Application Note

How Do Isolated I^2C Buffers with Hot-Swap Capability and IEC ESD Improve Isolated I^2C?

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ABSTRACT

Although the Inter-Integrated Circuit (I^2C or I2C) communication standard is one of the most widely used inter-chip communication standards in today's electronic systems, including in aerospace, automotive, personal electronics, and industrial applications, not everyone knows that a hot-swap-capable I2C device can prevent signal errors. Communication errors can suddenly be caused during operation by adding or removing I2C nodes and devices in a system if they do not have hot-swap functionality, potentially leading to bit errors which can cause data loss, data corruption, or even system failure.

I2C is an open-drain, open-collector communication standard, so each I2C device connected to an I2C bus connects the drain of an output switch (or FET) from its I2C pins, SDA and SCL, to the I2C bus. When a device is added or replaced in an I2C system without stopping, shutting down, or rebooting the system, a transient is caused within the device. If this transient is fast enough or strong enough, it could couple into the internal switch, causing the FET to turn ON momentarily, which in turn discharges the bus and could appear as a valid data signal to the other devices on the I2C bus (data corruption). Preventing this typically means systems communicating over I2C need to be powered down or rebooted when devices are added or replaced that are not hot-swap capable, but in some applications, such as for communications, data storage, and network servers, powering down is not an option.

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1 What is Isolated I²C?

I2C helps controllers communicate with sensors, data converters, and other nearby integrated circuits (ICs). Isolated I2C-compatible signal isolators like TI's ISO1640 and ISO1641 create opportunities for the protocol to be used in systems that are physically distant, operating at different local voltage potentials, and require isolation protection for operation or safety.

Sensitive systems or those in need of protection from large DC and AC currents, ground-potential differences, and high-voltage events can be protected by TI's digital isolators when used with isolated power supplies. Although most digital isolation devices isolate signals in one direction for communication across an isolation barrier, TI's bidirectional signal isolators isolate bidirectional signals for I2C. They accomplish this by combining two unidirectional signal paths internally, as Figure 1-1 shows, across the industry's strongest silicon dioxide (SiO2) isolation barrier.

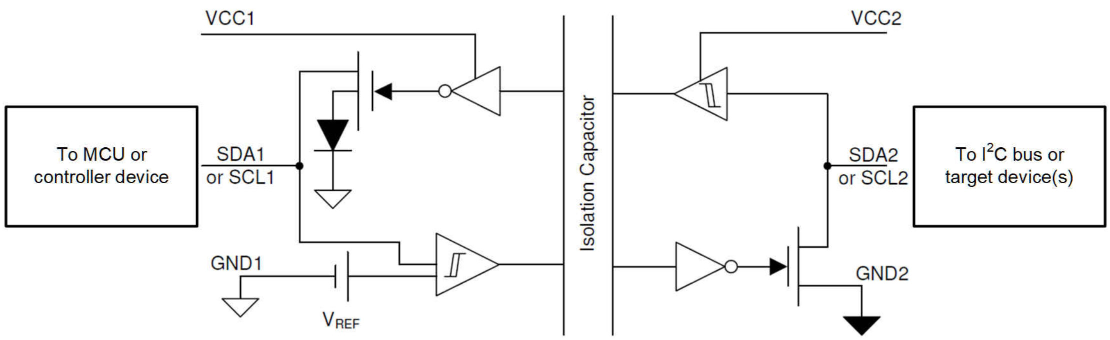

Figure 1-1. Simplified Schematic of a Bidirectional I2C Isolation Channel

Bidirectional communication is inherent to I2C, and using an isolator with integrated bidirectional lines provides the benefits of: a low discrete component count, small footprint, less system-wide variations, and built-in protection over discrete solutions.

2 What is Hot Swap?

Hot swap is the replacement or addition of components to a powered system without pausing, powering down, or restarting the system and maintaining normal operation. Preserving normal operation of an I2C bus includes not affecting communication by loading the bus or corrupting an ongoing bitstream. When an I2C node or device is first connected to a system, there is no power supply holding the gates of the internal I2C output FETs to ground, and if the power-up transient on the drain of these pins is fast enough, it may couple to the gate of these output FETs, lifting the gate voltage enough to turn the switch ON momentarily. This, in turn, could reduce bus voltage levels enough to cross the HIGH/LOW thresholds of different devices, resulting in communication errors or data corruption across the bus.

