Designing for high common-mode voltages in analog input modules

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Introduction

Reliability requirements for programmable logic controller (PLC) analog input modules in harsh factory and process environments demand support of high common-mode voltage that can go up to hundreds of volts. This common-mode voltage arises from different sources and is caused by coupling or wiring issues. Maintaining the precision required for analog conversion in the presence of a high common-mode voltage poses a challenge for module designers.

In this document, the sources of high common-mode voltage signals and typical industrial requirements are explored. Signal isolation and signal scaling implementations are also introduced. You can apply signal isolation to the entire channel or just the interface using high-voltage switches or a high-voltage multiplexer. Scaling is implemented scaling discretely or with an integrated difference amplifier. The different implementations and their effect on other signal-chain parameters such as input impedance, noise, bandwidth and common-mode rejection are compared.

Common-mode voltage sources and their effect on reliability

It is quite common to have PLC analog input modules and data acquisition cards with isolated ground to increase module reliability and enable the input stage to track the source ground. When connecting two sources with differences in ground point to the input through differential signals, as shown in **Figure 1**, one of the input channels will experience a common-mode voltage signal. This is a very simplified explanation; in reality, there could be connections to chassis ground, earth ground or protective ground, as well as shielded cables and the connection of the cables' shield, which is ignored in the diagram for the sake of simplicity.

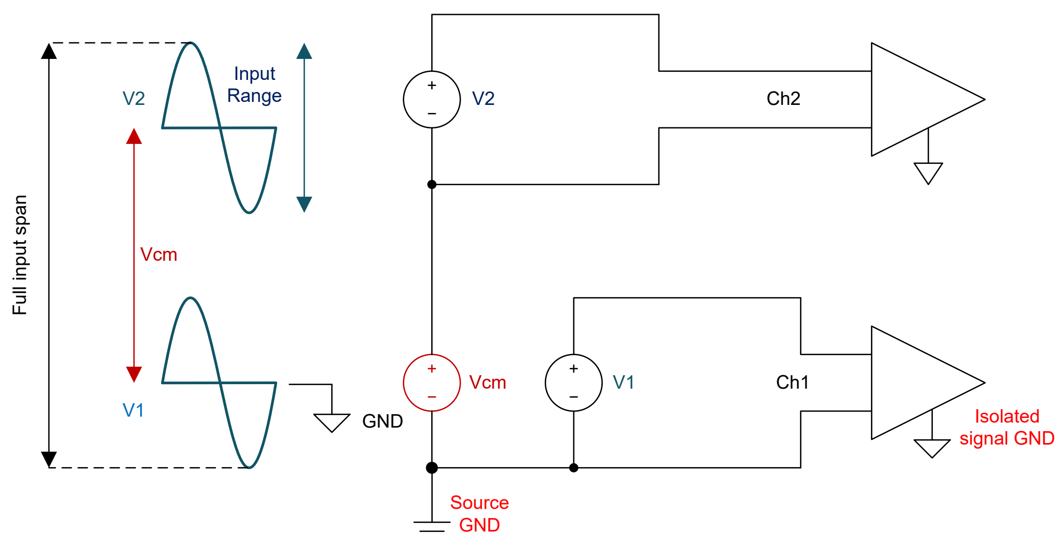

Figure 1. *Common mode signal absolute input range (full input span): differential input range plus common-mode voltage range.*

The common-mode voltage might be a DC or AC signal, according to its source. Sources in industrial installations may come from:

- Wiring or grounding faults.
- Capacitive or inductive coupling to cables or terminals caused by electromagnetic interference from nearby motors, machines or high-power transients.
- Lightning strikes to cables.

For example, ungrounded wires often have a common-mode noise level of 4 to 5 V at 50 to 60 Hz. Some chemical plants can experience as much as 60 V of common-mode noise. Marine systems are known to have up to 35-V common-mode noise signals [1].

The presence of a common-mode voltage is not always unintentional, either. Some applications have a common-mode voltage difference by design, such as inputs connecting to battery cells in high-voltage batteries, exposed thermocouples immersed in electrolyte solutions or molten metal furnaces.

