Application Report

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Fully Differential Amplifiers Applications: Line Termination, Driving High-Speed ADCs, and Differential Transmission Lines

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ABSTRACT

In high-speed systems, proper line termination requires considering the termination resistors and adjusting the gain-setting resistors to maintain symmetrical feedback. Integrated, fully differential amplifiers are well suited for driving differential ADC inputs. They provide an easy means for anti-alias filtering and for setting the common-mode voltage.

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1 Introduction

The August 2000 issue of *Analog Applications Journal* introduced the fully differential amplifiers from Texas Instruments and illustrated their basic operation. The November 2000 issue delved into the topic more deeply, by analyzing gain and noise.This issue investigates some typical applications, such as transmission lines and driving ADC inputs.

To simplify calculations and formulas, assume that the amplifier is used at frequencies where the open-loop gain is very large (A_F >> 1) and will not include its effects in the analysis.

The circuit analysis assumes that symmetrical feedback is being used (β1 = β2). Before going into the application circuits, this document will detour briefly into how termination affects the feedback factor, and how to account for it.

2 Terminating the Input Source

Double termination is typically used in high-speed systems to reduce transmission-line reflections. With double termination, the transmission line is terminated with the same impedance as the source. Common values are 50 W, 75 W, 100 W, and 600 W. When the source is differential, the termination is placed across the line. When the source is single-ended, the termination is placed from the line to ground.

Figure 1 shows an example of terminating a differential signal source. The situation depicted is balanced so that half of V_S and half of R_S is attributed to each input, with V_{IC} being the center point. R_S is the source impedance and R_t is the termination resistor. The circuit is balanced, but there are two issues to resolve: (1) proper termination and (2) gain setting.

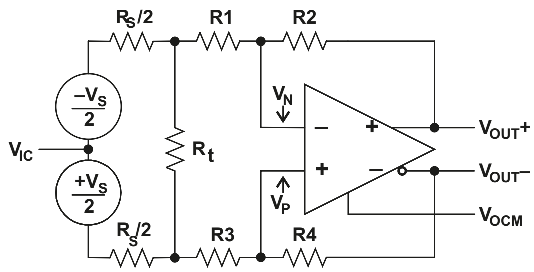

Figure 1. Terminating a Differential Input Signal

As long as A_F >> 1 and the amplifier is in linear operation, the action of the amplifier keeps $V_N \approx V_P$. Thus, to first-order approximation, a virtual short is seen between the two nodes as shown in Figure 2. The termination impedance is the parallel combination: $R_t \parallel (R1+R3)$. The value of R_t for proper termination is calculated as shown in Figure 2.

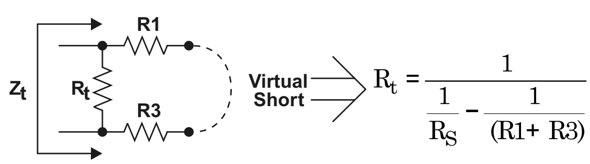

Figure 2. Differential Termination Impedance

Once R_t is found, the required gain is found by generating a Thevenin equivalent circuit. The circuit is broken between R_t and the amplifier input resistors R1 and R3. V_{IC} is not a concern at this point, so leave it out. Then:

$$V_{TH} = V_S \times R_t / (R_t + R_S) \tag{1}$$

and $R_{TH} = R_S \parallel R_t$ (half is attributed to each side). The resulting Thevenin equivalent is shown in Figure 3.

The proper gain is calculated by:

$$\frac{V_{OUT}}{V_{TH}} = \frac{R_F}{R_G + \frac{R_S||R_t}{2}}$$

where

- where $V_{OUT} = (V_{OUT+}) - (V_{OUT-})$. (2)

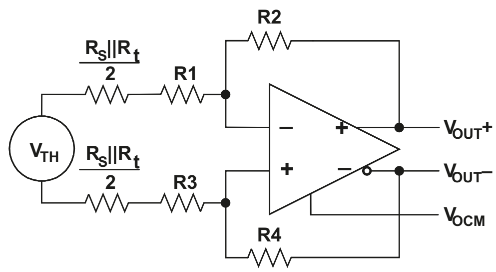

Figure 3. Differential Thevenin Equivalent

Substituting for V_{TH}, this becomes:

$$\frac{V_{OUT}}{V_S} = \frac{R_F}{R_G + \frac{R_S||R_t}{2}} \times \frac{R_t}{R_S + R_t}$$

where

- R_F is the feedback resistor (R2 or R4)
- R_G is the input resistor (R1 or R3) (3)

Remember: for symmetry, keep the gain equal on the two sides with R2 = R4 and R1 = R3.

