Fully differential amplifiers remove noise from common-mode signals

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14–18 Minuten

Differential amplifiers offer many advantages for manipulating differential signals. They provide immunity to external noise; a 6-dB increase in dynamic range, which is a clear advantage for low-voltage systems; and reduced second-order harmonics. Integrated fully differential amplifiers are well-suited for driving differential ADC inputs and differential transmission lines. They provide an easy means of antialias filtering, and a dedicated input easily sets the required common-mode voltage. These amplifiers are also well-suited for driving differential transmission lines, and active termination provides for increased efficiency. You can easily adapt inverting-amplifier topologies to fully differential amplifiers by implementing two symmetric feedback paths.

Differential amplifiers are one way of implementing differential signaling, which has been a common design approach in audio, data-transmission, and telephone systems for years because of its inherent resistance to external-noise sources. Professional audio engineers use the term "balanced" to refer to differential-signal transmission. This description imparts the idea of symmetry, which is important in differential systems. The driver has balanced outputs, the line has balanced characteristics, and the receiver has balanced inputs. Differential signaling is now also becoming popular in high-speed data acquisition for which the ADC's inputs are differential and a differential amplifier is necessary to properly drive the inputs.

You can also use another common component, a transformer, to accomplish differential signaling. Transformers offer good CMRR (common-mode-rejection-ratio)-versus-frequency characteristics, galvanic isolation, power consumption with efficiencies near 100%, and immunity to hostile EMC environments. However, IC differential amplifiers have low cost, small size and weight, and superior frequency response at low frequencies and dc.

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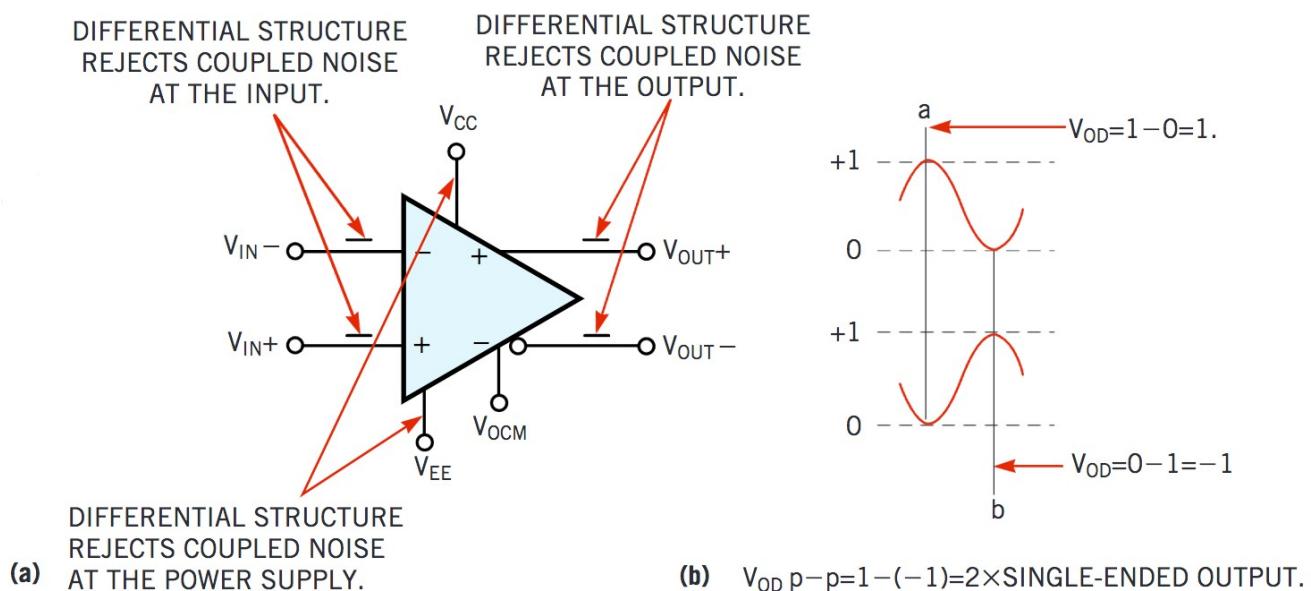
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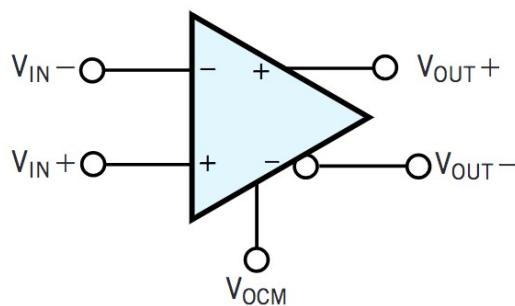
When signals travel, noise invariably couples into the wiring. In a differential system, keeping the transport wires as close as possible to one another makes the noise coupled into the conductors appear as a common-mode voltage. Noise that is common to the power supplies also appears as a common-mode voltage. Because differential amplifiers reject common-mode voltages, the system is more immune to external noise. Also, due to the change in phase between the differential outputs, the dynamic range is two times more than a single-ended output with the same voltage swing (**Figure 1**).

Figure 1 Differential amplifiers provide increased noise immunity (a) and a 6-dB increase in the dynamic range (b).
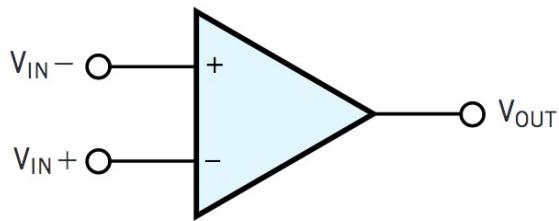
An integrated, fully differential amplifier is similar in architecture to a standard, voltage-feedback op amp (**Figure 2**). Both types of amplifiers have differential inputs. A standard op amp's output is single-ended, but a fully differential amplifier has differential outputs. Fully differential amplifiers offer the ability to control the output common-mode voltage independently of the differential voltage. The purpose of the V_{OCM} input in the fully differential amplifier is to set the output common-mode voltage. In a standard op amp with a single-ended output, the output common-mode voltage and the output signal are the same. In a standard op

amp, one feedback path typically goes from the output to the negative input. In a fully differential amplifier, multiple feedback paths exist.

NOTES:
FULLY DIFFERENTIAL AMPLIFIER:
● DIFFERENTIAL IN
● DIFFERENTIAL OUT
● V_{OCM} SETS THE OUTPUT COMMON-MODE VOLTAGE
● MULITPLE FEEDBACK PATHS

(a)

NOTES:
STANDARD OP AMP:
● DIFFERENTIAL IN
● SINGLE-ENDED OUT
● OUTPUT COMMON-MODE VIOLTAGE IS SIGNAL
● SINGLE FEEDBACK PATH

(b)

Figure 2 Integrated fully differential amplifiers (a) are very similar to standard single-ended op amps (b) but have differential outputs, use V_{OCM} to set the output common-mode voltage, and can have more than one feedback path.