If analog input modules are not designed for high voltages, a high common-mode voltage might result in the voltage exceeding the absolute maximum rating of the input stage amplifier, multiplexer or analog-to-digital converter (ADC), leading to permanent circuit damage. Even when an input is protected against high voltages, a high common-mode voltage could cause accuracy degradation and result in unreliable readings.

Support levels

There are different support levels for a high common-mode voltage on analog input modules:

- Overvoltage protection. The module is protected from a high common-mode voltage but does not necessarily operate during an overvoltage event. Readings during such events are faulty.
- Overvoltage diagnostics and fault alerts. The overvoltage event is detected by the module and reported to the processor to indicate a fault. This ensures reliability of all readings. There are no readings during the overvoltage.
- Normal operation, reduced accuracy. Some modules can operate during a high common-mode voltage event, but with reduced accuracy.
- Normal operation, with full accuracy. In this level of high common-mode voltage support, the input module maintains high accuracy, even during the event.

The design challenge is how to achieve normal operation in the presence of a high common-mode voltage, either with full or reduced accuracy.

Support techniques

There are three general techniques to support a high common-mode voltage on the analog input, with multiple topologies:

- Ground isolation.
- Common-mode blocking using:
  - photoMOS switches or
  - A high-voltage multiplexer
- Common-mode scaling:
  - Using a resistive divider and instrumentation amplifier (INA).
  - A discrete or integrated difference amplifier.

Ground isolation creates fully isolated channels with a separate local ground for each channel. The common-mode difference between channels can be as high as the isolation barrier of isolation devices.

This technique typically reaches the maximum common-mode voltage possible, in the several kilovolts range.

Using the common-mode blocking technique, the active channel passes through the signal chain, with the negative terminal assumed as ground (the module ground is isolated). All other channels are blocked through switches with a high blocking voltage.

In the common-mode scaling technique, the high common-mode voltage is scaled down through passive attenuation before or around an amplifier, so as not to exceed the amplifier voltage limits. Both blocking and scaling-techniques can achieve low to medium common-mode voltage support based on the devices and power supply.

The channel-to-channel isolated topology

This topology can achieve the largest common-mode range. It relies on building separate input channels in galvanically isolated islands with a separate floating ground for each island, as shown in **Figure 2**. The ADC connects to the processing unit through a digital signal isolator. The analog front-end and the ADC both are powered through an isolated power stage. Digital isolators such as the ISO6742 can achieve a 5-kVRMS isolation voltage, possibly higher than an off-the-shelf transformer isolation voltage, which ranges from 1.5 to 5 kVRMS. If the power required for one channel is below 0.5 W, an integrated power and data isolator such as the ISOW7741 can help save both space and cost.

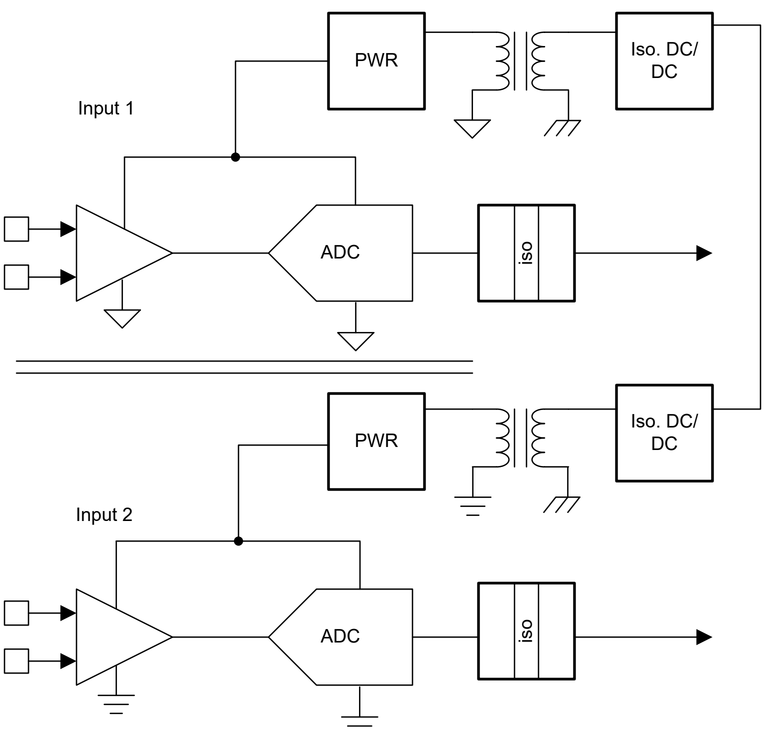

Figure 2. *Channel-to-channel isolated topology.*

The channel-to-channel isolated topology requires a separate analog front end, converter, isolator and power stages per channel. It costs the most, has the highest power consumption and takes up the most board area. It also achieves the highest common-mode voltage range, the best performance and the highest reliability.

