

APPLICATION NOTE 656

Design Trade-Offs for Single-Supply Op Amps

Abstract: The trend toward low-voltage, single-supply systems is fueled by designers' attempts to balance the often contradictory goals of lower product size and cost vs. longer battery life and better system performance. This trend may be good for consumers, but it complicates the task of choosing an appropriate op amp for a given application.

Single-supply operation is generally synonymous with low-voltage operation, and moving from $\pm 15V$ or $\pm 5V$ to a single 5V or 3V supply rail reduces the available signal range. Consequently, the common-mode input range, output-voltage swing, CMRR, noise, and other op-amp limitations become much more important. As in all engineering, you must often sacrifice one aspect of system performance to improve another. The following discussion of trade-offs among single-supply op amps also explains how these low-voltage amplifiers differ from their higher voltage predecessors.

Input Stage Concerns

Input common-mode voltage range is one of the first issues a designer should consider in specifying a single-supply op amp. The first impulse is to eliminate this concern by specifying a Rail-to-Rail input capability. Certain penalties must be paid, however, for true rail-to-rail operation.

Most of Maxim's low-voltage op amps have input common-mode voltage ranges that include the negative supply rail (**Table 1**), but only some allow inputs that extend to the positive rail as well. Others allow input voltages only within one or two volts of the positive rail. Op amps that allow signals only to the negative rail will be referred to as ground-sensing amplifiers. Those that allow signals to either rail will be referred to as rail-to-rail input amplifiers.

Table 1. Maxim low-voltage op amps

Part	Input Voltage Range		Output Voltage Swing			Supply-Voltage Range (V)	Max Supply Current (mA)	Max Offset Voltage (mV)	Bandwidth (MHz)	Slew Rate (V/ μ s)	Voltage Noise (nV/ \sqrt Hz)	Current Noise (pA/ \sqrt Hz)	Voltage Gain at Load		Min Stable Gain (V/V)	Comments
	V _{CC} - V _{EE} (V)	V _{EE} (V)	V _{CC} - V _{EE} (V)	V _{EE} (V)	Load (Ω)								(dB)	(Ω)		
MAX4124/5	-0.25	-0.25	0.24	0.125	250	2.7 to 6.5	0.825	0.6	26	10	22	0.4	106 84	100k 250	10	Single, rail-to-rail I/O, drives 500pF. MAX4125 has shutdown.
MAX4128	-0.25	-0.25	0.28	0.18	250	2.7 to 6.5	0.825	0.75	26	10	22	0.4	106 84	100k 250	10	Dual, rail-to-rail I/O, drives 500pF
MAX4130/1	-0.25	-0.25	0.24	0.125	250	2.7 to 6.5	1.15	0.6	10	4	22	0.4	108 82	100k 250	1	Single, rail-to-rail I/O, drives 160pF. MAX4131 has shutdown.
MAX4132/3	-0.25	-0.25	0.28	0.18	250	2.7 to 6.5	1.15	0.6	10	4	22	0.4	108 82	100k 250	1	Dual, rail-to-rail I/O, drives 160pF. MAX4133 has shutdown.
MAX4134	-0.25	-0.25	0.28	0.18	250	2.7 to 6.5	1.15	0.6	10	4	22	0.4	108 82	100k 250	1	Quad, rail-to-rail I/O, drives 160pF
MAX4122/3	-0.25	-0.25	0.24	0.125	250	2.7 to 6.5	0.825	0.6	5	2	22	0.4	106 84	100k 250	1	Single, rail-to-rail I/O, drives 500pF. MAX4123 has shutdown.
MAX4126/7	-0.25	-0.25	0.28	0.18	250	2.7 to 6.5	0.825	0.75	5	2	22	0.4	106 84	100k 250	1	Dual, rail-to-rail I/O, drives 500pF. MAX4127 has shutdown.
MAX4129	-0.25	-0.25	0.28	0.18	250	2.7 to 6.5	0.825	1.5	5	2	22	0.4	106 84	100k 250	1	Quad, rail-to-rail I/O
MAX4165-9	-0.25	-0.25	0.36	0.26	25	2.7 to 6.5	1.5	0.65	5	2	26	0.4	124 100 87	100k 1k 25	1	Guaranteed 80mA output current drive, drives 500pF loads. Outputs high impedance in shutdown.
MAX4330-4	-0.25	-0.25	0.125	0.1	2k	2.7 to 6.5	0.325	0.65	3	1	28	0.26	120 95	100k 2k	1	Single/dual/quad, 300pF capacitive drive. MAX4331/3 have shutdown.
MAX4162/3/4	-0.25	-0.25	0.02 0.02	0.02 0.2	100k 10k	2.7 to 10	0.035	5	0.2	0.08	80		110 110	100k 10k	1	Single/dual/quad, drives 500pF, internal charge pump
MAX492/4/5	0	0	0.15	0.15	1k	2.7 to 6	0.15	0.5	0.5	0.2	25	0.1	108	1k	1	Dual/quad/single, precision, rail-to-rail I/O
MAX480	1	0	0.8mV	0.1mV	10k	1.6 to 36	0.015	70 μ V	0.02	0.012	55	0.6	112 105	100k 10k	1	Low V _{OS} and drift, micropower, I/O to negative rail
MAX478/9	1.1	-0.3	1.2	0.2	2k	2.2 to 36	0.017	70 μ V	0.06	0.025	49	0.01	104	50k	1	Micropower, precision
MXL1178/9	1.1	-0.3	1.2mV	0.2mV	2k	2.2 to 36	17	70 μ V	0.06				106	50k	1	Dual/quad, precision
MAX409/17/19	1.1	0	0.01	0.01	1M	2.5 to 10	0.0012	10	0.15	0.08	150		120	1M	10	Single/dual/quad, lowest power
MAX406/7/18	1.1	0	0.01	0.01	1M	2.5 to 10	0.0012	10	0.008 to 0.04	0.02	150		120	1M		Single/dual/quad, lowest power
MAX4180- MAX4187*	1.1	1.1	1.8	1.8	1.50	4.5 to 11	1.2	5	400	1200	2	4	66 61	1k 150	1	Single/dual/quad, low power, high bandwidth, high slew rate,

