

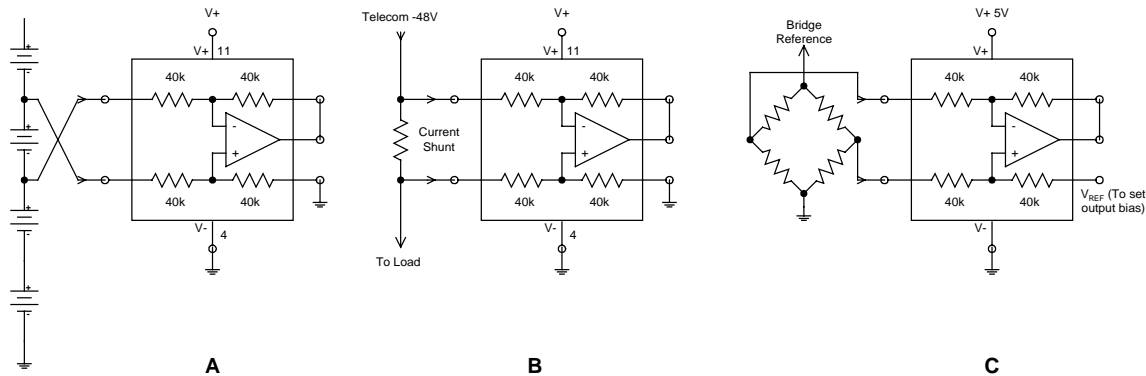
What's Different About Difference Amplifiers?

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The Difference Amplifier is uniquely valuable in its ability to differentially grab signals from lines or sensors subject to common-mode voltages. Furthermore, the flexible difference amplifier enables easy connection for non-inverting or inverting circuits, as well as output biasing. While the Difference Amplifier is a simple, easy-to-use solution, attention to a few design details will help get the most out of them.



**Fig. 1: A Difference Amplifier Makes It Simple To Create:
(A) Non-Inverting, (B) Inverting, Or (C) Level-Shifting Circuits
To "Pick-Off" Floating (Or Grounded) Signals**

The Difference Amplifier

A committed difference amplifier is designed to accept large differential voltages across its inputs (while rejecting common-mode voltages.) This is most often accomplished using an op amp in a committed circuit with four resistors (see Fig. 2.) While difference amplifiers are easy to use, they do have practical limitations that all designers should be aware of.

Difference amplifiers are one of the classic make-or-buy decision components because of the matching requirements of the resistors. Modern IC difference amplifiers achieve performance that is difficult and expensive to achieve in discrete designs. Discrete designs would require resistor networks with tolerances of 0.1% or better and tempcos of 50 ppm or better. Even then only active trimming can optimize performance because of real world parametric limits on op amps (finite open loop gain and common-mode rejection.)

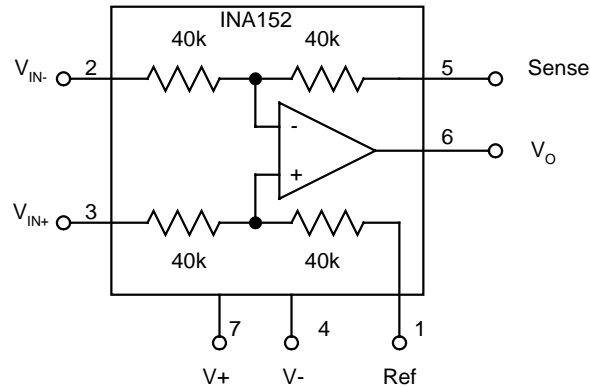


Fig. 2: The TI INA152 Typifies A Modern Difference Amplifier IC

In addition to the regular non-inverting (V_{IN+}) input, inverting (V_{IN-}) input, and output, the difference amplifier includes a Reference pin. This pin sets the quiescent (zero voltage between V_{IN+} and V_{IN-} at the input) output voltage. In typical split supply applications this pin is most often connected to ground setting the output voltage to ground.

Key Difference Amplifier Specifications

Common-mode rejection is a cornerstone specification for this amplifier and is directly dependent on resistor matching (which is why it is so difficult to build these with discrete parts.) In simple terms, a common-mode rejection ratio of 80 dB corresponds to 1 part in 10,000, or matching to better than 0.01%. This matching needs to be accomplished while meeting gain accuracy specifications on the order of $\pm 0.1\%$.

Beyond these specifications are the typical offset voltage and drift specifications similar to those of an op amp and various bandwidth specifications (bandwidth, slew rate, settling, etc.)

