN THIS ISSUE

Volume 29, Number 3, 1995, 24 Pages

rails. This headroom is determined by the NPN architecture at the input stage, and by the V_{CESAT} of the output transistor stage, for a given output load condition, and changes but little with supply voltage. The op amp, operating on ±15-volt supplies, has an input/output range of ±13 V.

If the supply voltage is now reduced to a single +5 V supply (Figure 1 right), the full-scale range is severely limited to 2 × (2.5 V – 2 V) = 1.0 V p-p, because of the essentially fixed headroom. If one can assume that the amplifier's noise floor is unchanged, the reduction in signal swing reduces the effective dynamic range in the same proportion.

Input Offset Voltage: Another effect of reducing the power supply voltage is a shift in the amplifier's *input offset voltage*. The problem stems from the fact that most conventional op amps, with a typical operating range down to ±4.5 volts, are generally tested, and have their input offset trimmed, at a specific supply voltage, e.g., ±15 volts. Reducing the supply voltage can produce a shift in the input offset voltage. The shift in the offset voltage can be determined by looking at the "power-supply rejection ratio" (PSRR), or "power-supply sensitivity" of offset voltage specification; it provides a measure of the change in offset for a given change in supply voltage.

For example, an OP177 has an initial offset of 20 microvolts at ±15 volts, and a PSRR of 1 µV/V. If the power supply is reduced to ±5 V, the offset changes as follows:

Initial Input Offset Voltage @ ±15 V	±20 µV
Power Supply Rejection Error (1 µV/V × 20-V change)	±20 µV
Derated Input Offset Voltage	±40 µV

Ground Reference: Selecting a suitable ground reference also becomes critical, because, with a single supply rail and depending on the application requirements, "ground" may be anywhere within the range of the supply. For one-sided dc measurements, the negative supply rail, ($-V_S$) is an excellent choice for two main reasons:

- Maximum dynamic range is achieved between the supply rails (to within the amplifier's headroom requirements)
- the negative supply rail provides a low-impedance return path for the positive supply current

For bipolar dc measurements or for ac applications, however, the choice is not as simple. A "pseudo" ground is needed to handle "bipolar" voltages or alternating excursions of the ac waveform about a "zero" value. An obvious choice for this pseudo ground (but not necessarily the best) is at a midpoint between the positive and negative (ground) supply rails. This ground can be created in various ways. A simple method for creating a pseudo ground is to use a resistive divider, as shown in Figure 2.

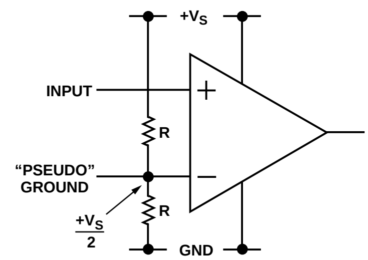


Figure 2. Simple resistive ground reference.

This approach has several problems: the inaccuracy of the ground point due to mismatch of the resistors, the drift of the resistors, and the inability to load the circuit (Figure 3). Variations of the positive supply rail will also move the ground point. And, perhaps most tellingly, it can only be used as an input ground reference, not as an output ground return.

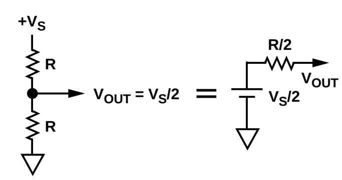


Figure 3. Equivalent circuit of resistive ground reference.