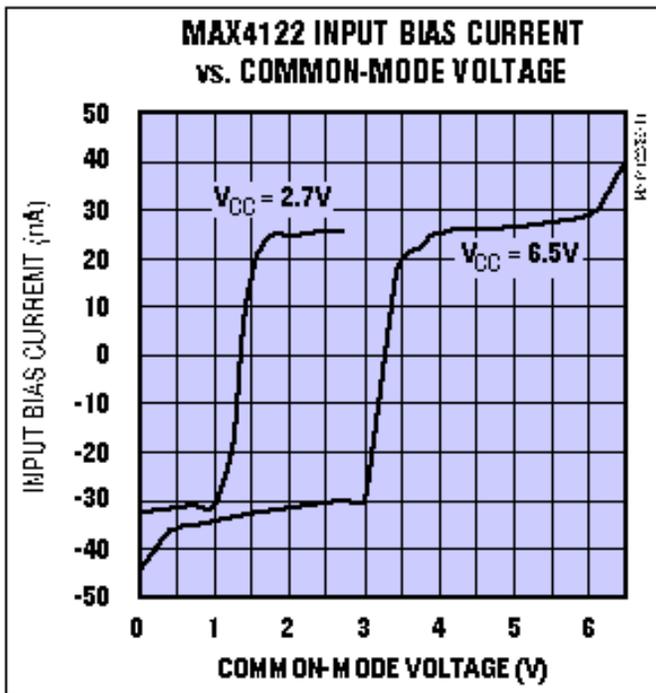


Figure 2. As the common-mode input voltage of a rail-to-rail input amplifier sweeps from one supply rail to the other, the input bias current can change, both in sign and in magnitude.

Figure 3 shows how to match impedances in the classic inverting and noninverting op-amp configurations. The inverting configuration (Figure 4) offers one way to eliminate changes in the input bias current by keeping the amplifier's common-mode input voltage constant at a reference voltage (V_{REF}). The output is given by $V_{OUT} = (-V_{IN} \times R2/R1) + V_{REF}(1 + R2/R1)$. If $R2 = R1$, this becomes $V_{OUT} = -V_{IN} + 2V_{REF}$. For $V_{REF} = 2V$ and V_{IN} between $0V$ and $3V$, V_{OUT} ranges from $4V$ to $1V$. The common-mode range is fixed, so CMR errors are eliminated as well. Table 2 lists references suitable for use in low-voltage systems.