Hot-swapping capabilities help preserve the communication integrity of an I2C bus when replacing nodes or devices, making them most beneficial to high-reliability or zero down-time systems that must be maintained or upgraded while operating. Hot-swappable parts must protect sensitive components against electrical shocks, so using components that are not designed to be hot-swapped or that are partially hot-swappable instead of fully hot-swappable could result in instant errors and possibly hardware failure or damage. To preserve communication during hot-swap events in a system with multiple removable nodes or modules, each removable node must have the ability to be withdrawn and replaced without affecting the operation of any adjacent nodes, regardless of power supply levels and bus activity.

3 Benefits of Hot-Swappable Isolated I²C

Digital signal isolation protects low voltage, logic-level subsystems from mid-to-high-voltage sensors, actuators, and transient events. In systems with long cables or in noisy environments, high voltage transients can occur and damage low-voltage circuitry. I2C-compatiable digital isolators, like ISO1640 and ISO1641, help protect low-voltage circuitry from high voltages, and their hot-swap capability combines bus dependability when adding or removing I2C nodes with isolation protection from undesired or unexpected voltage shifts.

By design, ISO1640 and ISO1641 isolated I2C devices have full "hot-swap" compliance and can help prevent the common modes of failure from using regular I2C devices without the following hot-swap feature:

1. Data corruption due to transients while plugging in the part
2. Loading the bus at every low to high bus transition if the supply is not present, as partially hot-swappable devices can
3. Excessive voltages on the I2C bus appearing on the local supply rail due to parasitic leakage paths if the part has non-failsafe ESD

Examples of how TI's fully hot-swappable I2C devices outperform other devices to prevent some of the modes of failure listed above are demonstrated in the following section.

4 How Hot-Swap Capability is Achieved Today

Today's sensitive, high-speed serial communication devices are not all designed to support hot-swap capabilities. In isolated I2C buses where it is necessary, hot swap is typically implemented with a staggered-pin design at the point of connection, which ensures grounds and local power supplies are reliably connected before other connections are made. Figure 4-1 shows an example of a staggered male connector.

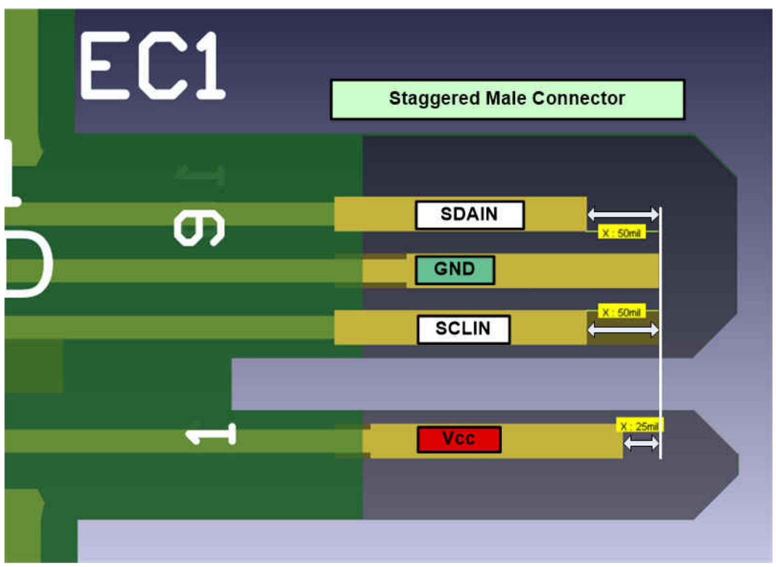

Figure 4-1. Example of a Staggered Male Connector Used in Hot-Swap Applications

Some I2C isolation devices are compatible with "power-on hot-swap" using staggered connectors or hot-swap controllers, which means I2C nodes using these devices might preserve communication on the bus only if the bus-side power supply (V_{CC}) level of the device is always above or equal to the bus voltage levels during connection, and this is typically accomplished via hardware.

