# Finding the Needle in a Haystack:

## Measuring small differential voltages in the presence of large common-mode voltages

by Scott Wayne

### Introduction
In applications such as motor control, power-supply current monitoring, and battery cell-voltage monitoring, a small differential voltage must be sensed in the presence of a high common-mode voltage. Some of these applications require galvanic isolation, others do not. Some applications use analog control, others use digital control. Four cases of such measurements will be considered, each requiring unique considerations. They are:

1) galvanic isolation with analog output;

2) galvanic isolation with digital output;

3) no galvanic isolation, analog output;

4) no galvanic isolation, digital output.

### Differential Signals Versus Common-Mode Signals
Figure 1 shows the input of a measurement system. $V_{DIFF}$ represents the *differential voltage*, the signal of interest. $V_{CM}$ represents the *common-mode voltage*, which contains no useful information about the measurement and could in fact reduce the measurement accuracy. The common-mode voltage could be an implicit part of the measurement system, as in a battery cell-voltage monitoring application, or it could be created by a fault condition where the sensor accidentally comes in contact with a high voltage. In either case, that voltage is unwanted, and it is the job of the measurement system to reject it, while responding to the differential-mode voltage.
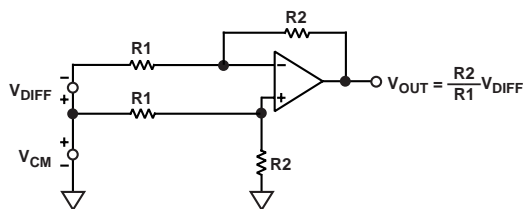


Figure 1. Measurement system with differential and common-mode voltages.

### Common-Mode Rejection (CMR)
The measurement system has both a differential-mode gain and a common-mode gain. The differential-mode gain is usually greater than or equal to one, while the common-mode gain is ideally zero. Resistor mismatches cause the dc gain from the inverting input to differ slightly from that of the noninverting input. This, in turn, results in a dc common-mode gain that is nonzero. If the differential

gain is $G = \dfrac{R_2}{R_1}$, the common-mode gain will be

$\dfrac{\%mismatch}{100} \times \dfrac{G}{G+1}$. The *common-mode rejection ratio* (CMRR) is the differential-mode gain divided by the common-mode gain, or

$\dfrac{100}{\%mismatch} \times (G+1)$. The logarithmic equivalent (CMR—in dB),

is $20\log_{10}\left[\dfrac{100}{\%mismatch} \times (G+1)\right]$.

In real-world applications, external interference sources abound. Pickup will be coupled from the ac power line (50/60 Hz and its harmonics), from equipment switching on and off, and from radio-frequency transmission sources. This type of interference is induced equally into both differential inputs, and therefore appears as a common-mode signal. So, in addition to high dc CMR, instrumentation amplifiers also require high ac CMR, especially at line frequencies and their harmonics. DC common-mode errors are mostly a function of resistor mismatch. In contrast, ac common-mode errors are a function of differences in phase shifts or time delays between the inverting and noninverting inputs. These can be minimized by using well-matched high-speed components, and they can be trimmed with a capacitor. Alternatively, in low-frequency applications, output filtering can be used if necessary. While dc common-mode errors can usually be removed through calibration or trimming. AC common-mode errors, which can reduce the resolution of the measurement, are generally of greater concern. All Analog Devices instrumentation amplifiers are fully specified for both dc and low-frequency ac common-mode rejection.

### Galvanic Isolation
Some applications require that there be no direct electrical connection between the sensor and the system electronics. These applications require galvanic isolation in order to protect the sensor, the system, or both. The system electronics may need to be protected from high voltages at the sensor. Or, in applications requiring intrinsic safety, the sensor excitation and power circuitry may need to be isolated to prevent sparks or the ignition of explosive gases that could be caused by a fault condition. In medical applications, such as electrocardiograms (ECG), protection is required in both directions. The patient must be protected from accidental electric shock. If the patient's heart stops beating, the ECG machine must be protected from the very high voltages applied to the patient by emergency use of a defibrillator in an attempt to restore the heartbeat.