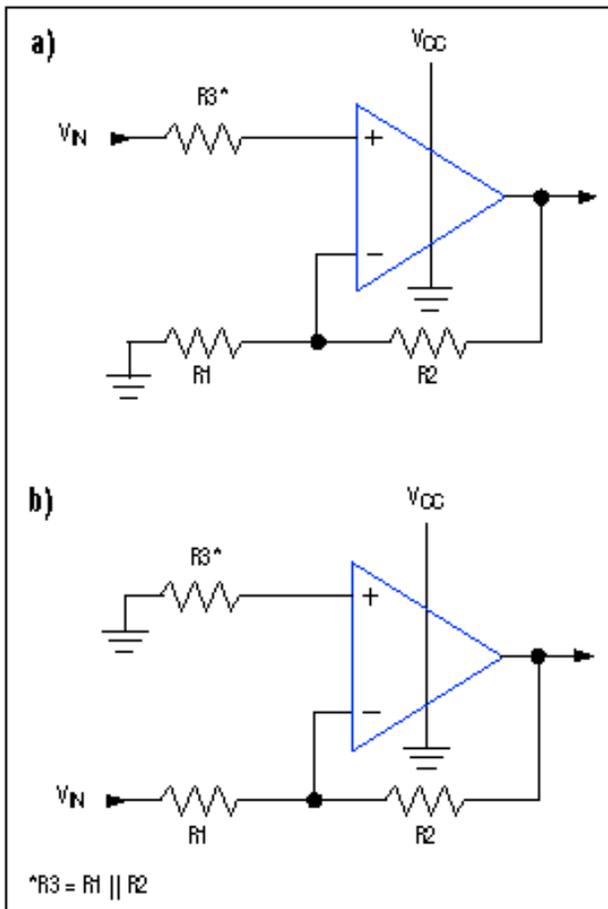


Figure 3. Matching the resistance at the inverting and noninverting nodes minimizes offset errors caused by input bias currents for both the noninverting (a) and inverting (b) configurations.

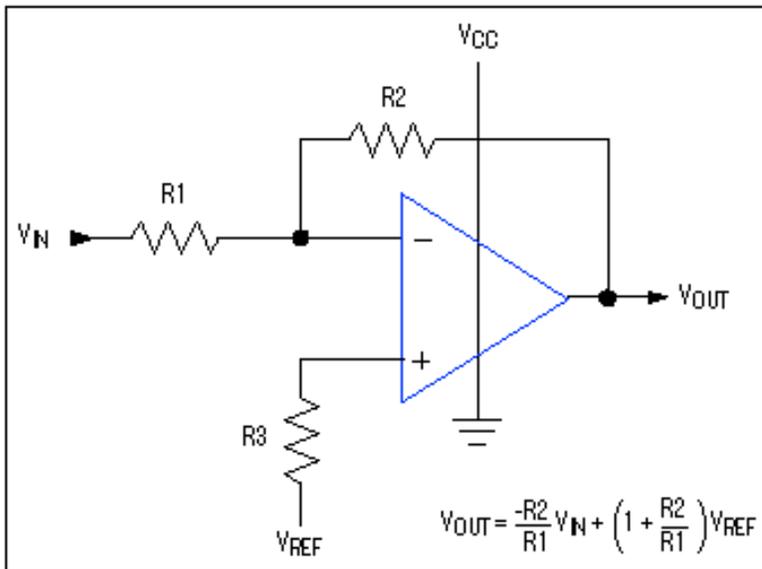


Figure 4. By holding the common-mode input voltage constant, the inverting-amplifier configuration eliminates common-mode-rejection errors.

Table 2. Maxim low-voltage references

Part	Output Voltage (V)	Input Voltage Range (V)	Temp. Drift (ppm/°C max)	Max Initial Accuracy, TA = +25°C (% F.S.)	Max Quiescent Current (µA)	Max Noise, 0.1Hz to 10Hz (µVp-p, typ)	Package Options ¹	Temp. Ranges ²	Features
MAX6120	1.2	2.4 to 11	100 (30 typ)	1	58	10	SOT23, SO	E	Low-cost, micropower, three-terminal reference
MAX6620	1.2	2.4 to 11	50	1	70	10	SOT23, SO	E	Low-cost, micropower, three-terminal reference; low drift
ICL8069	1.2	>VOUT	10 to 100	2	50	5 (10Hz to 10kHz)	TO-52, TO-92, SO	C, E, M	Micropower, two-terminal reference
MAX6125	2.5	2.7 to 12.0	50	1	130	15	SOT23, SO	E	Low-cost, low-dropout, three-terminal reference
MAX872	2.5	2.7 to 20	40	0.2	10	60	DIP, SO	C, E	Lowest-power, lowest-dropout precision reference. V _{CC} = V _{OUT} + 200mV.
MAX873	2.5	4.5 to 18	7 to 20	0.06 to 0.1	280	16	DIP, SO	C, E, M	Low-power/drift, REF43 upgrade
MX580	2.5	4.5 to 30	10 to 85	0.4 to 3	1.5mA	60	TO-52, SO	C, M	Low-drift bandgap reference
MX584	2.5	4.5 to 30	5 to 30	0.05 to 0.3	1mA	50	TO-99, DIP, SO, CERDIP	C, M	Low-drift programmable reference
MAX6141	4.096	4.7 to 12.6	50	1	130	25	SOT23, SO	E	Low-cost, low-dropout, three-terminal reference
MAX676	4.096	4.5 to 18	1 to 3	0.02	10mA	1.2	DIP/SO/CERDIP	C, E, M	Lowest temperature drift in SO package, lowest long-term drift, low dropout
MAX874	4.096	4.3 to 20	40	0.2	10	60	DIP, SO	C, E	Lowest-power, lowest-dropout precision reference. V _{CC} = V _{OUT} + 200mV.
MAX6145	4.5	4.7 to 12.6	50	1	130	30	SOT23, SO	E	Low-cost, low-dropout, three-terminal reference
MAX6160	Adjustable 1.23 to 12.40	V _{OUT} + 0.2	50	1	130	15	SOT23, SO	E	Adjustable, low-cost, low-dropout, three-terminal reference

