
Five PC-based Industrial Measurements Traps (and how to avoid them)

By Roger W. Lockhart
DATAQ Instruments

When you move a data acquisition system from the controlled environment of the laboratory to the shop floor, a number of factors may combine to destroy your measurement accuracy at best, or your equipment at worst. An understanding of these factors is therefore crucial to measurement success. Through our applications support program at DATAQ Instruments, we've identified five recurring roadblocks to successful measurements in industrial situations, which I'll discuss here in the order of most to least common, together with some real-life examples to enhance your understanding of the concepts involved. By the time we're through, I hope you'll gain a greater understanding of the rigors of industrial measurements, and be better equipped to choose instruments that are appropriate for any given industrial application.

Crosstalk

By far the most common question we field involves a phenomenon that superimposes the content of one data acquisition channel on another. This condition, known as crosstalk, can lead to subtle measurement errors that may take a while to detect. In its most gross form, however, a nearly exact duplicate of one channel appears on an adjacent channel to which nothing is connected.

The PC-based instrumentation revolution spawned active use of an electronic device called a multiplexer, driven by the promise of a low cost-per-channel in the range of \$30 to \$40 each. But along the way many products have dropped a hallmark of traditional instrumentation: an amplifier per channel. Products that lack this feature connect the multiplexer's inputs directly to the system under test. The problem with this, as in many of the other measurement situations that follow, is that the multiplexer is not an ideal device. Its inputs have capacitance that can, and do, store a charge in a magnitude directly proportional to sample rate and the impedance of the signal source. It is this characteristic that causes crosstalk.

Consider an application where a multiplexer's inputs are connected directly to the output of an amplifier. In this situation, the impedance the multiplexer sees is stable and low, on the order of about 10 ohms. Crosstalk is greatly minimized, or eliminated altogether, since the impedance of the source is low enough to bleed the charge on the multiplexer's input capacitance before the ADC converts and reports a value. However, even under this nearly ideal impedance situation, a high sample rate can conspire to boost crosstalk by minimizing the dwell time on the multiplexer's channels. In effect, the capacitance has less time to bleed its charge before A-D conversion takes place resulting in cross talk where none existed before.

From the foregoing discussion, you can see that as source impedance and sample rate increase, the probability for cross talk increases as well. To avoid this trap, keep these points in mind.

1. Minimize the source impedance of your signal source. As a rule-of-thumb, try to keep it below 100 ohms, although at very high sample rates even this value may be too high.

2. If you can't control source impedance to minimal levels, consider placing an amplifier between your signal source and the PC-based instrument. Better yet, choose an instrument with a built-in amplifier on each channel.
3. Minimize the instrument's sample rate whenever possible. Consider an instrument that allows you to control the burst sample rate of the product for added flexibility.

Common Mode Voltage (CMV)

Although crosstalk leads the pack in sheer volume of application inquiries, CMV leads in its ability to confuse. More traditional measurement methods, like battery-powered hand-held DVMs, are almost completely impervious to CMV problems. Naturally, customers think they can simply extend this success to PC-based measurement approaches. In many cases, however, they do so with poor or even disastrous results. The problems they encounter can be tied to two specifications that can be found on the manufacturer's data sheet. Those are: Full Scale Range and Maximum Input Voltage Without Damage. The former tells you how much voltage connected right across the instrument's inputs (the so-called normal mode voltage) you can successfully measure. As its name implies, the latter indicates how much normal mode voltage the instrument will tolerate before it's damaged.

Common mode voltage, the voltage that appears simultaneously and in phase on each of the instrument's inputs with respect to power ground, will combine with the normal mode voltage to test the limits of your instrument. Most data acquisition products for the PC will permit measurements when a combination of common mode and normal mode voltages exist only as long as their sum is equal to, or less than the instrument's full scale range. However, the measurement can be made under these conditions only if the input of the data acquisition product is configured for differential operation, as shown in Figure 1.

