

Single-Supply Op Amp Design Techniques

*Application
Report*

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Ron Mancini

ABSTRACT

This application report describes single-supply op amp applications, their portability and their design techniques. The single-supply op amp design is more complicated than a split- or dual-supply op amp, but single-supply op amps are more popular because of their portability. New op amps, such as the TLC247X, TLC07X, and TLC08X have excellent single-supply parameters. When used in the correct applications, these op amps yield almost the same performance as their split-supply counterparts. The single-supply op amp design normally requires some form of biasing.

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 straight forward because the 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, there is no need to consider input common-mode voltage problems.

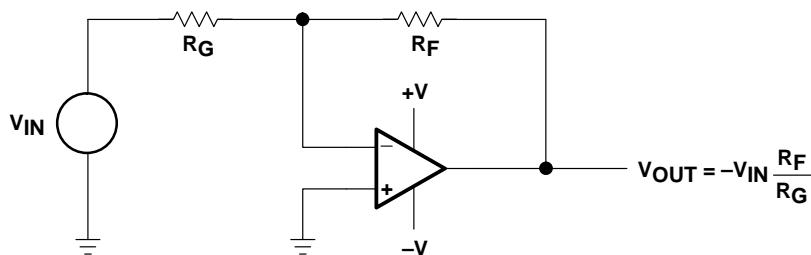


Figure 1. Split-Supply Op Amp Circuit

When the signal source is not referenced to ground (see Figure 2), the voltage difference between ground and the reference voltage shows up amplified in the output voltage. Sometimes this situation is okay, but other times the difference voltage must be stripped out of the output voltage. An input-bias voltage is used to eliminate the difference voltage when it must not appear in the output voltage (see Figure 3). The voltage (V_{REF}) is in both input circuits, hence it is named a common-mode voltage. Voltage-feedback op amps, like those used in this application note, reject common-mode voltages because their input circuit is constructed with a differential amplifier (chosen because it has natural common-mode voltage rejection capabilities).

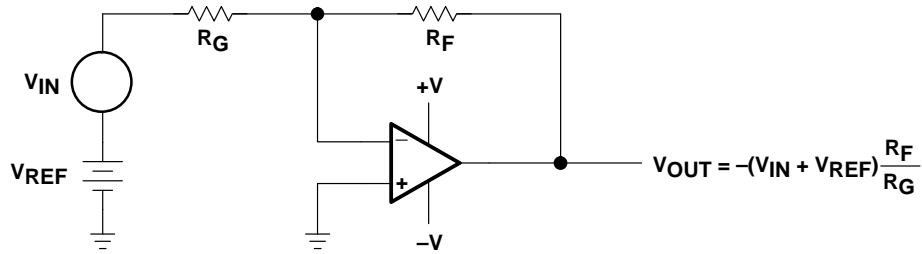


Figure 2. Split-Supply Op Amp Circuit With Reference-Voltage Input

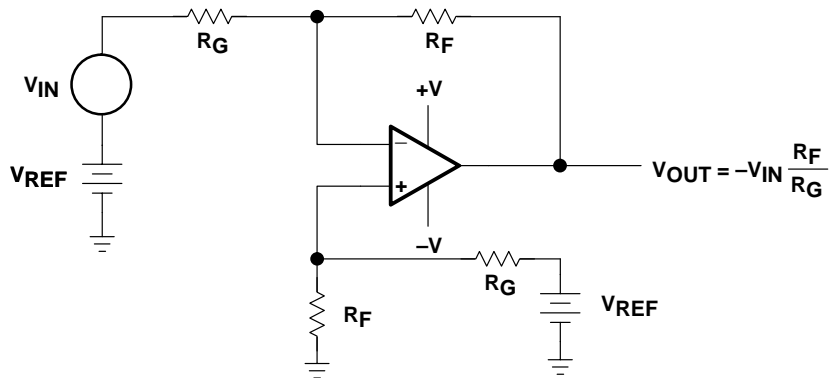


Figure 3. Split-Supply Op Amp Circuit With Common-Mode Voltage

When signal sources are referenced to ground, single-supply op amp circuits exhibit a large input common-mode voltage. Figure 4 shows a single-supply op amp circuit that has its input voltage referenced to ground. 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 does not operate when the input voltage is positive because the output voltage would have to go to a negative voltage, hard to do with a positive supply. It operates marginally with small negative input voltages because most op amps do not function well when the inputs are connected to the supply rails.

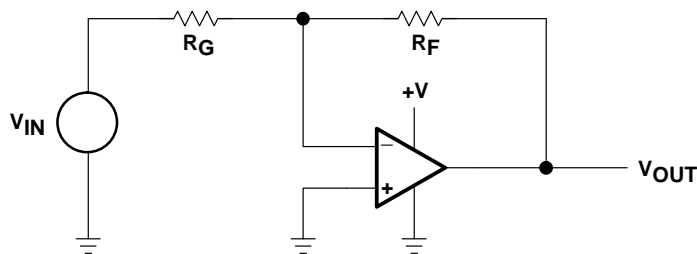


Figure 4. Single-Supply Op Amp Circuit

The constant requirement to account for inputs connected to ground or other reference voltages makes it difficult to design single-supply op amp circuits. This application note develops an orderly procedure which leads to a working design every time. If you do not have a good working knowledge of op amp equations, please reference the *Understanding Basic Analog...* series of application notes available from Texas Instruments. Application note SLAA068 titled, *Understanding Basic Analog-Ideal Op Amps* develops the ideal op amp equations. Circuit equations are written with the ideal op amp assumptions as specified in *Understanding Basic Analog-Ideal Op Amps*; the assumptions are tabulated below for your reference.

PARAMETER NAME	PARAMETERS SYMBOL	VALUE
Input current	I_{IN}	0
Input offset voltage	V_{OS}	0
Input impedance	Z_{IN}	∞
Output impedance	Z_{OUT}	0
Gain	a	∞

Unless otherwise specified, all op amps circuits are single-supply circuits. The single supply may be wired with the negative or positive lead connected to ground, but as long as the supply polarity is correct, the wiring does not affect circuit operation.

Use of a single-supply limits the polarity of the output voltage. When the supply voltage (V_{CC}) = 10 V, the output voltage is limited to the range $0 \leq V_{OUT} \leq 10$. This limitation precludes negative output voltages when the circuit has a positive supply voltage, but it does not preclude negative input voltages when the circuit has a positive supply voltage. 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 (positive) input voltages when the op amp is powered from a positive (negative) supply because op-amp inputs are highly susceptible to reverse voltage breakdown. Also, insure that all possible start-up conditions do not reverse bias the op-amp inputs when the input and supply voltage are opposite polarity.