¹ Package options: DIP = dual-in-line package; PLOC = plastic leadless chip carrier (quad pack); FP = flat pack
² Temperature ranges: C = 0°C to +70°C, E = -40°C to +85°C, M = -55°C to +125°C

Slew Rate

Slew rate can also suffer when a rail-to-rail input amplifier is used in place of a ground-sensing amplifier. The ground-sensing amplifier's simpler input stage can take advantage of many slew-rate-enhancing circuit techniques that are simply not available to amplifiers with the two-pair, rail-to-rail input. For example, MAX4212 family op amps (Table 1) have ground-sensing inputs that help them achieve 600V/µs slew rates and 300MHz bandwidths with supply currents of only 7mA maximum. If they had rail-to-rail input stages and all other specs remained unchanged, the slew rates would be several times lower.

Output Stage Concerns

While low-voltage designs may not require op amps with rail-to-rail input stages, they typically require rail-to-rail output stages to maximize dynamic range. Because op amps provide gain in most applications, the output voltage is usually larger than the input voltage. Thus, a rail-to-rail input stage is not always required, but a rail-to-rail output stage usually is. These output stages differ from

those in dual-supply op amps and cause different circuit behavior in the rail-to-rail output amplifiers.

Rail-to-rail output stages usually incorporate a common-emitter configuration, and standard output stages usually have an emitter-follower configuration (**Figure 5**). For common-emitter output stages, the voltage drop from input to output is relatively low (a single collector-to-emitter saturation voltage, or $V_{CE(SAT)}$), but the classic emitter-follower output stage cannot get closer to the rail than $V_{CE(SAT)}$ (due to the current source) plus V_{BE} (due to the output transistor).

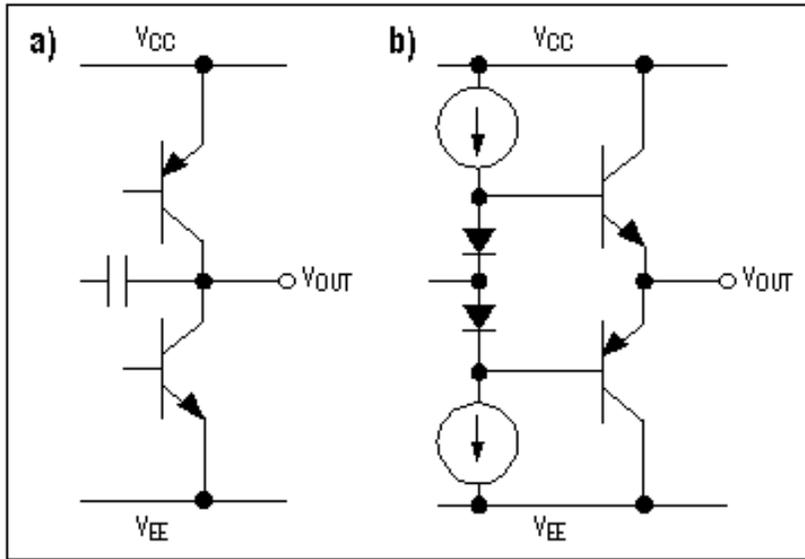


Figure 5. A rail-to-rail output stage (a) has a common-emitter configuration, while a standard output stage (b) has an emitter-follower configuration.

Because a bipolar transistor's $V_{CE(SAT)}$ depends on the current through the transistor, the output swing of a bipolar op amp depends on its load current. Thus, despite claims of rail-to-rail performance, an amplifier's output stage never truly reaches the supply rail. A MAX4122 with $100k\Omega$ load, for instance, swings to within 12mV of the positive rail and 20mV of the negative rail. With a 250Ω load, however, it swings only to within 240mV of the positive rail and 125mV of the negative rail. For CMOS output stages, the analogy to the bipolar transistor's collector-emitter voltage is the MOSFET's drain-source voltage, which is caused by the product of on-resistance and channel current in the MOSFET. Thus, the output voltage swing for a MOSFET output stage is also a function of the load.

Gain vs. Load

Besides offering a low input-to-output voltage drop, the common-emitter stage of a rail-to-rail amplifier differs from the emitter-follower stage in other important ways. Common-emitter stages provide voltage gain and have relatively high-impedance outputs; emitter-follower stages provide unity voltage gain and have low-impedance outputs. For that reason, rail-to-rail op amps usually include the output node as part of the compensation network, while standard op amps typically take their compensation at a preceding stage. For rail-to-rail op amps, the resulting dependency of gain on load current can make them unstable when driving capacitive loads.