Table 1 lists some important voltage definitions. The voltage difference between the plus and minus inputs is the input differential voltage, V_{ID}. The average of the two input voltages is the input common-mode voltage, V_{IC}. The difference between the voltages at the plus and minus outputs is the output differential voltage, V_{OD}. The output common-mode voltage, V_{OC}, is the average of the two output voltages and is controlled by the voltage at V_{OCM}. Finally, a(f) is the frequency-dependent differential gain of the amplifier, so that $V_{OD} = V_{ID} \, \acute{} a(f)$.
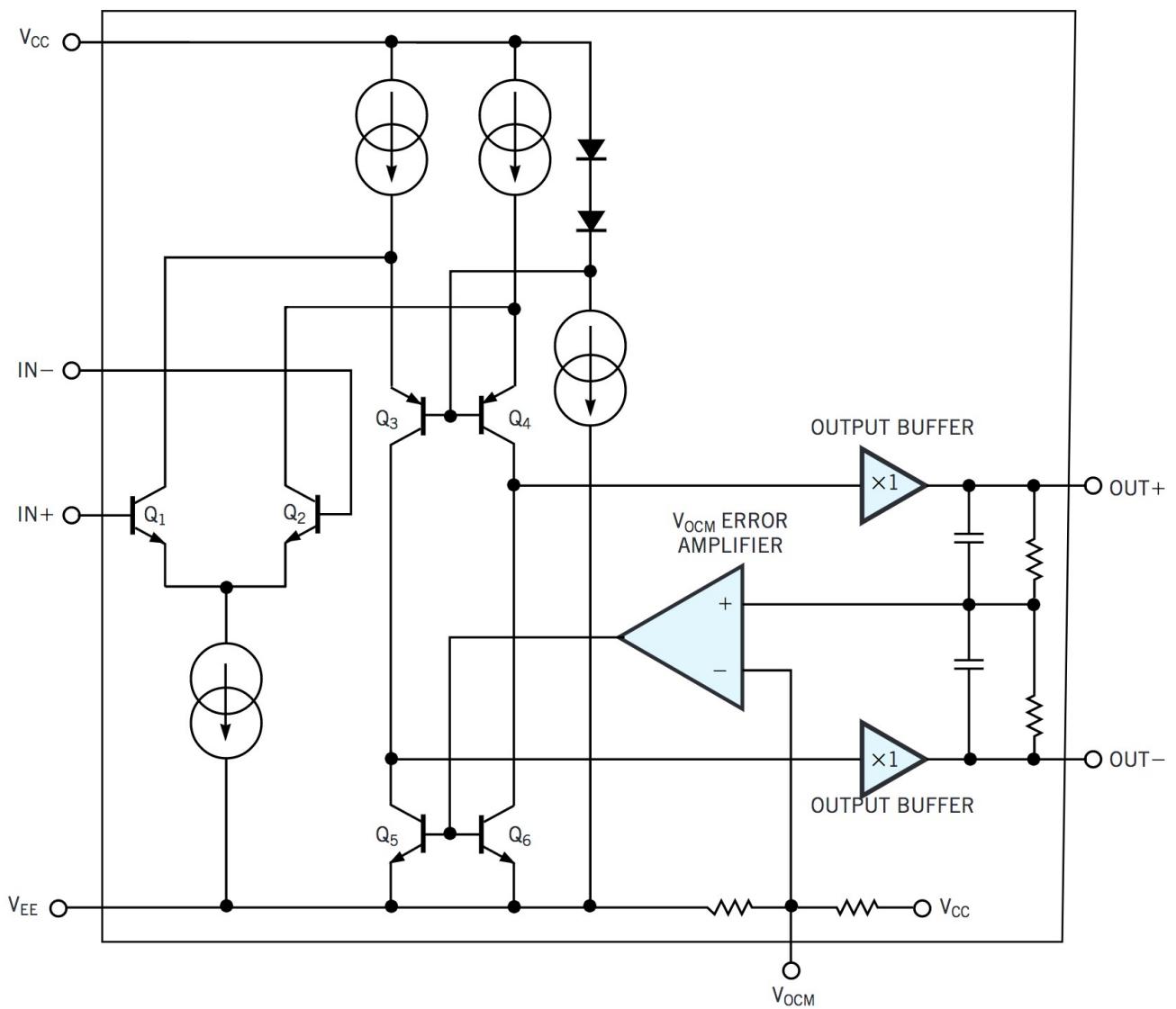
TABLE 1—VOLTAGE DEFINITIONS

Voltage parameter	Definition
Input differential voltage (V_{ID})	$V_{ID} = V_{IN+} - V_{IN-}$
Input common-mode voltage (V_{IC})	$V_{IC} = (V_{IN+} - V_{IN-})/2$
Output differential voltage (V_{OD})	$V_{OD} = V_{OUT+} - V_{OUT-}$
Output common-mode voltage (V_{OC})	$V_{OC} = V_{OCM} = (V_{OUT+} + V_{OUT-})/2$
Transfer function	$V_{OD} = V_{ID} \times a(f).$

Amps reject common-mode voltages

Figure 3 shows a simplified version of an integrated, fully differential amplifier. Q_1 and Q_2 are the input differential pair. A standard op amp takes output current from

only one side of the input differential pair to develop a single-ended output voltage. A fully differential amplifier uses currents from both sides to develop voltages at the high-impedance nodes formed at the collectors of Q_3 /Q_5 and Q_4 /Q_6 . The IC then buffers these voltages to produce the differential outputs OUT+ and OUT−. To a first-order approximation, voltage common to IN+ and IN− produces no change in the current flow through Q_1 or Q_2 and thus produces no output voltage. Thus, the amplifier rejects common-mode voltages. The input does not control the output common-mode voltage. Instead, the V_{OCM} error amplifier maintains the output common-mode voltage at the same voltage as the V_{OCM} pin by sampling the output common-mode voltage, comparing it with the voltage at V_{OCM} , and adjusting the internal feedback. If the external circuit leaves V_{OCM} disconnected, the IC biases V_{OCM} to the midpoint between V_{CC} and V_{EE} using an internal voltage divider. Due to the change in phase between the differential outputs, the dynamic range is twice that of a single-ended output with the same voltage swing (**Figure 1b**).