Figure 4-2 is an example of a hot-swappable isolated I2C device without pin pre-charge connected to an idle 3.3-V bus. Upon connection, plugging this partially hot-swappable device to a loaded bus reduces the bus voltage by over 60%, even in a "power-on hot swap" condition. The magnitude of this bus voltage dip varies for each system based on external factors, like the R and C values of the bus, and it could be low enough to cross the V_{IL}, or low-level input voltage thresholds of several I2C devices, potentially causing false LOW readings by other devices connected to the bus. Compare this with an about 30% reduction when plugging ISO1640 to the same bus as shown in Figure 4-2 and Figure 4-3 .

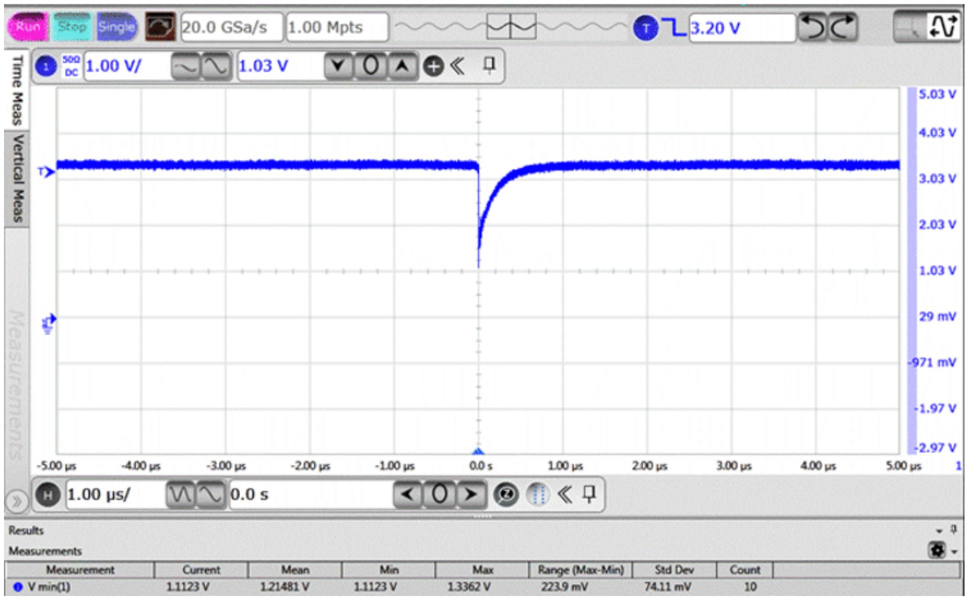

Figure 4-2. Regular I2C Device Without pin Pre-charge Loading the 3.3-V bus Down to 1.2 V During Plug-in

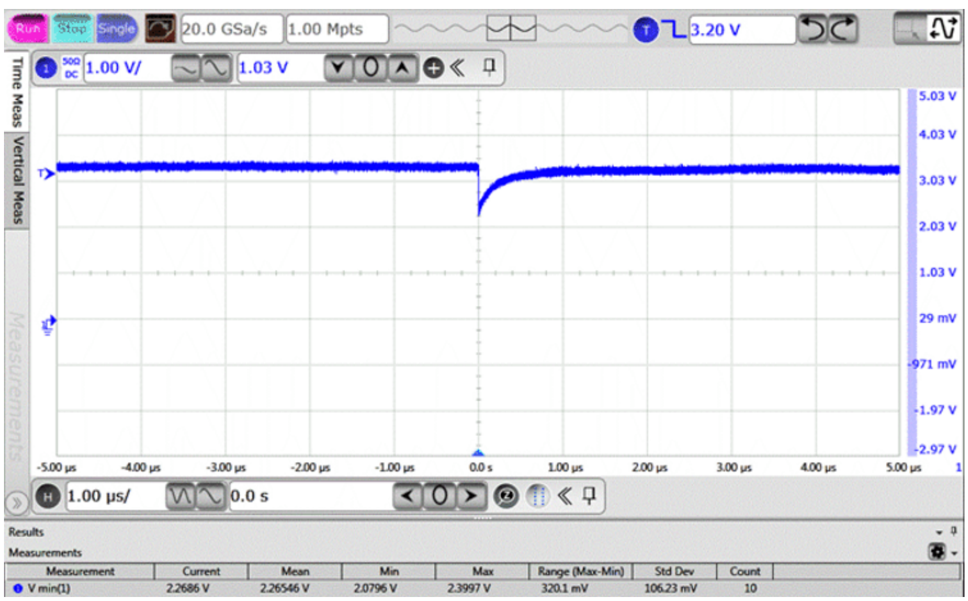

Figure 4-3. Pin Pre-charge in ISO1640 Reduces bus Loading to 2.3 V During a Hot-Swap Plug-in