These properties of rail-to-rail outputs can be suppressed with careful op-amp design, but the trade-off tends to be a higher supply current than required by op amps with emitter-follower output stages. The MAX4122–MAX4129 family of op amps offers good capability for driving capacitive loads (Table 1). Featuring rail-to-rail inputs and outputs that remain stable while driving 500pF, these op amps are useful for driving both improperly terminated cables and the capacitive inputs of analog-to-digital converters. The features that allow them to drive heavy capacitive loads also allow them to maintain good large-signal voltage gain, even with heavy resistive loads.

Open-Loop Gain vs. Output Swing

As is true for all op amps, the open-loop gain for a rail-to-rail output amplifier is a function of the output voltage swing. Thus, to evaluate a rail-to-rail output amplifier, you must specify the gain both at a given output voltage and with a given load. Maxim specifies gain this way, but not all vendors include such data in their data sheets. For example, an op amp may have 106dB of open-loop gain and the capability to drive a 250Ω load to within 125mV of the rails, but it may not be able to exhibit those capabilities at the same time. The MAX4122–MAX4129 data sheet, for instance, properly specifies large-signal voltage gain and output voltage swing in its *Electrical Characteristics* table (**Figure 6**). Large-signal voltage gain vs. output voltage and load graphs for these devices are shown in Figure 7.

DC ELECTRICAL CHARACTERISTICS

($V_{CC} = +2.7V$ to $+6.5V$, $V_{EE} = 0V$, $V_{CM} = 0V$, $V_{OUT} = V_{CC}/2$, R_L tied to $V_{CC}/2$, $\overline{SHDN} \geq 2V$ (or open), $T_A = +25^\circ C$, unless otherwise noted.)

PARAMETER	CONDITIONS		MIN	TYP	MAX	UNITS	
Large-Signal Voltage Gain	$V_{CC} = 2.7V$	$V_{OUT} = 0.25V$ to $2.45V$, $R_L = 100k\Omega$	92	104		dB	
		$V_{OUT} = 0.4V$ to $2.3V$, $R_L = 250\Omega$	72	80			
	$V_{CC} = 5V$	$V_{OUT} = 0.25V$ to $4.75V$, $R_L = 100k\Omega$	94	106			
		$V_{OUT} = 0.4V$ to $4.6V$, $R_L = 250\Omega$	75	84			
Output Voltage Swing	MAX4122/ MAX4123/ MAX4124/ MAX4125	$R_L = 100k\Omega$	$V_{CC} - V_{OH}$		12	20	mV
			$V_{OL} - V_{EE}$		20	25	
	$R_L = 250\Omega$	$V_{CC} - V_{OH}$		240	290		
		$V_{OL} - V_{EE}$		125	170		
	MAX4126/ MAX4127/ MAX4128/ MAX4129	$R_L = 100k\Omega$	$V_{CC} - V_{OH}$		15	30	
			$V_{OL} - V_{EE}$		25	40	
	$R_L = 250\Omega$	$V_{CC} - V_{OH}$		280	330		
		$V_{OL} - V_{EE}$		180	230		

Figure 6. A proper specification for large-signal voltage gain includes both the load and the output voltage swing. Output voltage swing is a function of the load being driven.

