Designing with op amps: Single-formula technique keeps it simple

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A simple single-op-amp design technique uses one formula—$R_F/|gain|$—for both positive and negative gains. The procedure works for all gain settings and produces designs with minimal bias-current error.

Numerous texts and application notes describe the design of op-amp circuits. Most designers use the R_F/R_I formula for inverting amplifiers and the $1+R_F/R_I$ formula for noninverting amplifiers, where R_F and R_I are the feedback and input resistors, respectively. These two formulas have been the basis of op-amp design for many years. Why learn a new procedure? One reason is that the new procedure is simple in that it uses the same formula—R_F divided by the magnitude of the gain—for both positive and negative gains.

Second, the procedure is universal and works for all sets of gains. Although you can use classic methods to design op-amp circuits with multiple negative-gain inputs and a single positive-gain input, circuits with multiple positive-gain inputs are difficult to design using classic methods. Another reason to learn this new procedure is that it creates designs that always exhibit minimal bias-current error.

The design procedure relies on two new circuit concepts: a gain formula and a circuit theorem (see **box** "Theoretical background") and is based on the following definitions and assumptions:

- The procedure applies to single op-amp circuits with any number of positive- and negative-gain inputs, and the op amp is ideal.
- All inputs are ideal voltage sources.
- Ground acts as an input and is a voltage source of value zero.
- If the input has a source impedance, the source impedance is part of the circuit.
- Gain is defined as the gain from the ideal voltage source to the op-amp output.
- The feedback resistor, R_F, connects from the op-amp output to the inverting input.
- The input resistor, R_i, connects from the ideal voltage source input to the op-amp input. Positive-gain inputs connect to the noninverting op-amp input terminal, and negative-gain inputs connect to the inverting op-amp input terminal. This definition differs from standard usage. In classic circuit analysis, the input resistor always connects to the inverting op-amp input. The R_i notation emphasizes the difference.
- The circuit's input im-pedance is equal to R_i only for negative inputs. For positive inputs, R_i is the impedance that connects the input to the noninverting op-amp terminal.

To implement the design, you must first specify the desired circuit gains. You then must calculate the ground gain, as follows:

Ground gain=1–the sum of the positive and negative gains from the desired circuit gains.

In other words, ground gain+Σcircuit gains=1. You must now choose a feedback-resistor value. For example, let R_F=100 kΩ. Next, calculate the resistor values for each input, including the ground-gain resistor, using $R_{i,G}=R_F/|gain|$.

You can have any number of positive-gain and negative-gain inputs, and each input must have a defined gain. Ground gain=1–sum of gains. Some op-amp circuits need a resistor to ground from the op amp's inverting input, and

FIGURE 1
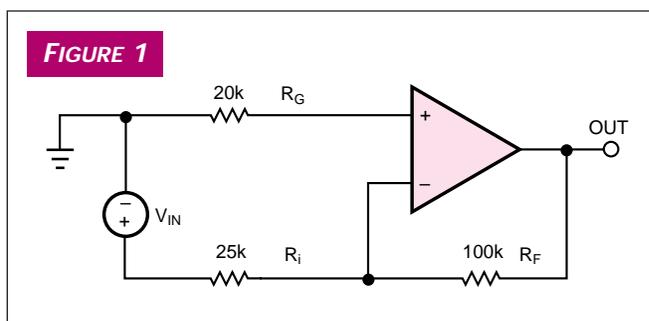
To design an inverting amplifier with a gain of –4 and an R_F of 100 kΩ, you connect an R_i of 25 kΩ to the inverting input and an R_G of 20 kΩ to the noninverting input.

OP-AMP DESIGN PROCEDURE

others need a resistor to ground on the noninverting input. The sign of the ground gain determines where to place the ground resistor. For positive ground gains, you connect the resistor to the op amp's noninverting terminal; for negative ground gains, you connect the resistor to the inverting terminal. If the desired gains add up to one, a ground resistor is unnecessary.

The feedback resistor you choose can theoretically be any value, but op-amp and circuit considerations usually limit the range of acceptable values. Selecting a feedback-resistor value that is a multiple of the gains avoids fractional values for the input resistors. Calculate the input resistor values as R_F divided by the magnitude of the gain for both positive and negative gains.