NOTE: THIS SCHEMATIC IS REPRESENTATIVE OF THE THS4130/1 OR THS4140/1 AMPLIFIERS.
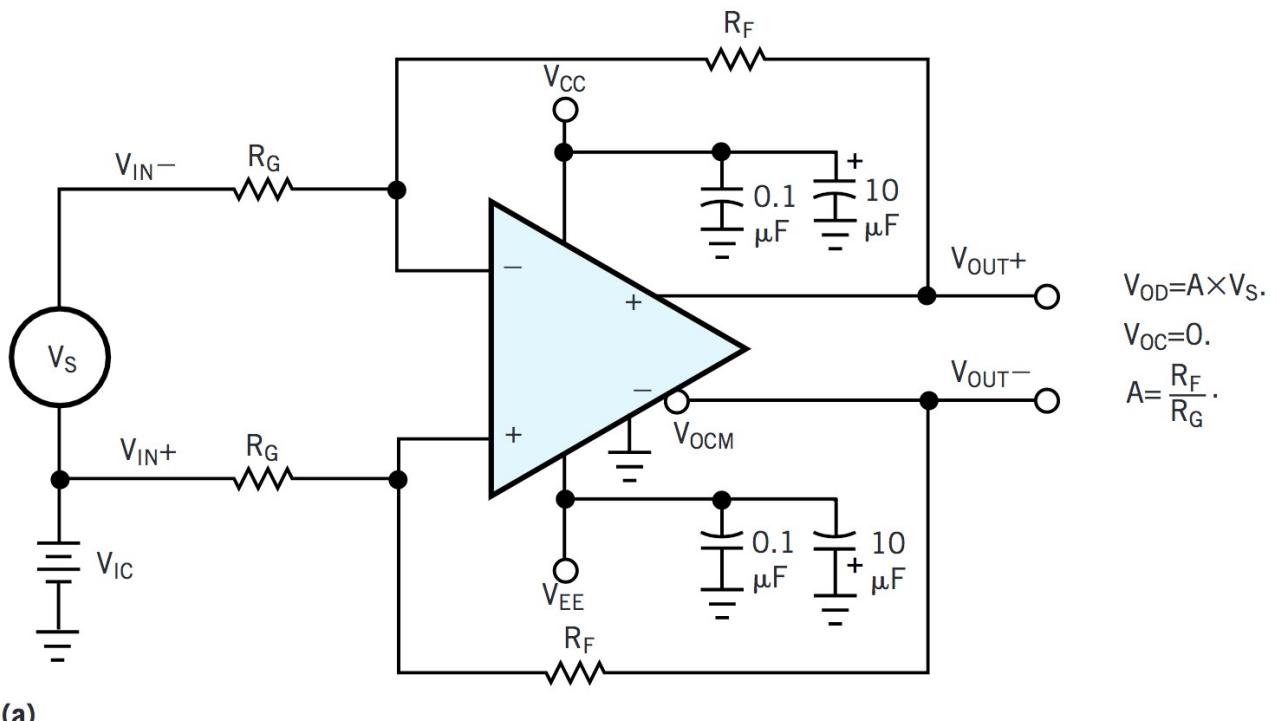
Figure 3 A fully differential amplifier uses currents from both sides of the input differential pair, Q_1 and Q_2 , to develop voltages at the high impedance nodes

formed at the collectors of Q_3 /Q_5 and Q_4 /Q_6 .
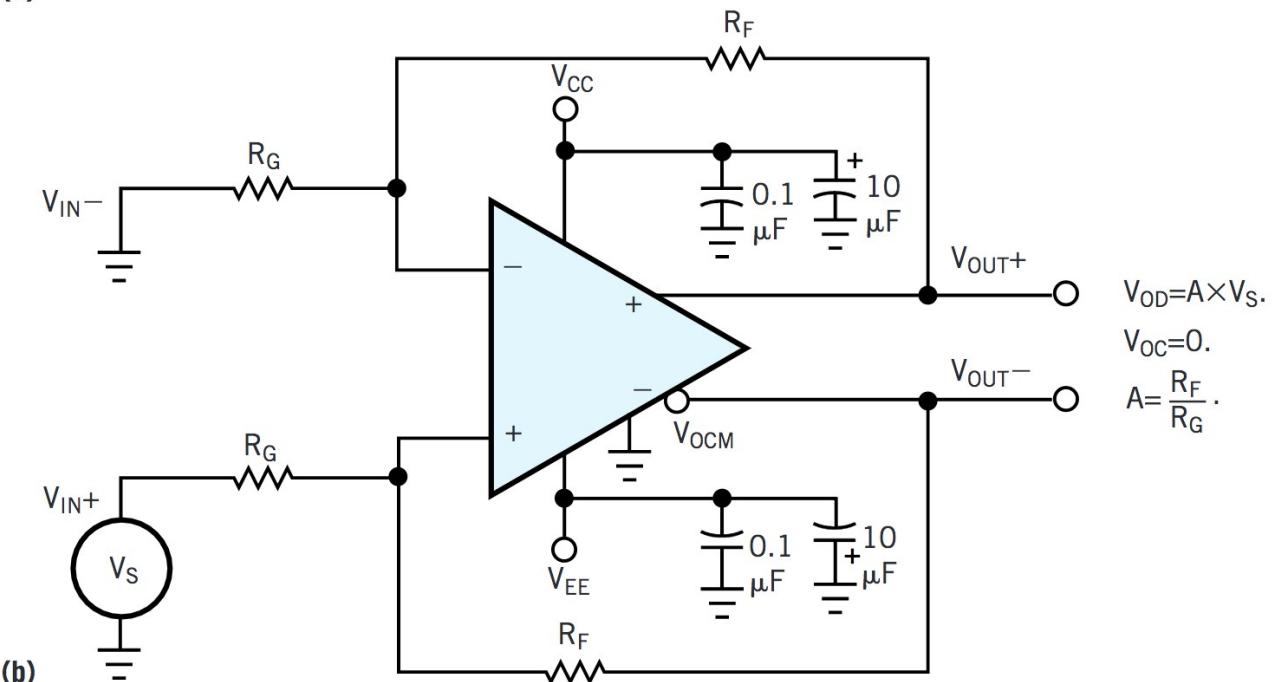
The two complementary amplifier paths in **Figure 3** share the same input differential pair, and their characteristics are well-matched. With symmetrical feedback, the architecture keeps the operating points close to each other. Therefore, distortion in the amplifiers is closely matched, resulting in symmetrical distortion of the differential signal. Symmetrical distortions tend to cancel even-order harmonics. Lab testing of the Texas Instruments THS4141 differntial amplifier at 1 MHz shows that the second harmonic at the output decreases by approximately 6 dB when measuring the signal differentially compared with measuring either output single-ended. The third harmonic remains unchanged between a differential and single-ended measurement.

Study basic circuits

In a fully differential amplifier, two feedback paths, one for each side, are possible in the main differential amplifier. This arrangement naturally forms two inverting amplifiers, and you can easily adapt inverting topologies to fully differential amplifiers. **Figure 4a** shows how to configure a fully differential amplifier with negative feedback to control the gain and maintain a balanced amplifier. Symmetry in the two feedback paths is important to have good CMRR performance. CMRR is directly proportional to the resistor-matching error, and an error of 0.1% results in 60 dB of CMRR.

(a)

$V_{IN}-$ R_G

V_S

$V_{IN}+$ R_G

V_{IC}

R_F

V_{CC}

$0.1\ \mu F$ $10\ \mu F$

$V_{OUT}+$

$V_{OUT}-$

V_{OCM}

V_{EE}

$0.1\ \mu F$ $10\ \mu F$

R_F

$V_{OD}=A{\times}V_S.$
$V_{OC}=0.$
$A=\dfrac{R_F}{R_G}.$

(b)

R_F

V_{CC}

R_G

$V_{IN}-$

$0.1\ \mu F$ $10\ \mu F$

$V_{OUT}+$

$V_{OUT}-$

V_{OCM}

R_G

$V_{IN}+$

V_S

V_{EE}

$0.1\ \mu F$ $10\ \mu F$

R_F

$V_{OD}=A{\times}V_S.$
$V_{OC}=0.$
$A=\dfrac{R_F}{R_G}.$

Figure 4 A configuration with negative feedback provides for gain control and maintains a balanced amplifier (a). Converting a single-ended signal to a differential one is also simple (b).

