ANALOG DEVICES

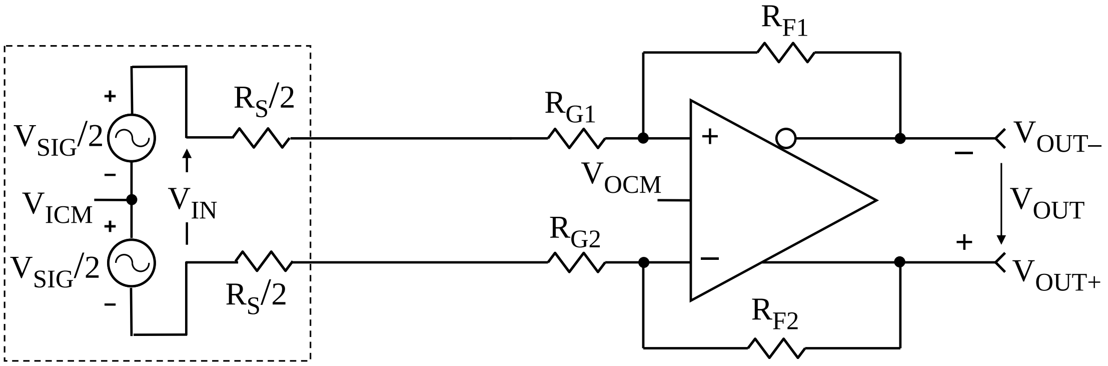
MT-076
TUTORIAL

Differential Driver Analysis

Differential drivers can be driven by either single-ended or differential signals. This tutorial analyzes both conditions using either an unterminated or a terminated source.

CASE 1: DIFFERENTIAL INPUT, UNTERMINATED SOURCE

Figure 1 shows a differential driver driven from a balanced unterminated source. This would typically be the condition for a low impedance source where the connection distance between the source and the driver is minimal.



$$R_{G1} = R_{G2}$$

$$R_{F1} = R_{F2}$$

$$G = \frac{V_{OUT}}{V_{IN}} = \frac{V_{OUT+} - V_{OUT-}}{V_{SIG}} = \frac{R_{F1}}{R_{G1} + R_S/2}$$

Figure 1: Differential Input, Unterminated Source

The design inputs are the source impedance R_S, the gain setting resistor R_{G1}, and the desired gain G. Note that the gain is measured with respect to the signal voltage source, V_{SIG}.

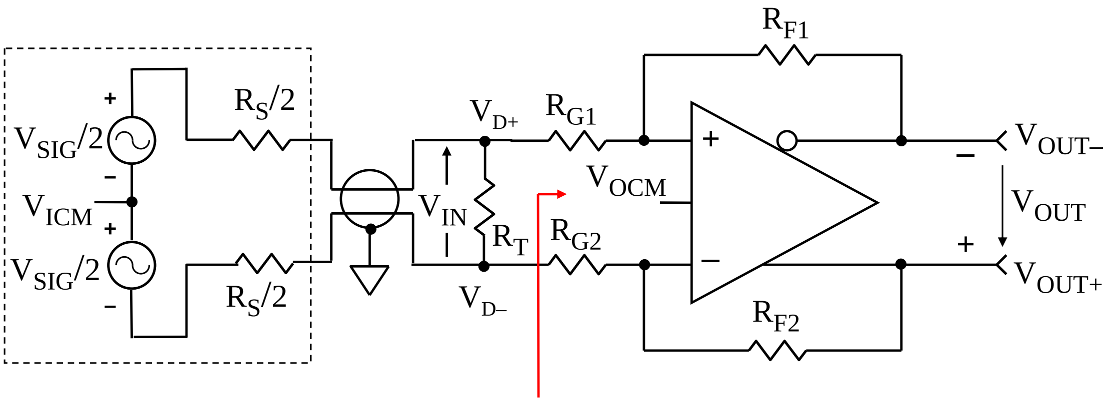
The total value of the gain setting resistor with respect to the signal source, V_{SIG}, is $R_{G1} + R_S/2$. Also, $R_{G2} = R_{G1}$.