Common-Mode Voltage Range

One of the most powerful features of Difference Amplifiers is their ability to handle common-mode voltages beyond their rails. This property is a result of the natural voltage divider action of the resistor network around the Difference Amplifier.

The common-mode voltage range is directly proportional to power supply voltage. The internal network attenuates voltages applied at the difference amplifier inputs, which ultimately must remain within the supply rails of the internal op amp by specific amounts (which vary from model to model of difference amplifier.)

Using the INA152 (Fig. 2, again) as an example, the data sheet specifies a common-mode voltage range from $2(V_-)$ to $2(V_+) - 2$ (see Fig. 3a.) When operating on ± 15 V supplies

this corresponds to the range from -30V to 28V . The relationship to power supply voltage is especially important for the negative limit, when operating from a single supply (see Fig. 3b.) where the negative supply is 0 (zero) V and 2(0) is simply 0 V, assuming the Ref. pin is grounded.

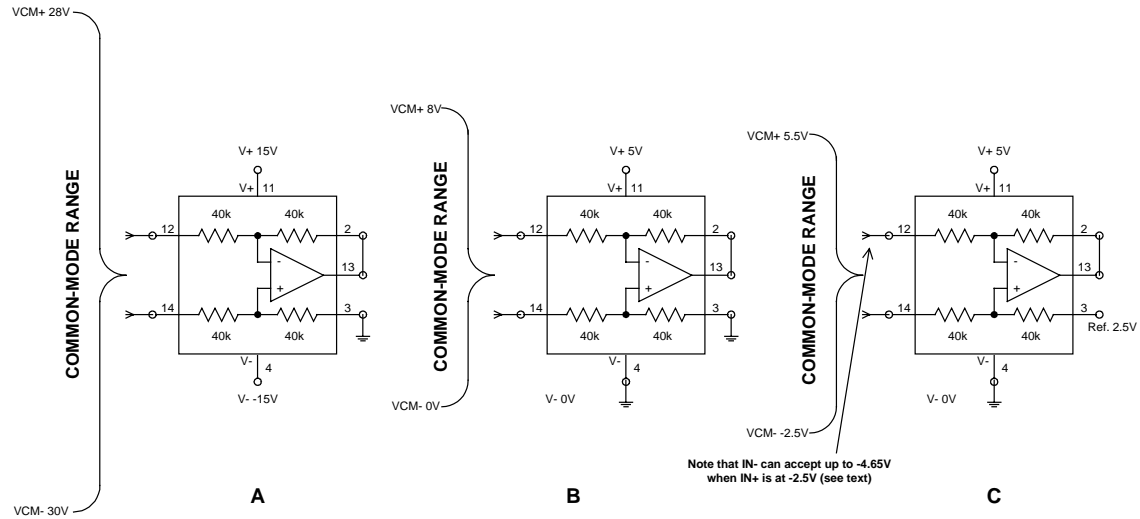


Fig. 3: The Relationship Between Common-Mode Voltage Range, Supply Voltage, And The Reference Pin (Especially Useful In That It Enables Negative Common-Mode Voltages On Single Supplies When A Bias Is Applied: c)

In single-supply applications the difference amplifier common-mode voltage range is shifted when a voltage is applied to the reference pin such that the amplifier can now accept positive as well as negative common-mode voltages. If the reference pin is connected to half-supply (2.5 Volts) as in Fig. 3c, the common-mode range is shifted to -2.5 to 5.5 V. With a biased reference pin the common-mode limits are referred to the reference pin rather than ground.

This straightforward portrayal of common-mode limits with a biased reference does not readily show an even more powerful attribute of this method. Assume the non-inverting input to be at the negative common-mode limit of Fig. 3c of -2.5 V. You can still apply even more negative potential to the inverting input of the amplifier while remaining within common-mode limits, a trait useful for negative-supply current sensing. Because the internal op amp inputs are at zero volts under negative common-mode limit conditions, the ultimate negative going limit at the non-inverting input is the inverse of the maximum available output swing (4.65 V in the case of the INA152 on a 5-V supply.) Fig.4 shows just such an example, able to accept up to -4.65 V at the non-inverting input.