The V_{OCM} error amplifier is independent of the main differential amplifier. The purpose of the V_{OCM} error amplifier is to maintain the output common-mode voltage at the same level as the voltage input to the V_{OCM} pin. With symmetrical feedback, output balance is maintained, and V_{OUT} + and V_{OUT} – swing symmetrically plus and minus from the voltage at the V_{OCM} input.

In the past, generating differential signals has been cumbersome. Designers have used different means, often requiring multiple amplifiers. The integrated fully differential amplifier provides a more elegant solution. **Figure 4b** shows an example
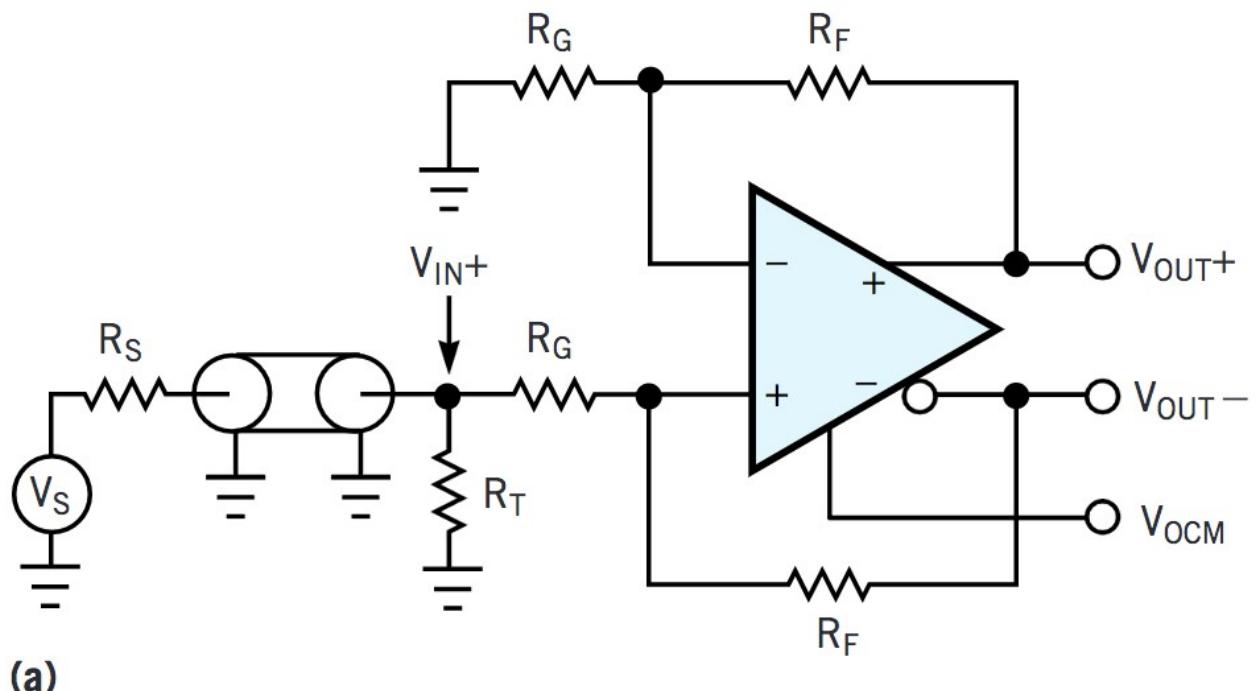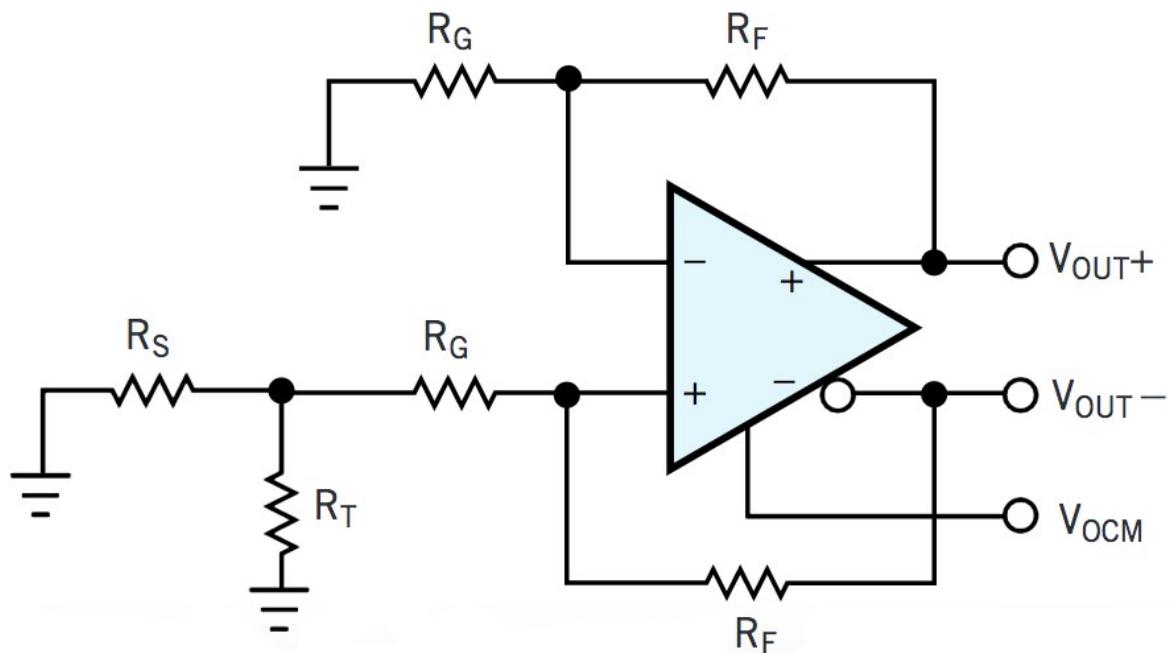
of converting single ended signals to differential signals.

