Application Report
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Removing Ground Noise in Data Transmission Systems

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ABSTRACT

Although it is commonly stated that isolating interfaces removes ground potential differences (GPD) and ground loops, it is also often unknown how and where these GPDs originate, what their waveforms or frequency content is, and why ground loops can represent a real nuisance.

This application report explains how electrical installation systems, wired correctly (or incorrectly), in combination with time-varying loads can create large GPDs between remote transceiver stations. It also explains the frequency content of GPDs and demonstrates how to isolate a data transmission system by avoiding ground loops and GPDs that might adversely affect the quality of the transmission signal. It provides product examples for increasing tolerance to GPDs.

Remote data links such as large computer networks in commercial buildings or fieldbus systems in industrial networking can experience system lock-down and even destruction of network components due to dangerously high ground noise levels.

The generation and/or existence of ground noise can have several sources such as:

- Large ground potential differences (GPDs) due to the electrical installation system
- Large currents in the signal return and ground wires due to the accidental design of ground loops
- High voltage and current transients due to lightning, ground fault conditions and induced noise conducted or radiated from switching inductive loads
- Electrostatic discharges through human intervention during network installation or maintenance

In contrast to high energy transients and electrostatic discharges, which only allow for the reduction of their potentially damaging effects through solid grounding and controlled discharge paths, ground potential differences and ground loops can be proactively avoided through careful system design.

This application report therefore explains where GPDs originate and how ground loops are created unintentionally. The document also gives an example of a robust data transmission design that prevents both noise sources from occurring by using electrically isolated transceiver stations.

The Electrical Installation

Figure 1 shows a simplified electrical installation with the secondary windings of a Δ-Y transformer as supply.