High-voltage multiplexers

High-voltage multiplexers are an attractive solution to high common-mode voltage support. They do not affect the input impedance and enable fast switching and a wide bandwidth. They are relatively new – a result of recent advancements in high-voltage metal-oxide semiconductor technology. They require a supply that spans the common-mode voltage range plus the input differential signal. Also, further devices in analog signal chain, such as the amplifier need protection against possible high voltages.

Figure 3 shows the TMUX8109 4-to-1 differential high-voltage multiplexer. This 100-V multiplexer can support a common-mode voltage difference of 80 V, in addition to the typical differential input of ±10 V. The use of an overvoltage-protected amplifier after the multiplexer, such as the INA823 shown in **Figure 3**, eliminates the need for external protection diodes and enables the use of a typical voltage signal chain (such as the ±15 V).

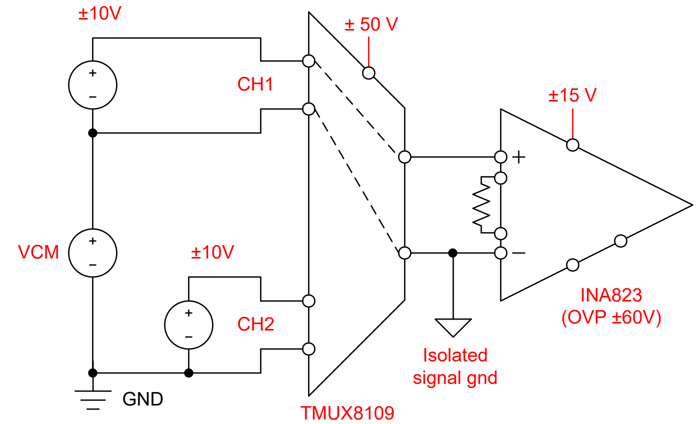

Figure 3. *High-voltage multiplexer topology block diagram.*

Connecting the signal ground (typically isolated in analog input modules) to the negative input of the active channel (CH1 in **Figure 3**) ensures that the active channel is properly biasing the module signal chain. The switching time between channels is limited by the switching time of the amplifier, which is around 14 µs for 0.001% settling. The high-voltage multiplexer supports common-mode voltage differences in the range of 50 to 80 V if generation of a high-voltage supply on the board is possible. Note that the high-voltage supply current needed is below 0.5 mA per supply rail. If you only need a high blocking voltage, consider a high-voltage switch such as the **TMUX8212** with a multichannel input, as shown in **Figure 4**.

