A Cookbook Approach to Single-Supply DC-Coupled Op Amp Design

Introduction

Using op amps on a split power supply is straight forward because the op amp inputs are referenced to the center of the supplies which is normally ground. Most signal sources are also referenced to ground, so input referencing is not consciously considered when designing with op amps powered from split supplies. In those rare instances when the signal source is not referenced to ground, split-supply op amp design becomes an equivalent challenge to single-supply design. When an op amp is powered from a single supply all the op amp inputs appear to be referenced from half the power supply voltage, $V_{CC}/2$. When the signal sources are referenced to ground or any potential other than $V_{CC}/2$, some type of bias must be introduced into the circuit if it is desirable to have the output referenced to ground. Designing the bias circuit is a time consuming detail job which is not always approached correctly; therefore, this paper takes a general purpose circuit which includes bias circuitry, and reduces it to a cookbook procedure. The general purpose circuit looks formidable at first glance, but do not be intimidated by the complex looking circuit because the analysis shows that some components can be eliminated during the design process.

Contents

1. Developing an Equation for the General Case . . . 2
1.1 The Equation of a Straight Line . . . 3
1.2 Consider the Boundary Conditions . . . 3
2. Design Procedure . . . 4
2.1 Design Example #1 . . . 4
2.2 Design Example #2 . . . 5
2.3 Design Example #3 . . . 5
2.4 Design Example #4 . . . 6
3. Conclusions . . . 7
4. Revision History . . . 8

© 1997-2026 Renesas Electronics

1. Developing an Equation for the General Case

The schematic for the general case op amp circuit is given in Figure 1. An op amp circuit normally can assume any one of the four possible equations for a straight line; therefore, the equation derived for this circuit configuration must adequately describe all of these cases.

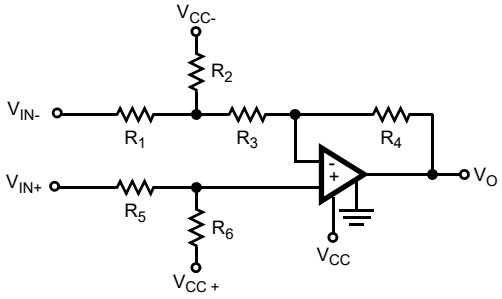


Figure 1. Schematic of the General Case Circuit

The equation derivation is done in two parts through the use of superposition. The final output voltage, V_O, equals the sum of the constituent output voltages resulting from the independent application of each input voltage as shown in Equation 1.

(EQ. 1) $V_O = V_{O+} + V_{O-}$

V_{O+} is the output voltage that results from the input voltage V_{IN+}, and V_{O-} is the output voltage that results from the input voltage V_{IN-}. The assumption that the parallel resistance of R_1 and R_2 is much less than R_3 is made to simplify the calculation complexity; this is a rather easy assumption to satisfy in practice. V_{CC+} and V_{CC-} are usually the same power supply, and much of the time they are equal to V_{CC} because only one power supply are available. Sometimes, it is convenient for V_{CC+}, V_{CC-} or both to be different from V_{CC}, so they are identified as different supplies during the development of Equation 4. Remember, all power supplies in op amp circuits must be decoupled to ground with at least a 0.1µF capacitor. The equation derivation uses the ideal op amp[1], and the design engineer must verify these assumptions. The ideal op amp equation requirement is not a detriment to this analysis because there are a multitude of op amps available that satisfy it.

(EQ. 2) $$V_{O-} = \left\{V_{IN-}\left(\frac{R_2}{R_1 + R_2}\right) + V_{CC-}\left(\frac{R_1}{R_1 + R_2}\right)\right\}\left(-\frac{R_4}{R_3}\right)$$

(EQ. 3) $$V_{O+} = \left\{V_{IN+}\left(\frac{R_6}{R_5 + R_6}\right) + V_{CC+}\left(\frac{R_5}{R_5 + R_6}\right)\right\}\left(\frac{R_4 + R_3}{R_3}\right)$$

Equation 2 and Equation 3 are combined to yield Equation 4, which mathematically describes the operation of the circuit shown in Figure 1.