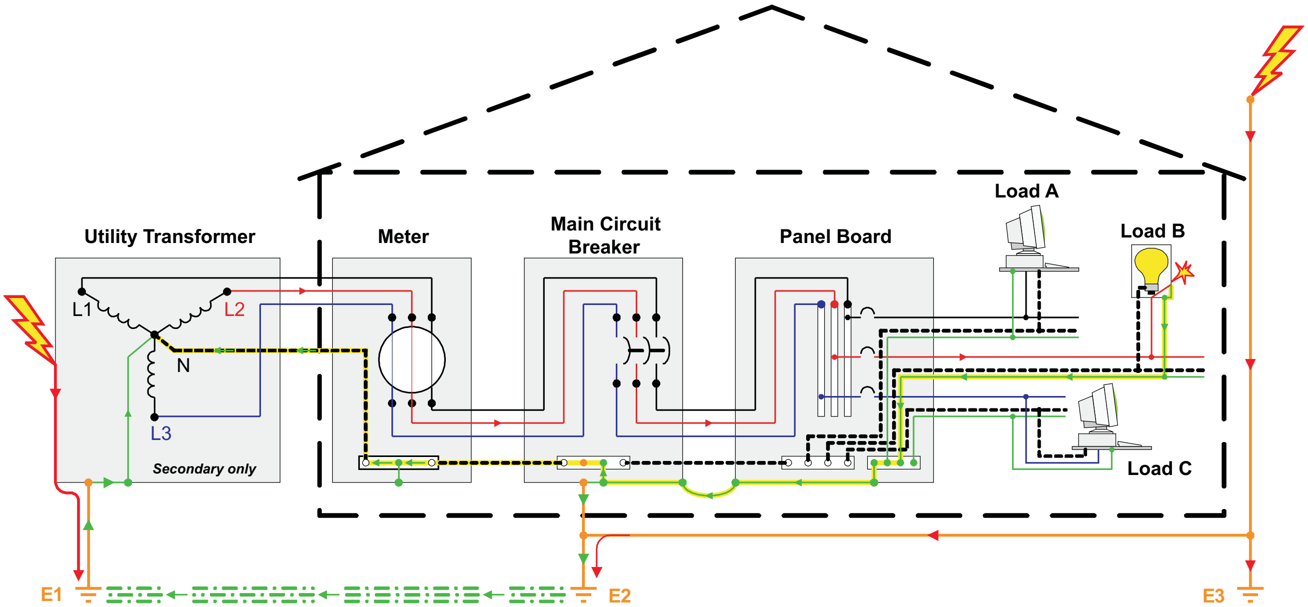

Figure 1. Basic Electrical Installation

The four wires leaving the transformer include the three phase conductors L1, L2, and L3 and the neutral conductor N (dotted line), which serves as return path for the ac phase currents. The wires run through the meter and the main circuit breaker to the panel boards, where they are split into separate load groups, (i.e., A, B, and C). A fifth wire, the protective earth conductor PE (green) connects the equipment chassis within a load group together and provides a low-impedance, fault-current path back to the source (transformer) during a ground-fault condition. Low impedance ensures sufficiently high fault-current to activate an overcurrent protection device, which removes high touch-voltage from faulty equipment.

Earthing

Earthing has two main objectives:

- Providing a solid reference potential (ideally 0 V) to the electrical installation system via a low-impedance connection to earth
- Protecting buildings and equipment exposed to lightning by diverting lightning strikes straight to earth

The grounding electrode E1 in Figure 1 grounds the center point of the transformer secondary, providing earth reference potential to the neutral conductor. Depending on the transformer's location, E1 might also protect against lightning.

Because utility transformers rarely provide a PE conductor and because voltage drops due to large neutral current can occur between the transformer and the service entrance, a second grounding electrode E2 is used to ground the supply system within the building. The structure of this electrode can be a metal rod, a metal water pipe system, or the metal frame of the building, provided that the latter two are in direct contact with earth for at least 10 feet.

Grounding electrodes in the form of water pipes and building frames also connect to the PE conductor at various locations within the building to ensure stable reference potential throughout the installation system.

Lightning protection is provided through electrode E3. This type of electrode usually has the structure of a long metal rod that must exceed the height of a building or outdoor equipment by a specified length. For lightning strikes, E3 provides a low-impedance path to earth. To further reduce the electrical impedance of the lightning-current path, the national electric code (NEC) requires that these electrodes also connect to the building's grounding system.

Many low-impedance connections between PE conductors and grounding electrodes in combination with multiple high-impedance paths between grounding electrodes and the line impedance of the conductors themselves create a highly complex impedance network, (see Figure 2), and currents flowing through it cause differing ground potentials at the various interconnections of this network.

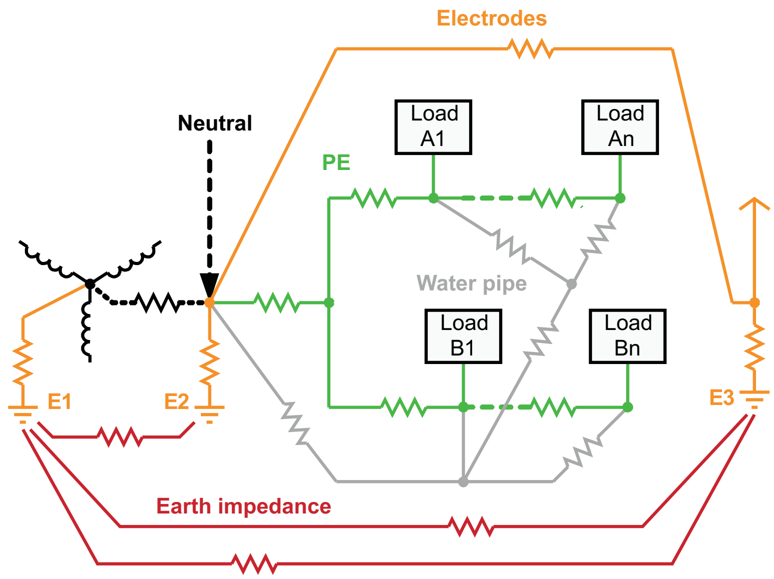

Figure 2. Complex Impedance Model of a Grounding Network

Literature often attributes the generation of ground potential differences to lightning or ground-fault conditions, but rarely mentions their existence during normal operation. The situation is further obscured by the National Electric Code (NEC) describing the PE as a currentless conductor, which would negate the existence of ground potential differences. That these assumptions are far from reality is discussed in the following sections. Currents in the neutral and the PE conductors can create GPDs ranging from small-to-large values depending on the type of loads connected to the installation and on the type of earthing system installed.