Terminate the input source
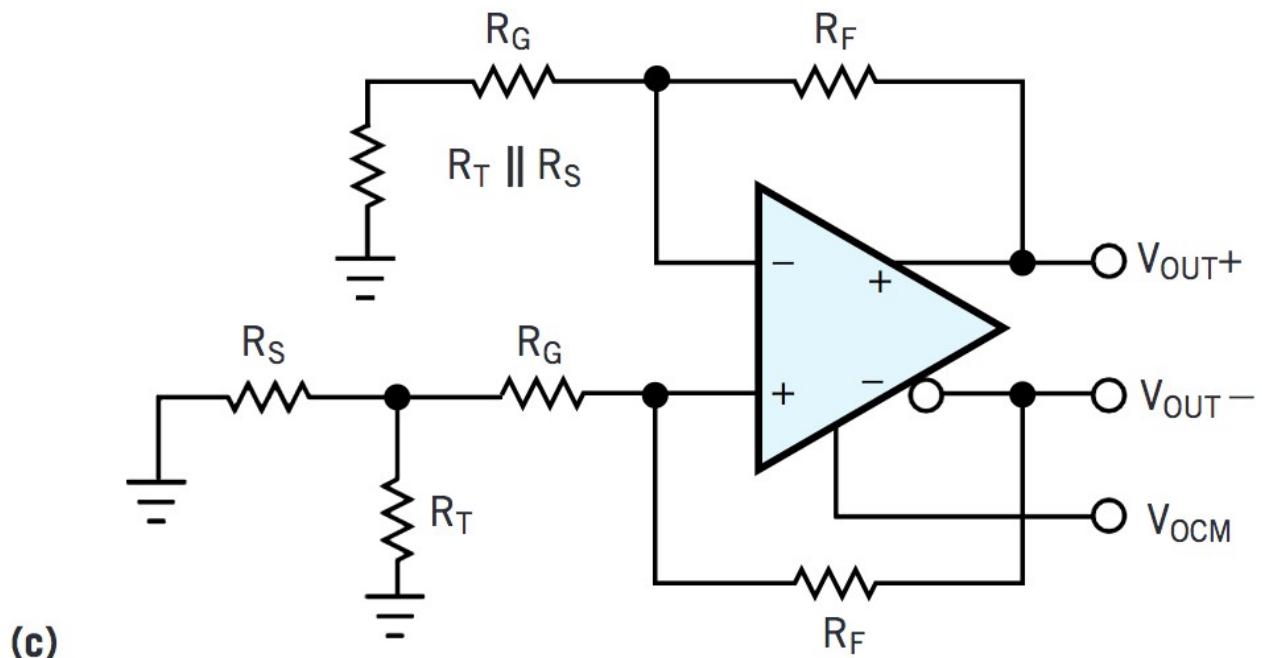
High-speed systems typically use double termination to reduce reflections in the transmission lines. Double termination implies that you terminate the transmission line with the same impedance as the source. Common values are 50, 75, and 100W. When the source is differential, the termination is across the line. When the source is single-ended, the termination is from the line to ground. The differential situation is balanced and raises no further design issues. The single-ended situation is not balanced and needs further attention if a balanced system, where $b_1 = b_2$ is desirable. b_1 and b_2 are the $V_{OUT}+$ and $V_{OUT}-$ feedback-resistor ratios, and for a balanced amplifier $b_1 = b_2 = R_G/(R_G + R_F)$ (**Figure 5**).

(a)

(b)

(c)

Figure 5 For a single-ended signal, the termination resistor connects from the line to ground (a). R_S and R_T add to the calculation of feedback factor from V_{OUT2} (b). An equivalent resistor in the upper feedback path balances the amplifier (c).

Figure 5a shows the source and termination resistors for a single-ended signal. To calculate the feedback factor, short the source. **Figure 5b** shows that the source impedance, R_S , and termination resistor, R_T , add to the calculation of the feedback from V_{OUT} – to the positive input. To balance the amplifier, a resistor equal to R_S ||R_T is necessary in the upper feedback path (**Figure 5c**). Given that R_T =R_S , then R_S ||R_T =R_T /2.
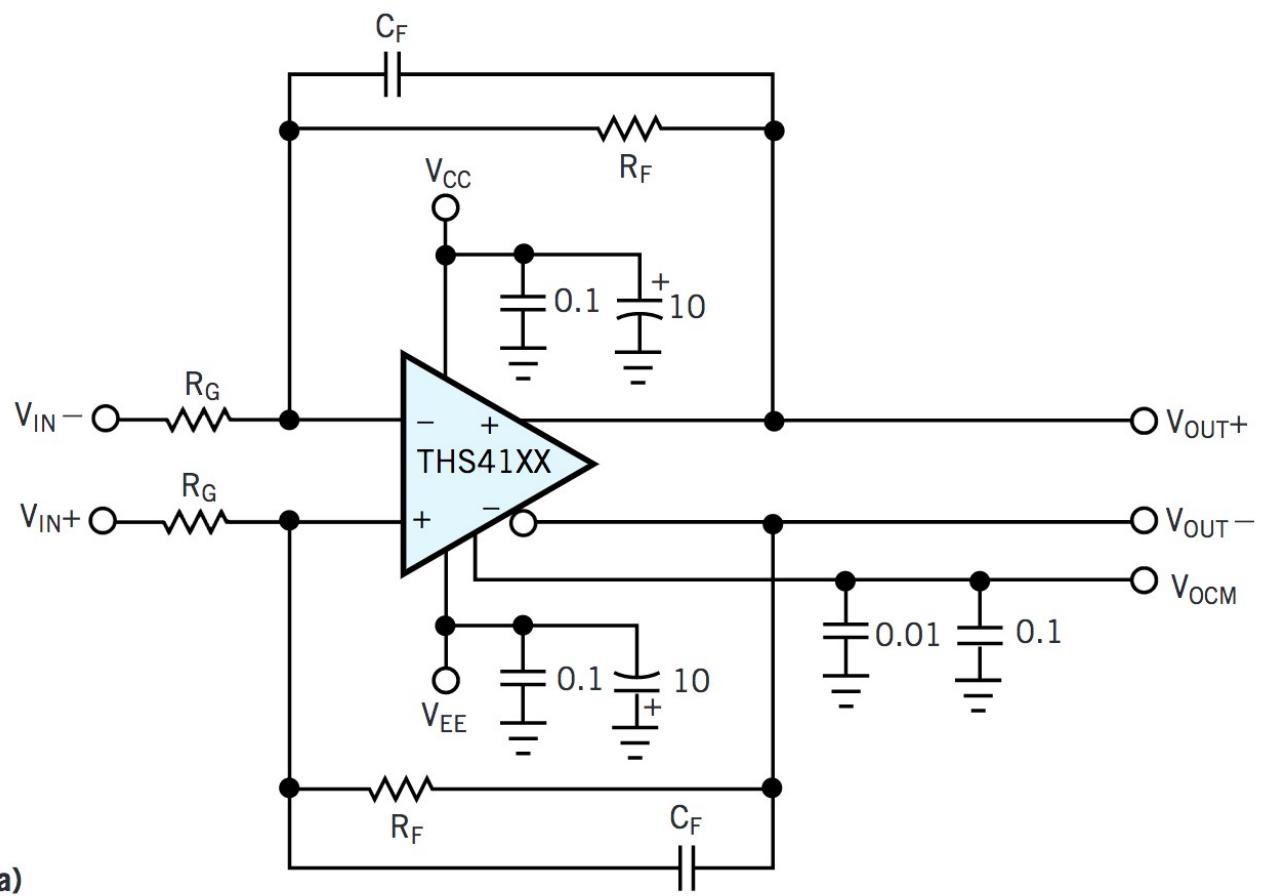
Typical applications of fully differential amplifiers include driving ADC inputs and transmission lines. For the circuits that follow and any related equations, you can assume that the amplifier is operating at frequencies for which a(f)>>1. Thus, the following equations do not include a(f) and its effects. Also, assume that the feedback is symmetrical, or that b_1 =b_2 =R_G /(R_G +R_F).