Table 1. Single Supply Amplifier Guide

Part No.-Devices/Chip				Temp	Supply Voltage				Rail-to-Rail		V_{OS}	Slew	e Noise	I_{OUT}	I_{SY}	I_{BIAS}	GBP		
	1×	2×	4×	Range	3 V	5 V	12 V	±15 V	In	Out	(mV)	(V/ms)	nV/√Hz	(mA)	(mA)	(nA)	(MHz)	Key Feature	Faxcode§
OP	113	213	413	I		•	•	•			125	0.9	4.7	±30	1.75	650	3.5	Low noise, low drift	1666
OP		279*		I		•	•		•	•	4000	3	22	±80	3.5	300	5	80 mA output currrent	1811
OP	183	283		I	•	•	•	•			1000	10	10	±25	1.5	600	5	5 MHz from +3 to +36 V	1675
OP		284	484†	H	•	•	•	•	•	•	65	2.4	3.9	±8	1.25	300	3.25	Like OP27, single supply	1871
OP	191	291	491*†	H	•	•	•		•	•	300	0.4	35	±13	0.4	50	3	Low power R-R in/out	1809
OP		292	492†	H		•	•	•			800	3	15	±8	1.2	700	4	Low cost	1697
OP	193	293	493	H	2 V	•	•	•			75	0.012	65	±8	0.015	15	0.035	Precision, long battery life	1856
OP		295	495	H	•	•	•	•		•	300	0.03	51	±18	0.15	20	0.075	Accuracy and output drive	1698
OP	196	296*	496*†	H	•	•	•		•	•	300	0.3	26	±4	0.05	10	0.35	Micropower R-R in/out	1926
AD	820	822	824†	I	•	•	•	•		•	400	3	16	±25	0.8	12 pA	1.8	FET input, low power	‡
SSM		2135		I		•	•	•			2000	0.9	5.2	±30	3.5	750	3.5	Excellent for audio	1794
												t_P			I_{SY}				
												(ns)			(mA)				
CMP			401*†	H	•	•	•			•	3000	17			7.7			23 ns comparator	1872
CMP			402†	H	•	•	•			•	3000	54			2.4			65 ns comparator	1872

Temperature Ranges I: –40°C to +85°C; H: –40°C to +125°C Rev. 12/15/95

Packages *TSSOP will be available; †Available in narrow SO package; ‡Faxcodes: AD820-1406, AD822-1407, AD824-1810; §Use AnalogFax™. Call 1-800-446-6212 and request Faxcodes.

For data sheets, use ADI's web site: http://www.analog.com

Specifications given at V_S = +5 V.

A second solution involves the use of a Zener diode or a reference regulator (Figure 4). This eliminates ground dependency on the supply rail; however, choice of Zener or regulator voltages may be limited. Its lower impedance allows it to be used as an output ground with a limited range of loads.

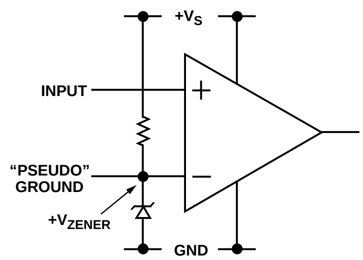
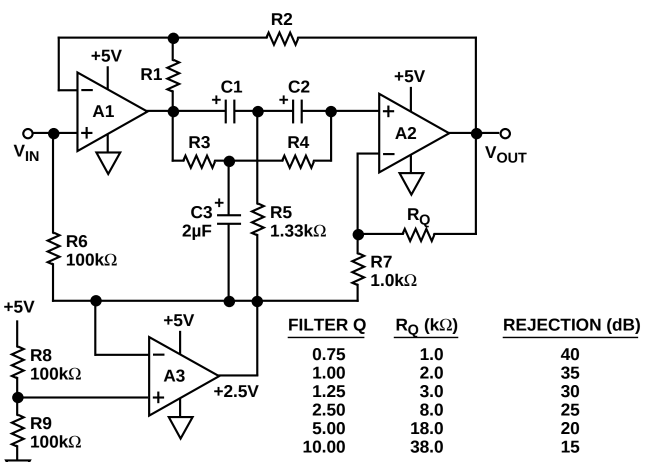


Figure 4. Zener diode as pseudo-ground.

Perhaps the most flexible approach is the equivalent of a regulator—combining a resistor divider or resistor-Zener pair, perhaps using single or stacked 1.23-V AD589s, and a low cost, general purpose op amp with appropriate output current range, used as a low-impedance ground generator.

Figure 5 illustrates the use of the pseudo-ground technique in designing a 50-Hz/60-Hz single-supply notch filter.



FILTER Q	R_Q (kΩ)	REJECTION (dB)
0.75	1.0	40
1.00	2.0	35
1.25	3.0	30
2.50	8.0	25
5.00	18.0	20
10.00	38.0	15

NOTES:
A1, A2 & A3 = 1/4 OP482
R1–R4 = 2.67kΩ
FOR 50Hz APPLICATIONS, CHANGE R1–R4 TO 3.16kΩ AND R5 TO 1.58kΩ

Figure 5. Single-supply 50/60-Hz notch filter.