Linking Grounds

The link between the direct current (DC) ground of your local electronic circuit and the earth reference potential of the mains is usually provided by the local, power supply that converts the line voltage into the required DC output. Figure 3 shows a simplified block diagram of a low-cost, switched-mode power supply (SMPS), typically used in personal computers, laser printers, and other equipment.

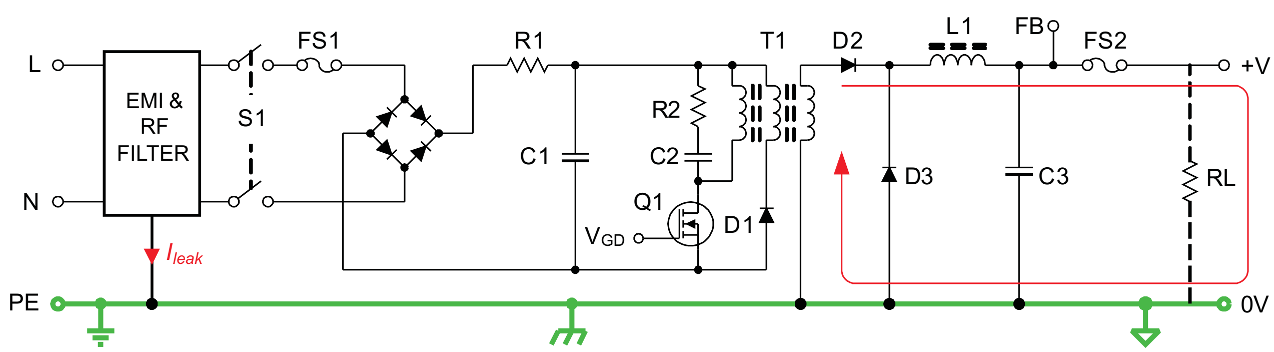

Figure 3. Simplified Block Diagram of an SMPS

The DC ground of the SMPS output is referenced to the protective earth (PE) conductor of the mains via the SMPS chassis. This direct link therefore acts as a sense wire, establishing the voltage at the PE conductor as the local DC ground potential.

Linear and Nonlinear Loads

Large office and industrial buildings operate a vast amount of nonlinear loads, such as PCs, laser printers, solid-state heater controls, fluorescent tubes, uninterruptible power supplies (UPS), and variable speed drives (VSD). In comparison to linear loads such as incandescent lamps, whose phase currents maintain a sinusoidal waveform, nonlinear loads distort phase currents, introducing large harmonic content. (see Figure 4).

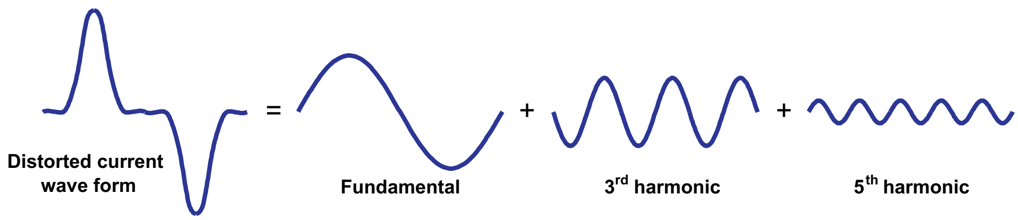

Figure 4. Distorted Phase Current and Its Frequency Components

Whereas the third and fifth harmonics of the fundamental 60-Hz line frequency comprise the majority of the harmonic content, the vector sum of all frequency components (including the 60-Hz fundamental) can reach peak values that exceed the amplitude of the fundamental phase current by more than 100%.

All neutral conductors merge into one neutral conductor of large diameter within the distribution panel running towards the transform (see Figure 5). In the case of linear loads, the neutral currents of different phase systems cancel each other to a certain extent and only a fraction of total neutral current remains due to loading imbalance (see Figure 5).