As an example, suppose you are terminating a 50-Ω differential source that is balanced, and you want an overall gain of 1 from the source to the differential output of the amplifier. Start the design by first choosing the values for R1 and R3, then calculate R_t and the feedback resistors.

With the voltage divider formed by the termination, assume that a gain of about 2 will be required in the amplifier. Also, feedback resistor values of approximately 500 Ω are reasonable for a high-speed amplifier. Using these starting assumptions, choose R1 and R3 equal to 249 Ω. Next calculate R_t from the formula:

$$R_t = \frac{1}{\frac{1}{R_S} - \frac{1}{(R1 + R3)}} = \frac{1}{\frac{1}{50} - \frac{1}{(249 + 249)}} = 55.6\ \Omega \qquad (4)$$

(the closest standard 1% value is 56.2 Ω). Then set the gain by calculating the value of the feedback resistors:

$$R_F = \frac{V_{OUT}}{V_S} \times \left(R_G + \frac{R_S||R_t}{2}\right) \times \frac{R_S + R_t}{R_t}$$

$$= 1 \times \left(249 + \frac{50||56.2}{2}\right) \times \frac{50 + 56.2}{56.2} = 495.5\Omega \qquad (5)$$

(the closest standard 1% value is 499 Ω). The solution is shown in Figure 4 with standard 1% resistor values.

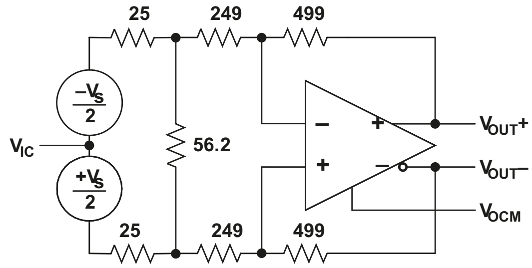

Figure 4. Differential Solution for Gain = 1

Figure 5 shows an example of terminating a single-ended signal source. R_S is the source impedance, and R_t is the termination resistor. The circuit is not balanced, so there are three issues to resolve:

- Proper termination
- Gain setting
- Balance

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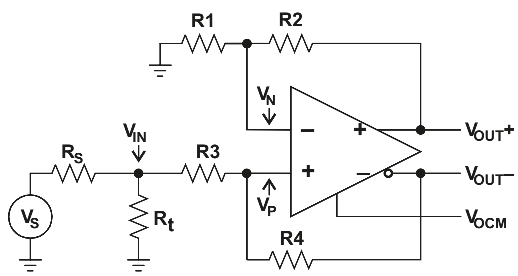

Figure 5. Terminating a Single-Ended Input Signal

To determine the termination impedance seen from the line looking into the amplifier's input at V_{IN}, remove V_S and R_S and short all other sources. As long as A_F >> 1 and the amplifier is in linear operation, the action of the amplifier keeps $V_N \approx V_P$. V_N will see the voltage at V_{OUT+} divided by the resistor ratio R1 / (R1 + R2). Assuming that the amplifier is balanced,

$V_{OUT+} = K \times V_{IN} / 2$

where

- K is the closed-loop gain of the amplifier (V_{OCM} = 0) (6)

The termination impedance is the parallel combination: R_t in parallel with:

$$\frac{V_{IN}}{I_{R3}} = \frac{R3}{1 - \frac{K}{2 \times (1 + K)}}. \quad (7)$$

The value of R_t for proper termination is then calculated as shown in Figure 6.

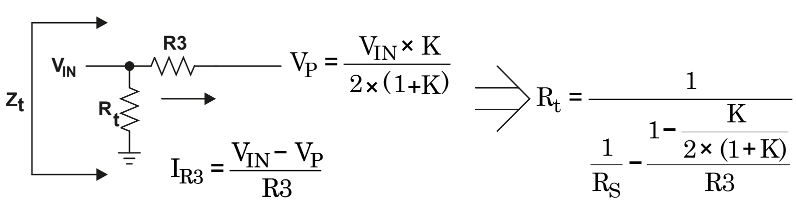

Figure 6. Single-Ended Termination AC Impedance

Once R_t is found, the required gain is found by generating a Thevenin equivalent circuit. The circuit is broken between R_t and the amplifier's input resistor R3.

$$V_{TH} = V_S \times \frac{R_t}{R_t + R_S} \tag{8}$$

and $R_{TH} = R_S \,||\, R_t$.