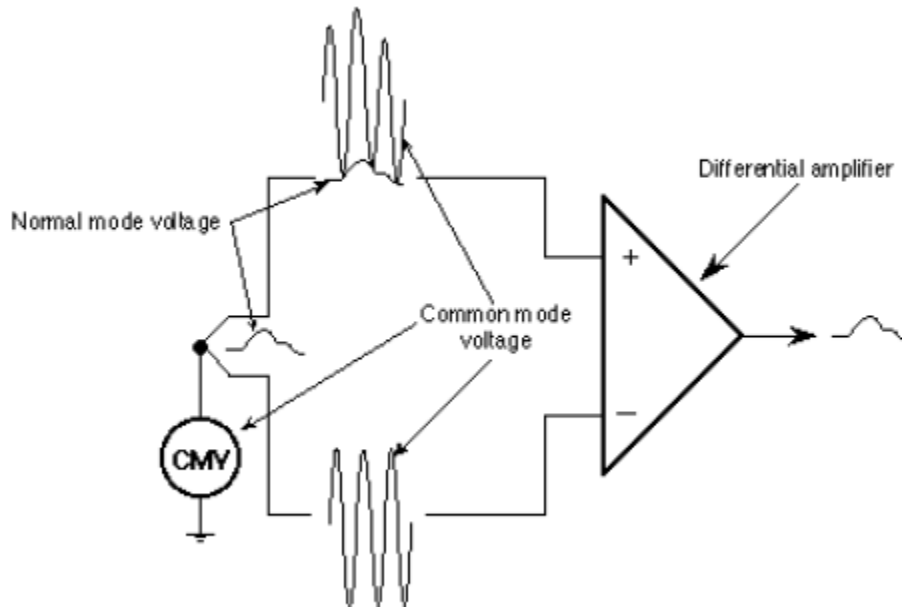


Figure 1 – The action of a differential amplifier cancels the common mode voltage (CMV) that appears simultaneously and in phase on each of its inputs. The signal of interest, the so-called normal mode voltage (NMV), is passed.

With the basic rule for differential measurements established, it's now appropriate to detail the three possible results of such measurements in order of best to worst:

1. $(CMV + NMV) \leq \text{Full Scale Range}$: A good measurement, subject to the common mode rejection specification of the instrument (more on this later).
2. $\text{Full Scale Range} \leq (CMV + NMV) \leq \text{Maximum input voltage without damage}$: Your measurement is latched at plus or minus full scale. You have no usable results, but no damage either.
3. $(CMV + NMV) > \text{Maximum input voltage without damage}$: Smell the aroma of ozone in the air? You just fried your data acquisition product, and you dodged a bullet if your computer still works.

For most data acquisition products, it doesn't take long to reach the terminal stage of step three. Most will tolerate a maximum input voltage without damage of only $\pm 30\text{VDC}$ or peak AC. In the realm of industrial measurements, with 120-440VAC motor supplies, or even 50VDC process current supplies, you can exceed this limit very quickly and irrevocably. How do you apply your comparatively expensive data acquisition instrument to the same measurements you make so effortlessly and safely with your hand-held DVM? You choose a product that provides isolation.

Isolation is what its name implies. As with your battery-powered DVM, there is no electrical connection between the common associated with the instrument's front-end input terminals, and the power common associated with the back-end of the instrument and the computer. As such, the instrument's frontend is free to float at a level defined by the magnitude of the CMV, without damage and with complete measurement accuracy. Here, the maximum CMV that can be tolerated is not dictated by its maximum input voltage specification, or even by its full scale range, but rather by the voltage at which the isolation barrier breaks down. For DATAQ Instruments' DI-730 data acquisition product, for example, that breakdown occurs at 1000VDC or peak AC, well within the expected CMV of most industrial applications. Figure 2 describes a typical application where isolation allows a measurement in the presence of a high CMV.

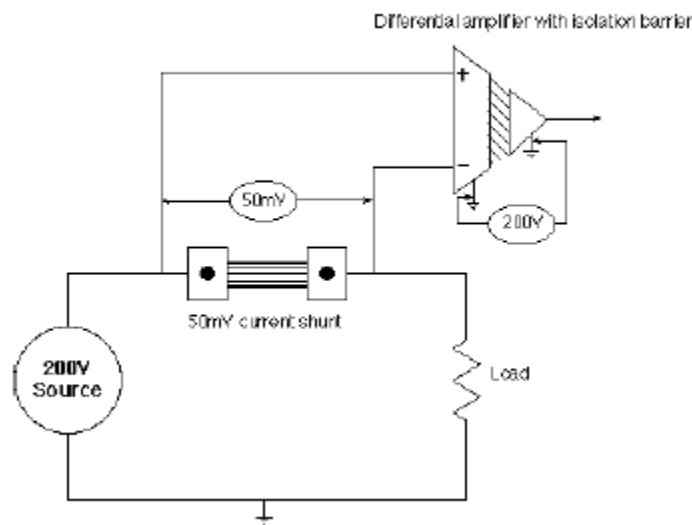


Figure 2 – An isolation barrier allows measurements in the presence of high common mode voltages. A differential amplifier's ability to cancel the high CMV in favor of the signal of interest is measured by its common mode rejection.