Drive and filter ADC inputs
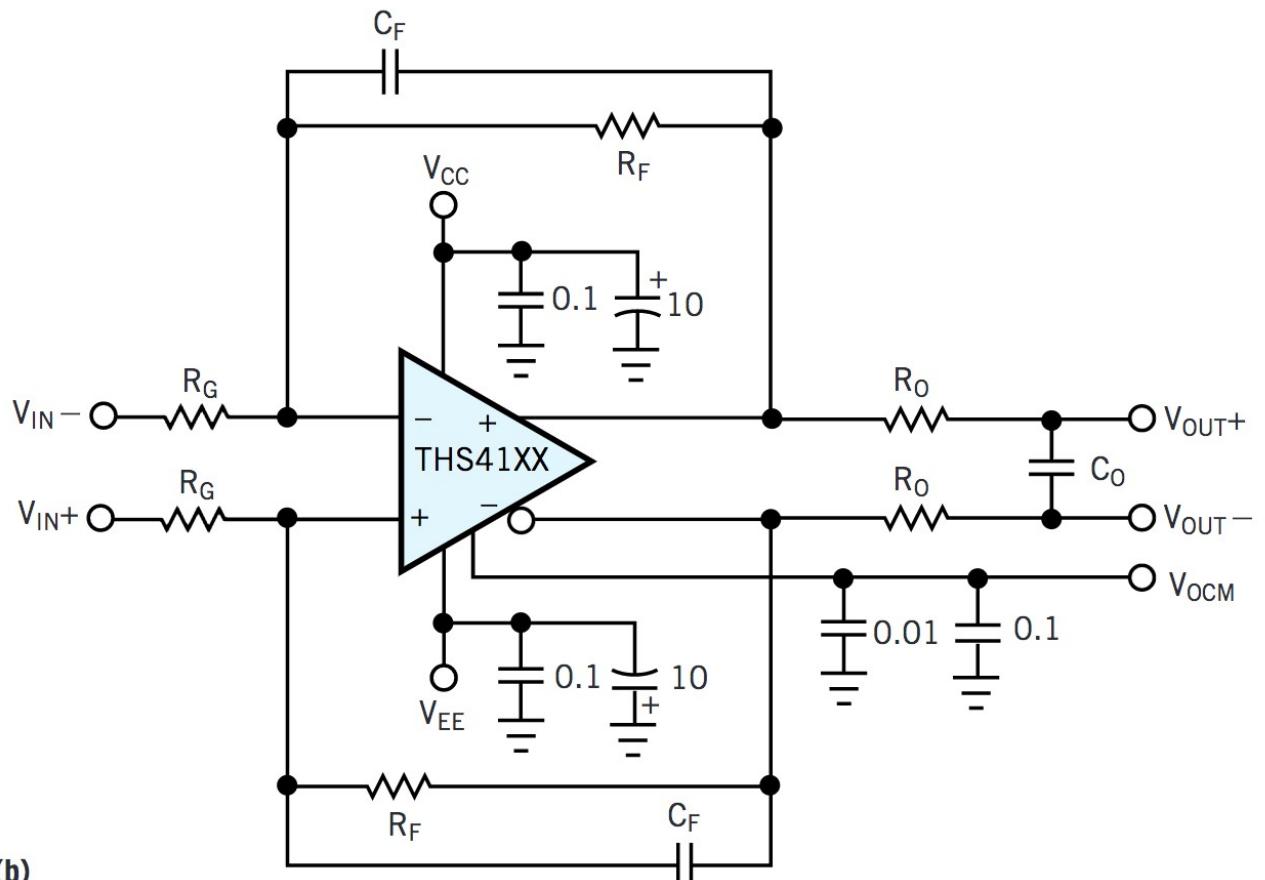
A major application for fully differential amplifiers is lowpass, antialias filters for signal-conditioning ADCs with differential inputs. You can easily create an active, first-order, lowpass filter by adding capacitors in the feedback paths (**Figure 6a**). With balanced feedback, the transfer function is:

$$\frac{V_{OD}}{V_{ID}} = \frac{R_F}{R_G} \times \frac{1}{1 + j2\pi f(R_F C_F)}.$$

The pole in the transfer function is a real pole on the negative real axis in the s-plane. Note that, for this circuit and all others that follow, each power pin should have a 6.8- to 10-µF tantalum capacitor in parallel with a nearby 0.01- to 0.1-µF ceramic capacitor. These circuits show bypass capacitors of 10 and 0.1 µF.

Figure 6 A first-order, active, lowpass filter is easy to accomplish (a). Adding R_O and C_O creates a second lowpass pole (b).
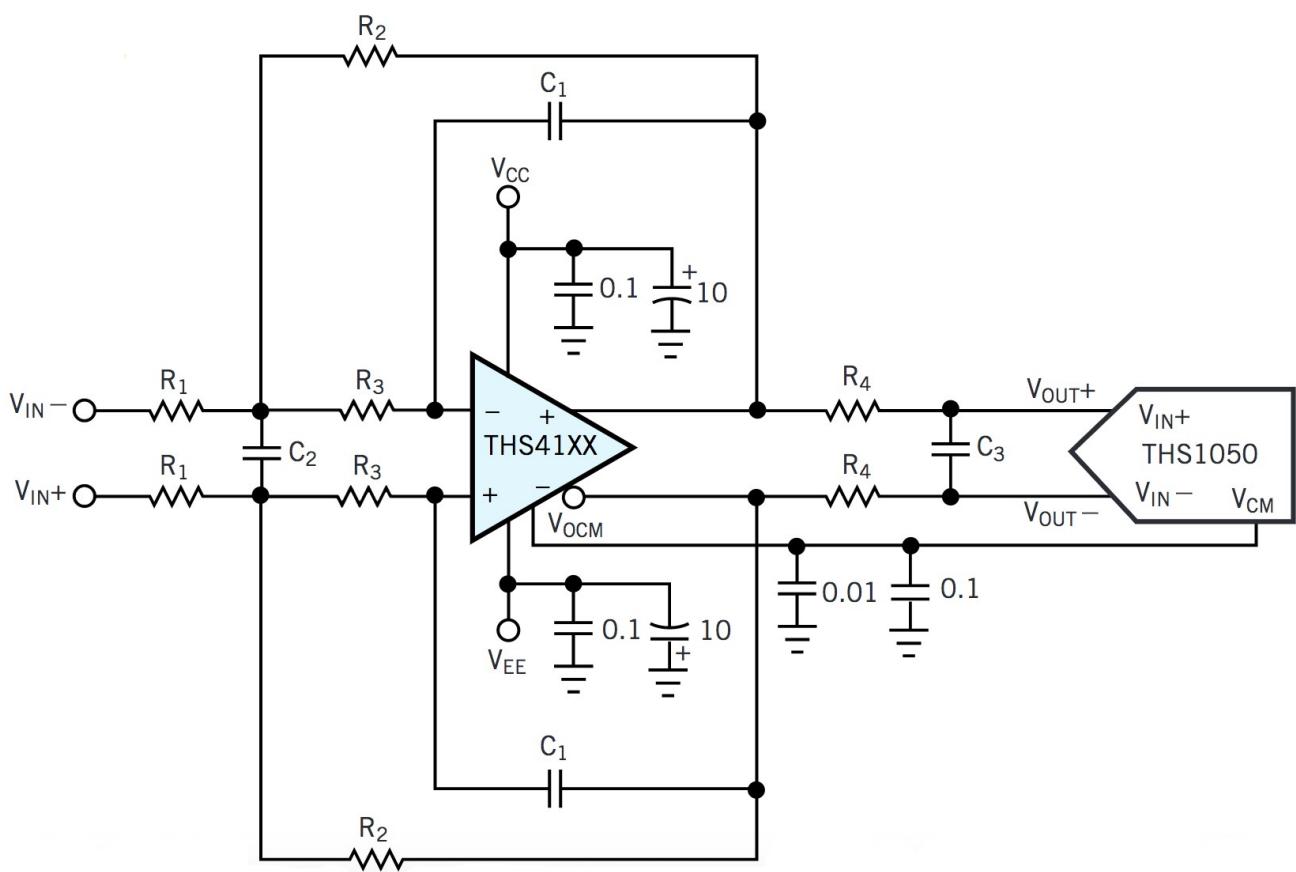
To create a two-pole, lowpass filter, you can add another passive real pole by placing R_O and C_O in the output (**Figure 6b**). With balanced feedback, the transfer function is:

