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

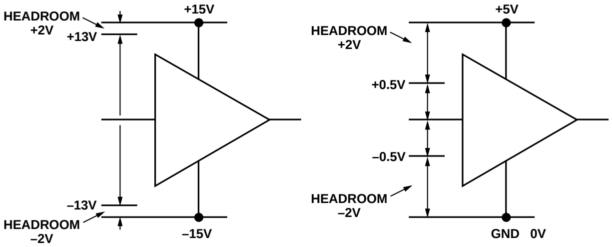

Figure 1. Illustration of headroom in relation to supply voltage.

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IN THIS ISSUE

Volume 29, Number 3, 1995, 24 Pages

New-Product Briefs:

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 $2 \times (2.5\text{ V} - 2\text{ V}) = 1.0$ 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.

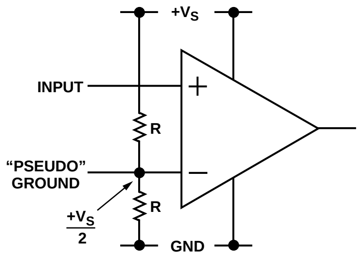

Figure 2. Simple resistive ground reference.

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.

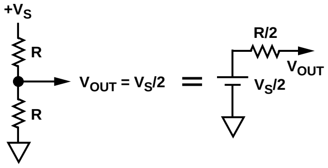

Figure 3. Equivalent circuit of resistive ground reference.

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

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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.

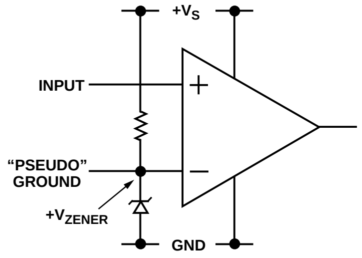
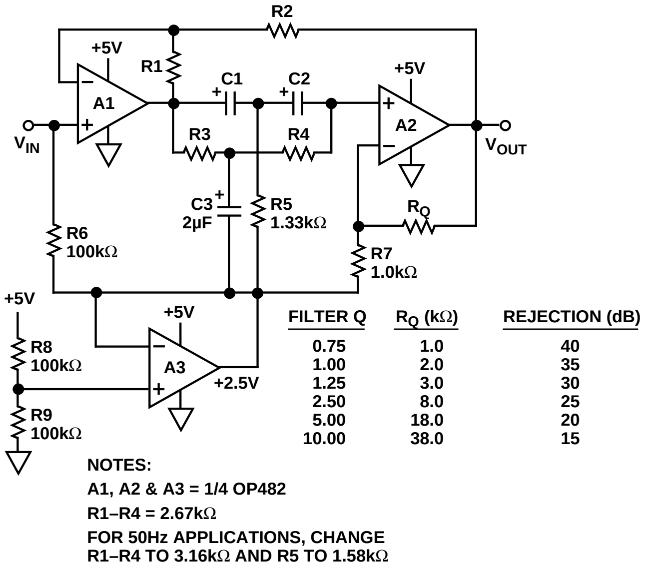


Figure 4. Zener diode as pseudo-ground.

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

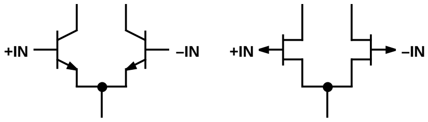


Figure 6. Conventional input stage uses paired BJT or JFET transistors.

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.

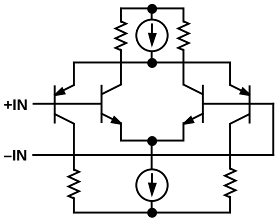


Figure 7. Rail-to-rail input stage uses back-to-back pairs of complementary transistors coupled to double folded-cascode gain stages (not shown).

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.

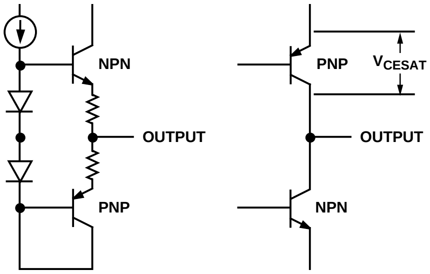
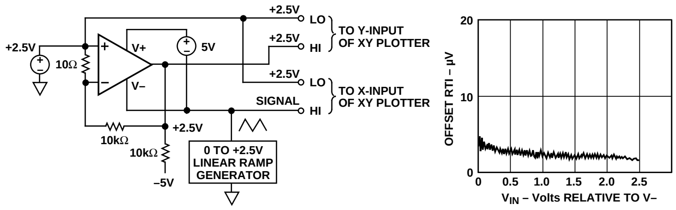


Figure 8. Conventional and rail-to-rail output stages.

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).

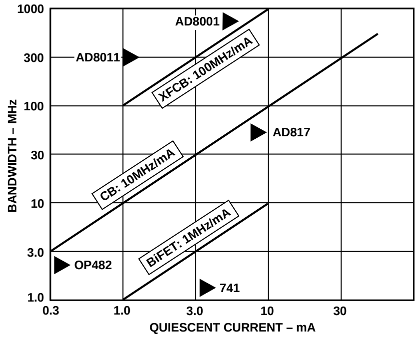


Figure 10. Bandwidth vs. quiescent supply current for IC op amps using various processing technologies.

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.

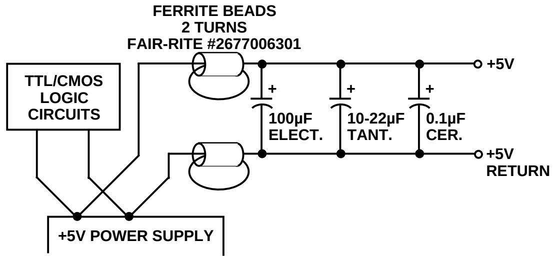


Figure 11. Filter to attenuate power-supply spikes. It should be located just outside the entrance to shielded circuit area.

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. ▶

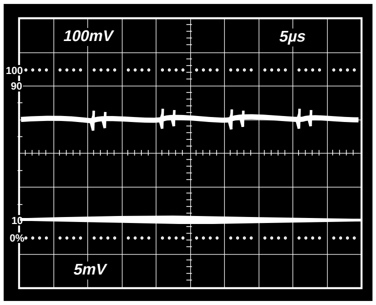


Figure 12. Spikes, "before" and "after" filtering. Note the 20× more sensitive scale.