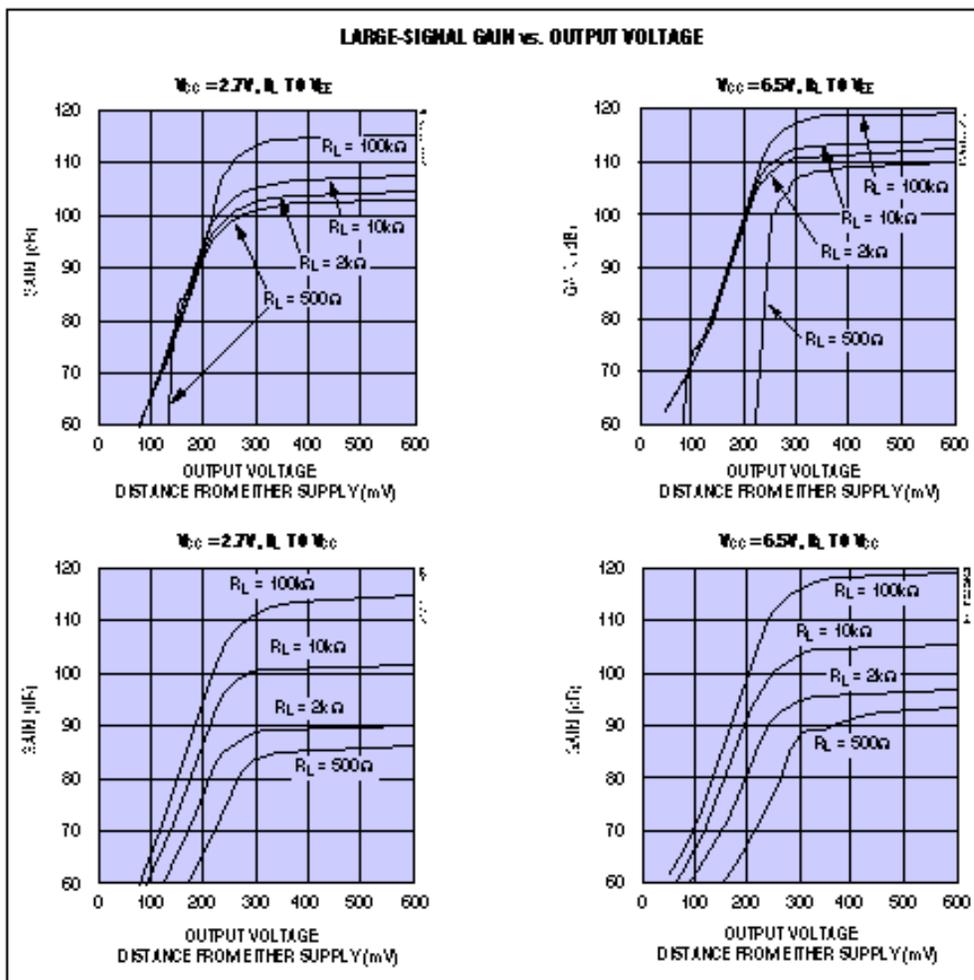


Figure 7. These graphs show a dependence of gain on the load and the output voltage swing for rail-to-rail output amplifiers.

Charge-Pump Op Amps

The MAX4162 op-amp family illustrates a novel approach to the problems of the standard rail-to-rail output stage. These op amps have a classic emitter-follower output stage, but achieve rail-to-rail outputs with an internal charge-pump converter that provides internal supply voltages to bias the output stage. The charge-pump converter also provides power to the amplifier's other stages. Thus, the input stage has a standard ground-sensing configuration, but allows inputs to swing from ground to V_{CC} . Specifications for this family are listed in Table 1. Each device draws only $35\mu A$ (including the charge-pump converter) while providing a $200kHz$ bandwidth. Supply currents are low, but these amplifiers can drive relatively heavy loads of $20k\Omega$ and $500pF$.

Because a charge pump enables the construction of op amps with standard input and output structures, such amplifiers can offer performance superior to that of rail-to-rail op amps. Charge-pump op amps have very good common-mode rejection, and their single input-transistor pair is not prone to the offset-voltage changes caused by switchover between input pairs. In addition, the classic emitter-follower output stage provides high open-loop gain, even with a relatively heavy resistive load. It also allows the amplifier to remain stable while driving large capacitive loads.

General Issues

Single-supply operation also aggravates the problems of noise, biasing, and distortion.

Noise

Single-supply applications are generally low voltage, and lower supply rails force the designer to make a corresponding reduction in noise just to maintain the system's signal-to-noise ratio. Unfortunately, low-voltage operation usually goes hand-in-hand with low-power operation, and as supply current decreases, amplifier noise tends to increase. All else being equal, a lower noise amplifier requires higher power dissipation.

To evaluate op-amp noise, consider all noise sources: input voltage noise, input current noise, and thermal noise caused by the gain-setting resistors. **Figure 8** illustrates these noise sources with a voltage-feedback op amp. C1 is stray capacitance at the op amp's inverting input, C2 limits noise gain and signal bandwidth at the higher frequencies, and R1/R2 are the standard gain-setting resistors. R3 balances the resistances seen by the inverting and noninverting inputs.

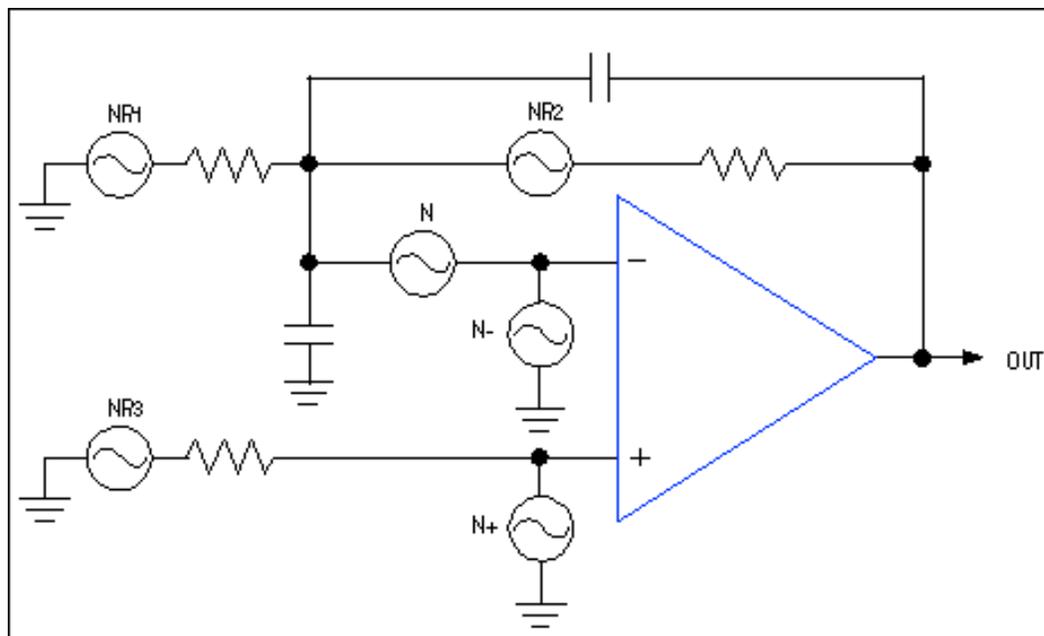


Figure 8. Major noise sources in a voltage-feedback op amp are as shown.