As mentioned in Section 3, an I2C bus can be affected in multiple ways by devices that are not fully hot-swap-capable. Depending on the internal structure of the SDA and SCL bus pins of a device, the bus may be prevented from communicating when the device is powered down or the bus-side voltage supply, Vcc2, is ramping or left floating. Waveforms of these conditions are shown by Figure 4-4 and Figure 4-6; waveforms of the same scenario when using ISO1640 instead are shown by Figure 4-5 and Figure 4-7 .

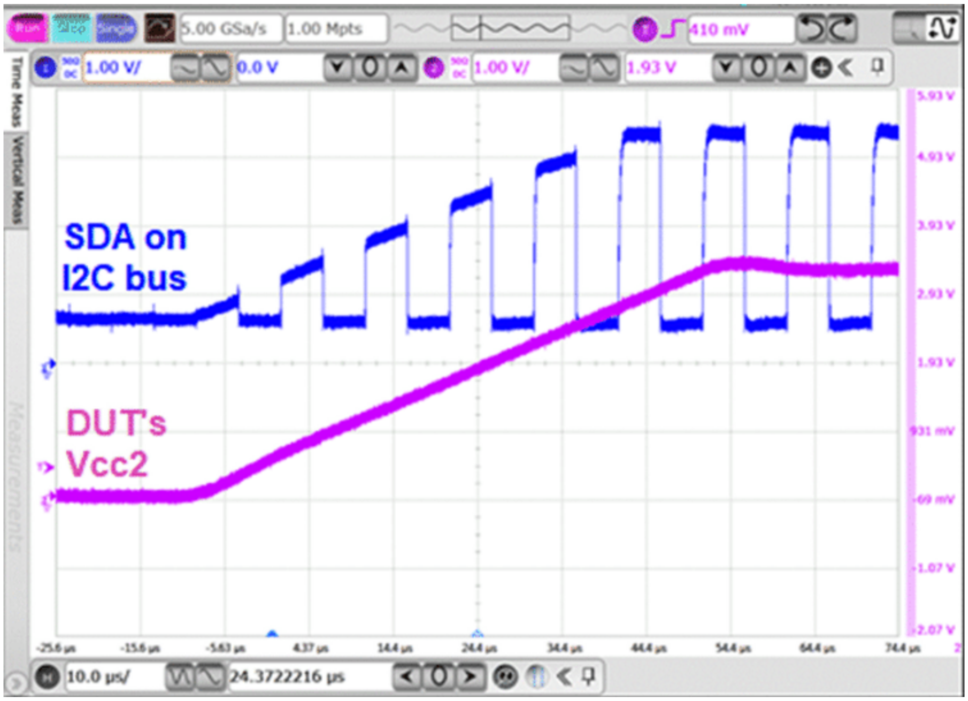

Figure 4-4. Regular I²C Device Corrupting bus Communication During Plug-in

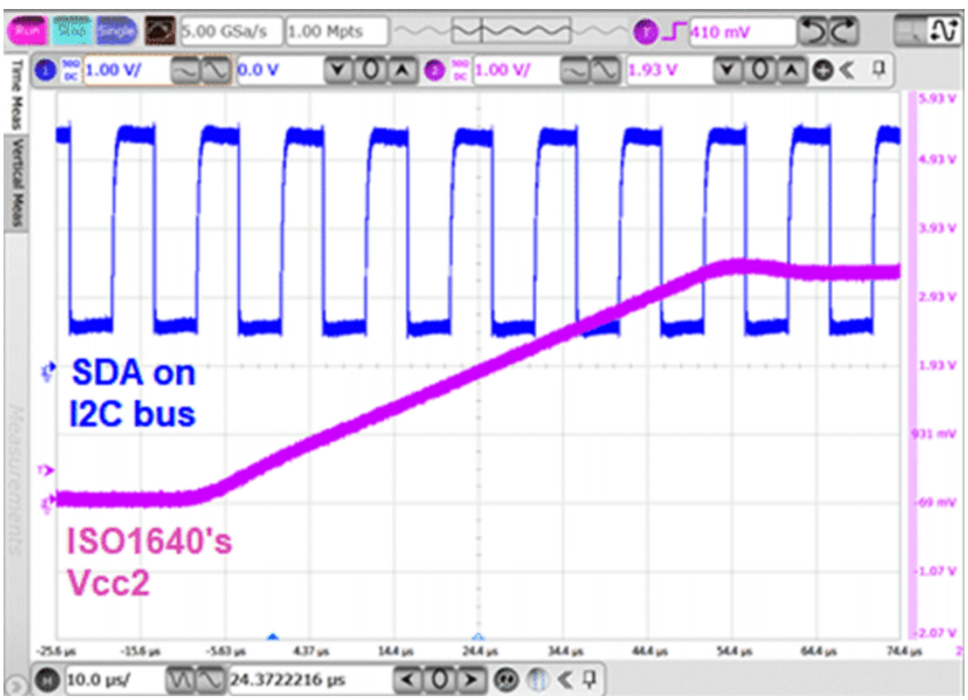

Figure 4-5. Hot-Swappable ISO1640 Maintains Data Integrity of the bus During Plug-in

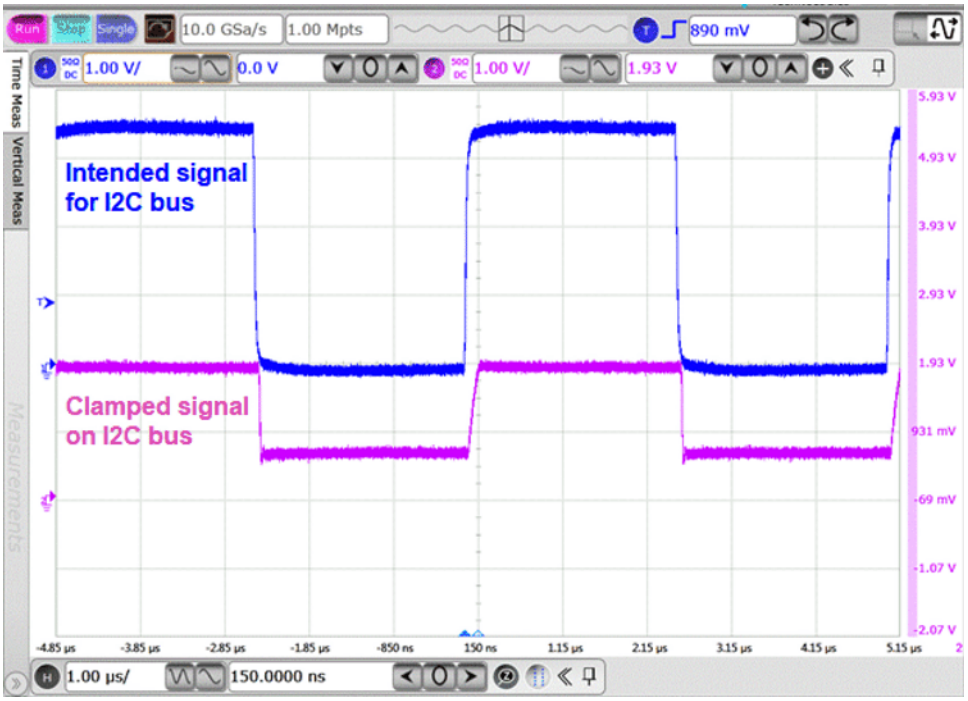

Figure 4-6. I^{2}C bus Clamped to Approximately 2 V From 3.3 V by a Regular I^{2}C Device When its Bus-Side Power Supply is Floating