Galvanic isolation is also used to break ground loops where even a small resistance between two system grounds may produce an unacceptably high potential. This could occur in precision conversion systems where milliamperes of current flowing through a few hundredths of an ohm could create hundreds of microvolts of ground error, which could limit the resolution of the measurement. Or it might occur in industrial installations where thousands of amperes of current could create hundreds of volts of ground error and a potentially hazardous situation.

Galvanic isolation may use magnetic fields (transformers), electric fields (capacitors), or light (opto-isolators). Each method has its own advantages and disadvantages. For all types, though, isolated power supplies (or batteries) are usually necessary for powering the floating side of the isolator. This can easily be combined with signal isolation in isolators that use transformer isolation barriers. Other methods may require separate transformer-coupled dc-to-dc converters, which increase cost.

### High Impedance Versus Galvanic Isolation

Many applications need the ability to sense a small differential voltage in the presence of a high common-mode voltage, but do not require the intrinsic safety or the ability to break ground loops that are provided by galvanic isolation. These applications require a high-CMR amplifier that can accept high common-mode voltage. This type of amplifier, sometimes called a "poor man's isolation amplifier," isolates the sensor from the system with a high impedance, rather than with a galvanic isolation barrier. While not isolation in the true sense, it can serve the same purpose in some applications at much lower cost. In addition, a dc-to-dc converter is not required, since the whole system is powered from the same power supply.

Figure 2 shows the *AD629*, a high-common-mode-voltage difference amplifier that was designed for these types of applications. It seems simple enough. It's "just" an op amp and five resistors. Can't users "roll their own?" Yes, but the resistors would have to be matched to better than 0.01% and would have to track to better than 3 ppm/°C. Resistor self-heating would degrade dc CMR, while capacitive strays would degrade ac CMR. Performance, size, and cost would all be sacrificed compared to what could be obtained in an 8-lead DIP or SOIC.
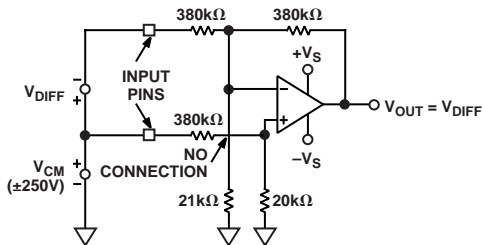


Figure 2. AD629 High-common-mode-voltage-difference amplifier.

Applications such as simple industrial process-control loops with analog inputs and outputs that require galvanic isolation could use the *AD202/AD204*. These are complete isolation amplifiers with galvanic isolation between the input and output stages. Transformer coupling means that they can also provide isolated power to the input stage, eliminating the need for an external dc-to-dc converter. The AD202/AD204 provide an uncommitted op amp for input signal conditioning, have CMR of 130 dB at a gain of 100, and 2000-V-peak CMV isolation. Figure 3 shows an AD202 circuit* to measure a ±5-V full-scale signal riding on a common-mode voltage of up to 2000 V. For applications that require isolated bridge excitation, cold-junction compensation, linearization, and other signal-conditioning functions, the *3B, 5B, 6B, and 7B* series provide a family of complete, well-isolated signal conditioners.
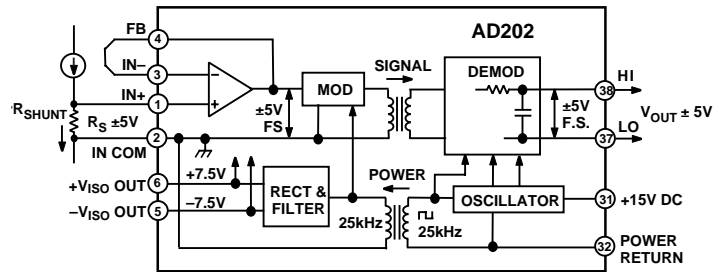


Figure 3. AD202/AD204 used in application requiring galvanic isolation and analog outputs.