Circuit Analysis

The complexities of single-supply op amp design are illustrated with the following example. Notice that the biasing requirement complicates the analysis by presenting several conditions that are not realizable. It is best to wade through this material to gain an understanding of the problem, especially since a cookbook solution is given later in this chapter. The previous chapter assumed that the op amps were ideal, and this chapter starts to deal with op amp deficiencies. The input and output voltage swing of many op amps are limited as shown in Figure 7, but if one designs with the selected rail-to-rail op amps, the input/output swing problems are minimized. The inverting circuit shown in Figure 5 is analyzed first.

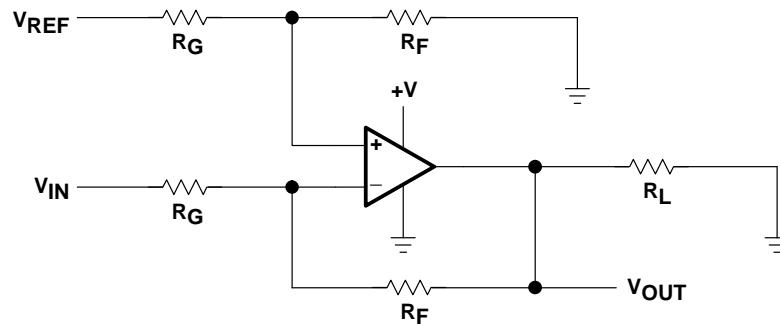


Figure 5. Inverting Op Amp

Equation 1 is written with the aid of superposition, and simplified algebraically, to acquire equation 2.

$$V_{OUT} = V_{REF} \left(\frac{R_F}{R_G + R_F} \right) \left(\frac{R_F + R_G}{R_G} \right) - V_{IN} \frac{R_F}{R_G} \quad (1)$$

$$V_{OUT} = (V_{REF} - V_{IN}) \frac{R_F}{R_G} \quad (2)$$

As long as the load resistor (R_L) is a large value, it does not enter into the circuit calculations, but it can introduce some second order effects such as limiting the output voltage swing. Equation 3 is obtained by setting V_{REF} equal to V_{IN} , and there is no output voltage from the circuit regardless of the input voltage. The author unintentionally designed a few of these circuits before he created an orderly method of op-amp circuit design. Actually, a real circuit has a small output voltage equal to the lower transistor saturation voltage, which is about 150 mV for a TLC07X.

$$V_{OUT} = (V_{REF} - V_{IN}) \frac{R_F}{R_G} = (V_{IN} - V_{IN}) \frac{R_F}{R_G} = 0 \quad (3)$$

When $V_{REF} = 0$, $V_{OUT} = -V_{IN}(R_F/R_G)$, there are two possible solutions to equation 2. First, when V_{IN} is any positive voltage, V_{OUT} should be negative voltage. The circuit can not achieve a negative voltage with a positive supply, so the output saturates at the lower power supply rail. Second, when V_{IN} is any negative voltage, the output spans the normal range according to equation 5.

$$V_{IN} \geq 0, \quad V_{OUT} = 0 \quad (4)$$

$$V_{IN} \leq 0, \quad V_{OUT} = |V_{IN}| \frac{R_F}{R_G} \quad (5)$$

When V_{REF} equals the supply voltage (V_{CC}) we obtain equation 6. In equation 6, when V_{IN} is negative, V_{OUT} should exceed V_{CC} ; that is impossible, so the output saturates. When V_{IN} is positive, the circuit acts as an inverting amplifier.

$$V_{OUT} = (V_{CC} - V_{IN}) \frac{R_F}{R_G} \quad (6)$$

The circuit is shown in Figure 6 and the transfer curve ($V_{CC} = 5\text{ V}$, $R_G = R_F = 100\text{ k}\Omega$, $R_L = 10\text{ k}\Omega$) is shown in Figure 7.

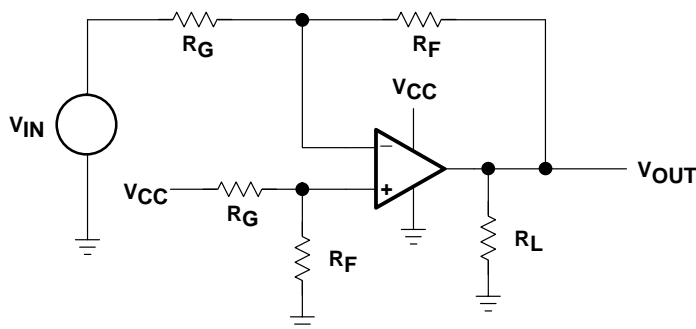


Figure 6. Inverting Op Amp With V_{CC} Bias

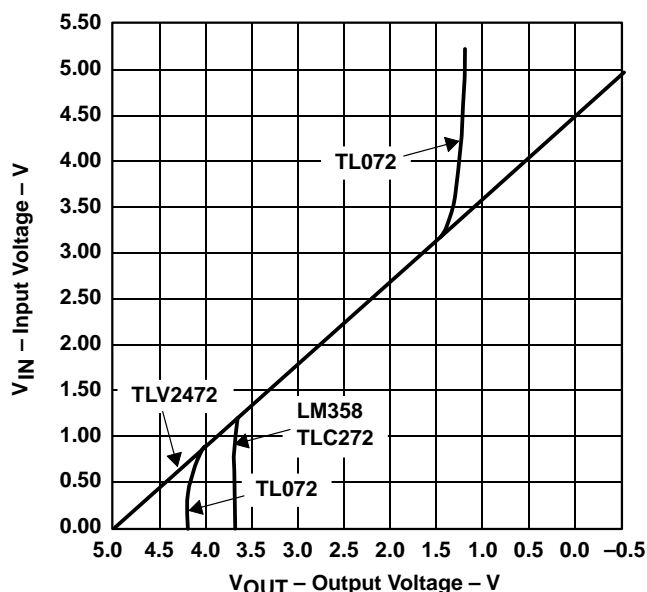


Figure 7. Transfer Curve for an Inverting Op Amp With V_{CC} Bias

Four op amps were tested in the circuit configuration shown in Figure 7. Three of the old generation op amps, LM358, TL07X, and TLC272 had output voltage spans of 2.3 V to 3.75 V. This performance does not justify the ideal op amp assumption that was made in the beginning of this application note unless the output voltage swing is severely limited. Limited output- or input-voltage swing is one of the worst deficiencies a single-supply op amp can have because the limited voltage swing limits the circuit's dynamic range. Also, limited-voltage swing frequently results in distortion of large signals. The fourth op amp tested was the newer TLV247X which was designed for rail-to-rail operation in single-supply circuits. The TLV247X plotted a perfect curve (results limited by the instrumentation), and it amazed the author with a textbook performance that justifies the use of ideal assumptions. Some of the older op amps must limit their transfer equation as shown in equation 7.