At low frequencies, the noise gain is given by $1 + R2/R1$ (**Figure 9**). The noise gain sees its first zero at a frequency given by $1/2\pi R1C1$, then increases at 6dB per octave until it hits the pole caused by C2. At this pole ($1/2\pi R2C2$), the noise gain is flat and equal to $1 + C1/C2$. Noise gain then intercepts the open-loop gain of the amplifier and rolls off at 6dB per octave (the standard single-pole rolloff of the amplifier's open-loop gain).

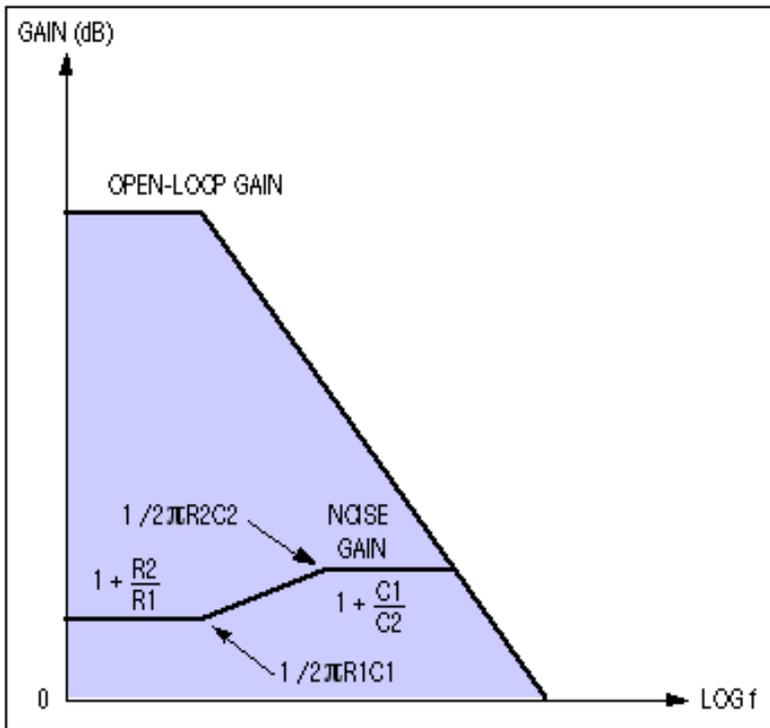


Figure 9. This graph shows noise gain and open-loop gain for the amplifier in Figure 8.

Because the input voltage noise, noninverting current noise, and noise due to R3 are integrated over the entire closed-loop bandwidth and multiplied by the circuit's noise gain, you can see (from the plots of noise gain and open-loop gain) that circuit noise can be minimized by choosing an op amp with a lower unity-gain-crossover frequency. For the inverting input, current noise and the thermal noise due to R1 and R2 are integrated only over the signal bandwidth ($1/2\pi R2C2$). Since capacitor C2 is not present for current-feedback op amps, noise for those types is integrated over the entire closed-loop signal bandwidth.

Distortion

An amplifier's loop gain minimizes the distortion that would otherwise result from nonlinearities in its input-to-output transfer function. Because amplifier gain falls off at higher frequencies, the amplifier's harmonic distortion increases.

Thus, for a given frequency, an op amp can achieve superior harmonic performance if it operates in its more linear region, with maximum loop gain. This usually means biasing the output away from the supply rails, as in Figure 4 (which introduces signal inversion and offset) or **Figure 10** (which introduces offset but no signal inversion).