1. *AN9510: Basic Analog for Digital Engineers Application Note*

(EQ. 4)

$$V_O = \left\{V_{IN+}\left(\frac{R_6}{R_5 + R_6}\right) + V_{CC+}\left(\frac{R_5}{R_5 + R_6}\right)\right\}\left(\frac{R_4 + R_3}{R_3}\right) - \left\{V_{IN-}\left(\frac{R_2}{R_1 + R_2}\right) + V_{CC-}\left(\frac{R_1}{R_1 + R_2}\right)\right\}\left(\frac{R_4}{R_3}\right)$$

1.1 The Equation of a Straight Line

The op amp is being used as a linear device in this application, so its transfer function can be described by the equation of a straight line. There are four possible transfer functions described by the equation of a straight line.

(EQ. 5) $y = \pm mx \pm b$

The dependent variable y represents the output voltage, VO, and the independent variable x represents the input voltage, VIN. The slope of the line is m, and it is represented by the coefficients of VIN. The y intercept, b, is represented by the coefficients of V_{CC}. The four different equations of a straight line can be extracted from Equation 4 by comparing Equation 4 and Equation 5:

(EQ. 6) $y = mx + b$

(EQ. 7) $$V_O = V_{IN+}\left(\frac{R_6}{R_5 + R_6}\right)\left(\frac{R_3 + R_4}{R_3}\right) + V_{CC+}\left(\frac{R_5}{R_5 + R_6}\right)\left(\frac{R_3 + R_4}{R_3}\right)$$

(EQ. 8) $y = -mx - b$

(EQ. 9) $$V_O = V_{IN+}\left(\frac{R_6}{R_1 + R_6}\right)\left(\frac{R_3 + R_4}{R_3}\right) - V_{CC-}\left(\frac{R_1}{R_1 + R_2}\right)\left(\frac{R_4}{R_3}\right)$$

(EQ. 10) $y = mx + b$

(EQ. 11) $$V_O = -V_{IN-}\left(\frac{R_2}{R_1 + R_2}\right)\left(\frac{R_4}{R_3}\right) + V_{CC+}\left(\frac{R_5}{R_5 + R_6}\right)\left(\frac{R_3 + R_4}{R_3}\right)$$

(EQ. 12) $y = -mx - b$

(EQ. 13) $$V_O = -V_{IN-}\left(\frac{R_2}{R_1 + R_2}\right)\left(\frac{R_4}{R_3}\right) - V_{CC-}\left(\frac{R_1}{R_1 + R_2}\right)\left(\frac{R_4}{R_3}\right)$$

1.2 Consider the Boundary Conditions

Because of the single-supply restrictions, if a supply with the negative end connected to ground and the positive end connected to V_{CC}, the condition $0 \le V_O \le V_{CC}$ must be satisfied. As long as the output voltage stays between the supply rails the circuit functions normally, but when the output voltage tries to go outside the supply rails, the

output saturates and becomes nonlinear. For example, if in Equation 13 V_{IN}- = -1V, V_{CC}- = -1V, $R_1 = R_2$, and $R_3 = R_4$, the output voltage is +1V and everything works fine, but if V_{IN}- goes to +2V, the output goes to the bottom rail and gives a false reading. Beware of working with negative input voltages because a negative voltage on some op amp inputs turns off the input transistors causing nonlinear operation or possibly damaging the op amp.

2. Design Procedure

Given the two input voltages and their corresponding desired output voltages, the signs and magnitude of m and b are calculated using simultaneous equations. Set up the equations without considering the signs of m and b; the solution determines their signs.

After determining the magnitude and sign for m and b, compare the signs of m and b to Equation 6, Equation 8, Equation 10, and Equation 12 to determine which of these equations fit. After determining which one of the four equations to use, select its corresponding equation from Equation 7, Equation 9, Equation 11, and Equation 13, and equate equivalent terms to m and b. The resistor ratios can be calculated at this time, and after values are selected for key resistors, each resistor value can be calculated.