$$V_{OUT} = (V_{CC} - V_{IN}) \frac{R_F}{R_G} \quad \text{for} \quad V_{OUTLOW} \leq V_{OUT} \leq V_{OUTH} \quad (7)$$

The noninverting op-amp circuit is shown in Figure 8. Equation 8 is written with the aid of superposition, and simplified algebraically, to acquire equation 9.

$$V_{OUT} = V_{IN} \left(\frac{R_F}{R_G + R_F} \right) \left(\frac{R_F + R_G}{R_G} \right) - V_{REF} \frac{R_F}{R_G} \tag{8}$$

$$V_{OUT} = (V_{IN} - V_{REF}) \frac{R_F}{R_G} \tag{9}$$

When $V_{REF} = 0$, $V_{OUT} = V_{IN} \frac{R_F}{R_G}$, there are two possible circuit solutions. First, when V_{IN} is a negative voltage, V_{OUT} must be a negative voltage. The circuit can not achieve a negative output voltage with a positive supply, so the output saturates at the lower power supply rail. Second, when V_{IN} is a positive voltage, the output spans the normal range as shown by equation 11.

$$V_{IN} \leq 0, \quad V_{OUT} = 0 \tag{10}$$

$$V_{IN} \geq 0, \quad V_{OUT} = V_{IN} \tag{11}$$

The noninverting op-amp circuit is shown in Figure 8 with $V_{CC} = 5\text{ V}$, $R_G = R_F = 100\text{ k}\Omega$, $R_L = 10\text{ k}\Omega$, and $V_{REF} = 0$. The transfer curve for this circuit is shown in Figure 9; a TLV247X serves as the op amp.

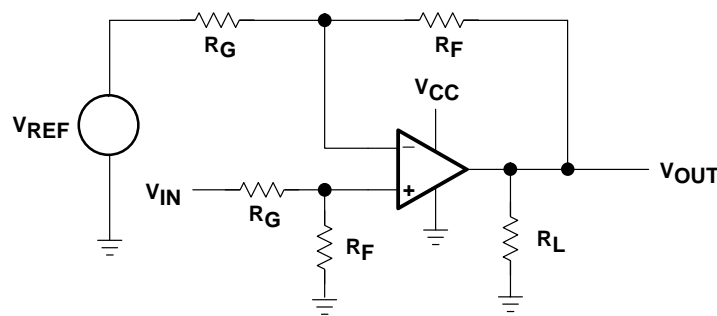


Figure 8. Noninverting Op Amp

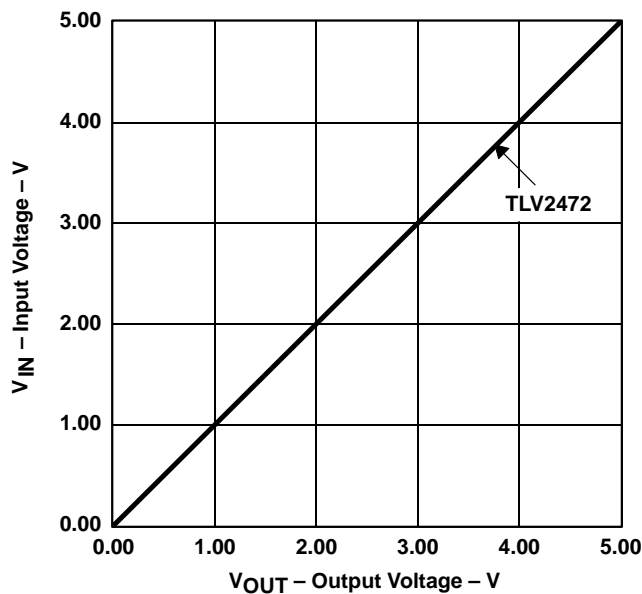


Figure 9. Transfer Curve for Noninverting Op Amp

There are many possible variations of inverting and noninverting circuits. At this point many designers analyze these variations hoping to stumble upon the one that solves the circuit problem. Rather than analyze each circuit, it is better to learn how to employ simultaneous equations to render specified data into equation form. When the form of the desired equation is known, a circuit that fits the equation is chosen to solve the problem. The resulting equation must be a straight line. Thus, there are only four possible solutions, each of which is given in this application note.

Simultaneous Equations

Taking an orderly path to developing a circuit that works the first time starts here; follow these steps until the equation of the op amp is determined. Use the specifications given for the circuit coupled with 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 equation 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.

$$y = \pm mx \pm b \quad (12)$$

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 must be 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 13 through 16, where electronic terminology has been substituted for math terminology.

$$V_{\text{OUT}} = + mV_{\text{IN}} + b \quad (13)$$

$$V_{\text{OUT}} = + mV_{\text{IN}} - b \quad (14)$$

$$V_{\text{OUT}} = - mV_{\text{IN}} + b \quad (15)$$

$$V_{\text{OUT}} = - mV_{\text{IN}} - b \quad (16)$$

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 V to 0.2 V must be interfaced into an analog-to-digital converter which has an input voltage range of 1 V to 4 V. These data points ($V_{\text{OUT}} = 1 \text{ V} @ V_{\text{IN}} = 0.1 \text{ V}$, $V_{\text{OUT}} = 4 \text{ V} @ V_{\text{IN}} = 0.2 \text{ V}$) are inserted into equation 13, as shown in equations 17 and 18, to obtain m and b for the specifications.

$$1 = m(0.1) + b \quad (17)$$

$$4 = m(0.2) + b \quad (18)$$

Multiply equation 17 by 2 to get equation 19, and subtract equation 19 from equation 18 to get equation 20.

$$2 = m(0.2) + 2b \quad (19)$$

$$b = -2 \quad (20)$$

After algebraic manipulation of equation 17, substitute equation 20 into equation 17 to obtain equation 21.

$$m = \frac{2 + 1}{0.1} = 30 \quad (21)$$

Now m and b are substituted back into equation 13 yielding equation 22.

$$V_{OUT} = 30V_{IN} - 2 \quad (22)$$

Notice, although equation 13 was the starting point, the form of equation 22 is identical to the format of equation 14. The specifications or given data determine the sign of m and b , and starting with equation 13, the final equation form is discovered after m and b are calculated. The next step required to complete the problem solution is to develop a circuit that has an $m = 30$ and $b = -2$. Circuits were developed for equations 13 through 16, and they are given under the headings Case 1 through Case 4 respectively. There are different circuits that all provide the same equations, but these circuits were selected because they do not require negative references.