Calculating Common-Mode Limits

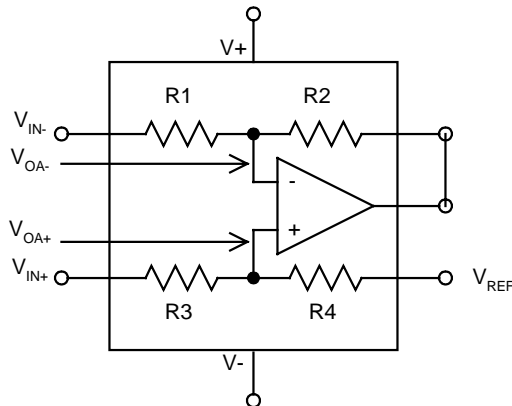


Fig. 4: Resistor Designations/Node Labels For Calculating Common-Mode Limits

- A. Use this procedure to determine the limits of a given amplifier (use Fig. 4 as a reference) and a given circuit:
1. First determine the acceptable common-mode voltage range at the inputs of the op amp internal to the difference amplifier
 2. Use the common-mode voltage range specification from the difference amplifier data sheet (such as the INA152 specification of $2(V_-)$ to $2(V_+)-2$)
 3. Assume that the amplifier output and V_{REF} is zero
 4. Assume an input equal to the maximum common-mode voltage
 5. Calculate the voltage at the amplifier input pins separately for both the negative and positive values. For these calculations, V_{OA+} and V_{OA-} are considered together (as if they are equal at all times):

$$\text{Eq. 1: } V_{OA} = \left(\frac{V_{CM}}{R3 + R4} \right) R4 \text{ (remember to calculate separate values for both negative and positive excursions)}$$

For the general case of unity gain difference amplifiers this may be simplified to:

$$V_{OA} = \frac{V_{CM}}{2}$$

The above calculations will provide two values for the actual input nodes of the internal amplifier. These values will always be within the power supply rails of the internal op amp by some measure, although many difference amplifiers have internal op amps that handle common-mode voltage all the way down to their negative rail.

B. Use the following equations to determine common-mode limits based on the op amps acceptable values and voltage reference:

$$\text{Eq. 2: } V_{CM} = V_{REF} - \left(\frac{V_{REF} - V_{OA}}{R4} \times (R3 + R4) \right) \text{ (again, calculate separately for positive and negative excursions using corresponding } V_{OA} \text{ values from Eq. 1)}$$

As amplifier output voltage (so far assumed to be equal to V_{REF}) varies, and the voltage at V_{IN-} varies, the voltage at V_{OA} will remain fixed until the output voltage swing limits are reached. Use Eq. 2 to evaluate the effects of output voltage swing by substituting the output swing limits (again calculate separately for negative and positive excursions) by substituting the amplifier output voltage for V_{REF} in Eq. 2.

To provide a definition-by-example, assume an INA152 operating on ± 10 -V supplies:

1. From the INA152 specifications, the acceptable common-mode input can range from $2(V-)$ to $2(V+)-2$. With ± 10 -V supplies this corresponds to a range of -20 to $+18$ V. Using Eq. 1 reveals that with ± 10 -V supplies the internal op amp of the INA152 has a common-mode range from -10 to 9 V.
2. This circuit will use a 2.5 -V reference. Re-evaluating for the effect of V_{REF} using Eq. 2 results in a common-mode range (assuming an amplifier output voltage equal to V_{REF}) from -22.5 to 15.5 V. Evaluating for amplifier output swing shows that when the amplifier output has swung to -9.7 V, the common-mode range is -10 V to $+27$ V, and at full positive output swing of 9.65 V the common-mode range is -29.65 to 8.35 V.

Don't forget that the most common use of the reference pin is to bias the quiescent voltage of the amplifier output. In single-supply circuits this will often be at one-half of supply voltage, especially if the amplifier is subject to bipolar inputs. When driving ADCs it is often useful to connect the difference amplifier reference pin to a voltage half that of the ADC reference, so that the amplifier output is biased to the mid-point of the ADC's dynamic range.

Input Impedance Considerations

Because the difference amplifier is constructed with an op amp and feedback resistors its input impedance is low in comparison to that of a non-inverting op amp. The INA152, used as an example in the circuits shown, is specified for an 80 k Ω input impedance (differential or common-mode.) {TI offers difference amplifiers with input impedance that spans the range of from 50 k Ω to 1 M Ω .}

External resistances that appear in series with the input terminals of the Difference Amplifier can result in an imbalance will impair common-mode rejection, depending on the impedance of the signal source. The circuit shown in Fig. 1b is an example of where the potential mismatch can be ignored since the value of current shunt resistors is often low enough to be inconsequential. As a rule of thumb, the degradation of common-mode rejection is in the same proportion as the external resistor to the internal difference

amplifier resistors. For example, the INA152 has 40 k Ω internal resistors. Common-mode rejection of 80 dB corresponds to approximately one part in ten thousand, indicating that 80 dB would be the highest achievable common-mode rejection if there was 4 Ω in series with the INA152 inputs. This is approximately the impedance level where adding an external resistor to match source impedances should be considered.