The resulting Thevenin equivalent is shown in Figure 7. The gain is set by:

$V_{OUT}/V_{TH} = R_F/R_G$

where

- RF = R2 = R4
- $R_G = R1 = R3 + R_S \,||\, R_t$
- $V_{OUT} = (V_{OUT+}) - (V_{OUT-})$ (9)

Substituting for V_{TH}, this becomes:

$$\frac{V_{OUT}}{V_S} = \frac{R_F}{R_G} \times \frac{R_t}{R_S + R_t} \tag{10}$$

Remember, for symmetry: R2 = R4 and R1 = R3 + (R_S || R_t).

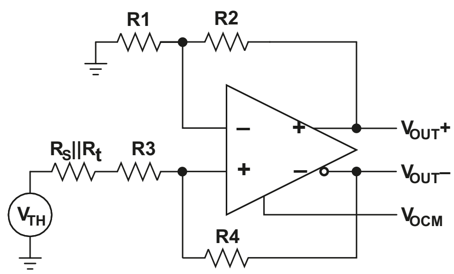

Figure 7. Single-Ended Thevenin Equivalent

As an example, suppose you are terminating a 50-Ω single-ended source and want an overall gain of 1 from the source to the differential output of the amplifier. Start the design by first choosing the value for R3, then calculate R_t and the feedback resistors. This will be an iterative process, starting with some initial assumptions that are then refined.

Start with the assumptions that R_t = 50 Ω and that a gain of 2 will be required in the amplifier. Also, feedback resistor values of approximately 500 Ω are reasonable for a high-speed amplifier. Using these starting assumptions, choose R1 = 249 Ω and R3 = R1 – R_S || R_t = 249 Ω – 25 Ω = 224 Ω. Next calculate R_t from the formula:

$$R_t = \frac{1}{\dfrac{1}{R_S} - \dfrac{1 - \dfrac{K}{2(1+K)}}{R3}} = \frac{1}{\dfrac{1}{50} - \dfrac{1 - \dfrac{2}{2(1+2)}}{224}} = 58.7 \tag{11}$$

Then calculate the value of the feedback resistors:

$$R2 = \frac{V_{OUT}}{V_S} \times R1 \times \frac{R_S + R_t}{R_t} = 1 \times 249 \times \frac{50 + 58.7}{58.7} = 460.9\,\Omega,$$

$$\text{and } R4 = \frac{V_{OUT}}{V_S} \times (R3 + R_S \,||\, Rt) \times \frac{R_S + R_t}{R_t}$$

$$= 1 \times (224 + 50 \,||\, 58.7) \times \frac{50 + 58.7}{58.7} = 464.7\,\Omega \tag{12}$$

The process is iterative because the gain is not 2, but rather 460.9/249 = 1.85; and R_t is calculated to be 58.7 Ω, not 50 Ω. Iterating through the calculations two more times results in: R3 = 221.9 Ω (the closest standard 1% value is 221 Ω), R_t = 59.0 (which is a standard 1% value), and R2 = R4 = 460.9 (the closest standard 1% value is 464 Ω). The solution is shown in Figure 8 with standard 1% resistor values.

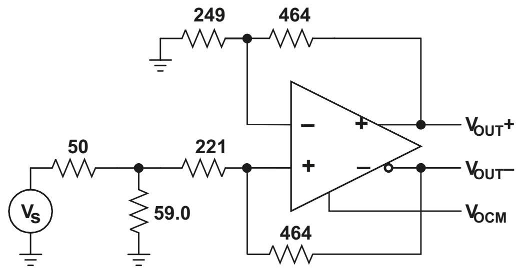

Figure 8. Single-Ended Solution for Gain = 1

Using a spreadsheet makes the iterative process very simple. Also, component values can be easily adjusted to find a better fit to the standard available values.

3 Active Anti-Alias Filtering

A major application for fully differential amplifiers is lowpass anti-alias filters for ADCs with differential inputs.