Case1: $V_{OUT} = mV_{IN} + b$

The circuit configuration which yields a solution for Case 1 is shown in Figure 10. The figure includes two 0.01- μF capacitors. These capacitors are called decoupling capacitors, and they are included to reduce noise and provide increased noise immunity. Sometimes two 0.01- μF capacitors serve this purpose. Sometimes one capacitor serves this purpose. However, when V_{CC} is used as a reference, special attention must be paid to the regulation and noise content because some portion of the noise content of V_{CC} will be multiplied by the circuit gain.

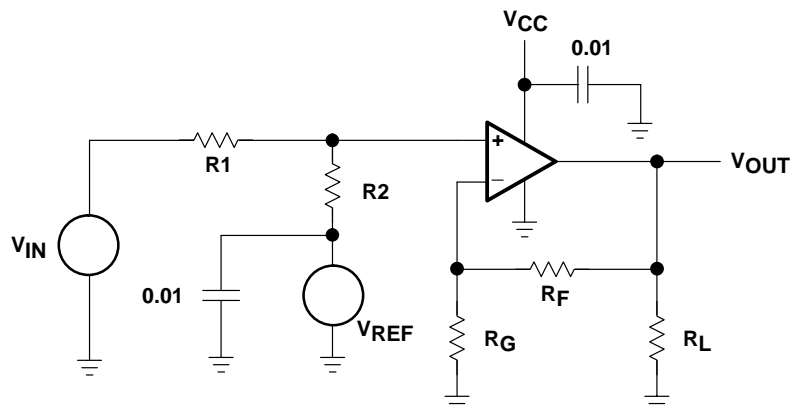


Figure 10. Schematic for Case1: $V_{OUT} = mV_{IN} + b$

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

$$V_{OUT} = V_{IN} \left(\frac{R_2}{R_1 + R_2} \right) \left(\frac{R_F + R_G}{R_G} \right) + V_{REF} \left(\frac{R_1}{R_1 + R_2} \right) \left(\frac{R_F + R_G}{R_G} \right) \quad (23)$$

The equation of a straight line (Case 1) is repeated below, so comparisons can be made between it and equation 23.

$$V_{OUT} = mV_{IN} + b \quad (24)$$

Equating coefficients yields equations 25 and 26.

$$m = \left(\frac{R_2}{R_1 + R_2} \right) \left(\frac{R_F + R_G}{R_G} \right) \quad (25)$$

$$b = V_{REF} \left(\frac{R_1}{R_1 + R_2} \right) \left(\frac{R_F + R_G}{R_G} \right) \quad (26)$$

Example: the circuit specifications are $V_{OUT} = 1$ V at $V_{IN} = 0.01$ V, $V_{OUT} = 4.5$ V at $V_{IN} = 1$ V, $R_L = 10$ k Ω , 5% resistor tolerances, and $V_{CC} = 5$ V. No reference voltage is available, thus, V_{CC} is used for the reference input, and $V_{REF} = 5$ V. A reference-voltage source is left out of the design as a space and cost savings measure, and it sacrifices noise performance, accuracy, and stability performance. Cost is an important specification, and the V_{CC} supply must be specified well enough to do the job. Each step in the subsequent design procedure is included in this analysis to ease learning and increase boredom. Many steps are skipped when subsequent cases are analyzed.

The data is substituted into simultaneous equations.

$$1 = m(0.01) + b \quad (27)$$

$$4.5 = m(1.0) + b \quad (28)$$

Equation 27 is multiplied by 100 (equation 29) and equation 28 is subtracted from equation 29 to obtain equation 30.

$$100 = m(1.0) + 100b \quad (29)$$

$$b = \frac{95.5}{99} = 0.9646 \quad (30)$$

The slope of the transfer function (m) is obtained by substituting b into equation 27.

$$m = \frac{1-b}{0.01} = \frac{1-0.9646}{0.01} = 3.535 \quad (31)$$

Now that b and m are calculated, the resistor values can be calculated. Equations 25 and 26 are solved for the quantity $(R_F + R_G)/R_G$, and then they are set equal in equation 32, thus, yielding equation 33.

$$\frac{R_F + R_G}{R_G} = m \left(\frac{R_1 + R_2}{R_2} \right) = \frac{b}{V_{CC}} \left(\frac{R_1 + R_2}{R_1} \right) \quad (32)$$

$$R_2 = \frac{3.535}{0.9646} R_1 = 18.316R_1 \quad (33)$$

Five percent tolerance resistors are specified for this design, so we choose $R_1 = 10 \text{ k}\Omega$, and that sets the value of $R_2 = 183.16 \text{ k}\Omega$. The closest 5% resistor value to $183.16 \text{ k}\Omega$ is $180 \text{ k}\Omega$; therefore, select $R_1 = 10 \text{ k}\Omega$ and $R_2 = 180 \text{ k}\Omega$. Being forced to yield to reality by choosing standard resistor values means that there is an error in the circuit transfer function because m and b are not exactly the same as calculated. The real world constantly forces compromises into circuit design, but the good circuit designer accepts the challenge and throws money or brains at the challenge. Resistor values closer to the calculated values could be selected by using 1% or 0.5% resistors, but that selection increases cost and violates the design specification. The cost increase is hard to justify except in precision circuits. Using ten cent resistors with a ten cent op amp usually is false economy.

The left half of equation 32 is used to calculate R_F and R_G .

$$\frac{R_F + R_G}{R_G} = m \left(\frac{R_1 + R_2}{R_2} \right) = 3.535 \left(\frac{180 + 10}{180} \right) = 3.73 \quad (34)$$

$$R_F = 2.73R_G \quad (35)$$

The resulting circuit equation is given below.

$$V_{OUT} = 3.5V_{IN} + 0.97 \quad (36)$$

The gain-setting resistor (R_G) is selected as $10 \text{ k}\Omega$, and $27 \text{ k}\Omega$, the closest 5% standard value is selected for the feedback resistor (R_F). Again, there is a slight error involved with standard resistor values. This circuit must have an output-voltage swing from 1 V to 4.5 V . The older op amps can not be used in this circuit because they lack dynamic range, so the TLV247X family of op amps is selected. The data shown in Figure 7 confirms the op amp selection because there is little error. The circuit with the selected component values is shown in Figure 11. The circuit was built with the specified components, and the transfer curve is shown in Figure 12.