RAIL-TO-RAIL

A special class of amplifiers with very low headroom requirements, known as rail-to-rail amplifiers, are increasing in popularity because of their unique ability to operate with the extremes of their input and/or output ranges at or near ground and/or near the positive rail (to within a few millivolts). This significantly increases the dynamic range of the system to practically the entire range of the supply voltage.

Conventional op amp input designs (Figure 6) employ either NPN bipolar junction transistors (BJT)—which offer the advantage of high bandwidth (f_t), lower noise and low drift, but higher current consumption—or junction field-effect transistors (JFETs), which

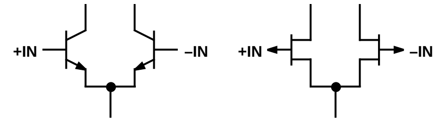


Figure 6. Conventional input stage uses paired BJT or JFET transistors.

have the advantage of very high input impedance, very low leakage (bias) current, and low distortion.

Unfortunately, both designs require operation using dual + and – supply voltages, and require 2-3 volts of headroom at either rail in order to operate effectively within their linear region.

The rail-to rail amplifier employs a special input structure, using back-to-back NPN and PNP input transistors and double-folded cascode circuitry to allow the inputs to reach to within millivolts of either rail.

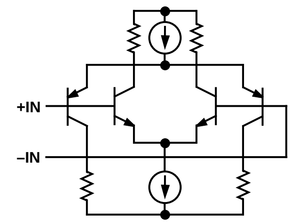


Figure 7. Rail-to-rail input stage uses back-to-back pairs of complementary transistors coupled to double folded-cascode gain stages (not shown).

The output stage of a conventional op amp (Figure 8 left) uses an NPN-PNP emitter-follower pair arranged in class AB operation. Output swing is limited by the V_{BE} of each transistor, plus the IR drop across the series resistors. The rail-to-rail amplifier output is from the collectors of an NPN-PNP pair configured as shown in Figure 8 right; the output swing is only limited by the V_{CESAT} of the transistors (which can be as little as several millivolts, depending on collector emitter currents), by R_{ON}, and by the load current.

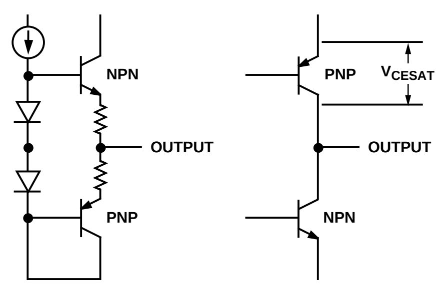
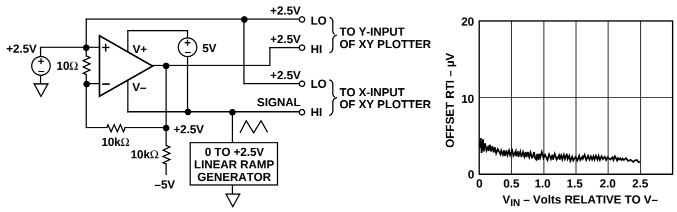


Figure 8. Conventional and rail-to-rail output stages.

An indication of how well a rail-to-rail amplifier performs is its ability to remain linear at or near zero volts. In the circuit of Figure 9a, the common-mode input to an OP90 is driven linearly through a 2.5-volt range from zero, and the amplifier is configured to multiply the resulting input error by 1000. The plot in (b) shows a small and essentially linear deviation over the 2.5-V range, without any hooks, bumps, or discontinuities, even in the vicinity of zero.



a. Test setup. b. Plot of output error, referred to input.

Figure 9. Testing linearity near the lower rail.

Table 1 (page 4) compares the specifications of amplifiers from Analog Devices for rail-to-rail applications.