The required value of the feedback resistors, $R_{F1} = R_{F2}$, is then calculated using:

$$R_{F1} = R_{F2} = G\left(R_{G1} + \frac{R_S}{2}\right) \qquad \text{Eq. 1}$$

CASE 2: DIFFERENTIAL INPUT, TERMINATED SOURCE

There are many cases where the differential driving source drives a twisted pair cable which must be terminated in its characteristic impedance to maintain high bandwidth and minimize reflections as shown in Figure 2.



$$R_{IN} = R_{G1} + R_{G2} = 2R_{G1}$$

$$R_{G1} = R_{G2}$$

$$R_{F1} = R_{F2}$$

$$G = \frac{V_{OUT}}{V_{IN}} = \frac{V_{OUT+} - V_{OUT-}}{V_{D+} - V_{D-}} = \frac{R_{F1}}{R_{G1}}$$

Figure 2: Differential Input, Terminated Source

The design inputs are the source impedance R_S, the gain setting resistor R_{G1}, and the desired gain G. Note that for the terminated case, the gain is measured with respect to the differential voltage at the termination, $V_{IN} = V_{D+} - V_{D-}$.

The input impedance, R_{IN}, is equal to $2R_{G1}$ for a balanced differential drive. The termination resistor, R_T, is selected so that $R_T||R_{IN} = R_S$, or

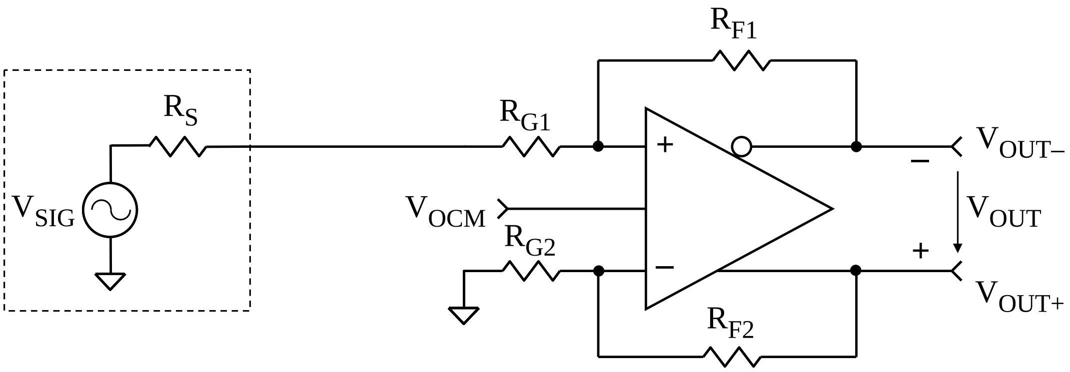
$$R_T = \frac{1}{\frac{1}{R_S} - \frac{1}{2R_{G1}}} \qquad \text{Eq. 2}$$

The required value of the feedback resistors, $R_{F1} = R_{F2}$, is then calculated using:

$$R_{F1} = R_{F2} = G \cdot R_{G1} \qquad \text{Eq. 3}$$

CASE 3: SINGLE-ENDED INPUT, UNTERMINATED SOURCE

There are many applications where a differential amplifier provides an effective means of converting a single-ended signal into a differential one. Figure 3 shows the case of an unterminated single-ended driver.



$$R_{G2} = R_{G1} + R_S$$

$$R_{F1} = R_{F2}$$

$$G = \frac{V_{OUT}}{V_{SIG}} = \frac{V_{OUT+} - V_{OUT-}}{V_{SIG}} = \frac{R_{F1}}{R_{G1} + R_S}$$

Figure 3: Single-Ended Input, Unterminated Source

The design inputs are the source impedance R_S, the gain setting resistor R_{G1}, and the desired gain G. Note that the gain is measured with respect to the signal voltage source, V_{SIG}.