$$\frac{V_{OD}}{V_{ID}} = \frac{R_F}{R_G} \times \frac{1}{1 + j2\pi f(R_F C_F)} \times$$

$$\frac{1}{1 + j2\pi f \times 2 \times R_O C_O}.$$

The second pole in the transfer function is also a real pole on the negative real axis in the s-plane.

The classic filter types, such as Butterworth, Bessel, and Chebyshev filters (second-order and greater) are unrealizable using real poles and require complex poles. The MFB (multiple feedback) is a good topology with which to create a complex pole pair and is easily adaptable to fully differential amplifiers (**Figure 7**). Adding the two R_4 resistors and C_3 at the output forms a third-order filter.

Figure 7 A third-order, lowpass filter drives an ADC's differential inputs.

The transfer function for this filter circuit is:

$$\frac{V_{OD}}{V_{ID}} = \left(\frac{K}{-\left(\frac{f}{FSF \times f_c} \right)^2 + \frac{1}{Q} \frac{jf}{Q\ FSF \times f_c} + 1} \right) \times$$

$$\left(\frac{1}{1 + j2\pi f \times 2 \times R_4 C_3} \right),$$

where $K = R_2/R_1$,

$$FSF \times f_C = \frac{1}{2\pi\sqrt{2 \times R_2 R_3 C_1 C_2}},$$

and

$$Q = \frac{\sqrt{2 \times R_2 R_3 C_1 C_2}}{R_3 C_1 + R_2 C_1 + K R_3 C_1}.$$

K sets the passband gain, f_C is the filter cutoff frequency, FSF is a frequency-scaling factor, and Q is the quality factor, where Re is the real part, and Im is the imaginary part of the complex pole pair:

$$FSF = \sqrt{Re^2 + |Im|^2},$$

and

$$Q = \frac{\sqrt{Re^2 + |Im|^2}}{2\,Re}.$$

Setting $R_2 = R$, $R_3 = mR$, $C_1 = C$, and $C_2 = nC$, results in
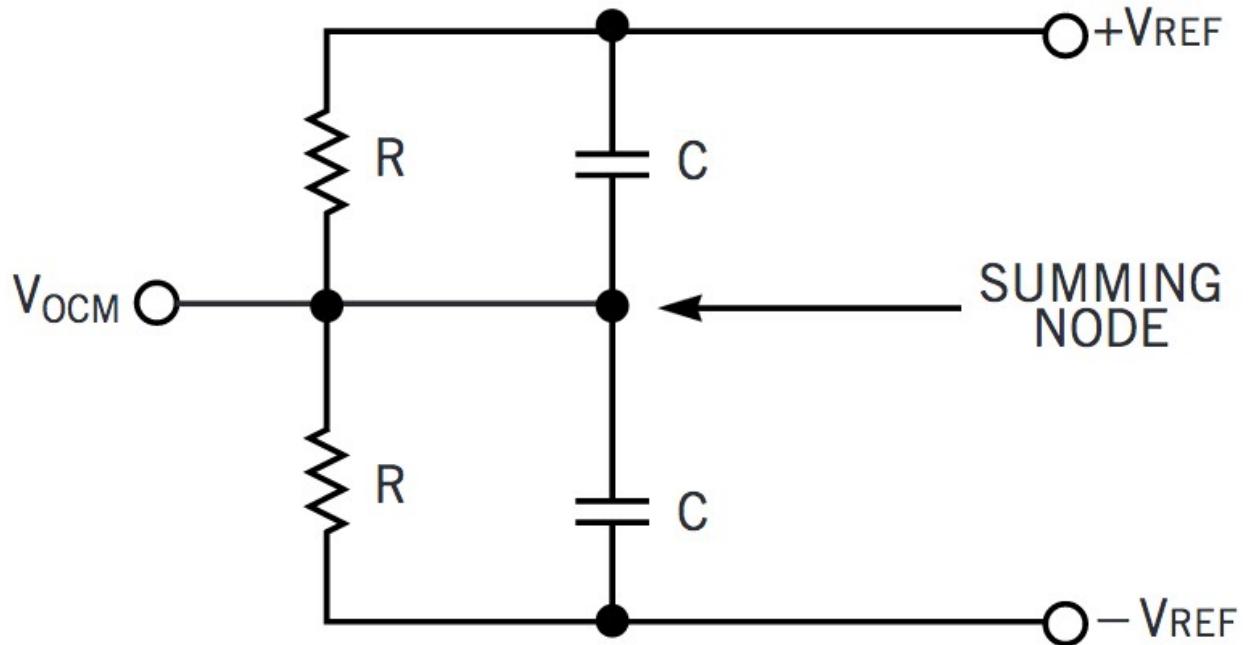
$$FSF \times f_C = \frac{1}{2\pi RC\sqrt{2 \times mn}},$$

