Understanding grounding, shielding, and guarding in high-impedance applications

James Niemann - February 15, 2013

Inadequate shielding and bad grounding are often blamed when measurements are inaccurate, especially in high-impedance applications. In fact, shielding and grounding problems are frequently responsible for measurement errors, but many test system developers aren’t quite sure why. Many measurement errors can be traced back to currents from external fields that have become coupled into the measurement test leads. This article explores how ground loops and poor or non-existent electrostatic shielding can cause error or noise currents to flow in measurement leads or the device under test (DUT), as well as techniques for identifying these error currents and preventing them from undermining measurement integrity. First, however, a review of electrostatics might provide a clearer understanding of the source of the problem.

Review of Electrostatics

Charges or charged particles are point sources of an electrostatic field (E-field). Field lines always emanate from the positive charge(s) and terminate on the negative charge(s). The force between charged particles is attractive when the charges on each particle are complementary and repulsive when the charges are identical. The E-field stores energy; the amount of energy stored is proportional to the total number of lines of flux (or to the total charge). The error current coupled into measurement conductors is directly proportional to the strength of the field. At any given voltage, the capacitance describes the relationship between charge and voltage on two conducting bodies. The energy stored in the field is equal to one-half of the capacitance multiplied by the square of the voltage: . Wherever a voltage is present, there’s also a distribution of positive and negative charges, even if one of the conductors is grounded.

Voltages generate a high-impedance field. Currents (magnetic fields) generate a low-impedance field. The field impedance is always the ratio of the electric field to the magnetic field for any electromagnetic wave. Shields work by both reflection and absorption of field energy. If the terminating impedance of an electromagnetic wave is orthogonal to the wave impedance, reflection will predominate. If they are of similar impedance, absorption is the only possibility.

Electrostatic Coupling

Charges unassociated with the measurement circuit are responsible for numerous measurement problems. If a charge is fixed in space around an unshielded measurement, the E-field from the charge will radiate to the measurement lead(s) and terminate on an image charge (a complementary charge of opposite polarity). Due to the E-field, a DC leakage current could potentially flow into the measurement leads. If a charge or a conductor with a charge distribution is moving in space with respect to the measurement circuit, an AC current (where C= the capacitance between the charge or the conductor and the measurement circuit) will flow into the measurement leads.

External conductors at a different voltage than the measurement circuit behave in exactly the same
way as point charges do. When the voltage on the external conductor changes, a current equal to will flow into the measurement. Both of these cases, i.e., point charges and differing voltages, will couple noise and error currents into the measurement. Any E-field line terminating on the measurement leads has the capacity to couple current into the circuit. E-fields dominate the interference landscape except when high currents are involved or whenever the instrument or measurement is operated near a transformer or a magnetic source. Ideally, all E-field lines from external sources should fall on a shield or guard instead of the measurement leads. Also, all E-field lines from the measurement and the instrument should fall on either the shield or the guard, never on outside conductors or charges. When the external E-field lines fall on either the shield or the guard, rather than the measurement leads, the measurement will be unaffected by these external electrostatic error sources.

RF Coupling
Radio frequency (RF) energy is ubiquitous. Any conductor of reasonable length, including the cables that connect instruments to devices, can act as an antenna for this energy. Although this radiation is outside the bandwidth of the source/measure instrumentation, the electromagnetic radiation will generate currents that travel up and down the antenna (in this case, the measurement leads). When these currents come in contact with the amplifiers inside the instrument, these currents may be rectified, causing a DC offset in the measurement. For this reason, both the HI and LO terminals require a shield to ensure that this current flows in the shield rather than in a measurement lead. The safety shield is usually used (outside the instrument common shield) as the shield for this source of noise. However, in order to provide complete shielding at these frequencies, the shield must not have any apertures (holes or slots) greater than $\lambda/2$, where $\lambda$ is the wavelength of the interfering radiation.

Magnetic Coupling
Magnetic coupling is unrelated to currents flowing in measurement leads but rather to the generation of voltages as predicted by Faraday’s law of induction. The magnetic field (M-field), unlike the E-field, is a low-impedance field. Conductors suitable for use as shields provide a matching impedance (unlike the high-impedance E-field) to the M-field; as a result, they will not reflect the energy away from the measurement conductors inside. To shield an M-field, either the magnetic lines of flux must be diverted through a magnetic material (this works well at DC and low frequencies with $\mu$-metal) or the shield must be thick enough to attenuate the field by absorbing the energy [1].

