Comparing discrete and integrated difference amplifiers

One of many useful circuits that you can create using an operational amplifier (op amp) and resistor network is a difference amplifier (DA). DAs allow you to measure the difference between two signals, which is useful for current and voltage sensing in systems such as solar panels, power banks and other DC/DC modules. Furthermore, many DAs can apply gain, add a reference voltage to the signal, and reduce common-mode noise from input signals.

There are two main types of DAs: discrete (with external resistors) and integrated (with monolithic or on-die resistors). In this article, we'll use measured data (offset voltage, common-mode rejection ratio [CMRR], gain error and gain error drift over temperature) to compare discrete and integrated DAs.

Gain error

As shown in **Figure 1**, a typical DA comprises an op amp and four resistors. The midpoint of the R1/R2 resistor ladder connects to the inverting terminal of the op amp, while the R3/R4 midpoint connects to the noninverting terminal.

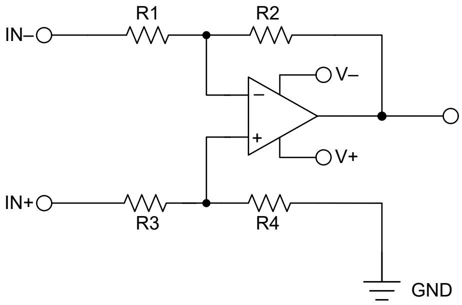


Figure 1. *A typical DA*

Equation 1 depicts the transfer function of a typical DA. Notice that the ratio of R2 and R1 (assuming that R1 = R3 and R2 = R4) determines the gain. You will need matched resistors if you are trying to achieve a low gain error. Resistors with a tolerance of ±1% can induce a gain error as high as 2%. While discrete resistors may exhibit large variations, the monolithic resistors found in integrated DAs are often trimmed to achieve a gain error of just 0.01%.

$$V_{OUT} = (V_{IN+} - V_{IN-}) \times \left(\frac{R2}{R1}\right) + V_{REF} \tag{1}$$

Gain error drift

Gain drift is another important parameter, especially in systems such as solar panels, motor drives and battery packs where temperature can fluctuate throughout the day or throughout operation. Because the thin-film resistors of TI's **INA600** DA are all within the same package and interdigitated with each other, all four resistors will equally observe any temperature fluctuation, making them drift together while maintaining the same gain ratio. A discrete implementation using external resistors may observe wide variances in the gain drift performance of your DA, since the stress from the temperature will appear as a gradient across the surface of the board, leading to changes in the applied gain to your input signal.

Offset voltage

When applying gain to an input signal, the amount of offset voltage can significantly influence the amount of error induced on the output signal. Therefore, we recommend selecting an op amp with an excellent offset voltage for any voltage or current sensing. When building a discrete DA, you have the flexibility to use whichever available op amp is at the core of your design, whereas the offset voltage of an integrated DA will be fixed and dependent on the internal op amp. With resistor trimming techniques such as the e-Trim™ operational amplifier technology, it is possible to lower the offset voltage in an integrated DA, however.

CMRR

The ability to reject common-mode signals in voltage- and current-sensing applications is a primary factor when considering a DA. Similar to gain error, the CMRR will depend on the matching of the components (such as resistors) used. While a typical op amp may have a CMRR as high as 100dB, introducing mismatched resistors could drop the CMRR as low as 60dB, making them nonideal for industrial systems in noisy environments. The CMRR of a typical integrated DA will generally be at least 90dB, but can be as high as 130dB.

Gain configurations enabling beyond-the-rail voltage monitoring

DAs are typically in a unity gain configuration (meaning that the gain = 1) but can vary from 0.5 up to 2. Changing the values of the resistor networks in a DA makes it possible to achieve a wide range of gain ratios for different applications that may require greater attenuation to scale the voltage down to the input range of an ADC (3.3V or 5V). As shown in Figure 2, changing resistor network values achieves greater attenuation.