Some industrial sensor applications require galvanic isolation, combined with the digital output of a smart sensor. Digital isolation, rather than analog isolation, could be used more cost-effectively but an external dc-to-dc converter is required. An example of this sort of application is in motor control, where a
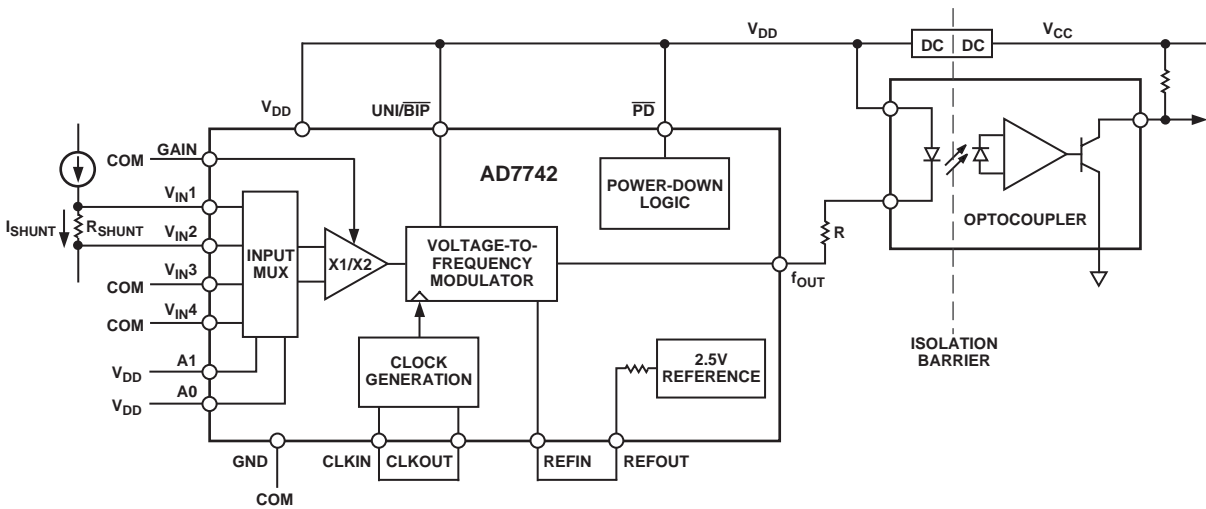


Figure 4. AD7742 used in application requiring galvanic isolation and digital outputs.