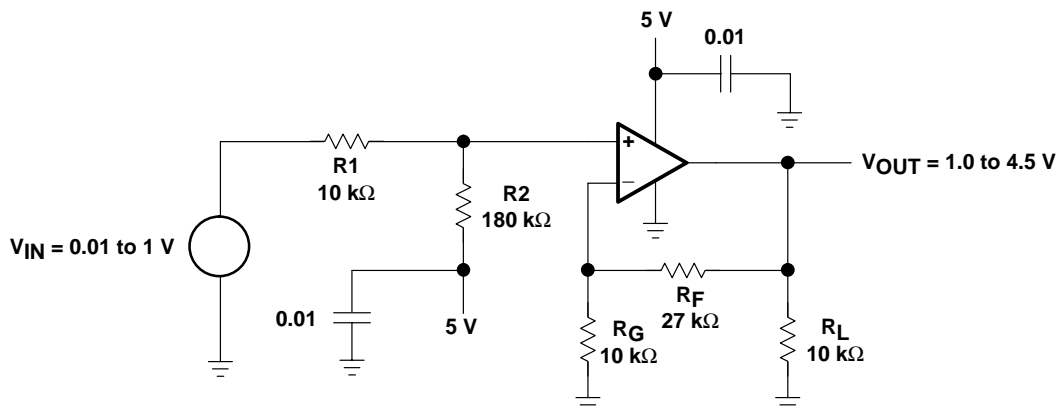


Figure 11. Case 1 Example Circuit

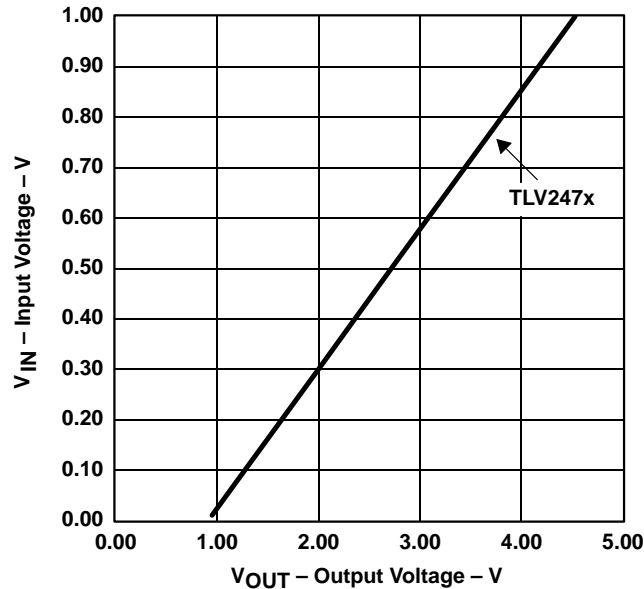


Figure 12. Case 1 Example Circuit Measured Transfer Curve

The transfer curve shown is a straight line, and that means that the circuit is linear. The V_{OUT} intercept is about 0.98 V rather than 1 V as specified, and this is excellent performance considering that the components were selected randomly from bins of resistors. Different sets of components would have slightly different slopes because of the resistor tolerances. The TLV247X has input-bias currents and input-offset voltages, but the effect of these errors is hard to measure on the scale of the output voltage. The output voltage measured 4.53 V when the input voltage was 1 V. Considering the low- and high-input voltage errors, it is safe to conclude that the resistor tolerances have skewed the gain slightly, but this is still excellent performance for 5% components. Often lab data, similar to that shown here, is more accurate than the 5% resistor tolerance. However, do not fall into the trap of expecting this performance, because you will be disappointed if you do.

The resistors were selected in the $k\Omega$ range arbitrarily. The gain and offset specifications determine the resistor ratios. The supply current, frequency response, and op-amp drive capability determine their absolute values. The resistor value selection in this design is high because modern op amps do not have input current offset problems, and they yield reasonable frequency response. If higher frequency response is demanded, the resistor values must decrease, and resistor value decreases reduce input current errors, while supply current increases. When the resistor values get low enough, it becomes hard for another circuit, or possibly the op amp, to drive the resistors.

Case 2: $V_{OUT} = mV_{IN} - b$

The circuit shown in Figure 13 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 (equation 37).

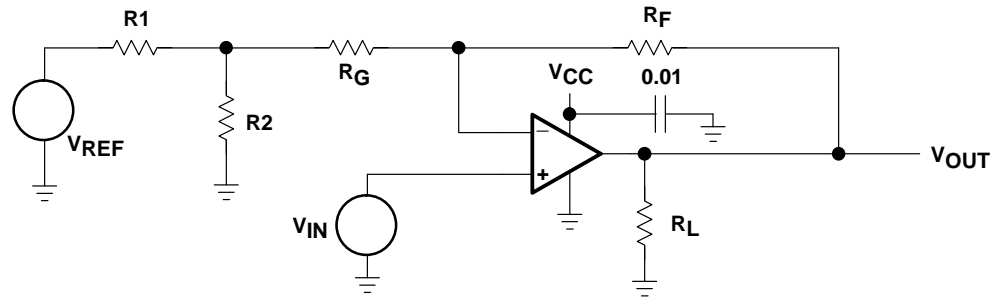


Figure 13. Schematic for Case 2; $V_{OUT} = mV_{IN} - b$

$$V_{OUT} = V_{IN} \left(\frac{R_F + R_G + R_1 \parallel R_2}{R_G + R_1 \parallel R_2} \right) - V_{REF} \left(\frac{R_2}{R_1 + R_2} \right) \left(\frac{R_F}{R_G + R_1 \parallel R_2} \right) \quad (37)$$

Comparing terms in equations 37 and 14 enables the extraction of m and b .

$$m = \frac{R_F + R_G + R_1 \parallel R_2}{R_G + R_1 \parallel R_2} \quad (38)$$

$$|b| = V_{REF} \left(\frac{R_2}{R_1 + R_2} \right) \left(\frac{R_F}{R_G + R_1 \parallel R_2} \right) \quad (39)$$

The specifications for an example design are: $V_{OUT} = 1.5 \text{ V} @ V_{IN} = 0.2 \text{ V}$, $V_{OUT} = 4.5 \text{ V} @ V_{IN} = 0.5 \text{ V}$, $V_{REF} = V_{CC} = 5 \text{ V}$, $R_L = 10 \text{ k}\Omega$, and 5% resistor tolerances. The simultaneous equations, 40 and 41, are written below.

$$1.5 = 0.2m + b \quad (40)$$

$$4.5 = 0.5m + b \quad (41)$$

From these equations we find that $b = -0.5$ and $m = 10$. Making the assumption that $R_1 \parallel R_2 \ll R_G$ simplifies the calculations of the resistor values.

