Instrumentation Amplifier (In-Amp) Basics

Probably the most popular among all of the specialty amplifiers is the *instrumentation amplifier* (hereafter called simply an *in-amp*). The in-amp is widely used in many industrial and measurement applications where dc precision and gain accuracy must be maintained within a noisy environment, and where large common-mode signals (usually at the ac power line frequency) are present.

OP AMP/IN-AMP FUNCTIONALITY DIFFERENCES

An in-amp is unlike an op amp in a number of very important ways. An op amp is a general-purpose gain block—user-configurable in myriad ways using external feedback components of R, C, and, (sometimes) L. The final configuration and circuit function using an op amp is truly whatever you make of it.

In contrast to this, an in-amp is a more constrained device in terms of functioning, and also the allowable range(s) of operating gain. And, in many ways, it is better suited to its task than would be an op amp—even though, ironically, an in-amp may actually be composed of a number of op amps within it! People also often confuse in-amps as to their function, calling them "op amps". But the converse is seldom (if ever) true. It should be understood that an in-amp is *not* just a special type op amp; the function of the two devices is actually fundamentally different.

Perhaps a good way to differentiate the two devices is to remember that an op amp can be programmed to do almost anything, by virtue of its feedback flexibility. In contrast to this, an in-amp *cannot* be programmed to do just anything. It can *only* be programmed for gain, and then over a specific range. An op amp is configured via a number of external components, while an in-amp is configured by either one resistor, or by pin-selectable taps for its working gain.

IN-AMP DEFINITIONS

An in-amp is a *precision* closed-loop gain block. It has a pair of differential input terminals, and a single-ended output that works with respect to a reference or common terminal, as shown in Figure 1 below. The input impedances are balanced and high in value, typically $\geq 10^9\ \Omega$. Again, unlike an op amp, an in-amp uses an *internal* feedback resistor network, plus one (usually) gain set resistance, R_G. Also unlike an op amp is the fact that the internal resistance network and R_G are *isolated* from the signal input terminals. In-amp gain can also be preset via an internal R_G by pin selection, (again isolated from the signal inputs). Typical in-amp gains range from 1 to 1,000.

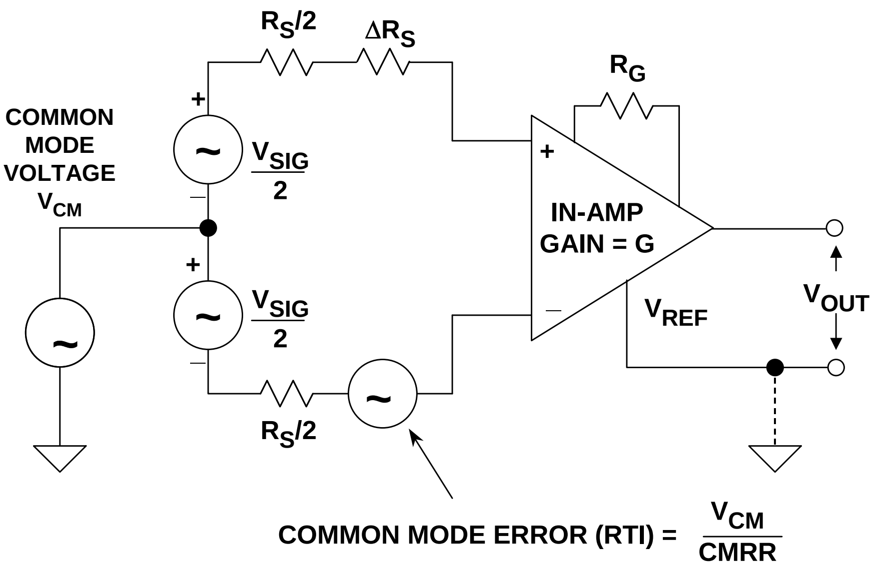


Figure 1: The Generic Instrumentation Amplifier (In-Amp)

The in-amp develops an output voltage which is referenced to a pin usually designated REFERENCE, or V_{REF}. In many applications, this pin is connected to circuit ground, but it can be connected to other voltages, as long as they lie within a rated compliance range. This feature is especially useful in single-supply applications, where the output voltage is usually referenced to mid-supply (i.e., +2.5 V in the case of a +5 V supply).

In order to be effective, an in-amp needs to be able to amplify microvolt-level signals, while simultaneously rejecting volts of *common mode* (CM) signal at its inputs. This requires that in-amps have very high *common mode rejection* (CMR). Typical values of in-amp CMR are from 70 to over 100 dB, with CMR usually improving at higher gains.

It is important to note that a CMR specification for dc inputs alone isn't sufficient in most practical applications. In industrial applications, the most common cause of external interference is 50/60 Hz ac power-related noise (including harmonics). In differential measurements, this type of interference tends to be induced equally onto both in-amp inputs, so the interference appears as a CM input signal. Therefore, specifying CMR over frequency is just as important as specifying its dc value. Note that imbalance in the two source impedances can degrade the CMR of some in-amps. Analog Devices fully specifies in-amp CMR at 50/60 Hz, with a source impedance imbalance of 1 kΩ.

SUBTRACTOR OR DIFFERENCE AMPLIFIERS

It is important to understand the difference between an in-amp and a *subtractor* or *difference* amplifier. A simple subtractor or difference amplifier can be constructed with four resistors and an op amp, as shown in Figure 2 below. It should be noted that this is *not* a true in-amp (based on the previously discussed criteria), but it is often used in applications where a simple differential to single-ended conversion is required. Because of its popularity, this circuit will be examined in more detail, in order to understand its fundamental limitations before discussing true in-amp architectures.

