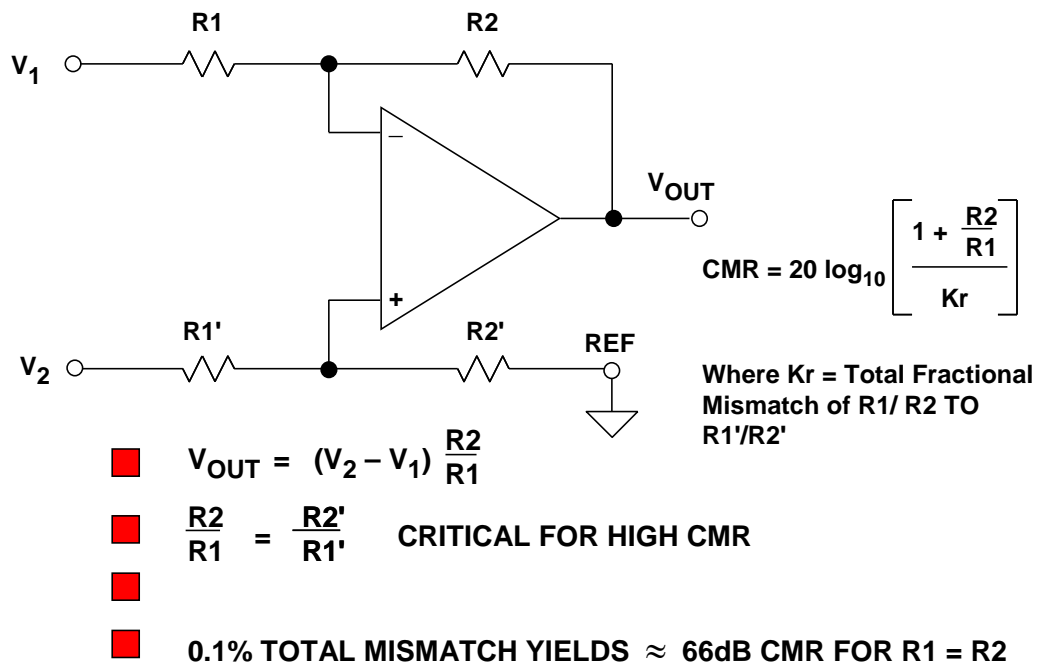


## Difference and Current Sense Amplifiers

### BASIC SUBTRACTOR OR DIFFERENCE AMPLIFIER

A simple subtractor or difference amplifier can be constructed with four resistors and an op amp, as shown in Figure 1 below. It should be noted that this is *not* an in-amp (see [Tutorial MT-061](#)), but it is often used in applications where a simple differential to single-ended conversion is required, such as current sensing.



**Figure 1: Op Amp Subtractor or Difference Amplifier**

There are several fundamental problems with this simple circuit. First, the input impedance seen by  $V_1$  and  $V_2$  isn't balanced. The input impedance seen by  $V_1$  is  $R_1$ , but the input impedance seen by  $V_2$  is  $R_1' + R_2'$ . The configuration can also be quite problematic in terms of CMR, since even a small source impedance imbalance will degrade the workable CMR. This problem can be solved with well-matched open-loop buffers in series with each input (for example, using a precision dual op amp). But, this adds complexity to a simple circuit, and may introduce offset drift and non-linearity.

The second problem with this circuit is that the *CMR is primarily determined by the resistor ratio matching, not the op amp*. The resistor ratios  $R_1/R_2$  and  $R_1'/R_2'$  must match extremely well to reject common mode noise—at least as well as a typical op amp CMR of  $\geq 100$  dB. Note also that the *absolute* resistor values are relatively unimportant.

Picking four 1% resistors from a single batch may yield a net ratio matching of 0.1%, which will achieve a CMR of 66 dB (assuming  $R1 = R2$ ). But if one resistor differs from the rest by 1%, the CMR will drop to only 46 dB. Clearly, very limited performance is possible using ordinary discrete resistors in this circuit (without resorting to hand matching). This is because the best standard off-the-shelf RNC/RNR style resistor tolerances are on the order of 0.1%.