Under the heading of Buyer Beware, however, isolation can be provided in more than one form: Input-to-output; channel-to-channel; and a combination of both. For the vast majority of multichannel industrial applications, you'll need both input-to-output and channel-to-channel isolation. Such an arrangement allows each channel to float with respect to the others. A CMV on channel one, for example, will not disrupt measurements on the other channels even if they're referenced to power common or an entirely different CMV. In contrast, systems designed with just input-to-output isolation essentially tie the commons of all channels together. A CMV on one channel floats all at the same potential with potentially disastrous results if another channel is connected to a ground-referenced signal or a different CMV. There's only one reason to buy a product that offers only input-to-output isolation. Cost. It's less expensive to build one isolation barrier into, say, an eight-channel product than one for each channel. And that cost savings is usually reflected in a lower system price. But in the actual application of such an instrument, you may find that you've simply purchased an expensive fuse.

Before leaving the topic of isolation, I want to establish one point firmly and clearly: You cannot and must not equate a product that offers differential measurement capability with one that offers isolation. These are two entirely different and unrelated features. Nonetheless, some people are still under the misimpression that a product with differential measurement capability allows them to apply the instrument in high CMV conditions. As we've seen, differential but non-isolated products tolerate only moderate CMVs without damage, and even lower CMVs with good measurement results.

DC Common Mode Rejection (CMR)

Whenever a measurement is made the presence of a CMV, accuracy will be adversely affected. The only remaining question is the magnitude of the inaccuracy, and you can determine this by looking up the spec for Common Mode Rejection in your product's data sheet. Any instrument that provides a differential input, isolated or not, offers the ability to reject a common mode voltage to a degree determined by its CMR. CMR is most commonly defined as a logarithmic ratio of input to output CMV in decibels. The common mode rejection ratio (CMRR) for most general-purpose A-D products for the PC is around 80db. How does this figure apply to the measurement? Lets look at a modest example and work through the math. Assume that you want to measure a 3VDC normal mode signal in the presence of a 6VDC common mode voltage:

$$80db = 20 \log \left(\frac{V_{CMV_{in}}}{V_{CMV_{out}}} \right)$$

$$80 = 20 \log \left(\frac{6VDC}{V_{CMV_{out}}} \right)$$

$$4 = \log \left(\frac{6VDC}{V_{CMV_{out}}} \right)$$

$$10,000 = \frac{6VDC}{V_{CMV_{out}}}$$

$$V_{CMV_{out}} = 0.6mV$$

$$\text{Measurement accuracy} = 3VDC \pm 0.6mV, \text{ or } \pm 0.02\%$$

Not bad for a first try. We started with a CMV that was twice the magnitude of our signal of interest, but our differential amplifier with its sterling 80db CMRR spec reduced its effect on the amplifier's output to mere fractions of a millivolt with negligible impact on accuracy. You might conclude, based on this evidence, that 80db rejection is suitable for all applications. Let's test this hypothesis in the real world application described by Figure 2. Here's the math, omitting the first three steps which are redundant:

$$10,000 = \frac{200VDC}{V_{CMV\ out}}$$

$$V_{CMV\ out} = 20mV$$

Measurement accuracy = 50mV ± 20mV, or ± 40%

The instrument that worked so well when the spread between the CMV and NMV potentials was narrow (only 2:1 in the first example), literally falls apart when the spread increases exponentially—a common situation in many industrial measurements like the 4,000:1 spread of the typical current shunt measurement of Figure 2. Since you can't lower the CMV in these situations, the only solution is to apply an instrument with better CMR. Stealing another specification from DATAQ Instruments' model DI-730, here's how the math stacks up for the same application using this instrument's 120db CMRR:

$$120db = 20 \log \left(\frac{V_{CMV\ in}}{V_{CMV\ out}} \right)$$

$$120 = 20 \log \left(\frac{200VDC}{V_{CMV\ out}} \right)$$

$$6 = \log \left(\frac{200VDC}{V_{CMV\ out}} \right)$$

$$1,000,000 = \frac{200VDC}{V_{CMV\ out}}$$

$$V_{CMV\ out} = 0.2mV$$

Measurement accuracy = 50mV ± 0.2mV, or ± 0.4%

As you can see, knowing how a CMV will affect measurement accuracy is at least as important as knowing that it exists at all. To help you evaluate an instrument you may already have or might purchase, I've prepared the quick-look guide of Table 1.