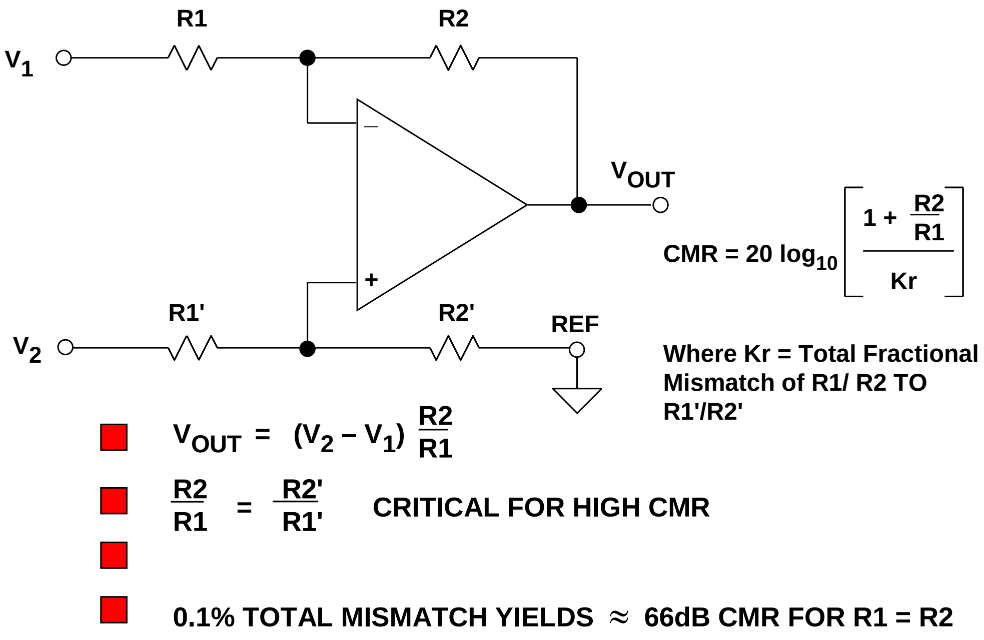


Figure 2: Op Amp Subtractor or Difference Amplifier

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 R1, but the input impedance seen by V_2 is R1' + R2'. 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 R1/R2 and R1'/R2' must match extremely well to reject common mode noise—at least as well as a typical op amp CMR of ≥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:

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

where Kr 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 Kr would probably be used for this circuit, in which case the expression would be as noted in the figure, or:

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

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 3 below. The typical CMR of the AMP03F is 100 dB, and the small-signal bandwidth is 3 MHz.

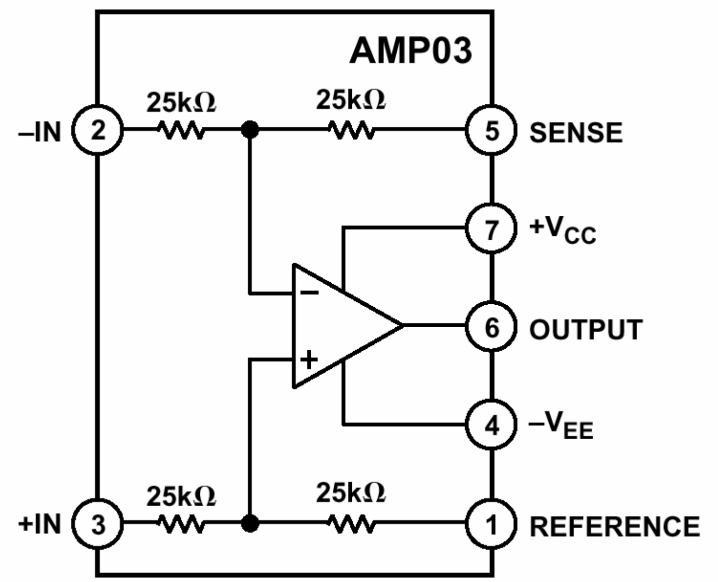
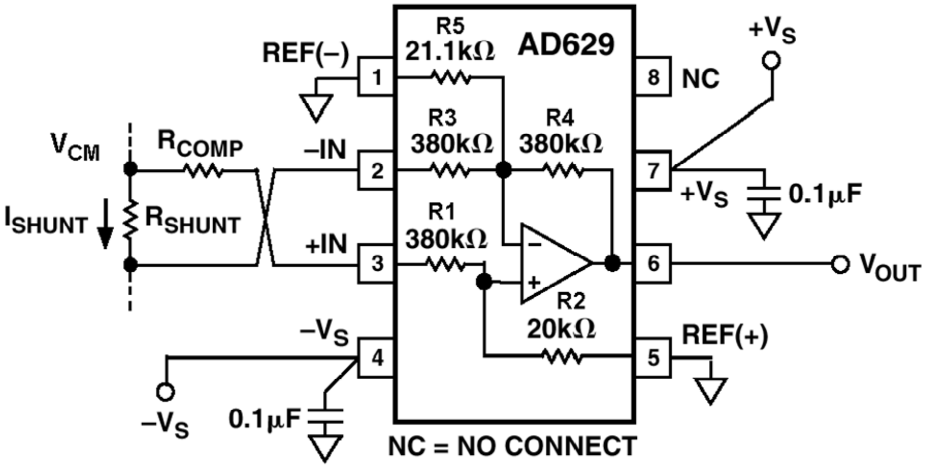


Figure 3: AMP03 Precision Difference Amplifier

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 4 below. The AD629 is a differential-to-single-ended amplifier with a gain of unity. It can handle a common-mode voltage of ±270 V with supply voltages of ±15 V, with a small signal bandwidth of 500 kHz.



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

Figure 4: 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||R3 equals resistor R2. The noise gain of the circuit is equal to 20 [1 + R4/(R3||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}.

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