

# Single-supply op amp design

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## Introduction

Most portable systems have one battery, thus the popularity of portable equipment results in increased single-supply applications. Split- or dual-supply op amp circuit design is straightforward because op amp inputs and outputs are referenced to the normally grounded center tap of the supplies. In the majority of split-supply applications, signal sources driving the op amp inputs are referenced to ground; thus with one input of the op amp referenced to ground, as shown in Figure 1, common-mode voltage and voltage bias problems are negligible.

When signal sources are referenced to ground, single-supply op amp circuits exhibit a large input common-mode voltage (Figure 2). The input voltage is not referenced to the midpoint of the supplies like it would be in a split-supply application; rather, it is referenced to the lower-power supply rail. This circuit malfunctions when the input voltage is positive because the output voltage should go negative; this is hard to do with a positive supply. It operates marginally with small negative input voltages because most op amps cannot function when the inputs are connected to the supply rails.

The constant requirement to account for input references makes it difficult to design single-supply op amp

circuits. This application note develops an orderly procedure for designing single-supply op amp circuits that leads to a working design every time. Application Note SLAA068, entitled, "Understanding Basic Analog—Ideal Op Amps," develops the ideal op amp equations. The ideal op amp assumptions used to write ideal op amp equations are shown in Table 1 for your reference.

Table 1. Ideal op amp parameter values

| PARAMETER NAME       | PARAMETER SYMBOL | VALUE    |
|----------------------|------------------|----------|
| Input current        | $I_{IN}$         | 0        |
| Input offset-voltage | $V_{OS}$         | 0        |
| Input impedance      | $Z_{IN}$         | $\infty$ |
| Output impedance     | $Z_{OUT}$        | 0        |
| Gain                 | $a$              | $\infty$ |

## Boundary conditions

Use of a single-supply limits the output voltage range to the positive supply voltage. This limitation precludes negative output voltages when the circuit has a positive supply voltage, but it does not preclude negative input voltages. As long as the voltage on the op amp input leads does not become negative, the circuit can handle negative input voltages.

Beware of working with negative input voltages when the op amp is powered from a positive supply because op amp inputs are highly susceptible to reverse voltage breakdown. Also, insure that all possible startup conditions do not reverse bias the op amp inputs when the input and supply voltage are of opposite polarity.

## Simultaneous equations

Taking an orderly path to developing a circuit that works the first time means following these steps until the equation of the op amp is determined. Use specifications and simultaneous equations to determine what form the op amp equation must have. Go to the section that illustrates that equation form (called a case), solve the equations to determine the resistor values, and you have a working solution.

A linear op amp transfer function is limited to the equation of a straight line.

$$y = \pm mx \pm b \quad (1)$$

The equation of a straight line has four possible solutions depending upon the sign of  $m$  (the slope) and  $b$  (the intercept), thus simultaneous equations yield solutions in four forms. Four circuits are developed, one for each form of the equation of a straight line. The four equations, cases, or forms of a straight line are given in Equations 2 through 5 where electronic terminology has been substituted for math terminology.

Figure 1. Split-supply op amp circuit

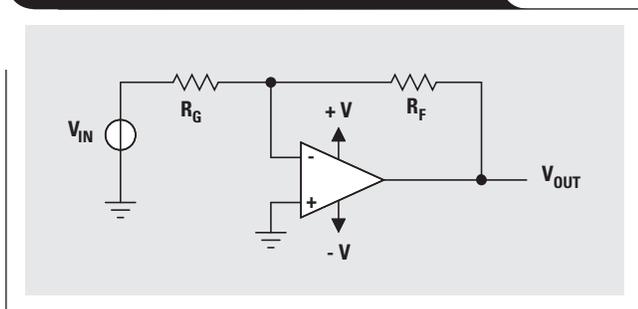
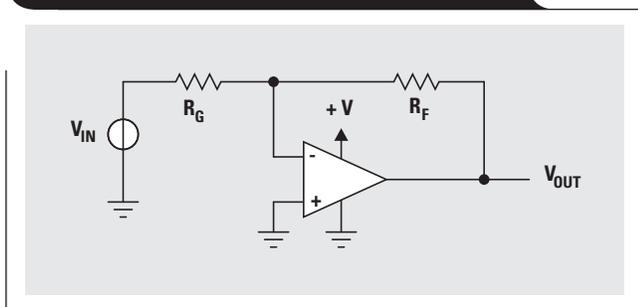


Figure 2. Single-supply op amp circuit



$$V_{OUT} = mV_{IN} + b \quad (2)$$

$$V_{OUT} = mV_{IN} - b \quad (3)$$

$$V_{OUT} = -mV_{IN} + b \quad (4)$$

$$V_{OUT} = -mV_{IN} - b \quad (5)$$

Given a set of two data points for  $V_{OUT}$  and  $V_{IN}$ , simultaneous equations are solved to determine  $m$  and  $b$  for the equation that satisfies the given data. The sign of  $m$  and  $b$  determines the type of circuit required to implement the solution.