$$m = 10 = \frac{R_F + R_G}{R_G} \quad (42)$$

$$R_F = 9R_G \quad (43)$$

Let $R_G = 20 \text{ k}\Omega$, and then $R_F = 180 \text{ k}\Omega$.

$$b = V_{CC} \left(\frac{R_F}{R_G} \right) \left(\frac{R_2}{R_1 + R_2} \right) = 5 \left(\frac{180}{20} \right) \left(\frac{R_2}{R_1 + R_2} \right) \quad (44)$$

$$R_1 = \frac{1 - 0.01111}{0.01111} R_2 = 89R_2 \quad (45)$$

Select $R_2 = 0.82 \text{ k}\Omega$ and $R_1 = 72.98 \text{ k}\Omega$. Since $72.98 \text{ k}\Omega$ is not a standard 5% resistor value, R_1 is selected as $75 \text{ k}\Omega$. The difference between the selected and calculated value of R_1 has about a 3% effect on b , and this error shows up in the transfer function as an intercept rather than a slope error. The parallel resistance of R_1 and R_2 is approximately $0.82 \text{ k}\Omega$ and this is much less than R_G which is $20 \text{ k}\Omega$. Thus, the earlier assumption that $R_G \gg R_1 \parallel R_2$ is justified. R_2 could have been selected as a smaller value, but the smaller values yielded poor standard 5% values for R_1 . The final circuit is shown in Figure 14 and the measured transfer curve for this circuit is shown in Figure 15.

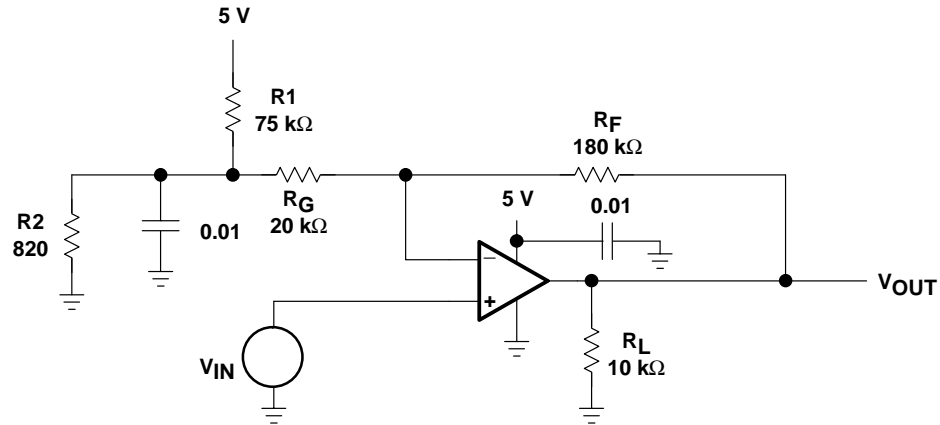


Figure 14. Case 2 Example Circuit

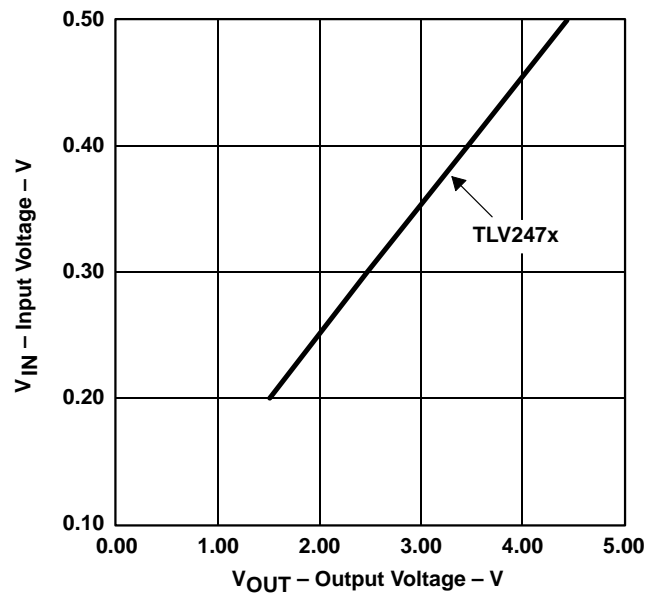


Figure 15. Case 2 Example Circuit Measured Transfer Curve

The TLV247X was used to build the test circuit because of its wide-dynamic range. The transfer-curve plots very close to the theoretical curve — the direct result of using a high-performance op amp.

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

The circuit shown in Figure 16 yields the transfer function desired for Case 3.

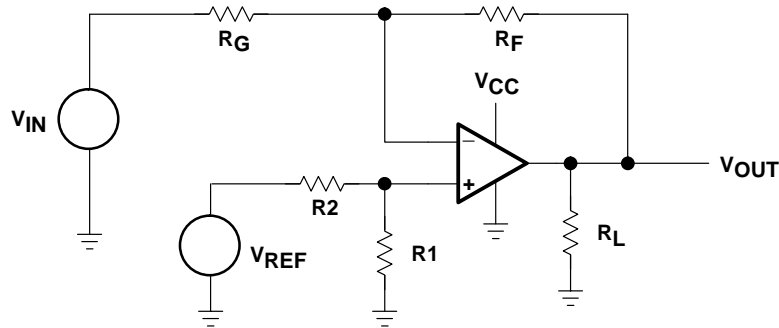


Figure 16. Schematic for Case 3; $V_{OUT} = -mV_{IN} + b$

The circuit equation is obtained with superposition.

$$V_{OUT} = -V_{IN} \left(\frac{R_F}{R_G} \right) + V_{REF} \left(\frac{R_1}{R_1 + R_2} \right) \left(\frac{R_F + R_G}{R_G} \right) \quad (46)$$

Comparing terms between equations 46 and 15 enables the extraction of m and b .

$$|m| = \frac{R_F}{R_G} \quad (47)$$

$$b = V_{REF} \left(\frac{R_1}{R_1 + R_2} \right) \left(\frac{R_F + R_G}{R_G} \right) \quad (48)$$

The design specifications for an example circuit are: $V_{OUT} = 1$ V at $V_{IN} = -0.1$ V, $V_{OUT} = 6$ V at $V_{IN} = -1$ V, $V_{REF} = V_{CC} = 10$ V, $R_L = 100$ Ω , and 5% resistor tolerances. The supply voltage available for this circuit is 10 V, and this exceeds the maximum allowable supply voltage for the TLV247X. Also, this circuit must drive a back-terminated cable which looks like two 50- Ω resistors connected in series, thus the op amp must be able to drive $6/100 = 60$ mA. The stringent op amp selection criteria limits the choice to relatively new op amps if ideal op amp equations are going to be used. The TLC07X has excellent single-supply input performance coupled with high-output current drive capability, so it is selected for this circuit. The simultaneous equations 49 and 50 are written below.