Creating an active first-order low-pass filter is easily accomplished by adding capacitors in the feedback, as shown in Figure 9. With balanced feedback, the transfer function is:

$$\frac{V_{OUT}}{V_{IN}} = \frac{R_F}{R_G} \times \frac{1}{1 + j2\pi f\,(R_F C_F)}$$

where

- $V_{OUT} = (V_{OUT+}) - (V_{OUT-})$
- $V_{IN} = (V_{IN+}) - (V_{IN-})$ (13)

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

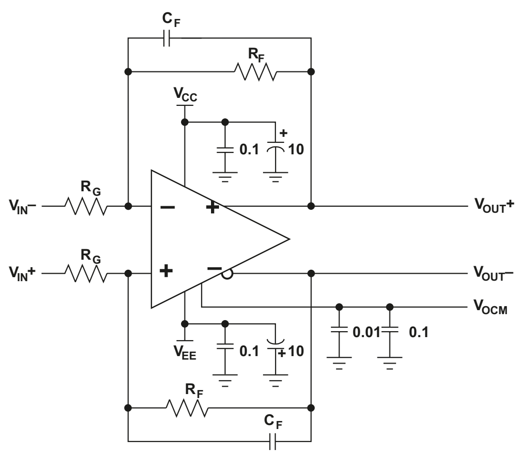

Figure 9. First-Order Active Low-Pass Filter

To create a two-pole low-pass filter, a passive real pole can be created by placing R_O and C_O in the output, as shown in Figure 10. With balanced feedback, the transfer function is:

$$\frac{V_{OUT}}{V_{IN}} = \frac{R_F}{R_G} \times \frac{1}{1 + j2\pi f\,(R_F C_F)} \times \frac{1}{1 + j2\pi f\ \ 2\ \ R_O C_O}$$

where

- $V_{OUT} = (V_{OUT+}) - (V_{OUT-})$
- $V_{IN} = (V_{IN+}) - (V_{IN-})$ (14)

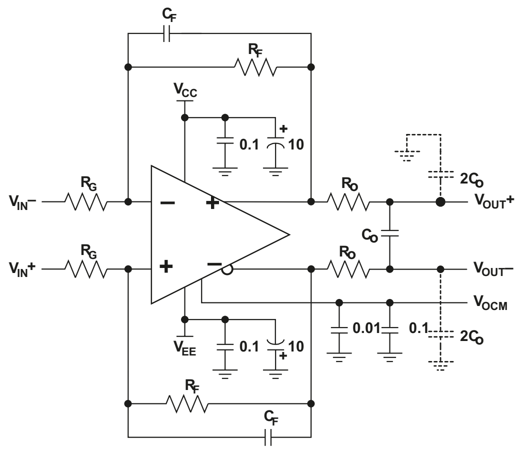

Figure 10. First-Order Active Low-Pass Filter With Passive Second Pole

The second pole created in the transfer function is also a real pole on the negative real axis in the s-plane. The capacitor C_O can be placed differentially across the outputs as shown in solid lines; or two capacitors (of twice the value) can be placed between each output and ground as shown in dashed lines. Typically, R_O will be a low value; and, at frequencies above the pole frequency, the series combination with C_O will load the amplifier. The extra loading will cause extra distortion in the amplifier's output. To avoid this, you might stagger the poles so that the R_OC_O pole is placed at a higher frequency than the R_FC_F pole.

The classic filter types like Butterworth, Bessel, Chebyshev, and so forth (second-order and greater), cannot be realized by real poles—they require complex poles. The multiple feedback (MFB) topology creates a complex pole pair, and is easily adapted to fully differential amplifiers, as shown in Figure 11. A third-order filter is formed by adding R4s and C3 at the output.