In general, the worst case CMR for a circuit of this type is given by the following equation:

$$\text{CMR(dB)} = 20 \log \left[ \frac{1 + R2/R1}{4K_r} \right], \quad \text{Eq. 1}$$

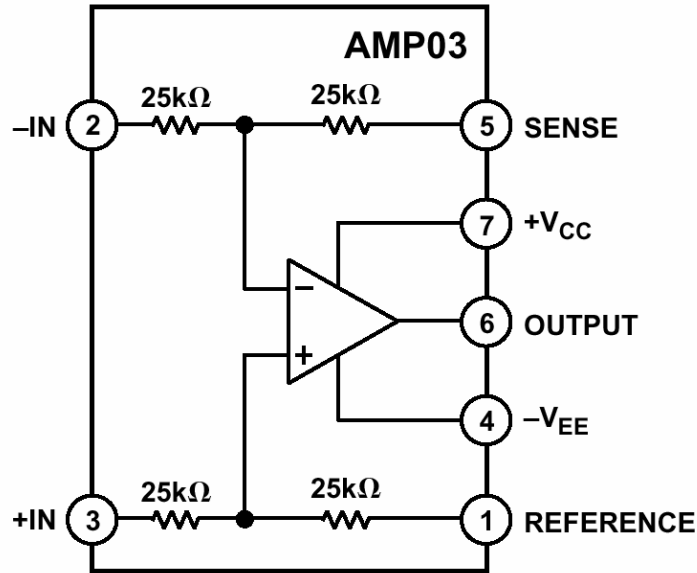
where  $K_r$  is the *individual* resistor tolerance in fractional form, for the case where 4 discrete resistors are used. This equation shows that the worst case CMR for a tolerance build-up for 4 unselected same-nominal-value 1% resistors to be no better than 34 dB.

A single resistor network with a net matching tolerance of  $K_r$  would probably be used for this circuit, in which case the expression would be as noted in the figure, or:

$$\text{CMR(dB)} = 20 \log \left[ \frac{1 + R2/R1}{K_r} \right] \quad \text{Eq. 2}$$

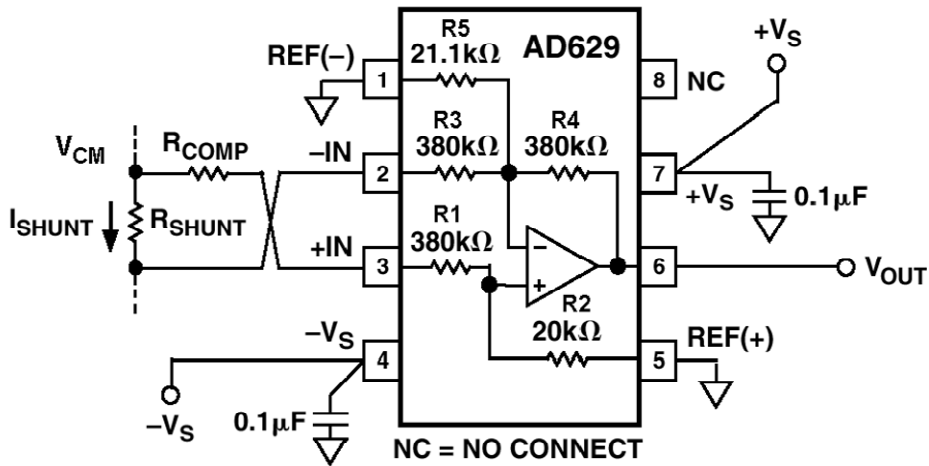
A net matching tolerance of 0.1% in the resistor ratios therefore yields a worst case dc CMR of 66 dB using Equation 2, and assuming  $R1 = R2$ . Note that either case assumes a significantly higher amplifier CMR (i.e., >100 dB). Clearly for high CMR, such circuits need four single-substrate resistors, with very high absolute and TC matching. Such networks using thick/thin-film technology are available from companies such as Caddock and Vishay, in ratio matches of 0.01% or better.

In implementing the simple difference amplifier, rather than incurring the higher costs and PCB real estate limitations of a precision op amp plus a separate resistor network, it is usually better to seek out a completely monolithic solution. The [AMP03](#) is just such a precision difference amplifier, which includes an on-chip laser trimmed precision thin film resistor network. It is shown in Figure 2 below. The typical CMR of the AMP03F is 100 dB, and the small-signal bandwidth is 3 MHz.