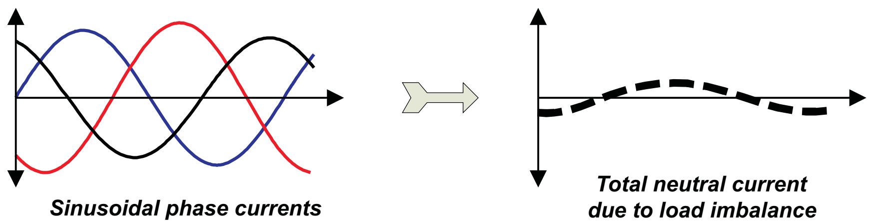

Figure 5. Sinusoidal Phase Currents and Total Neutral Current for Linear Loads

For nonlinear loads however, the individual currents add to a total neutral current primarily consisting of third harmonic content (see Figure 6).

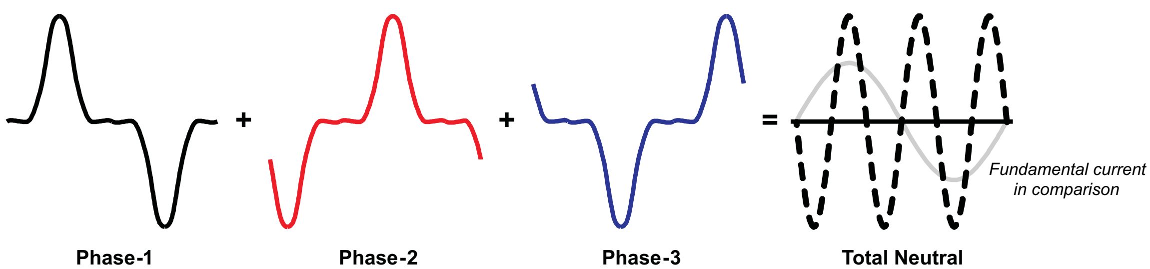

Figure 6. Total Neutral Current Mainly Consists of Third Harmonics

The large neutral currents of nonlinear loads, therefore, cause significantly higher voltage drops across the line resistance of the electrical installation than those of linear loads.

Besides large neutral currents, nonlinear loads can leak substantial current into the PE conductor. This is due to the design of the electromagnetic interference (EMI) filter, commonly used to prevent switching noise from the load entering the mains. Figure 7 shows that heavy capacitive loading not only exists between the phase and the neutral but also between neutral and the PE conductor.

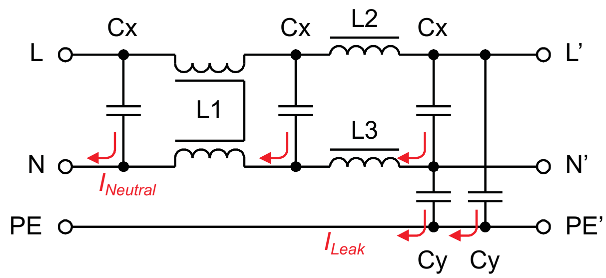

Figure 7. Typical Design of a Single-Phase, Two-Stage EMI Filter

The amount of leakage current is in the lower range of milliamperes and, although small for one unit, can easily reach amperes when considering that several hundreds of equipments contribute into the same strand.

Earthing Systems

Most electrical installations use one of the two earthing systems, TN-C or TN-C-S, shown in Figure 8 and Figure 9.

French Terre Neutral, or TN, means the neutral is grounded to earth at the transformer. The letter C indicates the combined use of protective earth and neutral via one conductor, designated as PEN.

The PEN runs through the entire system up to a distribution point, (i.e., a subpanel), close to the loads, where it is split into separate PE and neutral conductors that directly connect to the loads.

Although TN-C represents an old earthing system, it has regained in interest due to the cost savings achieved by avoiding the run of an additional PE conductor. This method however, has a major drawback. Because the split into PE and neutral occurs close to a load, the voltage potential at the local PE connect includes the large voltage drops across the line resistance R_{L-N} of long neutral conductors, caused by high neutral currents from nonlinear loads. TN-C systems, therefore, have the potential to cause large ground potential differences between remote grounds in the tens-of-volts.