Shielding
The purpose of shielding is to reduce or eliminate noise currents from coupling into electrical measurements. These currents can originate from point sources of charge, generating E-fields and voltage distributions. For example, people carry static charges with them wherever they go. AC line potentials in and around the laboratory or production environment can elicit AC E-fields, which, in turn, generate error currents. When devices under test are grounded outside the confines of the instrument, a different ground potential (different from the instrument) is responsible for yet another E-field generating current in the measurement ground lead. The isolation capacitance in the instrument’s power transformer completes the circuit that supports the error current. Thunderstorms and environmental changes can cause electrostatic field changes. Radiation from RF sources can also generate currents in test leads, causing EMI rectified offsets in the amplifiers internal to the measurement instrumentation. Even in fair weather, the earth itself has a field with respect to the upper atmosphere of ~100V/M. Electrostatic Shield
The electrostatic shield prevents external E-fields (a high impedance field) from affecting a measurement circuit by providing an equipotential surface to capture the E-field, deflecting it from the measurement leads inside. To prevent the shield from coupling internal circuits to one another,
the shield ground point is connected to LO inside the instrument. This grounding scheme ensures that internal measurement nodes see only the instrument LO (see Figure 1). To be effective, the shield must cover the entire measurement node. The instrument design should already include this shield wherever it is needed and provide for its extension to the outside world. Although this shield is a good idea for any measurement, it is imperative for high-impedance measurements (i.e., any measurement >100Kohms). The resulting interference voltage is: $V = I_i \times R$, where $I_i$ is the coupled current, and $R$ is the impedance of the measurement. This shield does not prevent DC or AC currents from flowing between the measurement circuits and the shield. The common shield only provides protection from external electrostatic interference.

![Diagram of shield ground point connected to LO inside the instrument.](image)

**Figure 1: The proper use of the shield in a test system. The electrostatic shield is grounded to circuit common. Notice that both the HI and the LO terminals are shielded.**

The driven guard accomplishes all that the common shield does, as well as eliminating the currents from the guard to the measurement circuits (see Figure 2). The guard is simply a common shield buffered or driven to the measurement circuit voltage (instead of connected to instrument LO) to eliminate the E-field between the guard and the measurement circuit. Guards are used in circuits designed to measure or source very low currents, and are usually mandatory for currents of less than 1nA.
Figure 2: The proper use of the guard in a test system. Notice that both the HI and the LO terminals are either shielded or guarded, and that the box surrounding the DUT provides a complete electrostatic shield.

When measuring currents of 1nA or less, the measurement node must first be guarded. Instruments used to measure or source these levels of current or lower will have the measurement guarded inside. It is not necessary to have a shield in addition to a guard around the measurement node, but the remaining measurement circuitry should be shielded. The electrometer configuration allows a common shield to act as a guard as well, by ensuring that the measurement node is at ground potential (see Figure 3).

Figure 3: An illustration of the shield and guard configuration for an electrometer.

This suggests that the fundamental difference between a shield and a guard is that a shield prevents
external fields from affecting measurements, while a guard adds protection from DC leakage currents by surrounding the measurement node with a voltage identical to that of the measurement node, both inside and outside the instrument, eliminating leakage currents.

**Safety Grounding**

The safety shield surrounds the electrostatic shield, protecting the instrument user from hazardous voltages on the DUT, or the measurement leads. The safety shield should be connected to earth ground at the instrument, and it should have a current capacity greater than the larger of the SMU output current and any earth-referenced source driving the LO terminal. When this safety shield is in place, if a measurement lead, the electrostatic shield, or the driven guard were to touch the inside of the safety shield, the earth connection would keep the safety shield at a low potential. The safety shield also provides protection from the AC mains inside the instrument. In this case, the safety shield is the instrument chassis, which is also connected to earth. The safety grounding system follows the power system to allow this connection to be made. Instrumentation is safety grounded at the power inlet, ensuring that the metal instrument enclosure is always safe to touch. Even if a line voltage connection were to come loose and contact the enclosure from the inside of the instrument, the safety ground would keep the instrument chassis at a low potential and safe to touch.

The safety ground shield should never be used as the electrostatic shield. Even well-designed instrumentation generates currents that travel down the safety ground in the line cord. Current from the power supply Y capacitors and higher frequency currents from a switching power supply can generate noise voltages on the instrument chassis with respect to external safety ground as the current flows through the inductance of the power cord. The resulting noise voltage appears as a common mode voltage from the safety ground to the instrument chassis. This voltage is troublesome because instrumentation measurement common is not completely isolated from the instrument chassis (earth grounded). Every instrument generates some DC and AC leakage current across the instrument mains isolation barrier, and a finite capacitance from instrument common to the instrument safety ground. This capacitance is what facilitates the flow of AC current. We do not want these currents to flow through any part of the measurement pathway (see Figure 4). These currents create voltage drops in the measurement leads, as well as voltages across other impedances in the measurement circuit.

Because instruments may be designed to float hundreds of volts above earth ground, and shield ground should be connected to the instrument measurement common, the measurement terminals and electrostatic shield should always be considered unsafe.
**Grounding the shield**
Should the instrument shield (which is instrument LO) be connected to safety ground? Only if the application does not drive LO, and it should be done in a way that does not allow currents to flow in the measurement leads. From an instrumentation perspective, the only reason to connect LO to safety ground is to keep the measurement terminals within the common mode specification of the instrument. Given that the measurement LO terminal is floating in many instrument designs, a higher value (~100K ohms) resistor can be added from safety ground to the measurement LO terminal.