**Figure 2: AMP03 Precision Difference Amplifier**

Another interesting variation on the simple difference amplifier is found in the AD629 difference amplifier, optimized for high common-mode input voltages. A typical current-sensing application is shown in Figure 3 below. The [AD629](#) is a differential-to-single-ended amplifier with a gain of unity. It can handle a common-mode voltage of  $\pm 270$  V with supply voltages of  $\pm 15$  V, with a small signal bandwidth of 500 kHz.



$$V_{CM} = \pm 270V \text{ for } V_S = \pm 15V$$

**Figure 3: High Common-Mode Current Sensing Using The AD629 Difference Amplifier**

The high common-mode voltage range is obtained by attenuating the non-inverting input (pin 3) by a factor of 20 times, using the R1-R2 divider network. On the inverting input, resistor R5 is chosen such that  $R5 \parallel R3$  equals resistor R2. The noise gain of the circuit is equal to  $20 [1 + R4 / (R3 \parallel R5)]$ , thereby providing unity gain for differential input voltages. Laser wafer trimming of the R1-R5 thin film resistors yields a minimum CMR of 86 dB @ 500 Hz for the AD629B. Within an application, it is good practice to maintain balanced source impedances on both inputs, so dummy resistor  $R_{COMP}$  is chosen to equal to the value of the shunt sensing resistor  $R_{SHUNT}$ .

## APPLICATIONS OF CURRENT SENSING USING DIFFERENCE AMPLIFIERS

Difference amplifiers are often used in current sensing applications. Figure 4 shows a block diagram of the [AD8202](#) difference amplifier which is optimized for automotive applications.

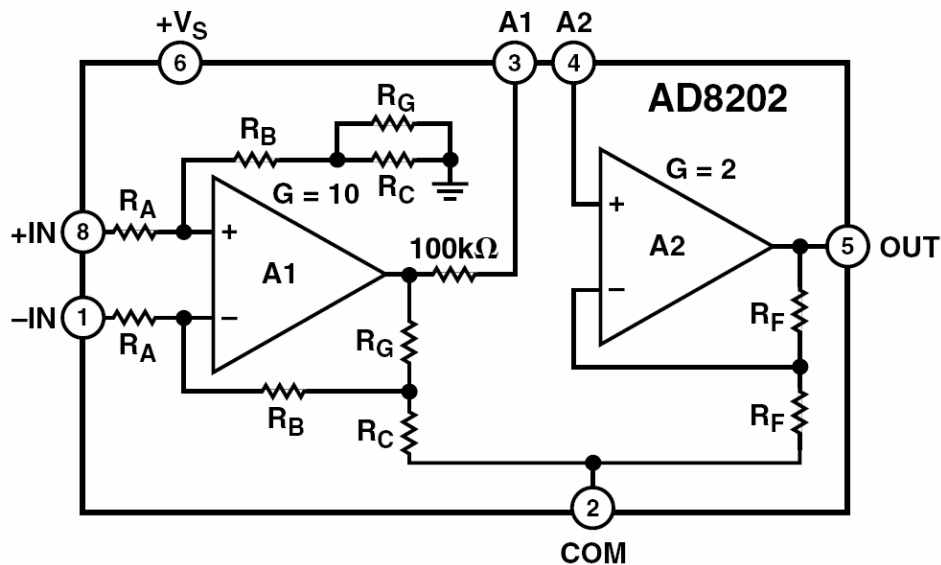
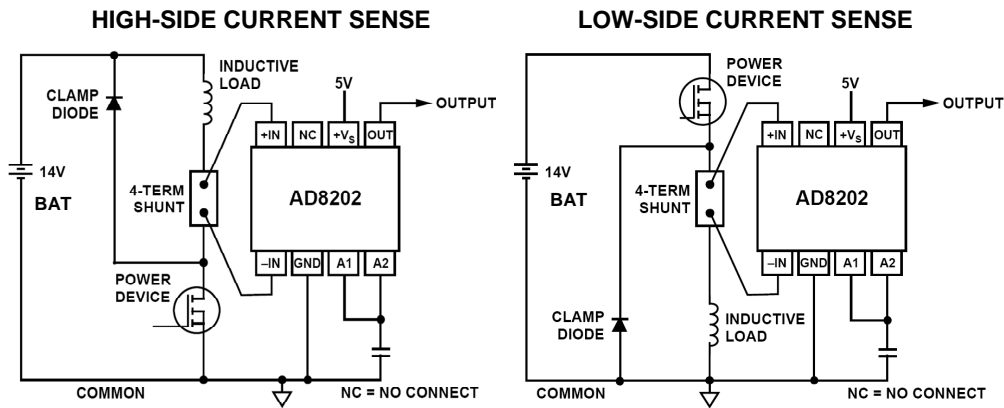