In order to prevent V_{OCM} from producing an unwanted offset voltage at the differential output, the net impedances seen by both inputs of the differential amplifier must be equal. Therefore,

$$R_{G2} = R_{G1} + R_S \qquad \text{Eq. 4}$$

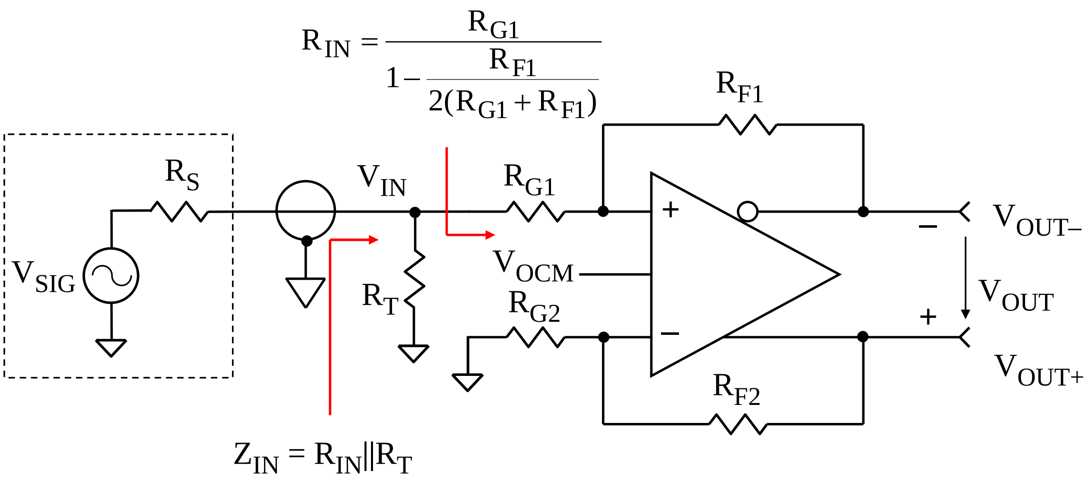
The value of the feedback resistors is then calculated using:

$$R_{F1} = R_{F2} = G(R_{G1} + R_S) \qquad \text{Eq. 5}$$

CASE 4: SINGLE-ENDED INPUT, TERMINATED SOURCE

Figure 4 shows a very common application where a single-ended source drives a coaxial cable which must be properly terminated to minimize reflections and maintain high bandwidth.

The design inputs are the source impedance R_S, the gain setting resistor R_{G1}, and the desired gain G. Note that the gain is measured with respect to the voltage at the termination, V_{IN}.



$$R_{G2} = R_{G1} + R_S||R_T$$
$$R_{F1} = R_{F2}$$

$$G = \frac{V_{OUT}}{V_{IN}} = \frac{V_{OUT+} - V_{OUT-}}{V_{IN}}$$

Figure 4: Single-Ended Input, Terminated Source

Knowing the desired gain, G, the gain-setting resistor R_{G1}, and the source resistance, R_S, calculate the initial value of the feedback resistor, R_{F1A}. The final value of this resistor will be slightly higher due to the increase in R_{G2} required to match input impedances. This will be included in later equations. The calculations proceed as follows:

$$R_{F1A} = G \cdot R_{G1} \qquad \text{Eq. 6}$$

$$R_{IN} = \frac{R_{G1}}{1 - \frac{R_{F1A}}{2(R_{G1} + R_{F1A})}} \qquad \text{Eq. 7}$$

$$R_T = \frac{1}{\frac{1}{R_S} - \frac{1}{R_{IN}}} \qquad \text{Eq. 8}$$

$$R_{TS} = \frac{R_S R_T}{R_S + R_T} \qquad \text{Eq. 9}$$

$$R_{G2} = R_{G1} + R_{TS} \qquad \text{Eq. 10}$$

The input voltage V_{IN} can be related to the source voltage V_{SIG} by:

$$V_{IN} = V_{SIG}\left[\frac{R_T \parallel R_{IN}}{(R_T \parallel R_{IN}) + R_S}\right] \qquad \text{Eq. 11}$$

$$V_{SIG} = V_{IN}\left[\frac{(R_T \parallel R_{IN}) + R_S}{R_T \parallel R_{IN}}\right] \qquad \text{Eq. 12}$$

In order to calculate the final value of the feedback resistors, the Thevenin equivalent circuit shown in Figure 5 is used.