CMRR (db)	Anti-log equivalent $\frac{db}{(10^{20})}$
20	10
30	32
40	100
50	316
60	1,000
70	3,162
80	10,000
90	31,623
100	100,000
110	316,228
120	1,000,000

General equation :

$$\text{Voltage error} = \frac{\text{Common mode voltage}}{\text{Common mode rejection ratio}}$$

Example :

Assume that CMV = 100V; CMRR = 90db

$$\text{Voltage error} = \frac{100}{31,623} = 3.2\text{mV}$$

Compare the calculated 3.2mV error with your signal of interest to determine overall accuracy.

Table 1 – Use this convenient guide to estimate the error caused by a common mode voltage as a function of your instrument's common mode rejection ratio.

To use it, simply determine the CMV of the application and look up your instrument's CMRR spec in its data sheet. Table 1 provides a range of CMRRs in decibels and their equivalent anti-log ratios so you don't have to work with logarithmic math as I did above. Plug your CMV and the appropriate anti-log ratio into the equation shown. The result is the expected measurement error in volts. Compare this figure with the NMV you need to measure to determine the instrument's suitability for the application.

AC Common Mode Rejection

The preceding discussion centered on pure DC common mode voltages with only passing references to AC. But AC CMVs are at least as prevalent as DC, and even more so when you include unpredictable noise sources such as motor brushes and inductive EMFs, both conducted and radiated. As such, my assumption of pure DC CMVs may not be supported in actual practice. It's worthwhile, therefore, to explore how AC CMVs can adversely affect an amplifier's CMRR and hence measurement accuracy.

A differential amplifier's ability to reject CMVs is tied directly to how well its two inputs are balanced. Falling back to an ideal example, if we connect 1VDC to one input and 1VDC to the other, we expect to see 0V on the amplifier's output. But we know the amplifier is not, and never will be ideal. Stated another way, its CMRR will never be infinite. Small tolerance variations within the amplifier, and even in the system under test will conspire to force the amplifier out of balance, however slightly, to yield a finite CMRR value and its attendant inaccuracies. When an AC CMV is applied, a whole new set of additive inaccuracies is introduced. The culprit heralds back to the beginning of this article: capacitance.

Under pure DC CMV conditions, any capacitance in the signal source, signal cable and connectors, and within the amplifier itself is inconsequential. As an AC component is introduced, these capacitances form a complex and unpredictable impedance that can force the amplifier out of balance. And this unbalance can and will change as a function of frequency. To account for this, most manufacturers spec CMRR not under ideal DC conditions, but at 50 or 60Hz with typically 1,000 ohm unbalance between the amplifier's inputs. This is done to provide you with a worst case estimate for CMRR under the most likely source of AC interference, the frequency of the AC power line. Beyond this, a manufacturer can't predict what particular frequencies your specific application may experience. You could find that an instrument spec'd at 100db CMR yields no better than 80db rejection in the presence of higher frequency noise. Yet, the product is still operating within spec as defined by the manufacturer.

How do you determine the suitability of an instrument in the presence of noise beyond that of the power line? Unfortunately there's no easy answer to this question. But bear in mind that a product that successfully addresses such an application does not do so by chance. Wide-spectrum AC rejection must be built into a product early in its design cycle. Contact the manufacturer and describe your specific situation. If they assure you of the instrument's suitability, put their confidence to the test and ask for a trial period. In extreme cases, like DC drive systems or other high speed and high voltage switching applications, only seeing is believing.

Measurement Range and Input Protection

To this point, I've examined some of the more esoteric, yet highly relevant issues that you must consider when you apply an instrument to demanding industrial applications. Other more obvious issues involve the instrument's measurement range and input protection.

Most industrial applications will test an instrument's mettle on both ends of the measurement spectrum—from large source voltages in the range of several hundred volts, to small shunt voltages in the range of tens of millivolts. The instrument you choose for these applications should have the ability to easily select among a variety of measurement ranges, and do so on a channel-by-channel basis, since it's very common to measure both voltage and current simultaneously.

But the very nature of these highly variable and wide dynamic range measurements carries with them an implied need for input protection. How many of us are not guilty of ever attempting to measure a few hundred volts on a millivolt range? It happens all the time. Practical input protection should allow any voltage within its maximum-without-damage-range to be connected indefinitely, regardless of the measurement range selected.