Bandwidth, Slew Rate: Besides lowering supply voltage, the op amp manufacturer can further reduce power requirements by designing the device to require less quiescent supply current. Supply current is not strongly affected by supply voltage; it is principally under control of internal bias currents, which are established by the designer's choice of resistance in the bias circuit. In general, however, bandwidth, slew rate, and noise specifications can be adversely affected by a reduction in quiescent current. For example, a 4× increase in resistance to reduce quiescent current in a given circuit, can double the Johnson noise, which is proportional to the square-root of resistance.

For dc to low-to-mid-frequency applications, such as portable medical, geological or meteorological equipment, power consumption is the critical factor, and bandwidth reduction is of less concern. However, a video-speed amplifier, operating at reduced supply voltage in order to reduce power consumption, suffers a reduction in bandwidth and slew rate due to the reduction in its quiescent current.

What limitations does this place on the design of high-speed, low-power amplifiers? While it is true that bandwidth is proportional to quiescent or operating current, the actual ratio of bandwidth to quiescent current, MHz/mA—among other properties— is a function of the specific manufacturing process the op amp family is designed for.

Figure 10 shows the reference slopes depicting the typical relationship between bandwidth and quiescent current for Analog Devices BiFET, complementary-bipolar (CB) and eXtra-fast complementary-bipolar (XFCB) processes, with representative product types. Note that the AD8011 is capable of 300-MHz bandwidth, while drawing a quiescent current of 1.0 mA maximum from a single +5-V supply (and it generates only 2 nV/$\sqrt{\text{Hz}}$ of noise at 10 kHz).

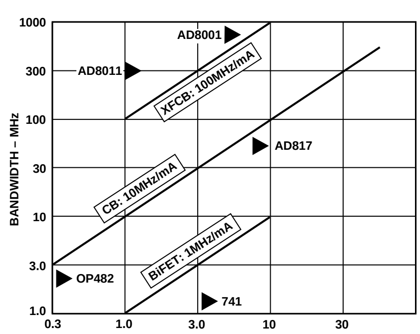


Figure 10. Bandwidth vs. quiescent supply current for IC op amps using various processing technologies.

Power Supply Noise: Noise on the power supply line can be a serious problem, especially in measuring low level signals. The problem is compounded by designers who, in order to reduce the need for dc-dc converters or inverters in a multi-supply system, are making use of the on-board +5-V logic supply to power op amps and data converters. The difficulty is that, in addition to having to supply output current randomly determined by changing logic and clock states, most logic supplies are derived from highly efficient, but noisy, switching supplies. Although carefully implemented logic circuitry is less susceptible to typical switching "spikes", op amps and data converters can be seriously affected, since the spikes may appear on both the supply rail and the ground return.

It's important to note that an op amp's PSRR, specified for dc and low frequencies, degrades with frequency. Not only can spikes from the power supply appear in the amplifier's output, but—if they are sufficiently large—they may be rectified in the amplifier input stage and cause dc offsets. Similarly, for A/D and D/A converters, the switching spikes can introduce errors in their analog sections, and they may even cause clocking errors. Defenses in all cases include careful attention to board layout (number of layers, circuit locations, and restrictions on track routing), filtering, bypassing, shielding, and grounding.

Solutions can be aided by a small investment in a highly efficient LC noise filter, using Ferrite beads, as shown in Figure 11a, at the power input to sensitive circuitry. Figure 11b illustrates how the use of such a filter can virtually eliminate the "glitches" and spikes" caused by pulses appearing on the power supply outputs.

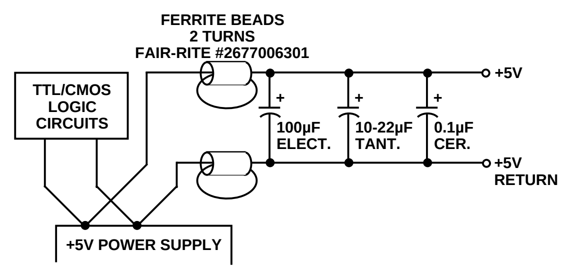


Figure 11. Filter to attenuate power-supply spikes. It should be located just outside the entrance to shielded circuit area.

We've discussed above the benefits and possible performance tradeoffs when designing a circuit or system using a single power supply, as well as products and techniques to help overcome some of the design limitations. In the next issue of *Analog Dialogue*, we'll take a closer look at some of the nuances of designing in a battery-powered system.