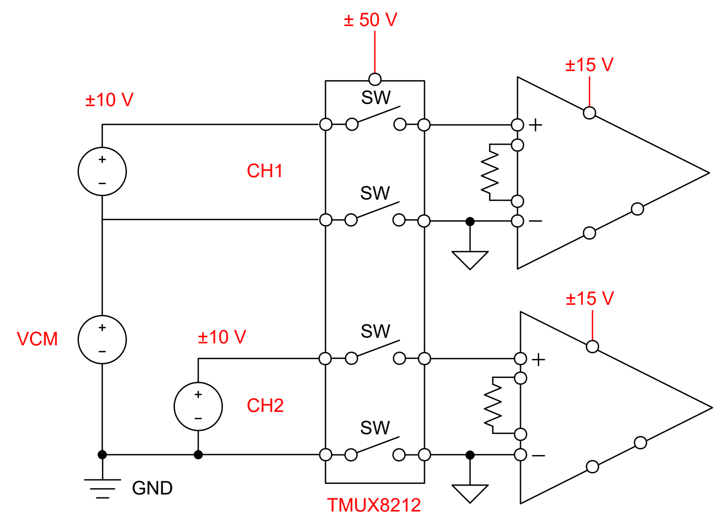

Figure 4. *High-voltage switch topology block diagram.*

PhotoMOS switches

It is possible to arrange single-pole, single-through photoMOS switches to create a differential N-to-1 multiplexer, or you can use them as switches as shown in **Figure 3** and **Figure 4**. Because the photoMOS switch has a high blocking voltage (60 V to 300 V), the resulting multiplexer is similar to a high-voltage multiplexer. The main advantage of photoMOS switches is that they do not require a high-voltage supply to operate, and they typically have low impedance, in the range of only a few Ω. They do have disadvantages, however; they require relatively high current on the control pin (approximately 7 mA for a differential input dual switch), have relatively high leakage in the off-state that can reach 1 µA, and have a slow switching time of a few milliseconds.

A resistive divider and INA

Figure 5 illustrates a resistor divider followed by the **INA826** INA. The divider scales down the common-mode voltage but scales the differential input signal as well. To maximize the dynamic range, the INA can amplify the differential signal to get it back to the original signal level.

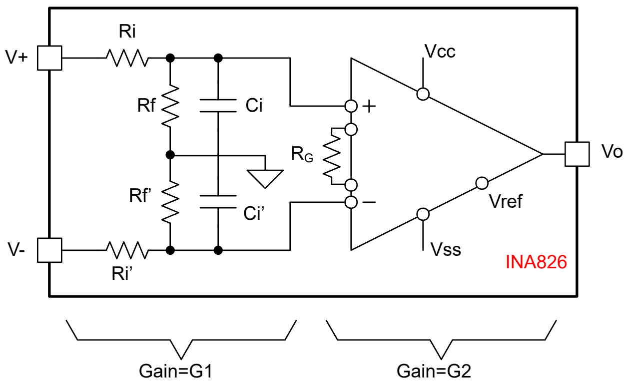

Figure 5. *A resistor divider followed by an INA topology.*

Equation 1 and **Equation 2** represent gain factors G1 and G2, respectively.

$$G_1 = \frac{R_f}{R_f + R_i} \quad (1)$$

$$G_2 = 1 + \frac{49.4k}{R_G} \quad (2)$$

The trade-offs in this topology are:

- The common-mode range vs. the input noise. The high ratio of R_i-to-R_f increases the common-mode voltage range, but attenuates the input signal as well and increases input noise when amplified again by G2.
- The input impedance vs. input noise. A high R_i plus R_f increases the input impedance, but also increases the input noise.

Precision high-value resistors are not readily available, which sets the practical upper limit of the input impedance to about 1 MΩ.

G1 = 0.249 and G2 = 4.01 leads to a common-mode voltage range of ±36 V if using a ±15-V supply. [2]

The common-mode rejection ratio (CMRR) of this topology is a function of the resistors' precision, typically in the 70- to 80-dB range. The offset is common mode-dependent. Because it is not possible to compensate for gain drift (the resistor temperature coefficient) and common mode-dependent offset, that puts the lower limit to the inaccuracy of the topology above 0.1% full scale.

A discrete difference amplifier

A discrete difference amplifier shown in **Figure 6** rejects the common-mode signal while maintaining the differential input signal. The amplifier gain is represented by **Equation 3**.

$$G = \frac{R_f}{R_i} \quad (3)$$

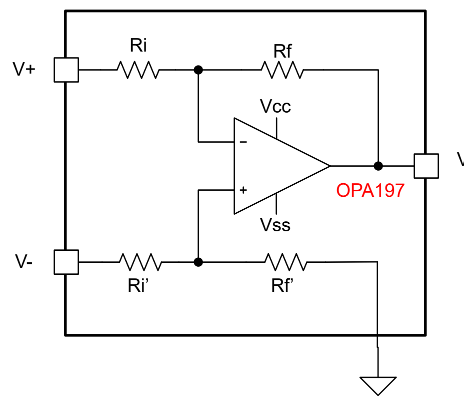

Figure 6. *Discrete difference amplifier topology.*

The common-mode voltage range calculation for this topology is ±36 V for a ±15-V supply. This topology has drawbacks similar to the resistor-divider topology – worse in some aspects. The most important trade-off is the input impedance vs. the bandwidth. In the case of a high-input impedance, the high R_f along with the output capacitance of the amplifier significantly limits the stage bandwidth. A 1-MΩ input impedance and G = 1 leads to a bandwidth <10 kHz. For practical reasons, the input impedance is typically limited to 1 MΩ. [3]