and

$$Q = \frac{\sqrt{2 \times mn}}{1 + m(1 - K)}.$$

To design the filter, you start by determining the ratios, m and n, necessary for the gain and Q of the filter type. Then you select C and calculate R for the desired f_C. Choose R_4 and C_3 to set the real pole in a third-order filter.
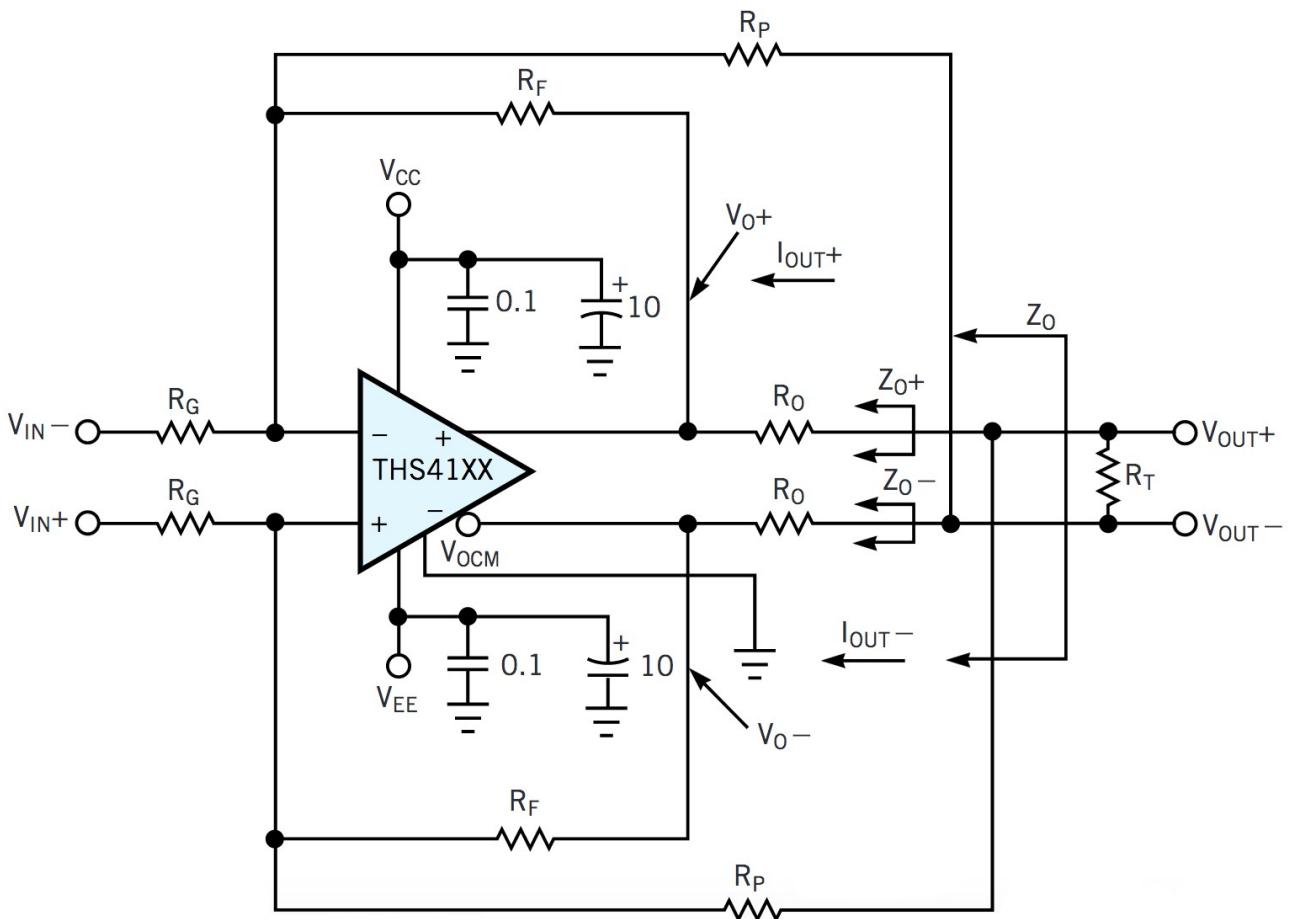
Most ADCs with differential inputs provide the proper V_{OCM} as an output. Typically, all you have to do is provide bypass capacitors; 0.1- and 0.01-µF capacitors are useful choices. If the ADC doesn't provide V_{OCM}, you can create it by forming a summing node using the ADC's plus and minus reference voltages to drive the amplifier's V_{OCM} pin (**Figure 8**). The voltage at the summing node is the midpoint value between $+V_{REF}$ and $-V_{REF}$.

Figure 8 If the ADC doesn't provide the proper V_{OCM} as an output, you can create V_{OCM} using the ADC's reference voltages.

Positive feedback for active termination

Driving transmission lines differentially is a typical use for fully differential amplifiers. By using positive feedback, the amplifiers can provide active termination (**Figure 9**). The positive feedback makes the output resistor appear to be a larger value than it actually is when you view it from the line. Still, the voltage dropped across the resistor depends on the actual resistor value. Thus, active termination provides for increased efficiency. Note that it is important to use symmetrical feedback with this application.

Figure 9 Differential amplifiers with positive feedback provide active termination.

For proper termination, the output impedance of the amplifier, Z_O , should equal the characteristic impedance of the transmission line, and the far end of the line will terminate with the same value resistor, so $R_T = Z_O$. To calculate the output impedance, ground the inputs, insert either a voltage or a current source between $V_{OUT} +$ and $V_{OUT} -$, and calculate the impedance from the circuit's response.

Due to symmetry, $Z_O += Z_O -$, $V_{OUT} +=-V_{OUT} -$, and $V_O +=-V_O -$. Calculation of the impedance of one side provides the solution:

$$Z_O+ = \frac{V_{OUT}+}{I_{OUT}+},$$

$$I_{OUT}+ = \frac{(V_{OUT}+)-(V_O+)}{R_O},$$

and

$$V_O+ = (V_{OUT}-) \times \left(\frac{-R_F}{R_P}\right).$$

Looking back into the amplifier's outputs, the impedance that each side of the line

sees will be the value of R_O divided by 1 minus the gain from the other side of the line, or

$$Z_O\pm = \frac{R_O}{1 - \frac{R_F}{R_P}}.$$

Equation 13

The value of Z_O is two times this result.

The positive feedback also affects the forward gain. Accounting for this effect and the voltage divider between R_O and $R_T \| 2R_P$ the gain, A, from V_{ID} to V_{OD} is:

$$A = \frac{V_{OD}}{V_{ID}} = \frac{R_F}{R_G} \times \frac{1}{\frac{2R_O + R_T\|2R_P}{R_T\|2R_P} - \frac{R_F}{R_P}}.$$

Equation 14

You can easily accomplish the design by first choosing the value of R_F and R_O. Then, calculate the required value of R_P to give the desired Z_O. Then, calculate R_G for the required gain.

For example, given that you want a gain of 1 and to properly terminate a 100W line with R_F =1 kW and R_O =10W. The proper value for Z_O and R_T is 100W (Z_O ±=50W).

Rearranging Equation 13 gives:

$$R_P = \frac{R_F}{1 - \frac{R_O}{Z_O}} = \frac{1k}{1 - \frac{10}{50}} = 1.25 \text{ k}\Omega.$$

Then, rearranging Equation 14 gives:

$$R_G = \frac{R_F}{A} \times \frac{1}{\frac{2R_O + R_T\|2R_P}{R_T\|2R_P} - \frac{R_F}{R_P}} =$$

$$\frac{1k}{\frac{20 + 100\|2.5k}{100\|2.5k} - \frac{1k}{1.25k}} = 2.45 \text{ k}\Omega.$$

Author Information

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Linear Division of Texas Instruments (Dallas), where he has worked for more than three years. In his current position, he provides new-product definition and support for high-speed amplifiers. He received his bachelor's degree in electrical engineering from the University of Washington (Seattle). Karki's leisure-time pursuits include building with wood, steel, and concrete.

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