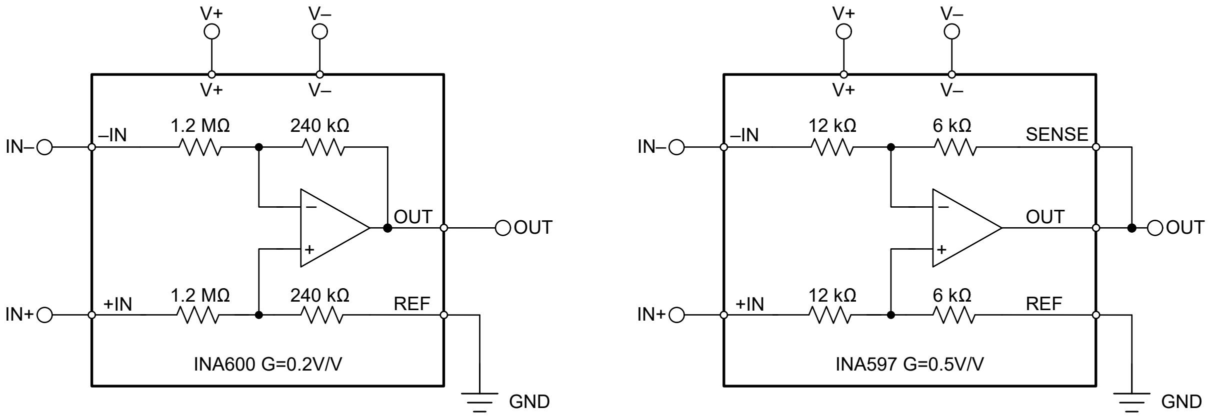
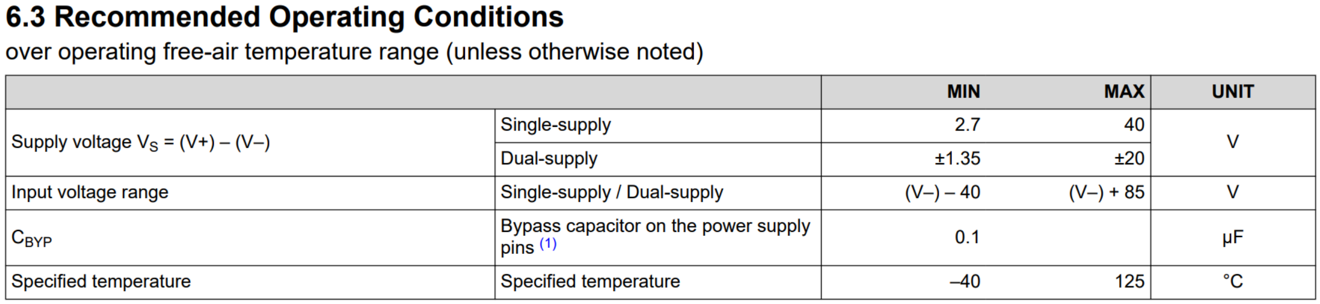


Figure 2. *The INA600A DA vs. the INA597 DA*

An overlooked benefit of DAs is their ability to allow your input to go beyond the rails. Because the resistor ladders divide down the input voltages of the DA, the input of the integrated amplifier will only see the attenuated voltage. With standard op amps, the supply voltage limits the common-mode voltage range. This flexibility of the DA makes them suitable for monitoring higher voltages when the amount of available power rails is limited. As shown in Figure 3, the input voltage range extends further than the recommended supply voltage of the DA.



6.3 Recommended Operating Conditions

over operating free-air temperature range (unless otherwise noted)

		MIN	MAX	UNIT
Supply voltage V_S = (V+) – (V–)	Single-supply	2.7	40	V
	Dual-supply	±1.35	±20	
Input voltage range	Single-supply / Dual-supply	(V–) – 40	(V–) + 85	V
C_{BYP}	Bypass capacitor on the power supply pins (1)	0.1		µF
Specified temperature	Specified temperature	–40	125	°C

Figure 3. *Recommended operating conditions of the INA600 DA*

In higher-power-density systems, the increase in switching frequencies and parasitic inductances caused by printed circuit board traces can lead to additional voltage disturbances that affect voltage monitoring accuracy, as common-mode noise cannot be completely eliminated. While using an integrated DA with high CMRR will remove any common-noise observed across the inputs, achieving high CMRR with the external resistors in a discrete DA will be difficult to achieve given the small mismatches of the resistors, especially at higher gain ratios.

Equation 2 expresses how parasitic inductances and switching frequencies influence the amount of voltage disturbance of your signal:

$$V = L \times \frac{di}{dt} \qquad (2)$$

Figure 4 illustrates the CMRR performance over frequency for an integrated DA.