An integrated difference amplifier

Integrated devices such as the **INA148** amplifier, shown in **Figure 7**, significantly eliminate the drawbacks of a discrete difference amplifier. The integration of the resistors allows for trimming to a very high resistor matching between resistors. The possibility for accurate trimming to an arbitrary resistor value enables a more complex feedback structure that uses a lower impedance, greatly expanding the difference amplifier's bandwidth.

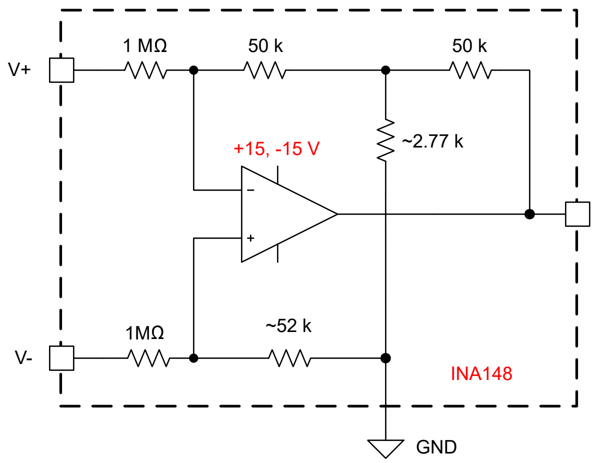

Figure 7. *An integrated difference amplifier.*

The complex feedback structure makes it possible to have a ±200-V common-mode range with a ±15-V supply, a very low-gain error (<0.1%) and very high CMRR (>86 dB). This topology can possibly achieve the highest common-mode voltage range after a channel-to-channel implementation. [4]

Choosing the right topology

Do not get overwhelmed by the number of topologies. The main parameters affecting topology selection are the common-mode voltage range, the signal bandwidth, whether fast switching is required (a multiplexed system), the required input impedance and the total cost. The blocking topologies are multiplexed, saving the number of ADC channels and bringing down system costs. The other topologies require an amplifier per channel but typically offer wider bandwidth and it is mandatory in case of simultaneous sampling.

Table 1 compares the different topologies.

Difference Amplifier (discrete)	Difference Amplifier (integrated)	Resistive Scaling + INA	High-Voltage Multiplexer
Low CMRR	High CMRR	Low CMRR	High CMRR
High noise	Low noise	High noise	Low noise
Moderate common-mode voltage range	High common-mode voltage range	Moderate common-mode voltage range	Moderate common-mode voltage range
Low bandwidth	Moderate bandwidth	Moderate bandwidth	High bandwidth
Moderate Rin	Moderate Rin	Moderate Rin	Very high Rin

Table 1. *Different Topolgies*

If you require a very high common-mode range (>200 V), the channel-to-channel isolated topology is the only choice. For common-mode range between 50 and 200, your choices are a photoMOS switch (if very slow switching is acceptable) or an integrated discrete amplifier per channel. For a common-mode range <50 V, choose a high-voltage multiplexer. If you need a high input impedance, you could use the multiplexer topology in multiplexed systems with up to 50 kSPS.

When you require simultaneous sampling or will be using a multichannel ADC anyway, choose an amplifier-based approach. An integrated difference amplifier offers the highest performance, while a discrete amplifier has the lowest performance but at the lowest cost. A resistive divider is in the middle for both performance and cost.

References

1. Liptak, Bela G. "Instrument Engineers' Handbook (Volume 2)." CRC Press, 2003.
2. Texas Instruments: ***Supporting High-Voltage Common Mode Using Instrumentation Amplifier Application Brief***
3. Texas Instruments: ***Supporting High Voltage Common Mode Using Difference Amplifier Application Brief***
4. Texas Instruments: ***16-Bit 8-Channel PLC Analog Input Module With High- Voltage (±150 V) Common-Mode Support Application Brief***
5. Texas Instruments: ***When to Replace a Relay with a Multiplexer***