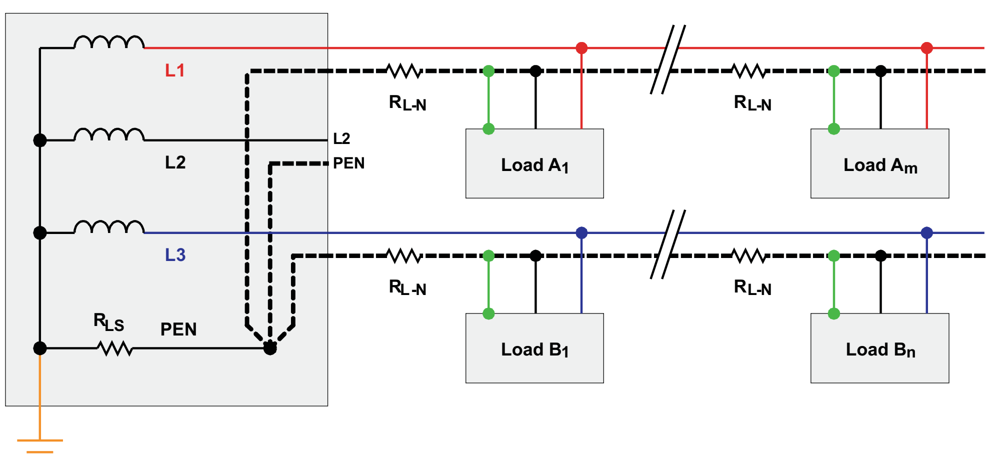

Figure 8. TN-C: The PEN Splits Into Separate Neutral and PE Close to the Loads

The TN-C-S system reduces GPDs by starting an extra PE-conductor within the distribution panel. Additionally, the star connection of the system's neutral and PE conductors receives a second grounding to earth, reducing the equipotential at this point and counteracting the otherwise large voltage drop at the PEN across the source line resistance R_{LS}.

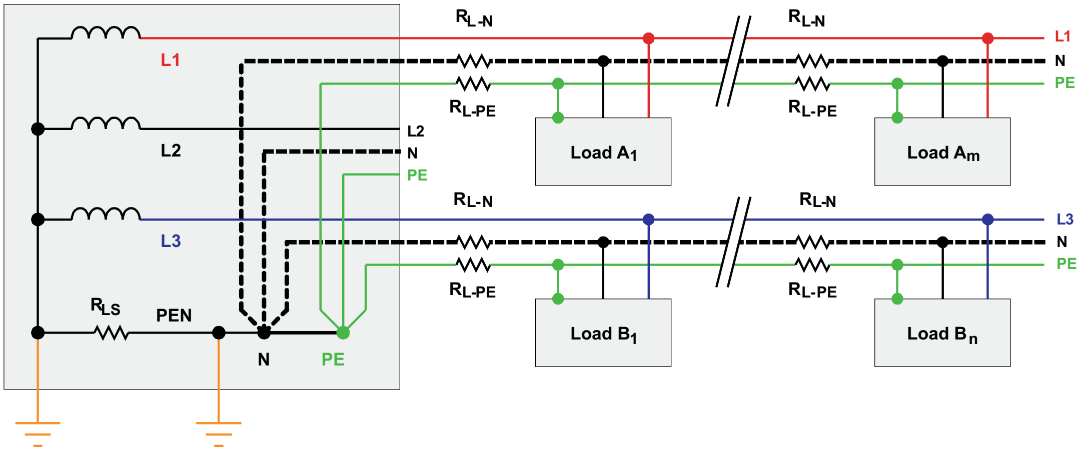

Figure 9. TN-C-S: The PEN Transformer Splits Into Separate Neutral and PE Within the Supply Systems

Although negligible in comparison with neutral currents, leakage currents do create potential differences between remote ground locations due to the voltage drops across the line resistance of the PE-conductors. These GPDs, however, are in the hundreds-of-millivolt or lower volt range and thus significantly lower than in TN-C systems.

Ground potential differences are not a problem for an electronic circuit limited to the operation from one local supply only. GPDs do become of concern when designing a communication link between two remote circuits, (i.e., fieldbus transceiver stations), each operating from a different supply.

Designing a Remote Data Link

When designing a remote data link, the designer must assume ground potential differences exist. These voltages add as common-mode noise Vn to the transmitter output. Even if the total superimposed signal is within the receiver's input common mode range, relying on the local earth ground as a reliable path for the return current is dangerous (see Figure 10a).