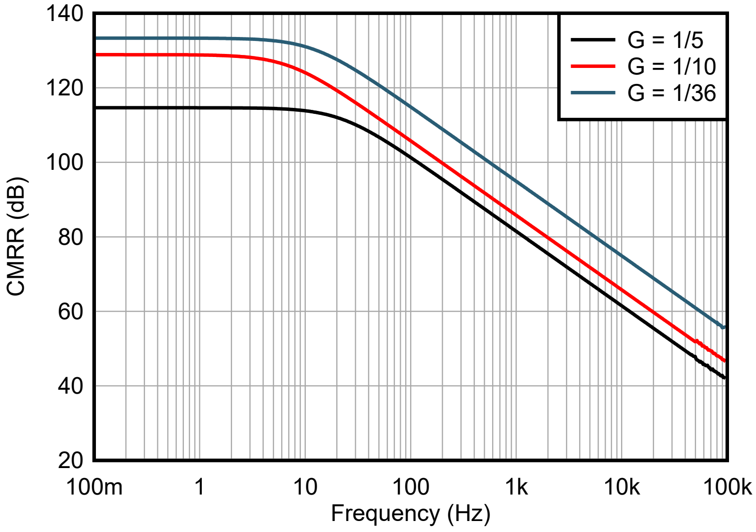


Figure 4. *Output-referred CMRR vs. frequency for the INA600 DA*

Test setup and comparison

We used CMRR and offset voltage errors as a measure of the relative performance of each circuit across temperature. For each device, we connected a precision source measure unit to both input pins of the DA and used a calibrated 8.5-digit multimeter to measure the change in offset voltage. We repeated all testing over five averaged sweeps to obtain an accurate representation of device performance, configuring the devices to sweep a common-mode voltage of -35V to 35V, with a split supply configuration of ±18V. We performed overtemperature testing with an oven, along with sufficient soak time to ensure uniform temperature across the test board.

Forcing a differential voltage across the device inputs while maintaining a common-mode voltage at mid-supply tests both the gain error and gain error drift. Sweeping each device with a corresponding input range forces the output to range from –10V to +10V, enabling you to compare the corresponding slope to the ideal slope and thus evaluate the percentage of gain error.

Table 1 compares the performance of CMRR and the offset between a discrete DA and two TI integrated DAs across different operating temperatures.

	Discrete Difference Amp		INA600		INA597	
Temperature (°C)	**CMRR (dB)**	**Offset (µV)**	**CMRR (dB)**	**Offset (µV)**	**CMRR (dB)**	**Offset (µV)**
125	73.06	-237.88	98.33	801.82	102.66	-26.12
85	71.89	-285.95	100.12	661.56	103.70	-10.22
25	70.35	-221.42	101.63	582.19	100.33	-3.24
-40	73.26	-206.95	106.82	500.60	105.97	13.4

Table 1. *CMRR and offset voltage comparison*

Table 2 compares the gain error and drift performance between the same discrete DA and integrated DAs across different operating temperatures.

	Discrete Difference Amp		INA600		INA597	
Temperature (°C)	**Gain Error (%)**	**GE Drift (ppm/°C)**	**Gain Error (%)**	**GE Drift (ppm/°C)**	**Gain Error (%)**	**GE Drift (ppm/°C)**
125	0.14806	17.12823	-0.0015	-0.08134	-0.0093	-0.20993
85	0.07448		-0.0011		-0.0085	
25	-0.03470		-0.0005		-0.0072	
-40	-0.13460		-0.0001		-0.0058	

Table 2. *Gain error and drift comparison*

As expected, the integrated DAs performed exceptionally well in achieving high CMRR, low gain error and low gain error drift compared to the discrete DA. While the offset voltage of the discrete DA outperformed one of the integrated DAs, it is possible to compensate for this through software calibration.

Figure 5 shows a simplified layout of each of the three DA variants and compares the sizes of each solution. For comparison purposes, we used the smallest device packages, along with resistors and capacitors in the 0402 package.

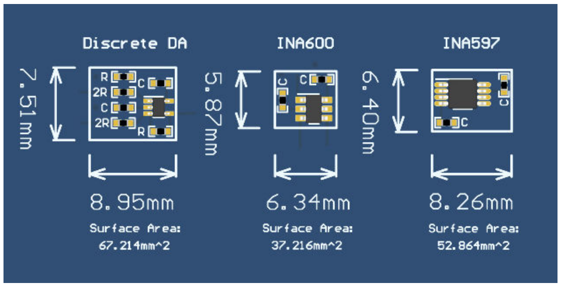


Figure 5. *Size comparison*

Conclusion

While there are many ways to accomplish voltage sensing, an integrated DA provides exceptional performance benefits that are not achievable with a discrete implementation. Input voltage limitations from the supply voltage of op amps become a nonfactor for integrated DAs such as TI’s **INA600**, and high attenuation ratios provide flexibility when monitoring voltages beyond the supply rail.

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