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*These Figures are illustrative examples; they are not detailed schematics of tested applications. Please consult product data sheets for more information. You will also find the online seminar notes, Practical Analog Design Techniques, and the book, *Practical Design Techniques for Sensor Signal Conditioning* (available from ADI), to be useful sources of design information. *Use extreme caution when working with high-voltage circuits.*
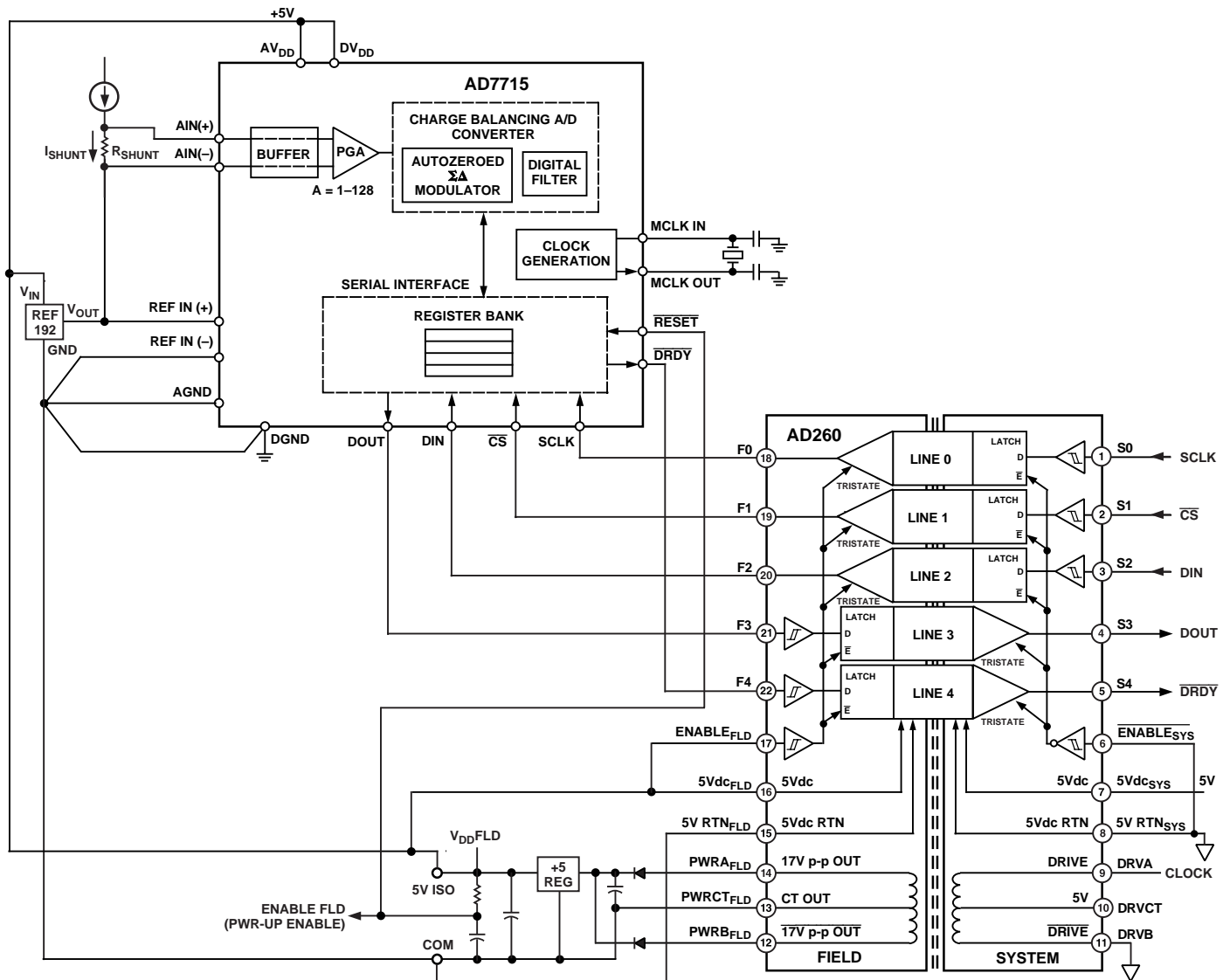
Figure 5. AD7715/AD260 used in application requiring galvanic isolation and digital outputs.

fault condition in the motor could destroy the control electronics. The *AD7742* synchronous voltage-to-frequency converter could be used, together with an opto-coupler and a dc-to-dc converter, as shown in Figure 4. A remote AD7742 can be interfaced with a system microprocessor or microcontroller to complete the A/D conversion. For stand-alone applications the serial-output *AD7715* analog front end, a 16-bit sigma-delta A/D converter, could be used, but it has five digital lines to isolate, rather than the single digital output from the V/F converter. However, instead of five opto-couplers and a dc-to-dc converter, an *AD260* five-channel high-speed logic isolator with its own on-board transformer could be used. Figure 5 shows the AD7715 and AD260.

When galvanic isolation is not required, the situation becomes simpler. An example of this type of application is in battery cell voltage monitoring. An *AD629* is used both to measure the voltage of an individual cell, and to reject the common-mode voltage provided by the stack of series-connected cells. No dc-to-dc converter is required, since the high impedance of the resistance

network protects the inputs of the op amp, even though its power supply voltage is much lower than the common-mode voltage. Figure 6 shows the AD629 measuring the voltage of a 1.2-V cell that is part of a 120-V battery.
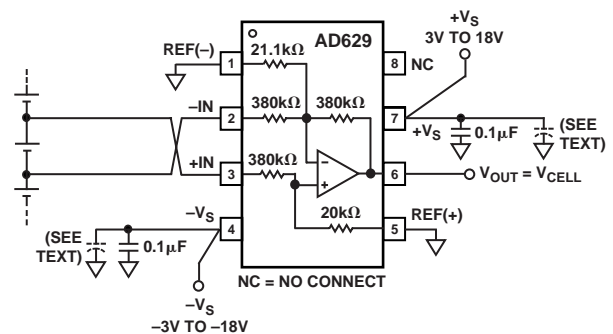


Figure 6. AD629 used in analog application where galvanic isolation is not required.