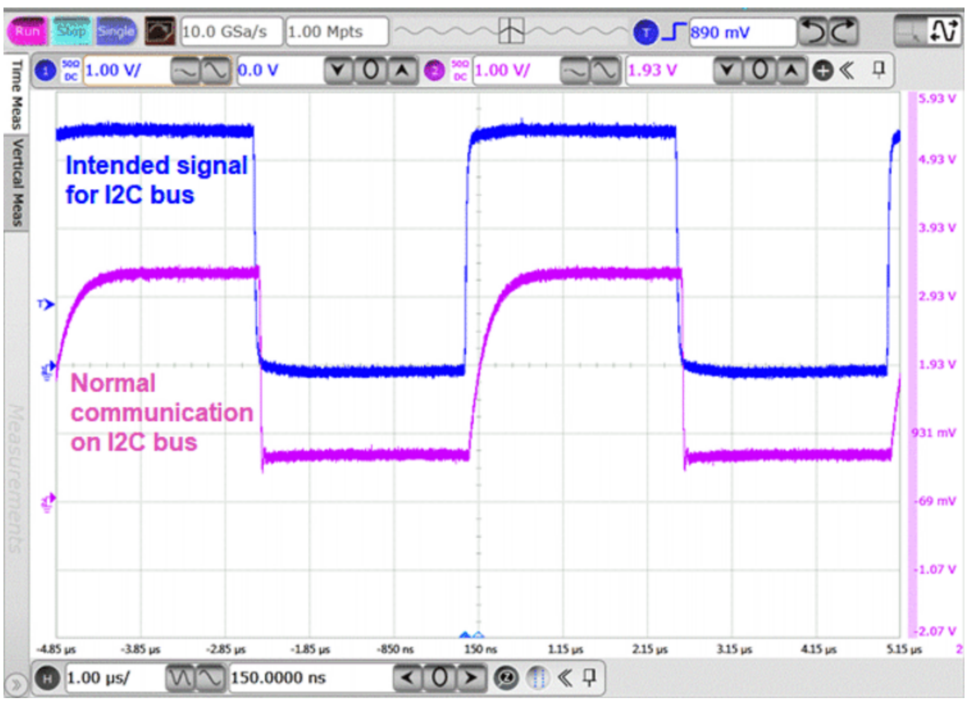

Figure 4-7. I^{2}C bus is Unaffected if the Vcc2 Supply of the ISO1640 is Floating

Along with these cases where unpowered “power-on hot swap” devices are first connected to I2C buses, similar communication errors can also occur in regular non-hot swappable devices resulting from transients coupling to unintended sections of the internal circuitry of an I2C device during every LOW-to-HIGH transition on an I2C bus if signal rise times are fast enough.

5 Robust Communication With the Built-in Hot-Swap Feature of the ISO164x

The ISO164x prevents loading an active I2C bus irrespective of whether a staggered connector is used or not. While Vcc2 is below the UVLO threshold, the ISO164x bus lines will avoid disrupting or corrupting an active I2C bus using internal circuitry, and if connected with a staggered connector, the SDA and SCL lines of the ISO164x are pre-charged to minimize inrush current required to charge the pin capacitance of the device, further reducing the effect of their addition to the bus as shown in Section 4.

In applications where staggered connectors are not used or are not possible to integrate, devices that are “power-on hot-swap” compliant only, requiring a staggered connector or hot-swap controller, have effects that can disrupt data communication when they are connected to systems like those shown in Section 4. TI’s ISO1640 and ISO1641, both “power-off hot-swap” devices, do not require staggered connectors, external hardware, or additional circuitry for hot swap. A specialized internal circuit that is agnostic to the presence or absence of a power supply ensures the open-drain output of the I2C pins remain in high-impedance mode and does not pull the data lines LOW during hot-swap or power-up transients. This ensures safe hot swap operation even while using standard connectors.

For conditions where generic connectors are used or Vcc2 levels on the I2C device are lower than on the bus, “power-off hot-swap” devices, including TI’s ISO164x devices, continue to help preserve signals on the bus as well. This saves users from having to power down a system to connect I2C nodes or cards since these devices do not corrupt the bus when connected whether they are powered on or powered off.