When finding that certain resistors are not required, eliminate them by setting them equal to shorts or opens. By observing which equation coincides with the signs of m and b, it becomes obvious which V_{CCX} connection is not required. The resistor connecting the unused V_{CCX} to the circuit must be removed. Furthermore, if R_2 is the correct resistor to remove, R_1 should be replaced with a short. Also, if R_6 is removed, R_5 must be replaced with a short. Finally, build and test the circuit to finish the design.

There are times, as in symmetrical supply op amp design, when the data just cannot be processed correctly with a simple circuit, and then have to look out for a new circuit. Increasing one of the supply voltages can provide additional design flexibility, limiting the output voltage range can simplify the problem, or a more involved configuration might be required.

2.1 Design Example #1

The provided data is as follows: V_{IN} = 0.05V to 1.0V, V_O must span the range of 0.5 to 4.3V, and $V_{CC} = V_{CC+} = V_{CC-}$ = 5V. The simultaneous equations are 0.5 = m(0.05) + b and 4.3 = m(1) + b. Solving these equations yields m = 4 and b = 0.3. Both signs are positive so Equation 6 applies, and the data is compared to Equation 7 to yield:

(EQ. 14) $$m = 4 = \left(\frac{R_6}{R_5 + R_6}\right)\left(\frac{R_3 + R_4}{R_3}\right)$$

(EQ. 15) $$b = 0.3 = 5\left(\frac{R_5}{R_5 + R_6}\right)\left(\frac{R_3 + R_4}{R_3}\right)$$

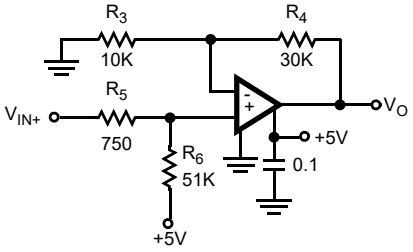


Figure 2. Schematic for Design Example #1

Because the V_{CC-} connection is not required, R_2 is an open and R_1 is a short. The revised circuit is shown in Figure 2. Solving Equation 14 and Equation 15 yields the ratios: $R_6/R_5 = 66.66$ and $R_4/R_3 = 3$. Using the closest standard values R_5 is selected as 750Ω and then R_6 = 51K. R_3 is selected as 10K and then R_4 = 30K. The selection of R_5 and R_3 was rather arbitrary in this example; in an actual design impedance levels, leakage currents, or some other parameter influence the selection of the initial resistor value.

2.2 Design Example #2

The provided data is as follows: V_{IN} = 0.25V when V_O = 1.0V, V_{IN} = 0.75V when V_O = 4.0V, and $V_{CC+} = V_{CC-} = V_{CC}$ = 5.0V. The simultaneous equations are 4.0 = m(0.75) + b and 1.0 = m(0.25) + b. Solving these equations yields m = 6 and b = -0.5. The slope, m, is positive and the vertical intercept, b, is negative so Equation 8 applies, and the data is compared to Equation 9 to yield:

(EQ. 16) $$|b| = 0.5 = 5\left(\frac{R_1}{R_1 + R_2}\right)\left(\frac{R_4}{R_3}\right)$$

(EQ. 17) $$m = 6 = \left(\frac{R_6}{R_5 + R_6}\right)\left(\frac{R_3 + R_4}{R_3}\right)$$

Because the V_{CC+} connection is not required R_6 is opened, R_5 is shorted, and Equation 16 is simplified as shown in Equation 18.