The given data is derived from the specifications; i.e., a sensor output signal ranging from 0.1 volts to 0.2 volts must be interfaced into an analog-to-digital converter that has an input voltage range of 1 volt to 4 volts. These data points ( $V_{OUT} = 1.0 \text{ V @ } V_{IN} = 0.1 \text{ V}$ ,  $V_{OUT} = 4.0 \text{ V @ } V_{IN} = 0.2 \text{ V}$ ) are inserted into Equation 2, as shown in Equations 6 and 7, to obtain  $m$  and  $b$  for the specifications.

$$1 = m(0.1) + b \quad (6)$$

$$4 = m(0.2) + b \quad (7)$$

Solving Equations 6 and 7 yields  $b = -2$  and  $m = 30$ . Now  $m$  and  $b$  are substituted back into Equation 2, yielding Equation 8.

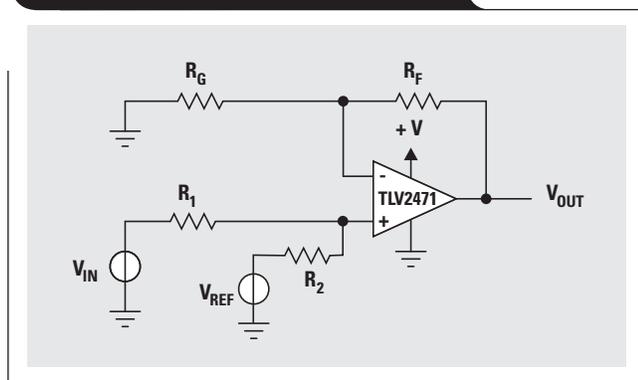
$$V_{OUT} = 30V_{IN} - 2 \quad (8)$$

Notice that, although Equation 2 was the starting point, the form of Equation 8 is identical to Equation 3. The specifications or given data determine the sign of  $m$  and  $b$ , and starting with Equation 2, the final equation form is discovered after  $m$  and  $b$  are calculated. The next step is to develop a circuit that has an  $m = 30$  and  $b = -2$  to complete the problem solution. Circuits were developed for Equations 2 through 5, and they are given under the headings Case 1 through Case 4, respectively.

#### Case 1 — $V_{OUT} = mV_{IN} + b$

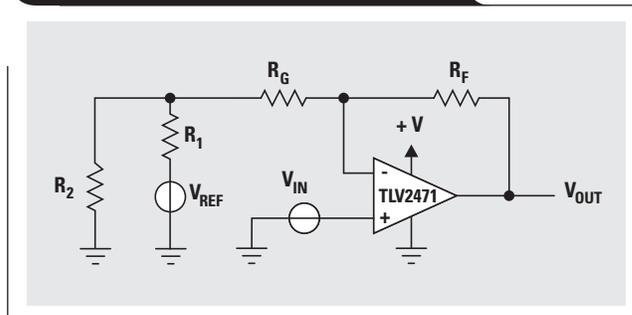
The circuit configuration that yields a solution for Case 1 is shown in Figure 3.

**Figure 3. Schematic for Case 1 —**  
 $V_{OUT} = mV_{IN} + b$



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**Figure 4. Schematic for Case 2 —**  
 $V_{OUT} = mV_{IN} - b$



The circuit equation is written using the voltage divider rule and superposition.

$$V_{OUT} = V_{IN} \left( \frac{R_2}{R_1 + R_2} \right) \left( \frac{R_F + R_G}{R_G} \right) + \dots \quad (9)$$

$$\dots V_{REF} \left( \frac{R_1}{R_1 + R_2} \right) \left( \frac{R_F + R_G}{R_G} \right)$$

$$m = \left( \frac{R_2}{R_1 + R_2} \right) \left( \frac{R_F + R_G}{R_G} \right) \quad (10)$$

$$b = V_{REF} \left( \frac{R_1}{R_1 + R_2} \right) \left( \frac{R_F + R_G}{R_G} \right) \quad (11)$$

