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).

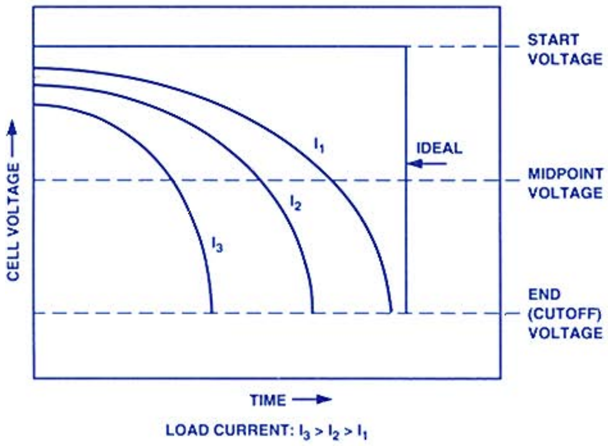


Figure 1. Cell discharge as a function of current discharge rate.]

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.

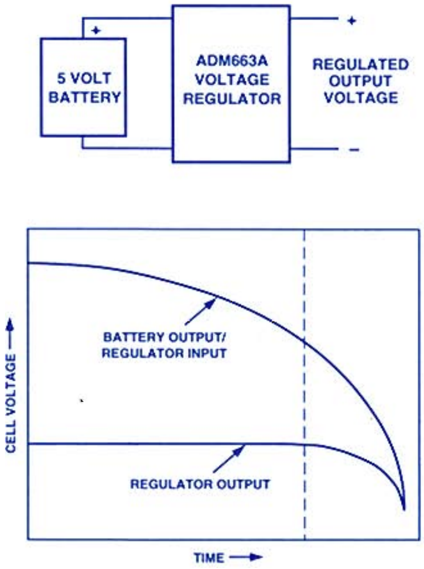


Figure 2. Voltage regulator and effect of battery discharge.

- 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.

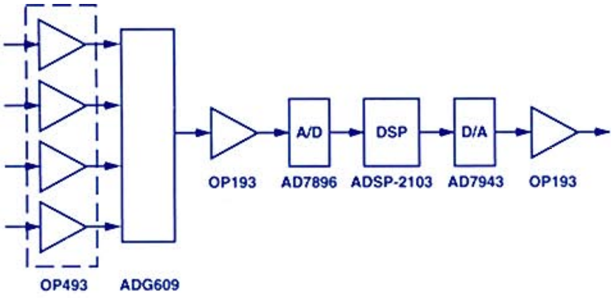
(*1*) *Minimizing quiescent current:* The overall quiescent current in the system can be minimized by

(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.

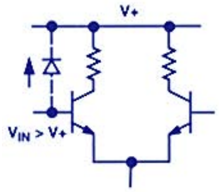


Figure 4. Forward-biased internal P-N junction.

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.

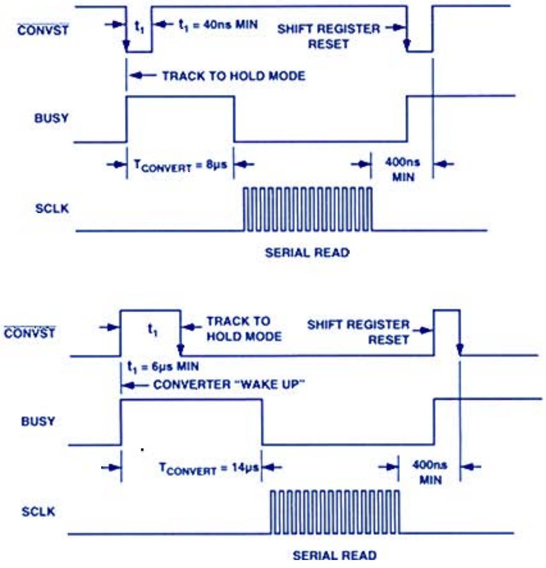


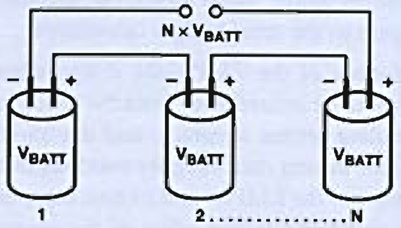
Figure 5. Timing diagrams for the AD7896, showing normal mode of operation (a) vs. sleep mode (b).

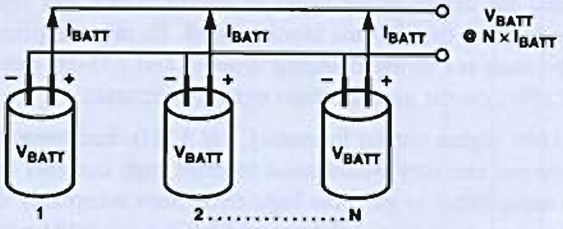
(c) Many of the newer, low power devices available on the market today feature a power-down or "sleep" mode of operation, where certain functions of the device are shut down to conserve power, but the device itself is still "active" in that it retains its operating state. For example, a D/A converter 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.

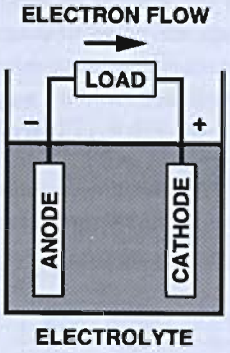
A PRIMER ON BATTERIES

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.

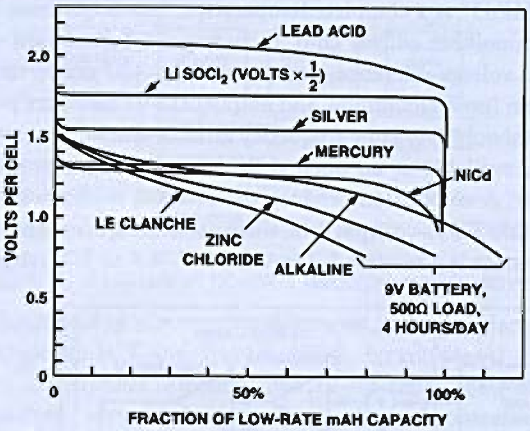




The electrical energy of a battery cell is produced by a chemical reaction between its anode, cathode and electrolyte materials. It is worth noting that, in battery terminology, the positive terminal is the *cathode*, the negative terminal is the *anode*.



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-Cadmium (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.