6 Simplified System-Level ESD Protection Design With ISO164x

In systems featuring ports or removable nodes, PCBs are exposed to the outside world through connectors, leaving them susceptible to damage from Electrostatic Discharge (ESD). These system-level ESD events are almost expected to happen on the exteriors of any product that has direct or indirect contact with humans or external items. Therefore, nodes that are typically susceptible to ESD events are terminals and connections, like power lines (AC, DC, or battery) and communications lines (like RS-485, CAN, or I2C), and they are required to withstand ESD stress levels defined by the IEC 61000-4-2 (referred to as IEC ESD) standard. The necessary level of IEC ESD protection is different from application to application.

Any end application or equipment can expect ESD events whether they are powered-on or unpowered, so modules and connection points should be protected against IEC ESD. The industry standard is: wherever there are exposed ports, those ports need to have IEC ESD protection. For example, I2C and RS-485 communication ports are typically protected against IEC ESD using external protection components near the connector as shown in Figure 6-1.

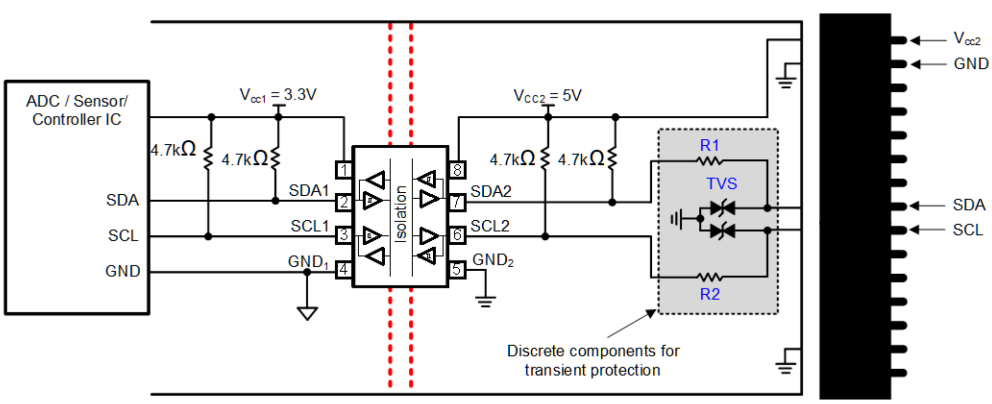

Figure 6-1. Discrete Transient Protection Against IEC ESD for I^{2}C

Since external TVS diodes usually clamp voltage above the maximum operating voltage (V_{CC}) of devices, resistors are included in the previous solution to drop voltage further and protect a device without damaging it, while higher resistances degrade the integrity of a bus.

Enhanced ESD protection cells are designed on the I2C bus pins of ISO164x to support up to 10-kV HBM ESD on side 1 of the device and 14-kV HBM ESD on side 2. This integrated protection replaces the discrete components traditionally necessary to protect I2C devices against IEC ESD, and the integrated ESD protection of the ISO164x makes system design easier and more reliable by removing the need for both TVS diodes and large resistors for ESD protection, complementing its I2C hot-swap abilities with the industry's-strongest local IEC ESD performance. The I2C bus pins on side 2 are designed to withstand a same-side IEC ESD strike of 8-kV when the device is unpowered, improving robustness and system reliability in hot-swap applications.

7 Conclusion

TI's ISO164x family of isolated I2C devices with hot-swap circuitry helps maintain the data integrity of I2C buses during device plug-in without the need for a staggered connector. In addition, the built-in system-level IEC ESD protection of the ISO164x eliminates the need for external protection components, simplifying reliable system-level design. Combined hot-swap features and the integrated IEC ESD will lead to improved robustness while shortening the bill of materials (BOM) of the system.

8 References

- Texas Instruments, *I2C Solutions for Hot Swap Applications Application Report*
- Texas Instruments, *ISO164x Hot-Swappable Bidirectional I2C Isolators with Enhanced EMC Data Sheet*
- Texas Instruments, *How to Isolate Signal and Power for I2C Interfaces Application Brief*

9 Revision History

NOTE: Page numbers for previous revisions may differ from page numbers in the current version.

Changes from Revision * (March 2021) to Revision A (March 2022)	Page
• Updated *Discrete Transient Protection Against IEC ESD for I2C* image	7