Add any impedance matching resistor to whichever input is on the side of the measurement (shunt resistor or transducer) that is connected back to a low-impedance source, in the case of Fig. 5 a power supply. The current shunt resistor appears in series with the –Input of the Difference Amplifier, so the matching resistor should be installed in series with the +Input.

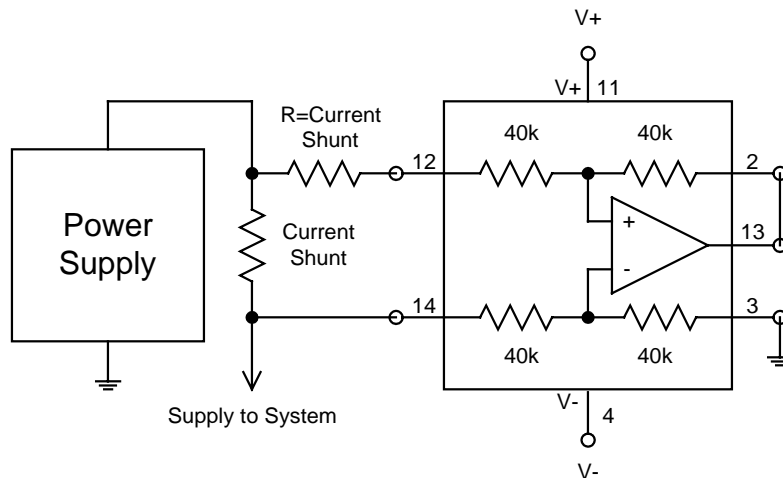


Fig. 5: For Best Common-Mode Rejection, Impedance Appearing At The Difference Amplifier Inputs Should Be Matched Whenever Current Shunt Resistors Are Several Ohms Or Higher. When Deciding Which Input Should Get The Series Matching Resistor, Pick The Input Closest To The Supply Or Low Impedance Source

High Common-Mode Voltage Difference Amplifiers

High common-mode voltage difference amplifiers are difference amplifiers with additional attenuating resistors at the op amps (see Fig. 6) enabling them to handle very large common-mode voltages, up to ± 200 V. Just like their lower-voltage brethren, acceptable common-mode voltage range is a function of the supply voltage the difference amplifier is operated at, as well as any voltage connected to its reference pin.

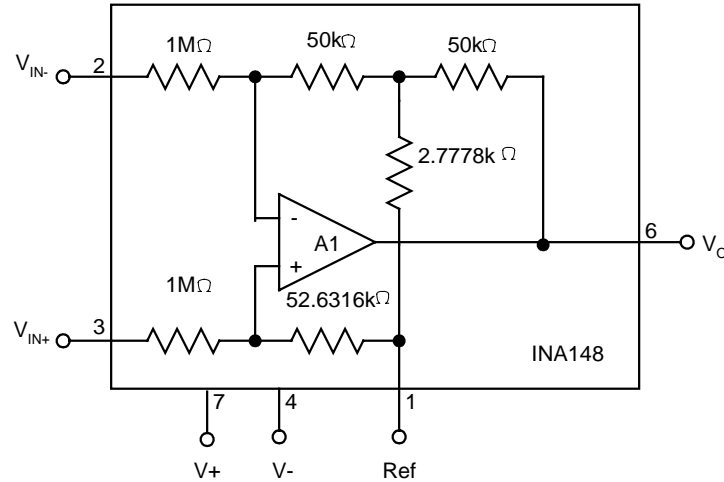


Fig. 6: High Common-Mode Voltage Difference Amplifiers Include Additional Resistors To Attenuate Large Common-Mode Inputs. This Allows Amplifiers Like The INA148, Shown Here, To Accept Up To ± 200 V Common-Mode (With ± 15 V Rails)

One tradeoff of the architecture of the high common-mode voltage difference amplifier is the high noise gain, on the order of 20 or more, of the internal op amp. This results in offset, drift, and noise 20 times worse than the op amp contained within.

Determine the common-mode range for the high common-mode voltage amplifiers using the same methods shown for low-voltage amplifiers, but using only the resistor values on the non-inverting input. Like the low-voltage amplifiers, tying the reference pin to a voltage offsets the common-mode range of the amplifier.