(EQ. 18) $$m = 6 = \left(\frac{R_3 + R_4}{R_3}\right)$$

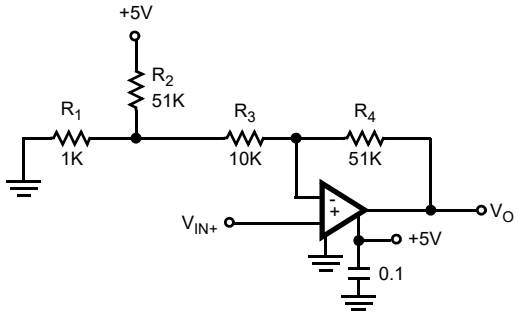


Figure 3. Schematic for Design Example #2

Figure 3 shows the revised circuit. Solving Equation 17 and Equation 18 yields the ratios $R_4/R_3 = 5$ and $R_2/R_1 = 50$. Using the closest standard values R_3 is selected as 10K and then R_4 = 51K. R_1 is selected as 1K and then R_2 = 51K. Again, the selection of R_1 and R_3 was rather arbitrary, but experience says that these values are not too far from appropriate for the average circuit built with modern op amps.

2.3 Design Example #3

The provided data is as follows: the input voltage range is -0.1 to -1.0V, the corresponding output voltage is to be 1.0 to 8.0V, and $V_{CC+} = V_{CC-} = V_{CC}$ =10V. The simultaneous equations are 1.0 = m(-0.1) + b and 8.0 = m(-1.0) + b. Solving these equations yields m = -7.777 and b = 2/9. The slope, m, is negative while the vertical intercept is positive, so Equation 10 applies. Equation 19 and Equation 20 result when the data is compared to Equation 11.

(EQ. 19) $$|m| = 7.777 = \left(\frac{R_2}{R_1 + R_2}\right)\left(\frac{R_4}{R_3}\right)$$

(EQ. 20) $$b = \frac{2}{9} = 10\left(\frac{R_5}{R_5 + R_6}\right)\left(\frac{R_3 + R_4}{R_3}\right)$$

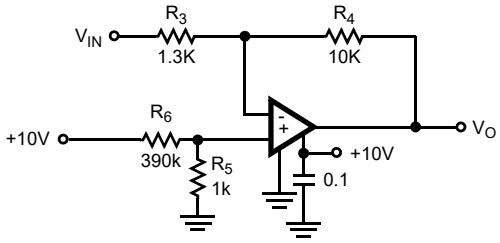


Figure 4. Schematic for Design Example #3

Because the V_{CC-} connection is not required, R_2 is opened and R_1 is shorted. Now Equation 19 is simplified as shown.

(EQ. 21) $$|m| = 7.777 = \left(\frac{R_4}{R_3}\right)$$

Solving Equation 19 and Equation 21 yields the resistor ratios $R_4/R_3 = 7.777$ and $R_6/R_5 = 390$. The selection of $R_3 = 1.3K$ results in $R_4 = 10K$, and the selection of $R_6 = 1K$ results in the selection of $R_5 = 390K$.

2.4 Design Example #4

The provided data is as follows: $V_{IN} = -1.0V$ when $V_O = 1.5V$, $V_{IN} = -2.5V$ when $V_O = 4.5V$, and $V_{CC} = 5V$. The simultaneous equations are $1.5 = m(-1.0) + b$ and $4.5 = m(-2.5) + b$. Solving these equations yields $m = -2$ and $b = -0.5$. Both signs are negative so Equation 12 applies, and the data is compared to Equation 13 to yield:

(EQ. 22) $$|m| = 2 = \left(\frac{R_2}{R_1 + R_2}\right)\left(\frac{R_4}{R_3}\right)$$

(EQ. 23) $$|b| = 0.5 = 5\left(\frac{R_1}{R_1 + R_2}\right)\left(\frac{R_4}{R_3}\right)$$

Because the V_{CC+} connection is not required R_6 is opened, and R_5 is shorted. Solving Equation 22 and Equation 23 yield the resistor ratios $R_4/R_3 = 2.1$ and $R_2/R_1 = 20$. Selecting standard value resistors which satisfy the assumption that $R_1 \parallel R_2 << R_3$ leads to the final values of $R_1 = 1K$, $R_2 = 20K$, $R_3 = 130K$, and $R_4 = 270K$. Figure 5 shows the schematic for Design Example #4.