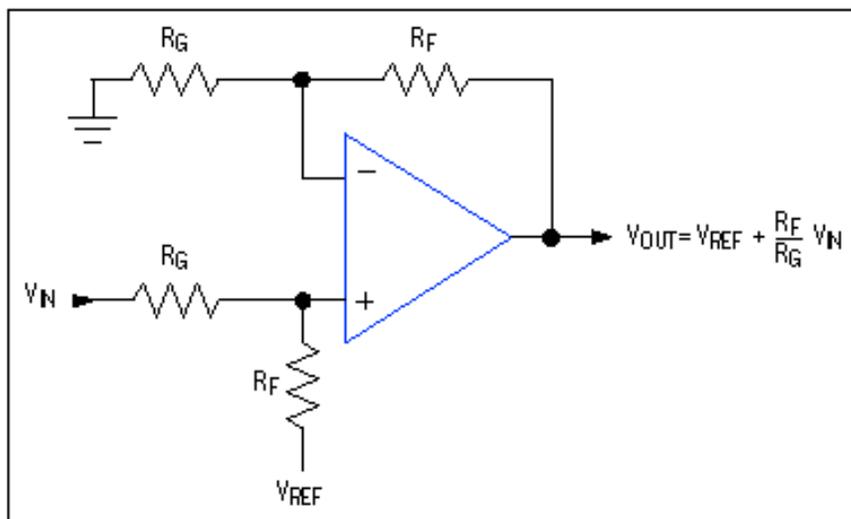


Figure 10. Providing both gain and offset to the input signal, this circuit biases the output voltage away from the supply rails.

The inverting method shown in Figure 4 eliminates common-mode nonlinearities by keeping the common-mode input voltage constant. This feature is particularly useful for rail-to-rail input amplifiers, whose nonlinearities are produced by changes in the common-mode input (as the input stage shifts from one input pair to the other).

Focus again on the output stage. A light load will improve the harmonic performance of rail-to-rail amplifiers, because gain is a

function of load current. An amplifier's voltage excursion also affects distortion. All op amps tend to benefit from loads that require a minimal voltage excursion (internal nodes don't have to travel too far, so they tend to remain in their linear regions). An amplifier's slew rate, which is related to full-power bandwidth, also affects harmonic distortion. In running the amplifier above its full-power bandwidth, the associated slew-rate limitations cause severe nonlinearities.

Generating a Second Supply

High-performance, single-supply op amps are becoming more common, but to maximize performance you must sometimes choose a dual-supply amplifier. The selection of dual-supply types is greater because dual-supply systems have been available longer, and dual-supply op amps are not designed with the same restrictions as their single-supply cousins.

Countless methods are available for generating a negative supply from an existing positive one. Switching regulators are the most flexible, but charge-pump voltage converters offer the simplest, smallest, and cheapest alternative. Because charge-pump converters provide voltage conversion with external capacitors rather than inductors, they excel at providing integer multiples of the input voltage ($-V_{IN}$, $+2V_{IN}$, etc.). Their output voltages are typically unregulated, but if load currents are relatively light, the output voltages remain fairly close to an integer multiple of the input.

Because charge-pump converters can have very low quiescent supply currents, they can be highly efficient under light loads. In **Figure 11**, a charge-pump converter is configured to generate a negative voltage that is equal to the input in magnitude but opposite in polarity. Pin-strap options set the internal oscillator frequency at 13kHz, 100kHz, or 250kHz, allowing the designer to trade off quiescent current consumption, charge-pump capacitor size, or output voltage ripple.

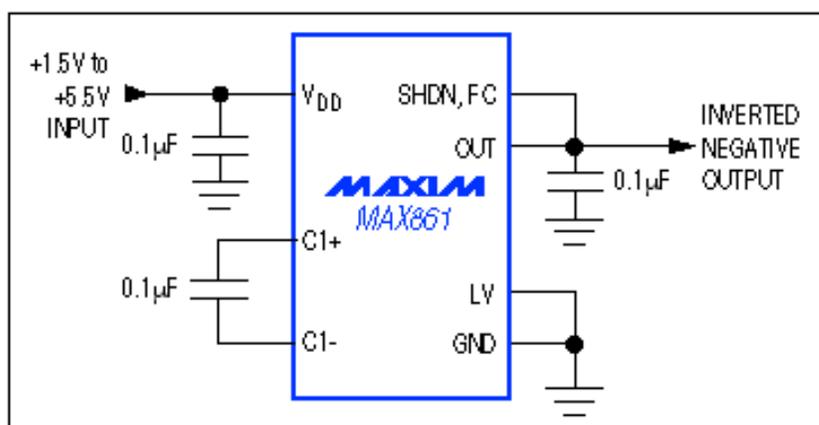


Figure 11. Simple, small, and inexpensive charge-pump converters can readily generate a negative supply rail from a positive one.

Application Note 656: <http://www.maxim-ic.com/an656>

More Information

For technical questions and support: <http://www.maxim-ic.com/support>

For samples: <http://www.maxim-ic.com/samples>

Other questions and comments: <http://www.maxim-ic.com/contact>

Related Parts

MAX4122: [QuickView](#) -- [Full \(PDF\) Data Sheet](#) -- [Free Samples](#)

MAX4165: [QuickView](#) -- [Full \(PDF\) Data Sheet](#) -- [Free Samples](#)

MAX861: [QuickView](#) -- [Full \(PDF\) Data Sheet](#) -- [Free Samples](#)

AN656, AN 656, APP656, Appnote656, Appnote 656

Copyright © by Maxim Integrated Products

Additional legal notices: <http://www.maxim-ic.com/legal>