$$1 = (-0.1)m + b \quad (49)$$

$$6 = (-1)m + b \quad (50)$$

From these equations we find that $b = 0.444$ and $m = -5.56$.

$$|m| = 5.56 = \frac{R_F}{R_G} \quad (51)$$

$$R_F = 5.56R_G \quad (52)$$

Let $R_G = 10$ k Ω , and then $R_F = 56.6$ k Ω which is not a standard 5% value, hence R_F is selected as 56 k Ω .

$$b = V_{CC} \left(\frac{R_F + R_G}{R_G} \right) \left(\frac{R_1}{R_1 + R_2} \right) = 10 \left(\frac{56 + 10}{10} \right) \left(\frac{R_1}{R_1 + R_2} \right) \quad (53)$$

$$R_2 = \frac{66 - 0.4444}{0.4444} R_1 = 147.64 R_1 \quad (54)$$

The final equation for the example is shown in equation 55.

$$V_{OUT} = -5.56 V_{IN} - 0.444 \quad (55)$$

Select $R_1 = 2 \text{ k}\Omega$ and $R_2 = 295.28 \text{ k}\Omega$. Since $295.28 \text{ k}\Omega$ is not a standard 5% resistor value R_1 is selected as $300 \text{ k}\Omega$. The difference between the selected and calculated value of R_1 has a nearly insignificant effect on b . The final circuit is shown in Figure 17, and the measured transfer curve for this circuit is shown in Figure 18.

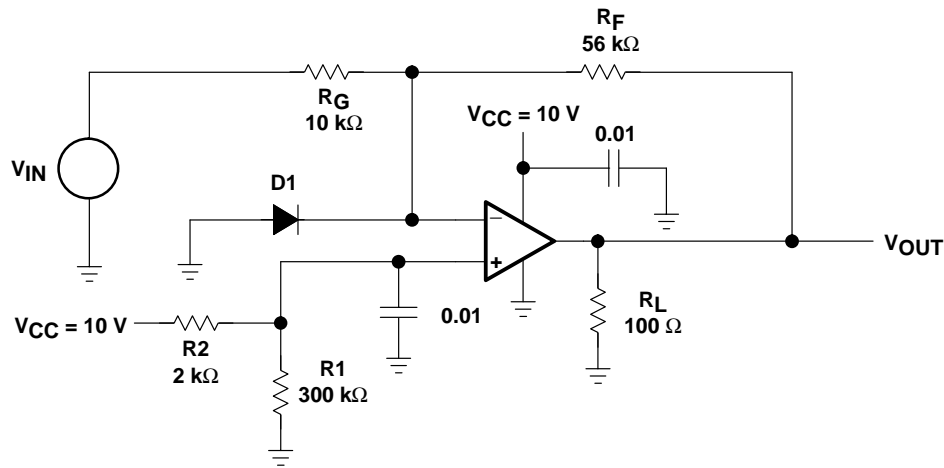


Figure 17. Case 3 Example Circuit

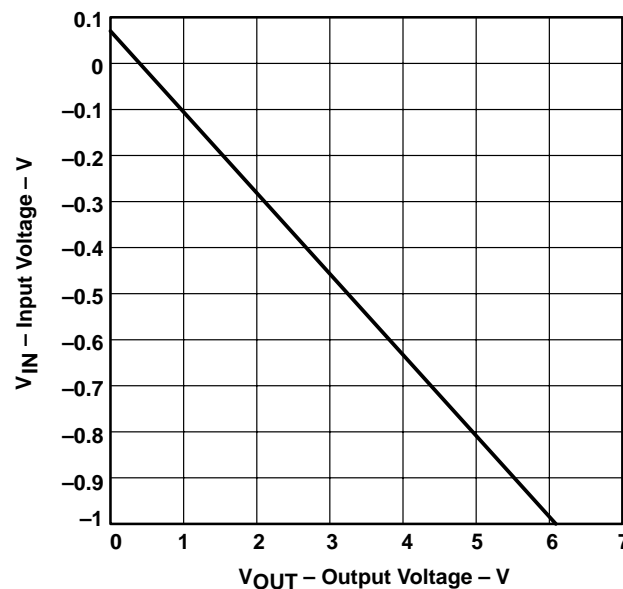


Figure 18. Case 3 Example Circuit Measured Transfer Curve

As long as the circuit works normally, there are no problems handling the negative voltage input to the circuit, because the inverting lead of the TLC07X is at a positive voltage. The positive op-amp input lead is at a voltage of approximately 65 mV, and normal op amp operation keeps the inverting op-amp input lead at the same voltage because of the assumption that the error voltage is zero. When V_{CC} is powered down while there is a negative voltage on the input circuit, most of the negative voltage appears on the inverting op-amp input lead.

The most prudent solution is to connect the diode (D_1) with its cathode on the inverting op-amp input lead and its anode at ground. If a negative voltage gets on the inverting op-amp input lead, it is clamped to ground by the diode. Select the diode type as germanium or Schottky, so the voltage drop across the diode is about 200 mV; this small voltage does not harm most op-amp inputs. As a further precaution, R_G can be split into two resistors with the diode inserted at the junction of the two resistors. This places a current limiting resistor between the diode and the inverting op-amp input lead.

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

The circuit shown in Figure 19 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 56.

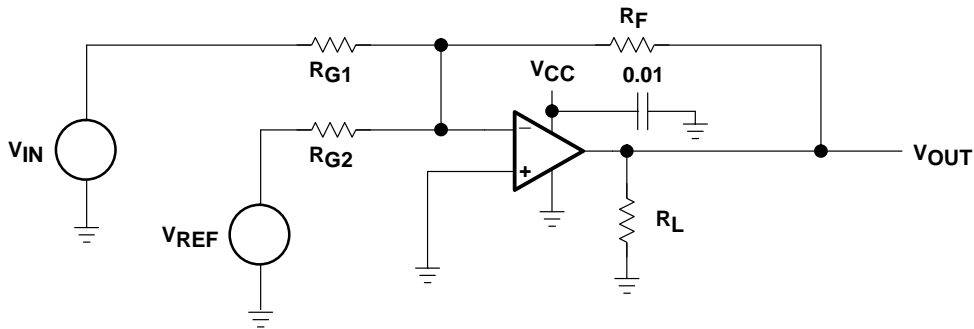


Figure 19. Schematic for Case 4; $V_{OUT} = -mV_{IN} - b$

$$V_{OUT} = -V_{IN} \frac{R_F}{R_{G1}} - V_{REF} \frac{R_F}{R_{G2}} \quad (56)$$

Comparing terms in equations 56 and 16 enables the extraction of m and b .