Finally, what are the consequences when you really goof and exceed an instrument's maximum-without-damage range? Is it okay if it's reduced to a burning cinder? Should you expect more? It's my opinion that an instrument designed for the applications we've discussed here should be more forgiving. Input protection schemes abound, and none can absolutely protect an instrument from a cataclysmic event. But the damage can be minimized. The technique used most successfully applies a combination of fuses and a device called a gas discharge tube (GDT) in a low-tech, but highly efficient and time-tested approach to circuit protection that has remained virtually unchanged for decades.

Borrowing again from DATAQ Instruments' model DI-730, Figure 3 is a schematic of the first analog input stage, which is typical for each of its eight channels.

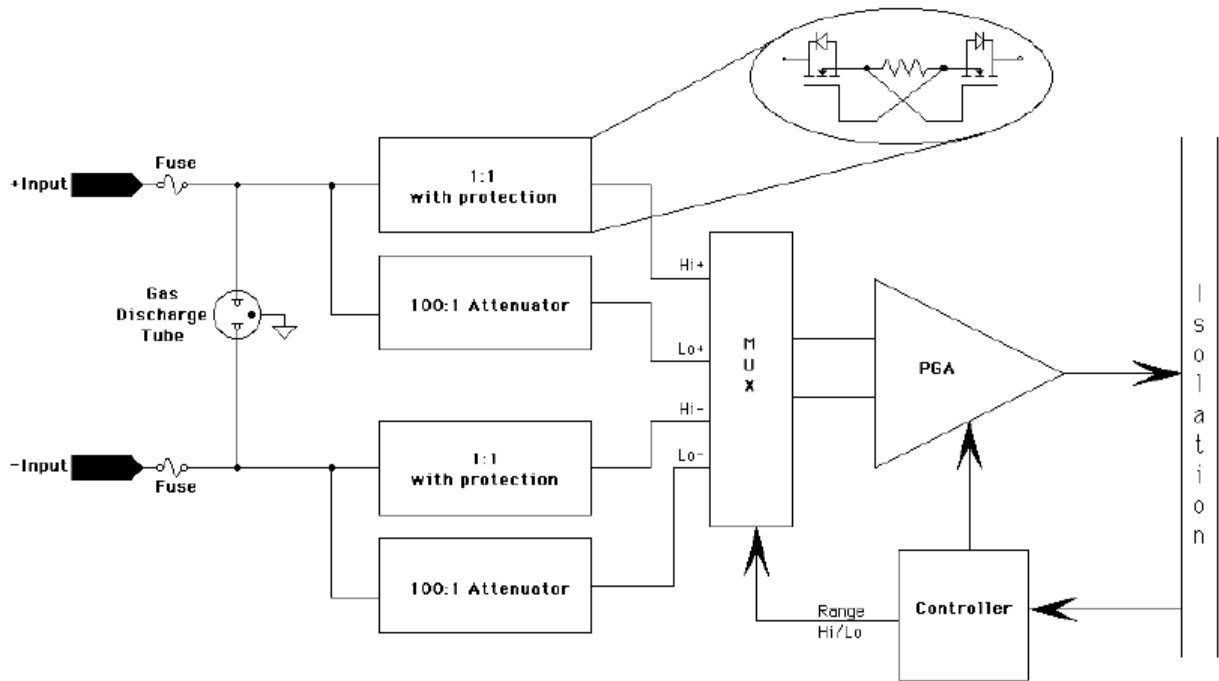


Figure 3 – This schematic of a typical DI-730 channel shows a time-proven technique for protecting instruments from accidental overvoltages using a combination of fuses and a gas discharge tube.

The theory at work here is simple and straight-forward. The GDT is designed to conduct at a specific voltage. At voltages below this threshold, it's an open circuit. When an over-voltage condition occurs (840V for the DI-730) and the GDT conducts, the fuses take over. At this stage, one or both fuses blow, essentially disconnecting the DI-730's input from the signal source and, in the process, protecting the bulk of the instrument and the bulk of your investment.

Conclusions

The landscape of data acquisition applications is replete with measurement challenges. But none are more demanding than day-to-day voltage and current measurements in the gritty world of industry. Even relatively benign 4-20mA process current signals, which on the surface seem straight forward, can in fact carry hidden CMVs that can confound your best measurement attempts. Careful planning through study of the application and the data sheets of candidate

instruments will help you avoid most of the traps. Even so, the ultimate proof is in the pudding. Express your concerns and questions to instrument suppliers. Factor their input with your experience. Eliminate any lingering doubt by insisting on an evaluation—in your facility, connected to your signals, exactly the way you want to measure them.