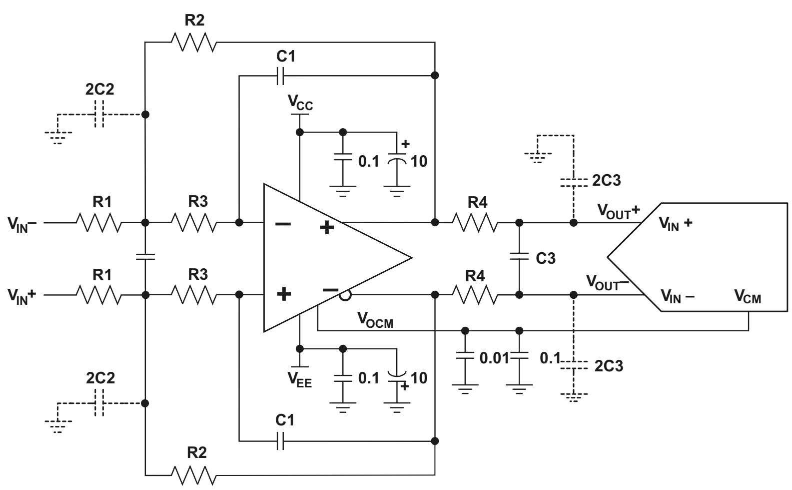

Figure 11. Third-Order Low-Pass Filter Driving an ADC

Capacitors C2 and C3 can be placed differentially across the inputs and outputs, as shown in solid lines. Alternatively, for better common-mode noise rejection, two capacitors of twice the value can be placed between each input or output and ground, as shown in dashed lines.

The transfer function for this filter circuit is:

$$\frac{V_{OUT}}{V_{IN}} = \left[\frac{K}{-\left(\frac{f}{FSF \times f_C}\right)^2 + \frac{1}{Q}\frac{jf}{FSF \times f_C} + 1}\right] \times \frac{1}{+ j2\pi f \times 2 \times R4C3}$$

where

- $V_{OUT} = (V_{OUT+}) - (V_{OUT-})$
- $V_{IN} = (V_{IN+}) - (V_{IN-})$ (15)

$$K = \frac{R2}{R1},\ FSF \times f_C = \frac{1}{2\pi\sqrt{2 \times R2R3C1C2}},$$

$$\text{and } Q = \frac{\sqrt{2 \times R2R3C1C2}}{R3C1 + R2C1 + KR3C1}$$ (16)

K sets the pass-band gain, f_C is the cut-off frequency of the filter, FSF is a frequency scaling factor, and Q is the quality factor.

$$FSF = \sqrt{Re^2 + |Im|^2} \text{ and } Q = \frac{\sqrt{Re^2 + |Im|^2}}{2Re}$$

where

- Re is the real part of the complex pole pair
- Im is the imaginary part (17)

Setting R2 = R, R3 = mR, C1 = C, and C2 = nC results in:

$$FSF \times f_C = \frac{1}{2\pi RC\sqrt{2 \times mn}} \text{ and}$$

$$Q = \frac{\sqrt{2 \times mn}}{1 + m(1 - K)}$$ (18)

Start by determining the ratios, m and n, required for the gain and Q of the filter type being designed, then select C and calculate R for the desired f_C.

R4 and C3 are chosen to set the real pole in a third-order filter. Exercise care when setting this pole. Typically, R4 will be a low value; and, at frequencies above the pole frequency, the series combination with C3 loads the amplifier. The extra loading causes extra distortion in the amplifier output. To avoid this, place the real pole at a higher frequency than the cut-off frequency of the complex pole pair.

Figure 12 shows the gain and phase response of a second-order Butterworth low-pass filter, with corner frequency set at 1 MHz and the real pole set by R4 and C3 at 15.9 MHz. The components used are: R1 = 787 Ω, R2 = 787 Ω, R3 = 732 Ω, R4 = 50 Ω, C1 = 100 pF, C2 = 220 pF, C3 = 100 pF, and the THS4141 fully differential amplifier. At higher frequencies, parasitic elements allow the signal to feed through.

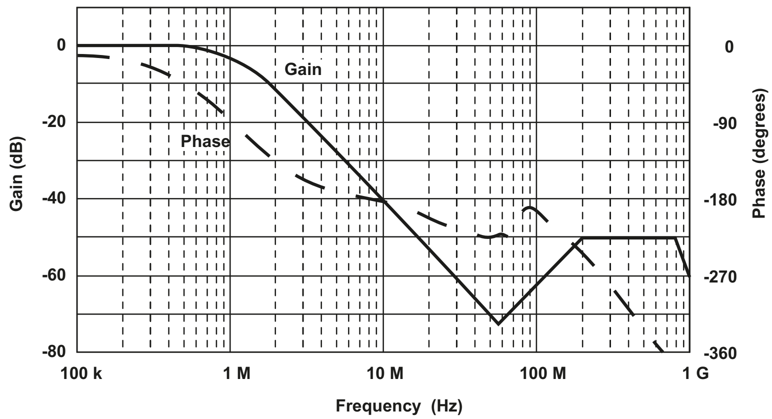

Figure 12. 1-MHz, Second-Order Butterworth Low-Pass Filter With Real Pole at 15.9 MHz