For those op-amp experts who have their doubts, consider an example: Design an inverting amplifier with a gain of –4. Thus, the circuit needs a ground gain equal to +5. Selecting R_F=100 kΩ yields an input-resistor value, R_i, of 25 kΩ and a ground-gain input-resistor value, R_G, of 20 kΩ (**Figure 1**). The –4-gain input resistor connects to the op amp's inverting input. The +5 ground-gain resistor connects to the noninverting input. The design of this inverting amplifier is similar to that of a classic inverting amplifier. The new procedure adds a ground resistor at the noninverting op-amp input. This ground resistor is necessary only to minimize bias-current error.

The noninverting op-amp input terminal sees a resistance of 20 kΩ looking into the circuit. The resistance at the inverting op-amp input is the parallel combination of the 100-kΩ feedback resistance and the 25-kΩ input resistance. Because the parallel resistance of 25-kΩ and 100-kΩ is 20-kΩ, both op-amp terminals see the same resistance looking into the circuit. The voltages that the op-amp bias current produces at the op-amp inputs are equal. The bias current creates only a common-mode input, which the op-amp rejects. Thus, the 20-kΩ grounded input resistor minimizes the bias-current error for this example.
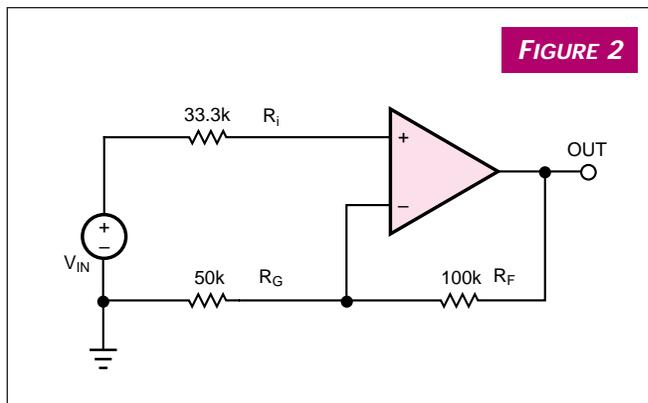
In another example, consider the design of a noninvert-

FIGURE 2

A noninverting amplifier with a gain of +3 and an R_F of 100 kΩ requires an R_i of 33.3 kΩ connected between the input and the noninverting terminal and an R_G of 50 kΩ connected between the inverting terminal and ground.
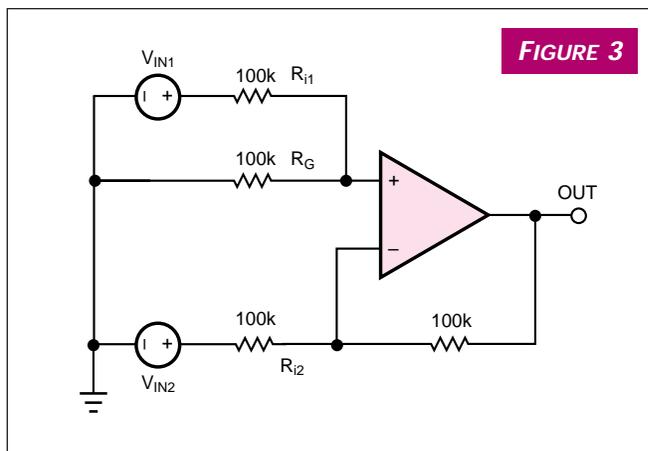

FIGURE 3

A differential amplifier with gains of +1 and –1 requires a ground gain of +1. With R_F=100 kΩ, all input resistors, including the ground resistor, are 100 kΩ.

THEORETICAL BACKGROUND

The design technique uses a new op-amp gain formula, Plato's gain formula, and a new circuit theorem, Daisy's theorem.

Plato's gain formula is

$$gain = p \times R_F/R_i,$$

where R_F is the feedback resistance, R_i is the resistor that connects the input to the op amp, and p is a circuit constant for positive-gain inputs and always equal to –1 for negative-gain inputs. For negative gains, Plato's gain formula is simply the classic R_F/R_i gain formula.

For positive gains, this formula differs from classic analysis. In classic analysis, the positive gain is the gain from the source to the noninverting op-amp terminal times $1+R_F/R_i$.

Alternatively, Plato's gain formula states that you can express positive gains as the product of a circuit-constant p and R_F/R_i. The value of p is the same for all positive gains in a given circuit. Different circuits may have different values for p. Don't assume p=1 for existing designs. For new designs, setting p=1 simplifies the formula and creates a better design. The only value that minimizes bias-current error is p=1.

Daisy's theorem, which you use to determine the ground gain, is as follows:

The sum of the gains=1.