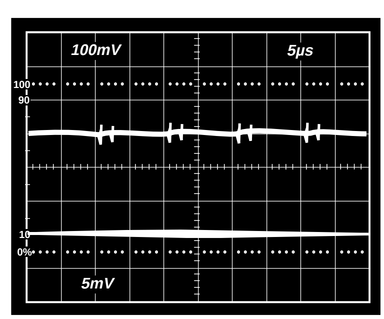


Figure 12. Spikes, "before" and "after" filtering. Note the 20× more sensitive scale.

Considerations In Designing Single Supply, Low-Power Systems Part II: Battery Powered Systems

by Steve Guinta

Part I of this two-part series (Designs using ac line power) appeared in the last issue of Analog Dialogue (29-3). In it, we discussed the implications and performance tradeoffs in converting to a single-supply system using conventional (i.e., non-single supply characterized) active devices, such as op amps, A/D and D/A converters, etc., then further described several new product families and processes from Analog Devices that provided single-supply operation without the limitations on speed and dynamic range of conventional devices. We continue here with the considerations involved in design for low-power operation, particularly for portable and remote applications with batteries.

BATTERY-POWERED SYSTEMS

In a battery-powered system, *time* is the critical parameter. Unlike ac-powered systems, where supply voltage varies within a specified range and the availability of rated current is unlimited in duration, a battery can only supply power for a finite length of time before it requires recharging or replacement. In addition, as the battery discharges, the greater the current drain, the greater the drop in battery voltage (or *supply rail*) (Figure 1).

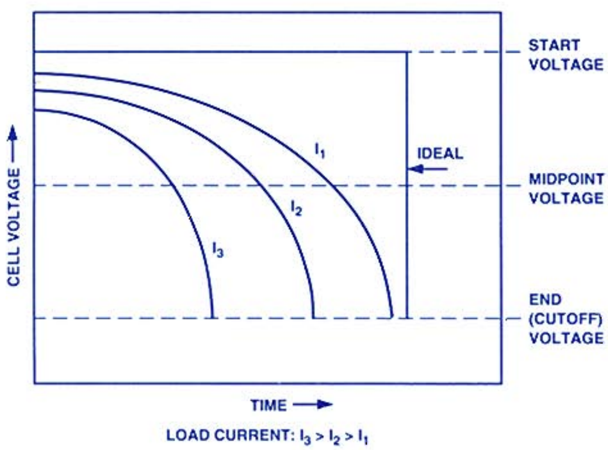


Figure 1. Cell discharge as a function of current discharge rate.]

The key to designing an efficient battery-operated system, then, is (a) to maximize battery life by minimizing the current drawn by the circuit, especially the continuous "quiescent current"; and (b) if necessary, to maintain the voltage supplied to the load at a constant level during discharge by using some form of regulating circuit between the battery and the load. For example, a battery with a capacity of 100 mA-hour powering a circuit that draws 1 mA will operate for approximately 100 hours before recharging or replacement is required. If this quiescent current is reduced to 100 µA, the battery life ideally increases to about 1,000 hours.

Before designing a battery-operated system, it is important to understand the environment, requirements, and operating conditions under which the system will be used; this will allow the designer to determine what type of battery should be used (for example, primary or secondary), and how often the batteries would need to be replaced or recharged.

For example, systems such as portable industrial data loggers or emergency medical monitors often can be recharged overnight (or when not in use), and so a *secondary*, or rechargeable, battery could be used. On the other hand, such low-power, battery-powered equipment as remote weather stations, seismic data recorders, or signalling beacons might be required to operate for weeks or even months without battery replacement or recharging; for such applications, a "throwaway" primary-type battery might be chosen.

Regulating the battery output: A regulator between the battery and the load keeps the supply rail at constant voltage during battery discharge. This can be important for several reasons:

• With operational amplifiers and other similar linear devices, changes in power-supply voltage can unbalance the dc input offset voltage from its pre-trimmed value. In most cases, this slight change in offset might have little or no effect on the accuracy of the system; however, in high-accuracy or low-level applications this could be a problem.