#### Case 2 — $V_{OUT} = mV_{IN} - b$

The circuit shown in Figure 4 yields a solution for Case 2. The circuit equation is obtained by taking the Thevenin equivalent circuit looking into the junction of  $R_1$  and  $R_2$ . After the  $R_1$ ,  $R_2$  circuit is replaced with the Thevenin equivalent circuit, the gain is calculated with the ideal gain equation.

$$V_{OUT} = V_{IN} \left( \frac{R_F + R_G + R_1 \parallel R_2}{R_G + R_1 \parallel R_2} \right) - \dots \quad (12)$$

$$\dots V_{REF} \left( \frac{R_2}{R_1 + R_2} \right) \left( \frac{R_F}{R_G + R_1 \parallel R_2} \right)$$

$$m = \frac{R_F + R_G + R_1 \parallel R_2}{R_G + R_1 \parallel R_2} \quad (13)$$

$$|b| = V_{REF} \left( \frac{R_2}{R_1 + R_2} \right) \left( \frac{R_F}{R_G + R_1 + R_2} \right) \quad (14)$$

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**Case 3 —  $V_{OUT} = -mV_{IN} + b$**

The circuit shown in Figure 5 yields the transfer function desired for Case 3.

The circuit equation is obtained with superposition.

$$V_{OUT} = -V_{IN} \left( \frac{R_F}{R_G} \right) + V_{REF} \left( \frac{R_1}{R_1 + R_2} \right) \left( \frac{R_F + R_G}{R_G} \right) \quad (15)$$

$$|m| = \frac{R_F}{R_G} \quad (16)$$

$$b = V_{REF} \left( \frac{R_1}{R_1 + R} \right) \left( \frac{R_F + R_G}{R_G} \right) \quad (17)$$

**Case 4 —  $V_{OUT} = -mV_{IN} - b$**

The circuit shown in Figure 6 yields a solution for Case 4. The circuit equation is obtained by using superposition to calculate the response to each input. The individual responses to  $V_{IN}$  and  $V_{REF}$  are added to obtain Equation 18.

$$V_{OUT} = -V_{IN} \left( \frac{R_F}{R_{G1}} \right) - V_{REF} \left( \frac{R_F}{R_{G2}} \right) \quad (18)$$

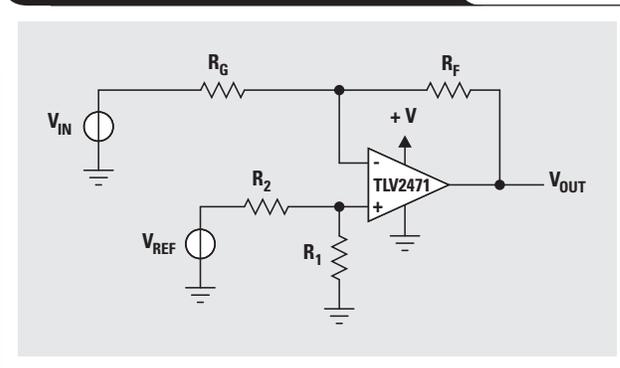
$$|m| = \frac{R_F}{R_{G1}} \quad (19)$$

$$|b| = V_{REF} \left( \frac{R_F}{R_{G2}} \right) \quad (20)$$

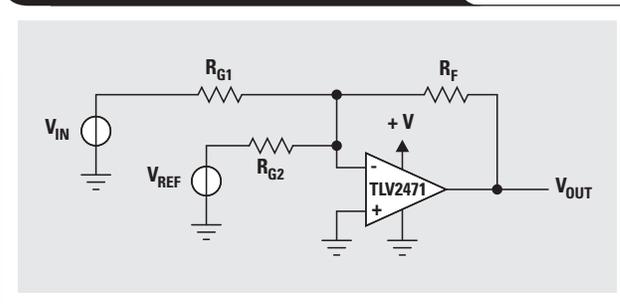
**Conclusion**

Single-supply op amp design is more complicated than split-supply op amp design, but with a logical design approach excellent results are achieved. Single-supply design was considered technically limiting because the older op amps had limited capability. Op amps such as the TI TLV247x, TLC07x, and TLC08x have excellent

**Figure 5. Schematic for Case 3 —  $V_{OUT} = -mV_{IN} + b$**



**Figure 6. Schematic for Case 4 —  $V_{OUT} = -mV_{IN} - b$**



single-supply parameters; thus, when used in the correct applications, these op amps yield rail-to-rail performance far surpassing their split-supply counterparts. More in-depth information concerning single-supply op amp design can be found in Texas Instruments Application Note SLOA030, entitled, “Single-Supply Op Amp Design Techniques.”

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