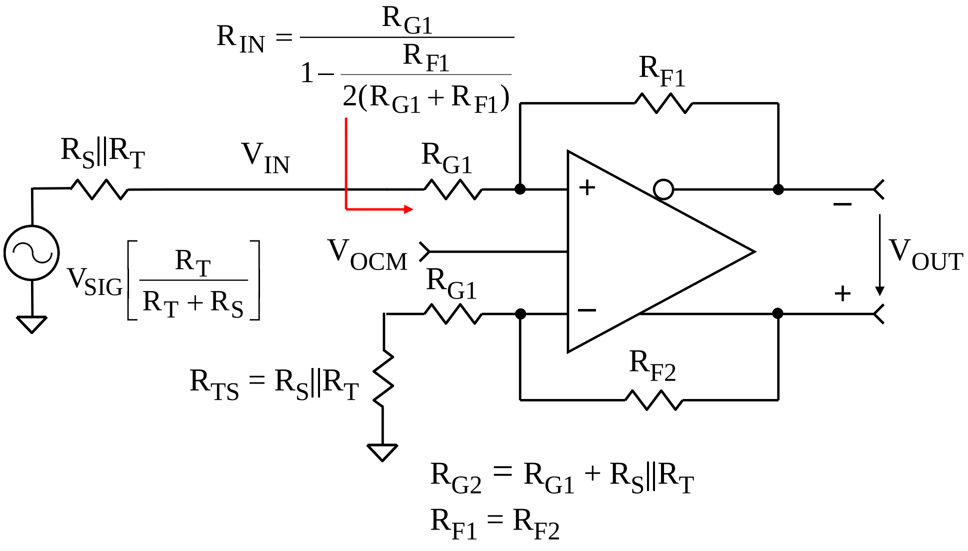


Figure 5: Thevenin Equivalent Input Circuit

The output voltage can be expressed as a function of the source voltage as follows:

$$V_{OUT} = V_{SIG}\left[\frac{R_T}{R_T + R_S}\right]\left[\frac{R_{F2}}{R_{G2}}\right] \quad \text{Eq. 13}$$

Substituting Eq. 12 for V_{SIG} into Eq. 13:

$$V_{OUT} = V_{IN}\left[\frac{(R_T \parallel R_{IN}) + R_S}{R_T \parallel R_{IN}}\right]\left[\frac{R_T}{R_T + R_S}\right]\left[\frac{R_{F2}}{R_{G2}}\right] \quad \text{Eq. 14}$$

$$G = \frac{V_{OUT}}{V_{IN}} = \left[\frac{(R_T \parallel R_{IN}) + R_S}{R_T \parallel R_{IN}}\right]\left[\frac{R_T}{R_T + R_S}\right]\left[\frac{R_{F2}}{R_{G2}}\right] \quad \text{Eq. 15}$$

In the case of a proper termination, $R_S = R_T \| R_{IN}$, and Eq. 15 reduces to:

$$G = \left[\frac{2R_T}{R_T + R_S}\right]\left[\frac{R_{F2}}{R_{G2}}\right] \quad \text{Eq. 16}$$