The design procedure assumes that the circuit inputs are ideal voltage sources and that ground is a voltage input of value 0. The overall gain is the gain from the ideal voltage source to the op-amp output. For new op-amp circuits, Daisy's theorem specifies whether a ground resistor is necessary at the op amp's noninverting or inverting input and specifies the magnitude of the ground gain.

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FIGURE 4
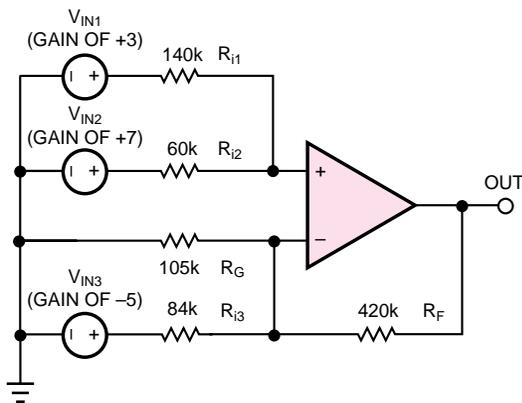
The procedure makes it easy to design an op-amp circuit with multiple positive-gain inputs.

ing op-amp circuit with a gain of +3. Thus, the circuit needs a ground gain of –2. With R_F=100 kΩ, the input resistor, R_i, is 100 kΩ/3=33.3 kΩ, and the grounded input resistor, R_G, is 100 kΩ/2=50 kΩ (**Figure 2**). The 33.3-kΩ resistor is necessary only to minimize the bias-current error. Note that 33.3 kΩ is equal to the parallel resistance of 50 and 100 kΩ.

Classic design states that the gain of a noninverting amplifier is $1+R_F/R_I$. In this case, R_I of the classic case is equivalent to the ground-gain resistor, R_G. Thus, the ground gain of **Figure 2** is equal to $–R_F/R_G$. Adding the input gain (+3) and ground gain (–2) yields the gain sum of 1. For noninverting amplifiers, the positive-gain input resistor, R_i, is necessary only to minimize the bias-current error.

In another design example, consider a differential amplifier with gains of +1 and –1, corresponding to inputs V_{IN1} and V_{IN2}, respectively. Thus, the circuit needs a ground gain of +1. With R_F=100 kΩ, all resistor values—R_{i1}, R_{i2}, and R_G—are 100 kΩ (**Figure 3**). In this circuit, R_G acts as an attenuator for the positive-gain input, V_{IN1}. Note that the equivalent resistance at each op-amp input terminal is the same.

You can check this design using the classic formulas. The gain from the op amp's inverting input is 100 kΩ/100 kΩ=1. The gain from V_{IN1} to the op amp's noninverting input is 0.5. The gain from the op amp's noninverting input to the output is $1+R_F/R_{i2}$=2. Thus, the gain from V_{IN1} to the output is 0.5×2=1.

In another example, design a summing amplifier with gains of +3, –5, and +7. The presence of two positive gains makes this example difficult to design using classic methods. The input gains are +3, +7, and –5, which add up to +5. Thus, a ground gain of –4 is necessary. With R_F=420 kΩ, positive-gain input-resistor R_{i1} is 420 kΩ/3=140 kΩ, and positive-gain input-resistor R_{i2} is 420 kΩ/7=60 kΩ. The negative-gain input resistor, R_{i3}, is 420 kΩ/5=84 kΩ. The ground-gain input resistor is 420 kΩ/4=105 kΩ (**Figure 4**).

Note that the op amp's input terminals see the same equivalent resistance: 140 kΩ||60 kΩ=105 kΩ||84 kΩ||420 kΩ. The gain from V_{IN1} to the op amp's noninverting input is 60 kΩ/(60 kΩ+140 kΩ)=0.3. The gain from the noninverting input to the output is equal to $1+R_F/(R_{i3}||R_G)$=1+420 kΩ/(84 kΩ||105 kΩ)=10. Thus, the gain from V_{IN1} to the output is 0.3×10=3. You can verify the gains from V_{IN2} and V_{IN3} to the output in a similar manner. **EDN**

Author's biography

Dieter Knollman, PhD, is a distinguished member of the technical staff of Lucent Technologies (Denver), where he has worked for 33 years. In his current position, he designs PBX port circuits. Knollman earned a BSEE from the Virginia Polytechnic Institute and State University (Blacksburg, VA) an MSEE from the University of Illinois—Urbana/Champaign, and a PhD from New York University (New York).