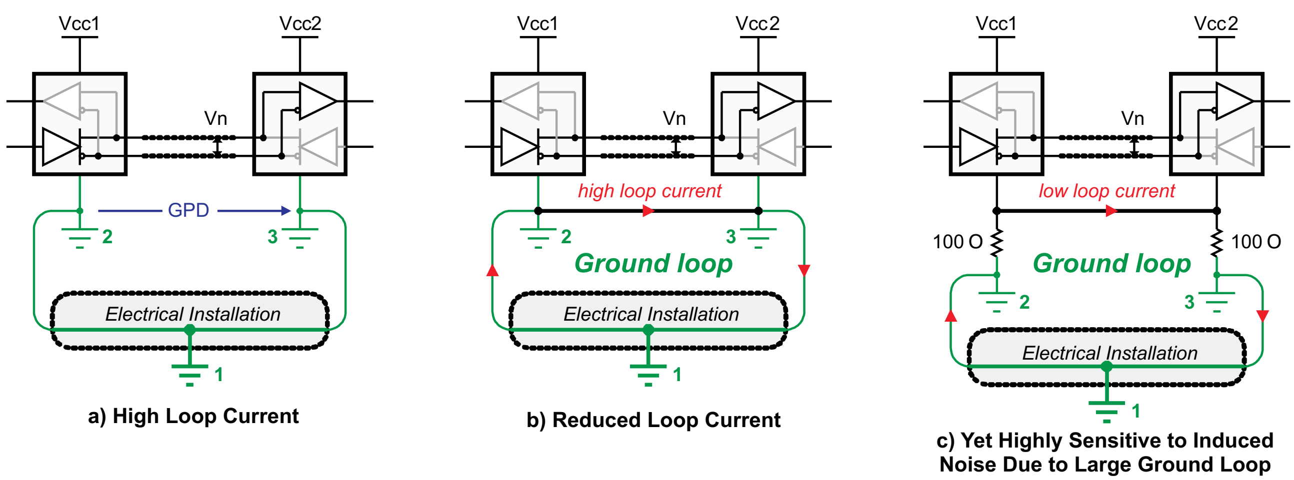

Figure 10. Design Pitfalls to be Aware Off: High GPD

Any modifications of the electrical installation, (e.g., during regular maintenance work), are out of the designer's control. The modifications can increase the GPD to the extent that the receiver's input common-mode range is either sporadically or permanently exceeded. Thus, a data link which perfectly works today might cease operation sometime in the future.

Removing the ground potential difference by directly connecting remote grounds through a ground wire is also not recommended (Figure 10b). As mentioned earlier, the electrical installation constitutes a highly complex impedance network. A direct connecting between remote grounds shunts this network while creating a current loop. The initial GPD tries to compensate its collapse by driving a large loop current through the low-impedance ground wire. The loop-current couples to the data line circuit and generates a noise voltage that is superimposed on the transmission signal (common-mode). This again carries the risk of a highly unreliable data transmission system.

To allow for a direct connection of remote grounds, the RS-485 standard recommends the separation of device ground and local system ground via the insertion of resistors (Figure 10c). Although this approach reduces loop current, the existence of a large ground loop keeps the data link sensitive to noise generated somewhere else along the loop. Thus, a robust data link has not been established yet.

The most robust RS-485 data link over long distance is via galvanic isolation of a bus transceiver from its local node circuitry (see Figure 11).