For example, most precision op amps exhibit a power supply rejection (PSR) at DC of the order of 120 to 100 dB. This is equivalent to 1 to 10 microvolts per volt of supply change. If the supply (battery) voltage were to drop from 5.0 V to 3.0 V, then the shift in input offset voltage would be

$$\Delta E_{OS} = \frac{\Delta Vsupply}{PSRR}$$

For a supply rejection of 100 dB (to 0.001%), this would equate to an offset change of 20 µV. This could represent a substantial number of degrees in a temperature monitoring system using sensitive B, R, and S type thermocouples, with temperature sensitivities of the order of 10 µV/°C or less.

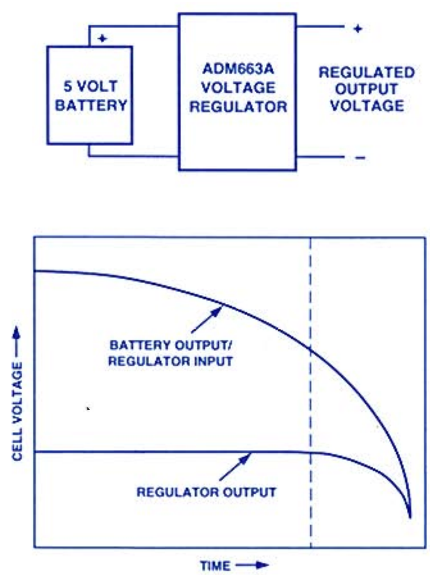


Figure 2. Voltage regulator and effect of battery discharge.

• Some designers may use the supply rail as the reference for analog-to-digital and/or digital-to-analog converters. Unless the measurement is ratiometric, the use of raw battery output as a voltage reference can lead to accuracy problems. For example, a two-volt shift in battery voltage can cause a 40% drop in the scale factor of a data converter. An n-bit A/D or D/A converter has an LSB (least-significant bit) weight of $V_{REF}/2^n$. Comparing 5 V with 3 V of supply voltage, used as a reference:

2^n	5 V	3	V
2^{-12}	1.22 mV	732	μV
2^{-16}	76 μV	46	μV

Voltage regulator devices, such as the REF19x series, are useful in stabilizing supply or reference voltage. They will maintain their output voltage at a constant level until the regulator reaches its "drop-out" voltage, i.e., the value at which the regulator can no longer hold its output constant (Figure 2).

The use of a regulator does require somewhat higher battery voltage, but a type with low dropout voltage can minimize the use of additional cells. For example, the 3-V REF193's dropout voltage ranges from 0.8 V with 10-mA load to 0.3 V with minimal load.

Extending Battery Life: Three ways to extend battery operation are: (1) Minimize the quiescent current if continuous operation is needed; (2) Pulse the load on and off so that the battery operates on a lower duty cycle; and (3) Power down the circuit when not in use.

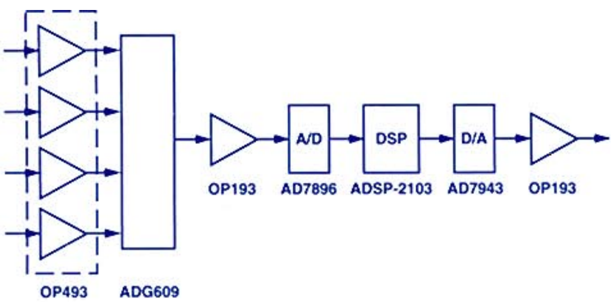
(1) Minimizing quiescent current: The overall quiescent current in the system can be minimized by

(a) proportionately increasing the values of all the bias resistors in the circuit (not always a good idea, since it can lead to higher levels of Johnson or resistor noise)

(b) using monolithic devices, such as op amps or data converters that have been designed to operate from a single +3-V to +5-V supply rail at low power (<1 mA) or "micropower" (<100 μA) levels. The choice of solutions is expanding as more devices become available on the market, to meet a variety of operating power budgets; included are: op amps, data converters, multiplexers, switches, references, etc.

Figure 3 is an example of a typical, battery-operated, multi-channel data acquisition "signal chain" using single-supply, low-power devices.