APPENDIX:

Understanding V_{CM} (Common-Mode Voltage) And V_{DIFF} (Differential Voltage)

Difference Amplifiers with their low gains, often around unity, will frequently be used with large differential inputs, (by contrast, high-gain instrumentation amplifiers will generally have small differential inputs) making defining common-mode and differential voltage especially important. Analyze common-mode and differential-mode voltages by using a system definition of the components of the input signal. These components, a differential component and a common-mode component, are shown in circuit Fig. 7a. To satisfy the definition of “common-mode” each V_{CM} must be the same value and polarity for both inputs. This simplifies to the difference amplifier circuit Fig. 7b. Fig. 8 depicts the unique case where one input is grounded.

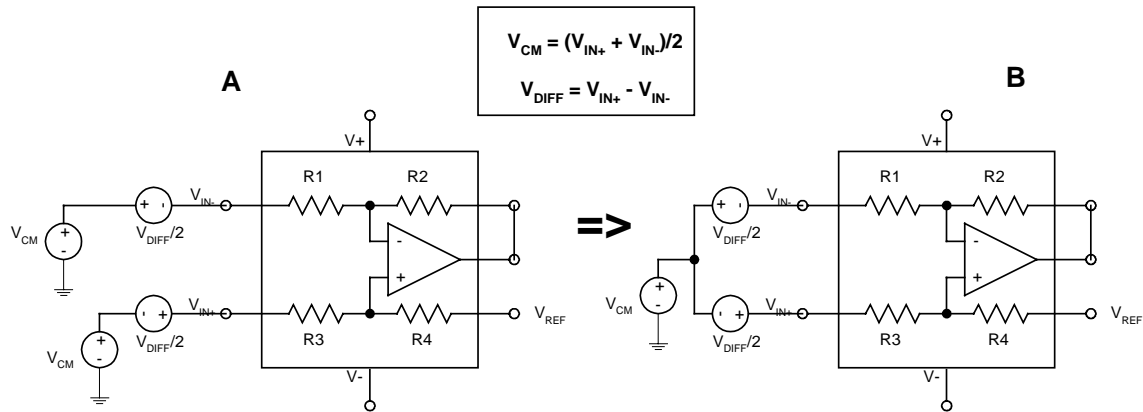


Fig. 7: System Definitions Of V_{CM} and V_{DIFF}

The maximum common-mode voltage rating of an amplifier cannot be exceeded by either the actual common-mode voltage, or common-mode voltage in combination with differential voltage. Using the example of Fig. 7 assume an amplifier rated at a maximum common-mode voltage of ± 10 V; assume a V_{CM} of 8 V, and a V_{DIFF} of 5 V ($V_{DIFF}/2$ of 2.5 V.) This results in 10.5 V at one of the amplifier inputs, exceeding its maximum common-mode voltage rating.

Expressed another way, if the data sheet indicates a maximum common-mode voltage of ± 10 V, the input pins cannot exceed ± 10 V under any combination of common-mode and differential voltages.

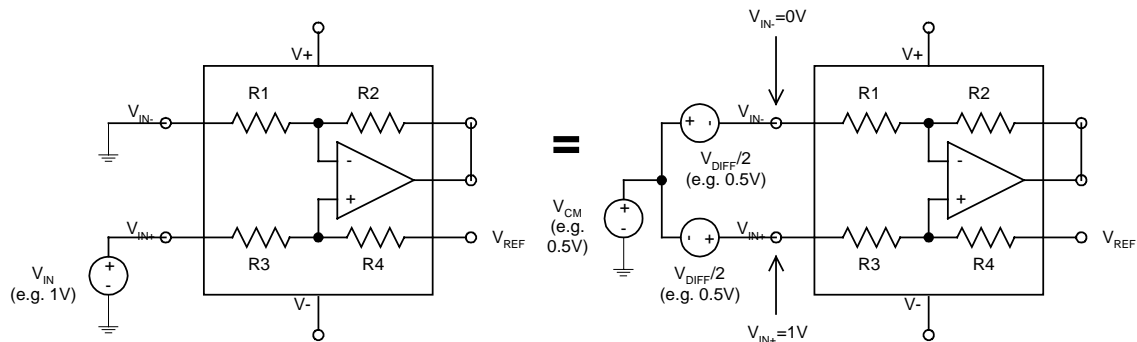


Fig. 2: V_{CM} & V_{DIFF} Analysis When One Input is Ground

Understanding common-mode voltage this way is more exact when calculating errors due to common-mode inputs. V_{CM} as shown here will be attenuated in proportion to the amplifiers common-mode rejection yielding the common-mode error.