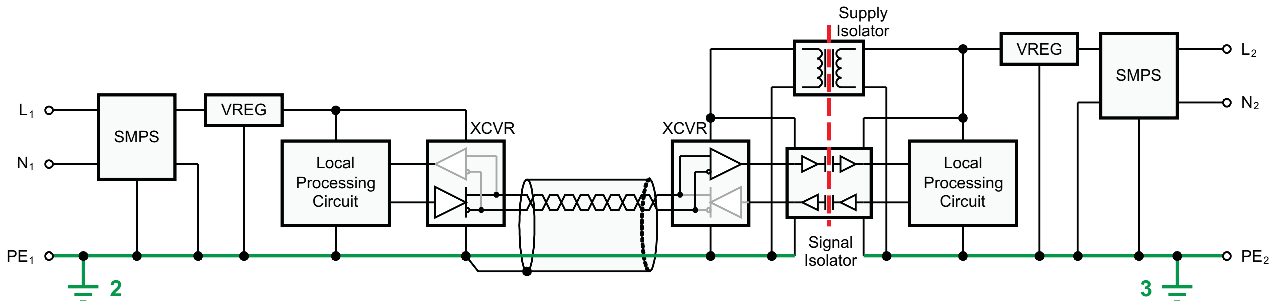

Figure 11. Isolation of Two Remote Transceiver Stations With Single-Ground Reference

Supply isolators such as isolated DC-DC converters and signal isolators such as digital, capacitive isolators prevent current flow between remote system grounds up to GPDs of several thousands-of-volts and avoid the creation of current loops.

Without a reference to ground, the bus transceiver would be operating from a floating supply. Thus, current or voltage surges caused by lightning, ground-faults, or other noisy environment would be able to lift the floating bus common to dangerously high levels. These events do not destroy components connected to the bus, as their signal and supply levels are referenced to bus common and ride on the varying common reference potential. However, where the transmission wires connect to PCB connectors at the various transceiver nodes, the high voltages, if not removed, can lead to arcing and destroy PCB components close to the connector. To suppress current and voltage transients on the bus common, it is necessary to reference bus common at one point to system ground. This location usually is at a nonisolated transceiver node, which builds the single-ground reference for the entire bus system.

While Figure 11 shows the detailed connection of two remote transceiver nodes, Figure 12 gives an example for an isolated data transmission system using multiple transceivers. Here all but one transceiver connect to the bus via isolation. The nonisolated transceiver on the left provides the single-ground reference for the entire bus.

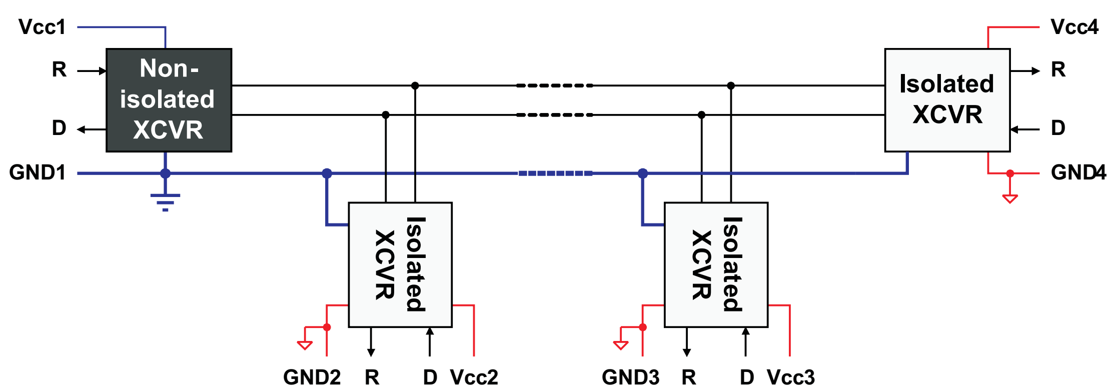

Figure 12. Isolation of Multiple Fieldbus Transceiver Stations

Conclusion

Designing remote data links requires the isolation of supply and signal lines of the bus transceiver stations to circumvent the detrimental effects from ground potential differences and ground loops on signal integrity and component health.

Although some of the figures presented refer to digital signaling, the principles discussed apply to almost any circuit in the data acquisition and data transmission domains. Data transmission circuits, however, are the more susceptible ones due to their large dimensions.

Texas Instruments has an extensive product range to support the design of isolated, industrial interfaces including: data transceivers complying with the RS232, RS422 and RS485 interface standards, digital isolators for unidirectional and bidirectional data flow in dual, triple and quad versions (from DC to 150 Mbps), and isolated DC/DC converters (3-V and 5-V regulated outputs), to provide the power supply across the isolation barrier.

For detailed information on reference designs of isolated data transmission circuits, visit: www.ti.com/interface.