4 V_{OCM}

The proper V_{OCM} is provided as an output by many ADCs with differential inputs. Typically, all that needs to be done is to provide bypass capacitors; 0.1 μF and 0.01 μF are useful choices. If V_{OCM} is not provided, it can be created by forming a summing node with the plus and minus reference voltages of the ADC to drive V_{OCM}, as shown in Figure 13. The voltage at the summing node is the midpoint value between $+V_{REF}$ and $–V_{REF}$. Depending on the loading of the V_{OCM} input, the summing node voltage may need to be buffered.

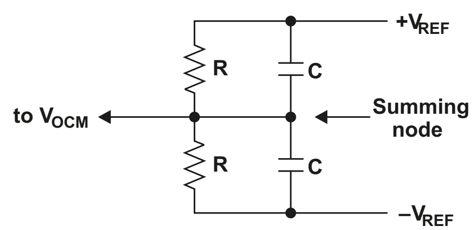

Figure 13. Driving V_{OCM} from ADC Reference Voltage

5 Power-Supply Bypass

Each power rail should have 6.8-μF to 10-μF tantalum capacitors located within a few inches of the amplifier, to provide low-frequency power-supply bypassing. A 0.01-μF to 0.1-μF ceramic capacitor should be placed within 0.1 inch of each power pin on the amplifier to provide high-frequency power-supply bypassing.

6 Layout Considerations

As with all high-speed amplifiers, minimize parasitic capacitance at the input of the amplifier by removing the ground plane near the pins and near any circuit traces. Also, make trace routing as direct as possible, and use surface-mount components.

7 Using Positive Feedback to Provide Active Termination

Driving transmission lines differentially is a typical use for fully differential amplifiers. Using positive feedback with amplifiers can provide active termination, as shown in Figure 14. Because of the positive feedback, the output line impedance appears larger than the value of output resistor R_O. The voltage dropped across the resistor depends on its actual value, resulting in increased efficiency.

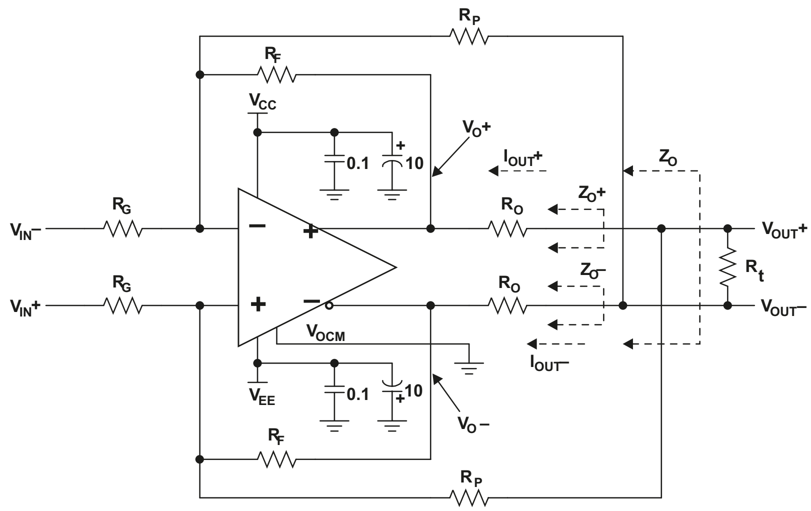

Figure 14. Using Positive Feedback to Provide Active Termination

Use symmetrical feedback with this application.

With double termination, the output impedance of the amplifier, Z_O, equals the characteristic impedance of the transmission line; and the far end of the line will be terminated with the same value resistor, that is, $R_t = Z_O$. For proper balance, half of Z_O is placed in each half of the differential output, so that $Z_O = 2 \times Z_{O\pm}$.

To calculate the output impedance, ground the inputs and insert either a voltage or current source between V_{OUT+} and V_{OUT-}.