**Common Mode Current**

In the section titled “Safety Grounding,” I mentioned that the instrument(s) themselves are responsible for some of the current that generates the common mode voltage, Vx (see Figure 4). These common mode currents are a direct result of the magnitude of the voltages on the primary and secondary windings of the power transformer acting on the unshielded capacitance across the transformer.

Figure 4 illustrates a typical instrument power transformer designed with primary and secondary shields. The shields within a power transformer perform the same function as the instrument shields already discussed. In the case of the instrument shield, when a portion of the measurement remains unshielded, external field lines can inject current into the measurement. The same is true with the power transformer, except due to the proximity of the primary to the secondary windings, as well as the magnitude of the voltages, the currents could be much higher if the transformer shields were absent. The capacitor C1 represents the unshielded capacitance from the secondary winding to the primary shield. This is the portion of the primary that remained unshielded. Likewise, the capacitor C2 represents the unshielded capacitance from the primary winding to the secondary shield. The total common mode current is the sum of the currents through each of these capacitors. The common mode current will increase as the primary and secondary transformer voltages increase or
when the frequency of the power supply operation increases. The unshielded capacitance offers increasingly lower impedance to higher frequency edges, increasing the magnitude of the common-mode current.

Common-mode current originating on the primary flows through the capacitor C2 into the secondary circuits, into the chassis through the measurement leads, and eventually returns to the primary ground that generated it. Common-mode current originating on the secondary flows through the capacitor C1 into the primary circuit, into the chassis at the power-entry module, then through the measurement leads, and eventually returns to the secondary ground that generated it. The net common-mode current causes a voltage drop in the instrument power cord inductance, as well as a voltage drop in the ground connection between the DUT and the instrument. For this reason, it is best to use the chassis connection provided by the instrumentation whenever possible to avoid introducing a new safety ground to the system. The unshielded capacitance and, to a lesser degree, the DC resistance across the transformer can couple noise currents from other sources that generate differences in safety grounds throughout the building.

**Example of a well-shielded and grounded single SMU test system**

In the example shown in Figure 5a, if the measurement LO terminal were to be grounded to earth at the DUT LO terminal, either directly or through a capacitance, ground currents would flow in the measurement leads, and remote sensing would have to be used to eliminate the error voltage generated by the E-field between the two safety grounds. In Figure 5b, if the shield surrounding the DUT were connected to earth, current would not flow through the measurement LO connection. In this case, the capacitance from the DUT to its surrounding shield should be minimized. In Figure 5c, the shield is connected to earth at the instrument through a current limiting resistor. In this case, the potential between safety earth grounds depicted by Vx does not force any current because only one safety earth ground has been introduced.

![Figure 5a. With a single SMU, grounding the DUT, either directly or through a](image_url)
capacitance, can channel ground current into the measurement LO lead.

Figure 5b. In this single SMU application, grounding LO at the DUT, either directly or through a capacitance, leads to no error currents in the measurement LO lead.

Figure 5c. With a single SMU, grounding the shield with a resistor, at the instrument leads to no error current in the measurement LO lead.

In all of these examples, the guard should be brought as close to the DUT as possible and dropped only after it is within the DUT shield.
Example of a well-shielded and grounded multi-instrument test system

Figure 5d introduces a second instrument into the test system. In this case, preventing all ground currents from entering into the measurement is difficult because there are two different safety ground connections. So, the resulting current can be reduced by connecting LO to safety earth with a high resistance at only a single point, by connecting both shields to the DUT shield, as shown in Figure 5d. In this case, the bulk of the current will flow through both power transformers and through the shield system. Some current will flow through the measurement leads, so remote sensing will also be necessary.

![Diagram of well-shielded multi-instrument test system]

**Figure 5d.** With two SMUs, the remote sense lines compensate for the current flowing in the measurement leads generated from the use of two different grounds.

Conclusions

Most measurement errors can be traced to currents coupled into the DUT or into the measurement leads from external electrostatic (high-impedance) fields. Adding an electrostatic shield properly grounded to the instrument LO can totally eliminate these noise sources. In some instances, a guard must be used instead of or in addition to an electrostatic shield, for very low current applications. Differences in the safety ground caused by safety-ground currents generated from line-operated equipment can also cause measurement errors if the current is allowed to flow through the measurement leads. Common-mode current from the test system’s instruments contribute to these errors. The instrument power transformer supports this current, so any connection to safety ground should be created as described. The safety shield used to maintain operator safety offers the added benefit of providing some low-frequency RF shielding. If the instrument common is connected to safety ground with a relatively large resistor, the RF energy will not enter the instrument, and voltages due to EMI rectification can be minimized.

References


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