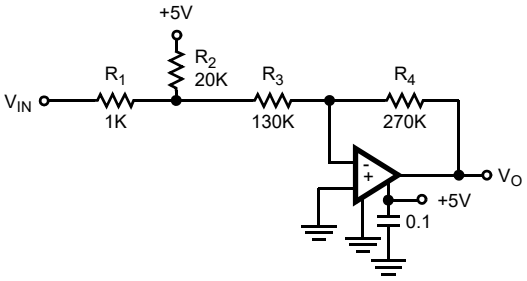


Figure 5. Schematic for Design Example #4

3. Conclusions

Implement all four forms of the equation of a straight line using a single-supply op amp operated when including proper bias circuitry. It is not harder to design single-supply op amp circuits than it is to design split-supply op amp circuits, but more attention must be paid to the details to achieve a successful single-supply design. Equation 4 contains all of the information required to design single-supply circuits.

Two cautions that apply to any op amp circuit design must be included: first, the inputs must be protected from input voltages that can fall out of the supply range (even for transient voltages); second, the output voltage saturates as it approaches either limit of the supply range. Within these two limits single-supply design is the equal of split-supply design, and it saves the cost of an additional power supply.

4. Revision History

Revision	Date	Description
2.00	Nov 5, 2026	▪ Applied latest template ▪ Added Revision History section
1.00	Dec, 2002	Fixed V_{IN} errors.
0.00	Jul 1997	Initial Release.

IMPORTANT NOTICE AND DISCLAIMER

RENESAS ELECTRONICS CORPORATION AND ITS SUBSIDIARIES (“RENESAS”) PROVIDES TECHNICAL SPECIFICATIONS AND RELIABILITY DATA (INCLUDING DATASHEETS), DESIGN RESOURCES (INCLUDING REFERENCE DESIGNS), APPLICATION OR OTHER DESIGN ADVICE, WEB TOOLS, SAFETY INFORMATION, AND OTHER RESOURCES “AS IS” AND WITH ALL FAULTS, AND DISCLAIMS ALL WARRANTIES, EXPRESS OR IMPLIED, INCLUDING, WITHOUT LIMITATION, ANY IMPLIED WARRANTIES OF MERCHANTABILITY, FITNESS FOR A PARTICULAR PURPOSE, OR NON-INFRINGEMENT OF THIRD-PARTY INTELLECTUAL PROPERTY RIGHTS.

These resources are intended for developers who are designing with Renesas products. You are solely responsible for (1) selecting the appropriate products for your application, (2) designing, validating, and testing your application, and (3) ensuring your application meets applicable standards, and any other safety, security, or other requirements. These resources are subject to change without notice. Renesas grants you permission to use these resources only to develop an application that uses Renesas products. Other reproduction or use of these resources is strictly prohibited. No license is granted to any other Renesas intellectual property or to any third-party intellectual property. Renesas disclaims responsibility for, and you will fully indemnify Renesas and its representatives against, any claims, damages, costs, losses, or liabilities arising from your use of these resources. Renesas' products are provided only subject to Renesas' Terms and Conditions of Sale or other applicable terms agreed to in writing. No use of any Renesas resources expands or otherwise alters any applicable warranties or warranty disclaimers for these products.

(Disclaimer Rev.1.01)

Corporate Headquarters

TOYOSU FORESIA, 3-2-24 Toyosu,
Koto-ku, Tokyo 135-0061, Japan
www.renesas.com

Contact Information

For further information on a product, technology, the most up-to-date version of a document, or your nearest sales office, please visit www.renesas.com/contact-us/.

Trademarks

Renesas and the Renesas logo are trademarks of Renesas Electronics Corporation. All trademarks and registered trademarks are the property of their respective owners.

© 2026 Renesas Electronics Corporation. All rights reserved.