Due to symmetry, $Z_{O+} = Z_{O-}$, $V_{OUT+} = -(_{VOUT-})$, and $V_{O+} = -(V_{O-})$. Calculating the impedance of one side provides the solution.

$$Z_O+ = \left(\frac{V_{OUT}+}{I_{OUT}+}\right) || R_P, I_{OUT}+ = \frac{(V_{OUT}+) - (V_O+)}{R_O},$$

$$\text{and } V_O+ = (V_{OUT}-) \times \left(\frac{-R_F}{R_P}\right) \tag{19}$$

The output impedance of the amplifier on each side of the line is R_O divided by 1 minus the gain from the opposite line:

$$Z_O\pm = \left(\frac{R_O}{1 - \frac{R_F}{R_P}}\right) || R_P \tag{20}$$

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 from $V_{IN} = (V_{IN+}) - (V_{IN-})$ to $V_{OUT} = (V_{OUT+}) - (V_{OUT-})$ is:

$$A = \frac{V_{OUT}}{V_{IN}} = \frac{R_F}{R_G} \times \frac{1}{\frac{2R_O + R_t || 2R_P}{R_t || 2R_P} - \frac{R_F}{R_P}} \tag{21}$$

Design is easily accomplished if 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: if you want a gain of 1, and to terminate a 100-Ω line properly with R_F = 1 kΩ and R_O = 10 Ω, the proper value for Z_O and R_t is 100 Ω ($Z_{O\pm}$ = 50 Ω). Rearranging Equation 20 yields:

$$R_P = \frac{R_F - R_O}{1 - \frac{R_O}{Z_O \pm}} = \frac{990\,\Omega}{1 - \frac{10\,\Omega}{50\,\Omega}} = 1.24\,k\Omega \tag{22}$$

Then, rearranging Equation 21 gives:

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

$$= \frac{1\ \text{k}\Omega}{\frac{20\,\Omega + 100\,\Omega \| 2.48\ \text{k}\Omega}{100\,\Omega \| 2.48\ \text{k}\Omega} - \frac{1\ \text{k}\Omega}{1.25\ \text{k}\Omega}} = 2.49\ \text{k}\Omega \tag{23}$$

The circuit is built and tested with the nearest standard values to those previously computed:

R_F = 1 kΩ, R_P = 1.24 kΩ, R_G = 2.49 kΩ, R_t = 100 Ω, and R_O = 10 Ω. Compare the output voltage waveforms ($V_{OUT} = 2V_{PP}$) with active termination and standard termination shown in Figure 15: [$V_O = (V_{O+}) - (V_{O-})$, and $V_{OUT} = (V_{OUT+}) - (V_{OUT-})$].

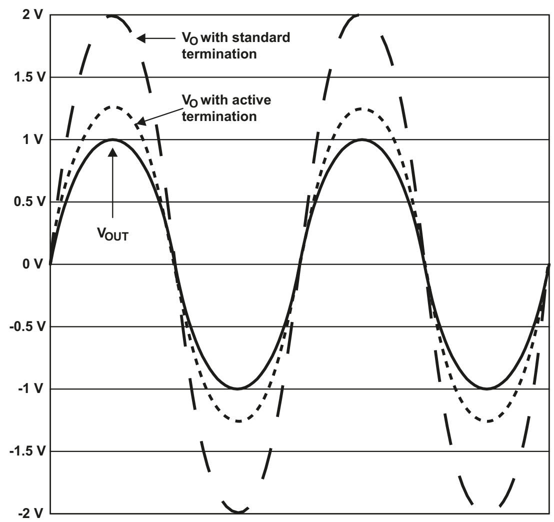

Figure 15. Output Waveforms With Active and Standard Termination

For standard termination, R_F = 1 kΩ, R_P = open, R_G = 499 Ω, R_t = 100 Ω, and R_O = 50 Ω.

With standard termination, 20 mW of power is dissipated in the output resistors, as opposed to 6.25 mW with active termination, which wastes 69% less power.

Another attractive feature about active termination, especially in low-voltage applications, is the effective increase in output-voltage swing for a given supply voltage.

8 Conclusion

In high-speed systems, proper line termination requires considering the termination resistors and adjusting the gain-setting resistors to maintain symmetrical feedback.

Integrated, fully differential amplifiers are well suited for driving differential ADC inputs. They provide an easy means for anti-alias filtering and for setting the common-mode voltage.

Integrated, fully differential amplifiers are also well suited for driving differential transmission lines, and active termination provides for increased efficiency.

9 Related Web Sites

www-s.ti.com/sc/techlit/slyt018

amplifier.ti.com