(2) Pulsing the load on and off: This is a useful approach when sampled measurements are required. The REF19x series, for example, have a TTL "sleep" control input, which permits a load drawing, say 15 mA, to be periodically switched on and off, with a residual quiescent current drain of 5 μA.



PART NO.	DESCRIPTION	SUPPLY CURRENT
OP193	OP AMP	22μA
OP493	OP AMP	88μA
ADG609	CMOS MUX	2μA
AD7896	A/D CONVERTER	4mA
AD7943	D/A CONVERTER	5μA
ADSP-2103	DSP	20mA

Figure 3. A complete, 3-V-powered data acquisition system.

(3) Powering Down The Circuit: Powering down the circuitry (the general case of pulsing the load on and off) is another way to conserve battery power. Like the pulsed case, it has some potential problems that need to be understood before it is implemented:

(a) Time must be allowed for all circuitry to settle out after the battery is turned on. A salient example is the internal (or external) voltage reference used for A/D and/or D/A converters. If sufficient time is not allowed after turn-on for the reference to stabilize, and an A-D conversion or D-A update is performed, a gain error will occur. The settling time required is further increased if the reference output is filtered to reduce noise; the filter capacitance will require additional time to charge up to its full value.

(b) It is not a good idea to power down an amplifier or data converter while an analog or digital signal is still applied. In the case of an op amp, applying a positive signal to an unprotected op amp's positive or negative input with no power to the supply rail causes a forward biasing of an internal p-n junction that causes current to flow from the signal source to the supply rail (Figure 4). If current is allowed to flow in an unprotected amplifier over a sufficient period of time, damage can occur to the amplifier due to "metal migration" or degradation (evaporation) of the trace.

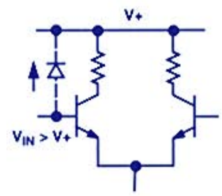


Figure 4. Forward-biased internal P-N junction.

The same problem exists for A-D and D-A converters, if the power supply is turned off, but input logic signals are still active at the converter's digital inputs.

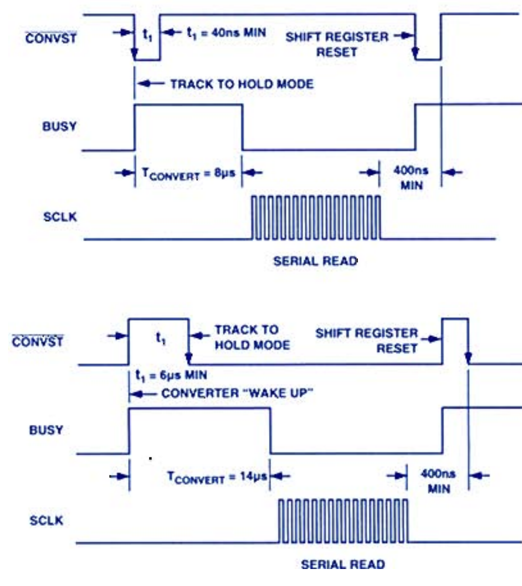


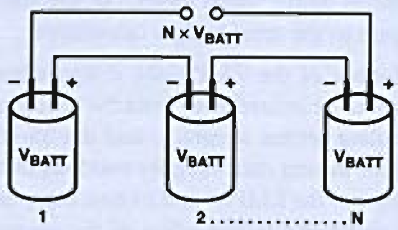
Figure 5. Timing diagrams for the AD7896, showing normal mode of operation (a) vs. sleep mode (b).

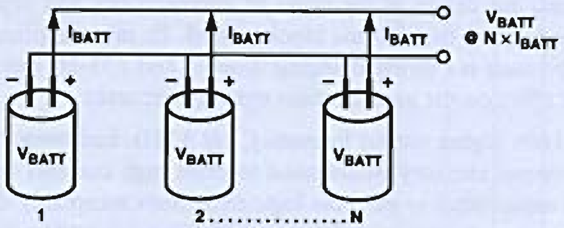
(c) Many of the newer, low power devices available on the market today feature a power-down or "sleep" mode of operation, where certain functions of the device are shut down to conserve power, but the device itself is still "active" in that it retains its operating state. For example, a D/A converter that is powered down will still retain its latched digital data. Devices that feature power-down or "sleep" mode of operation generally are designed not to be affected by analog or digital signals present at their inputs during power down mode.