$$|m| = \frac{R_F}{R_{G1}} \quad (57)$$

$$|b| = V_{REF} \frac{R_F}{R_{G2}} \quad (58)$$

The design specifications for an example circuit are: $V_{OUT} = 1$ V at $V_{IN} = -0.1$ V, $V_{OUT} = 5$ V at $V_{IN} = -0.3$ V, $V_{REF} = V_{CC} = 5$ V, $R_L = 10$ k Ω , and 5% resistor tolerances. The simultaneous equations 59 and 60, are written below.

$$1 = (-0.1)m + b \quad (59)$$

$$5 = (-0.3)m + b \quad (60)$$

From these equations we find that $b = -1$ and $m = -20$. Setting the magnitude of m equal to equation 57 yields equation 61.

$$|m| = 20 = \frac{R_F}{R_{G1}} \quad (61)$$

$$R_F = 20R_{G1} \quad (62)$$

Let $R_{G1} = 1 \text{ k}\Omega$, and then $R_F = 20 \text{ k}\Omega$.

$$|b| = V_{CC} \left(\frac{R_F}{R_{G2}} \right) = 5 \left(\frac{R_F}{R_{G2}} \right) = 1 \quad (63)$$

$$R_{G2} = \frac{R_F}{0.2} = \frac{20}{0.2} = 100 \text{ k} \quad (64)$$

The final equation for this example is given in equation 63.

$$V_{OUT} = -20V_{IN} - 1 \quad (65)$$

The final circuit is shown in Figure 20 and the measured transfer curve for this circuit is shown in Figure 21.

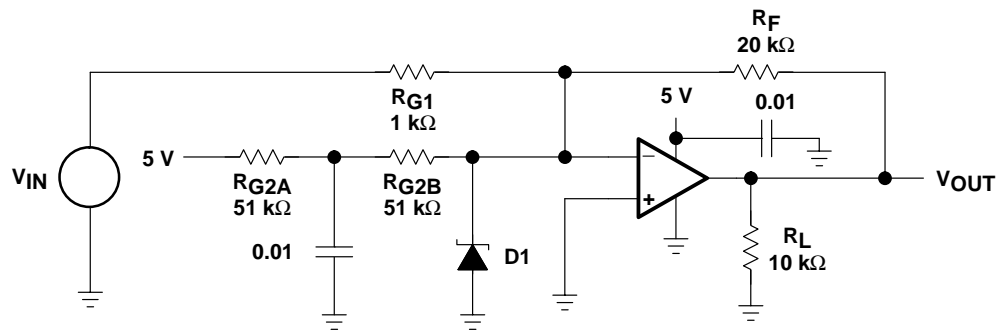


Figure 20. Case 4 Example Circuit

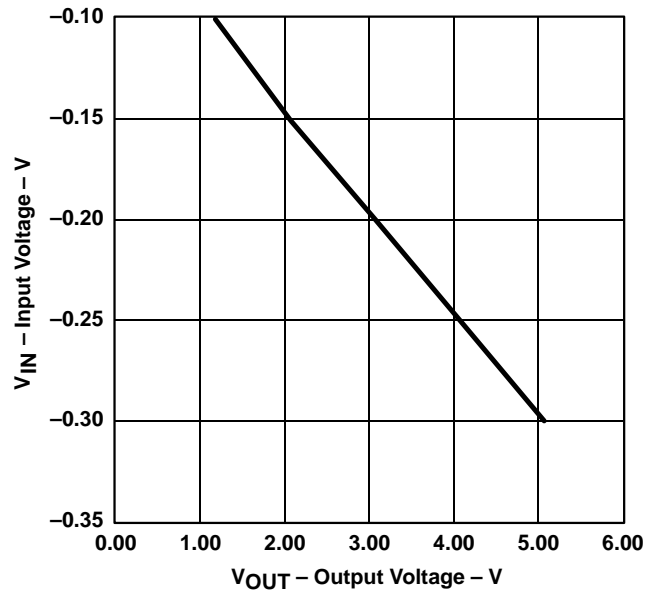


Figure 21. Case 4 Example Circuit Measured Transfer Curve

The TLV247X was used to build the test circuit because of its wide dynamic range. The transfer curve plots very close to the theoretical curve, and this results from using a high-performance op amp.

As long as the circuit works normally, there are no problems handling the negative voltage input to the circuit because the inverting lead of the TLV247X is at a positive voltage. The positive op-amp input lead is grounded, and normal op amp operation keeps the inverting op amp input lead at ground because of the assumption that the error voltage is zero. When V_{CC} is powered down while there is a negative voltage on the input circuit, most of the negative voltage appears on the inverting op-amp input lead.

The most prudent solution is to connect the diode (D_1) with its cathode on the inverting op-amp input lead and its anode at ground. If a negative voltage gets on the inverting op amp input lead it is clamped to ground by the diode. Select the diode type as germanium or Schottky, so the voltage drop across the diode is about 200 mV; this small voltage does not harm most op-amp inputs. R_{G2} is split into two resistors ($R_{G2A} = R_{G2B} = 51 \text{ k}\Omega$) with a capacitor inserted at the junction of the two resistors. This places a capacitor in series with V_{CC} .

Summary

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. The new op amps, such as the TLC247X, TLC07X, and TLC08X have excellent single-supply parameters; thus, when used in the correct applications, these op amps yield rail-to-rail performance equal to their split-supply counterparts.

Single-supply op amp design usually involves some form of biasing, and this requires more thought. So, single-supply op amp design needs discipline and a procedure. The recommended design procedure for single-supply op amp design is:

- Substitute the specification data into simultaneous equations to obtain m and b (the slope and intercept of a straight line).
- Let m and b determine the form of the circuit.
- Choose the circuit configuration that fits the form.
- Using the circuit equations for the circuit configuration selected, calculate the resistor values.
- Build the circuit, take data, and verify performance.
- Test the circuit for nonstandard operating conditions (circuit power off while interface power is on, over/under range inputs, etc.).
- Add protection components as required.
- Retest

When this procedure is followed, good results follow. As single-supply circuit designers expand their horizon, new challenges require new solutions. Remember, the only equation a linear op amp can produce is the equation of a straight line. That equation only has four forms. The new challenges may consist of multiple inputs, common-mode voltage rejection, or something different, but this method can be expanded to meet these challenges.