Figure 4: [AD8202](#) Current Sensing Difference Amplifier

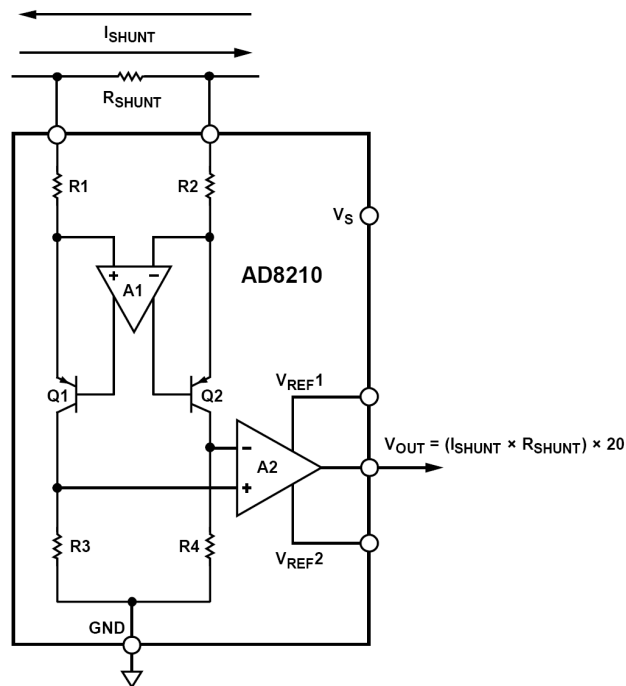
The A1 input amplifier is configured as a simple subtractor or difference amplifier with a gain of 10. The A2 amplifier provides an additional non-inverting gain of two. The use of thin film resistors allows an input common-mode voltage up to 28 V when the AD8202 operates on a single supply voltage of 3.5 V to 12 V. The thin film resistors also provide matching within 0.01% which yields an overall CMR of 80 dB.

Figure 5 shows how the AD8202 is configured for high-side and low-side operation in a battery current sense application. The clamp diodes protect the AD8202 input from large inductive spikes which can occur when the power device is suddenly turned off. A four-terminal (Kelvin sense) shunt resistor is used to sense the current.



**Figure 5: High and Low-Side Battery Current Sensing Using the AD8202 28V Difference Amplifier**

The difference amplifiers considered up to this point achieve their high common-mode input voltage by the use of thin film resistors to divide the input voltage down. The [AD8210](#), [AD8211](#), [AD8212](#), [AD8213](#) and [AD8215](#) difference amplifiers, on the other hand, achieve their high common-mode input voltage of 65 V by virtue of the high breakdown voltages of their input transistors. This provides the advantage of higher bandwidth, and higher input impedance. This architecture also features lower noise because the input signal is not first attenuated. In typical applications, the AD8210 amplifies a small differential input voltage generated by the load current flowing through a shunt resistor. The AD8210 rejects high common-mode voltages (up to 65 V) and provides a ground referenced buffered output that interfaces with an analog-to-digital converter (ADC). Figure 6 shows a simplified schematic of the AD8210.



**Figure 6: AD8210 High Voltage (65V) Bidirectional Current Shunt Monitor**

The AD8210 is comprised of two main blocks, a differential amplifier and an instrumentation amplifier. A load current flowing through the external shunt resistor produces a voltage at the input terminals of the AD8210. The input terminals are connected to the differential amplifier (A1) by R1 and R2. Amplifier A1 nulls the voltage appearing across its own input terminals by adjusting the current through R1 and R2 with Q1 and Q2. When the input signal to the AD8210 is 0 V, the currents in R1 and R2 are equal. When the differential signal is nonzero, the current increases through one of the resistors and decreases in the other. The current difference is proportional to the size and polarity of the input signal.

The differential currents through Q1 and Q2 are converted into a differential voltage by R3 and R4. A2 is configured as an instrumentation amplifier. The differential voltage is converted into a single-ended output voltage by A2. The gain is internally set with precision-trimmed, thin film resistors to 20 V/V.

The output reference voltage is easily adjusted by the  $V_{REF1}$  pin and the  $V_{REF2}$  pin. In a typical configuration,  $V_{REF1}$  is connected to  $V_{CC}$  while  $V_{REF2}$  is connected to GND. In this case, the output is centered at  $V_{CC}/2$  when the input signal is 0 V.

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