Finally, there are applications that do not require galvanic isolation, but where digital outputs are desired. An example of this application is supply-current monitoring of a microprocessor-controlled power supply. Here the AD629 is used with an *AD7887* 12-bit ADC. The AD629 provides the signal conditioning and common-mode rejection, while the AD7887 provides the digital output. Again, no dc-to-dc converter is required because of the high input impedance and common-mode attenuation of the AD629. Figure 7 shows the AD629/AD7887 in a power-supply current monitoring application.
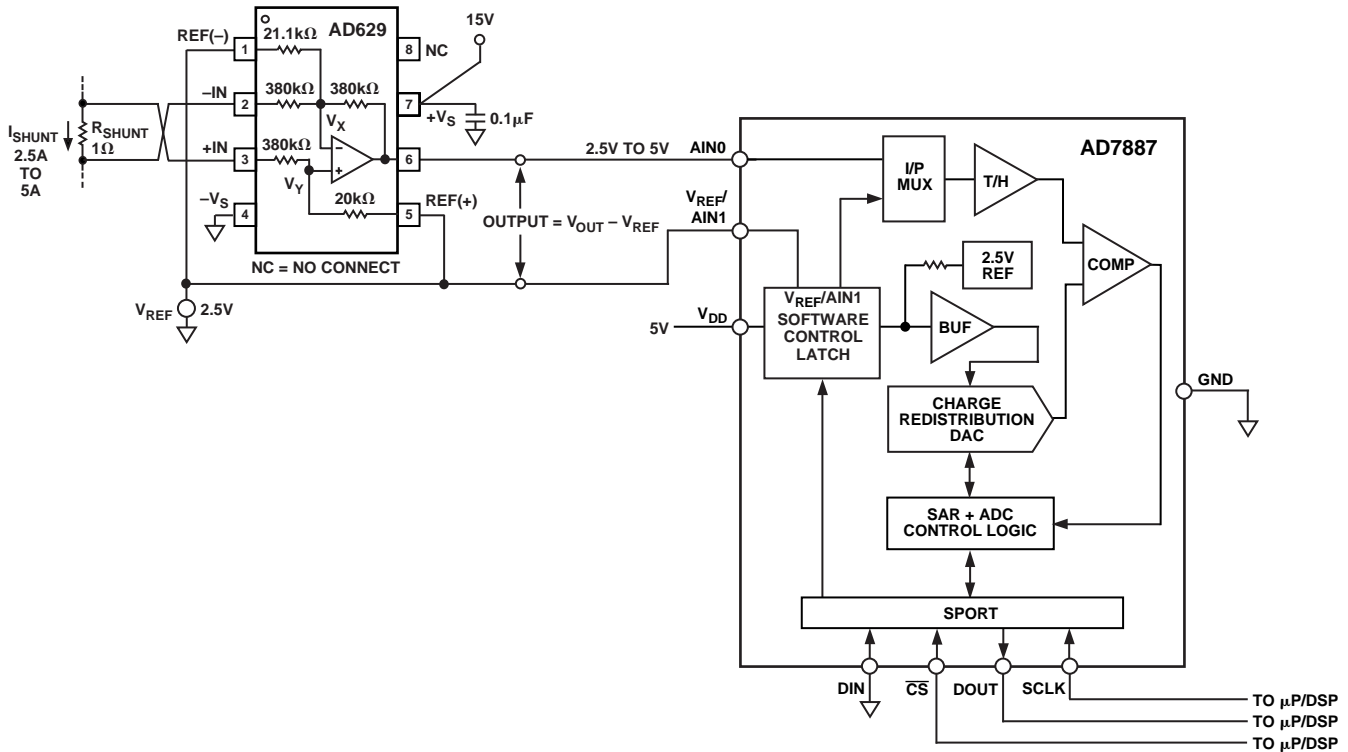


Figure 7. AD629/AD7887 used in digital application where galvanic isolation is not required.