An example of a device that offers a unique feature is the AD7896 12-Bit Sampling A/D Converter. The AD7896 features a proprietary, automatic power down mode, in which the A/D automatically goes into a "sleep" mode once conversion is complete, and "wakes up" automatically before the next conversion cycle. During the "sleep" mode of operation, quiescent current is reduced thousandfold, from 4 mA to 5 μA.

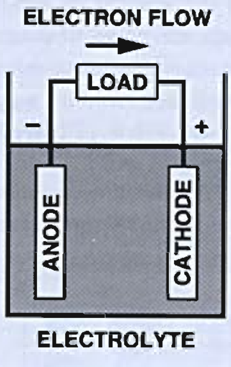
A PRIMER ON BATTERIES

A *battery* consists of an energy cell or a group of cells stacked in series for higher voltage or in parallel for higher output current.

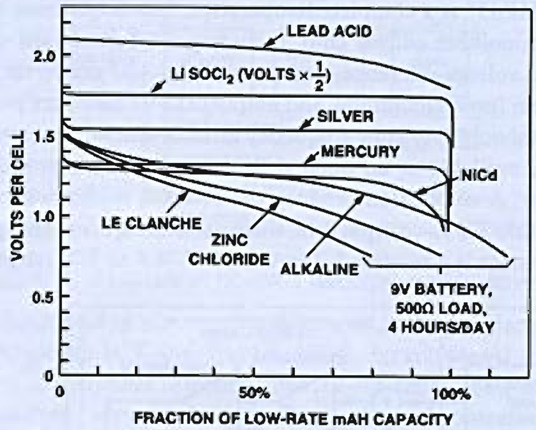




The electrical energy of a battery cell is produced by a chemical reaction between its anode, cathode and electrolyte materials. It is worth noting that, in battery terminology, the positive terminal is the *cathode*, the negative terminal is the *anode*.



The materials used for the anode, cathode and electrolyte and their quantity, primarily determine the battery's output capacity, specified in ampere-hours (Ah) or watt-hours, (Wh). Other factors, such as energy density (Ah/kg), relative size, cost, thermal stability, storage life, etc., are also a function of the choice of materials. The illustration compares discharge characteristics for several primary battery types. [from *The Art of Electronics*, 2nd edition, by Paul Horowitz and Winfield Hill, as adapted by the authors from battery literature. Cambridge (UK): Cambridge University Press, 1989.]



Batteries are classified as either primary (non-rechargeable), secondary (rechargable) or reserve (inactive until activated):

a) Primary batteries are often relatively inexpensive; they are usually found in applications where long-term operation with minimal current drain is expected. Examples include a car's miniature, remote activation device for "keyless" entry/alarm, portable hand-held multimeters, portable remote data-loggers, remote or emergency signalling devices, etc. The standard AA, C and D-size dry-cell batteries found in radios, flashlights, toys, etc., are examples of low-cost, consumer-type primary batteries.

b) Secondary batteries have the advantage of being rechargeable; they are often found in applications such as the battery backup in an ac-powered system, (e.g., mainframe computers or emergency lighting systems) where the secondary battery is continuously charged by the system, or in applications where bursts of high-energy output for short periods of time are required, such as in portable power tools.

c) Reserve batteries are designed for very long term storage, and cannot provide any output until a key chemical element (usually the electrolyte) is added. A car's 12 volt battery on the automotive dealer's shelf is an example of a reserve battery.

The following chart lists the most commonly known battery types, and their properties:

Battery	Type	Anode	Cathode	Cell Volts	Ah/kg
Alkaline	Primary	Zn	MNO_2	1.5	224
Lithium	Primary	Li	MNO_2	3.5	286
Lithium	Primary	Li	SO_2	3.1	379
Lead-acid	Secondary	Pb	PbO_2	2.1	120
Nickel-Cad'mium (Ni-Cd)	Secondary	Cd	Ni Oxide	1.35	181
Nickel Metal-Hydride	Secondary	MH	Ni Oxide	1.35	206

Source: Handbook of Batteries, 2nd edition, by David Linden. New York: McGraw-Hill, 1995.