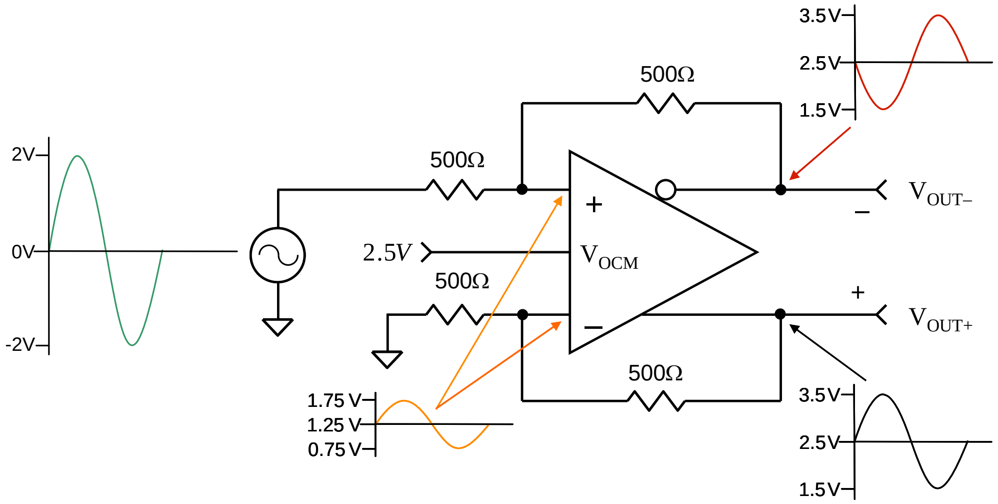
Solving Eq. 16 for $R_{F2} = R_{F1}$:

$$R_{F2} = R_{F1} = G\left[\frac{R_{G2}(R_S + R_T)}{2R_T}\right] \quad \text{Eq. 17}$$

COMMON-MODE INPUT AND OUTPUT CONSIDERATIONS

Care must be taken in applying differential amplifiers to make sure the input and output common-mode voltage ranges are not exceeded. This is especially true in single-supply applications.

Figure 6 shows an application of a differential amplifier where a single-ended bipolar ground-referenced signal must be converted into a differential signal suitable for driving an ADC. In this example, the common-mode input voltage of the ADC is +2.5 V, and the differential input swing of the ADC is 4 V p-p. Many differential amplifiers can handle the output swing provided the power supply is at least +5 V.



- **Input CM Voltage is a Scaled Replica of the Input Signal**
- **Input CM Voltage Partially Bootstraps Rg, Raising Effective Input Resistance**
- **Single-Supply Application can Accept Bipolar Input**
- **Must Ensure That Input Common-Mode Voltage Stays Within Specified Limits**

Figure 6: Input/Output Common-Mode Requirements for Single-Ended to Differential Converter with Bipolar Input Signal

The corresponding input signal swing at the (+) and (–) amplifier terminals is also shown in Figure 6. Note that it is a scaled replica of the input signal. The specifications on the differential amplifier must allow for an input common-mode voltage between +0.75 V and +1.75 V under these conditions. This is also possible with many differential amplifiers.

Figure 7 shows an application where a single-ended unipolar signal is converted with a differential amplifier.

In this case, the common-mode output voltage is set for +2 V. The input signal swings from 0 V to +4 V. The corresponding signal swing on the amplifier input terminals is from +1.5 V to +2.5 V. The amplifier outputs must swing from +1 V to +3 V. The differential amplifier selected must be able to handle these requirements when operating on the desired supply voltage(s).

The ADIsimDiffAmp interactive design tool performs these input/output signal calculations for the various Analog Device's differential amplifiers and greatly simplifies the selection process. Error flags are generated if the signals fall outside the allowable ranges on either the input or output.

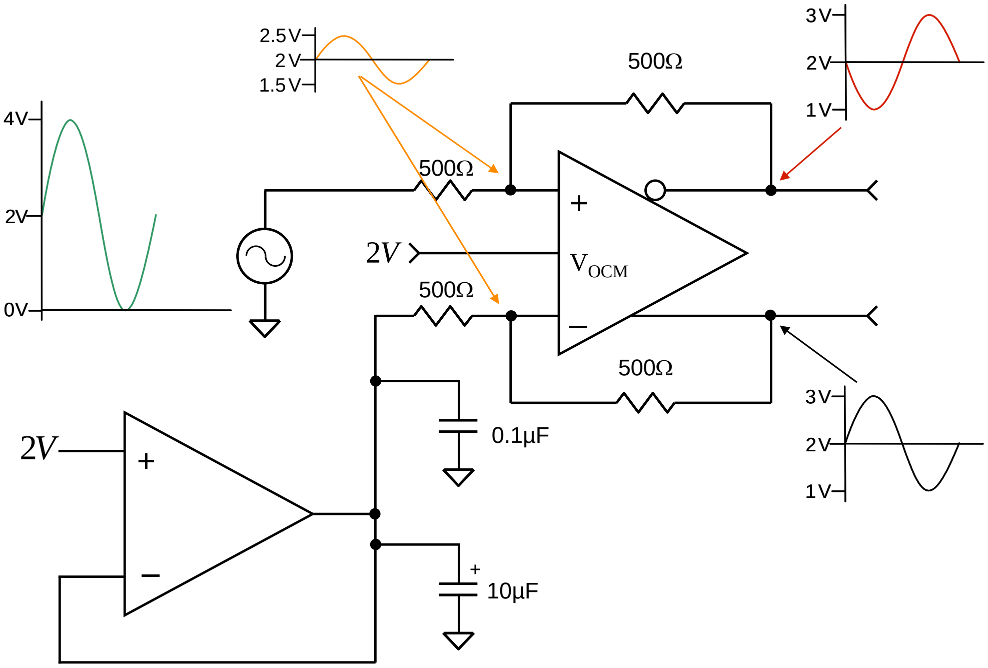


Figure 7: Input/Output Common-Mode Requirements for Single-Ended to Differential Converter with Unipolar Input Signal

AC-COUPLED DRIVER APPLICATIONS

AC-coupled applications of differential drivers are straightforward. Figure 8 shows a typical single-ended to differential ac-coupled driver. Note that the impedances are balanced on each input in order to achieve the best distortion performance. The low frequency cutoff of the input circuit is equal to:

$$f_C = \frac{1}{2\pi R_{G1} C_C} \qquad \text{Eq. 18}$$

The value of C_C should be chosen so that this frequency is at least 10 times less than the minimum desired signal frequency.

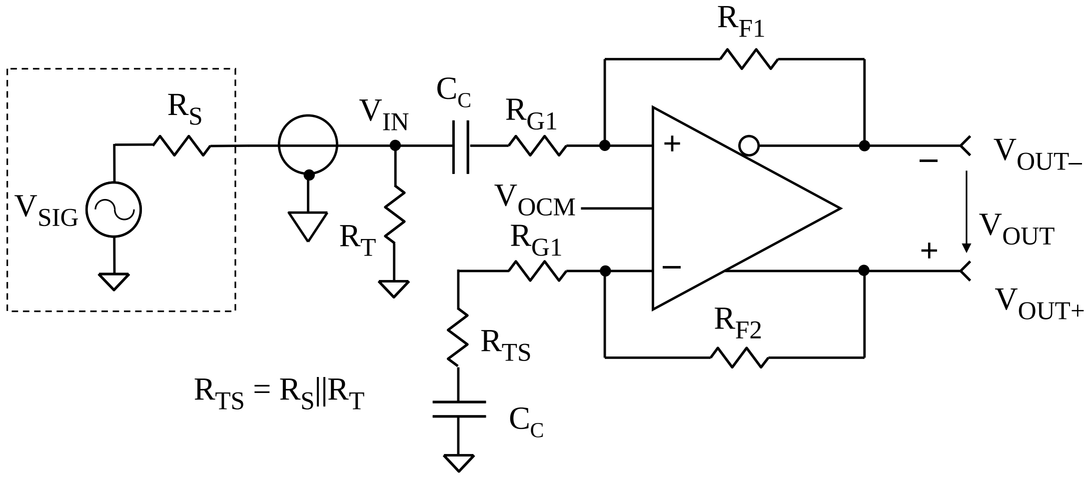


Figure 8: Typical AC-Coupled Driver Application

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5. ADIsimDiffAmp , an Analog Devices' on-line interactive design tool for differential amplifiers.