Signal Integrity for Vacuum Processing Systems

Successful operation of power supplies and instrumentation in vacuum processing systems requires detailed attention to signal integrity. This paper introduces techniques involving signal grounding, shielding, coaxial cables, twisted pair cables, and quad cables, as well as methods for preventing electrical interference. These techniques and methods effectively reduce electrical noise emitted from power systems and decrease the sensitivity of control and instrumentation systems to electrical noise.

¡caution regarding safety grounding!

Safety grounding must be done properly, in accordance with applicable local codes and regulations. The details of safety grounding are beyond the scope of this document. Please refer to applicable standards for your location.

Various commercial and governmental agencies, including UL, CSA, VDE, TÜV, LGA, FCC, IEEE, SAE, CISPR, and many other local agencies, promulgate information on grounding to meet governmental standards such as the U.S. and Japanese National Electric Codes, Canadian Safety Agency Regulations, and European Community Norms (EN documents).

overview

Vacuum processing systems are often composed of equipment and instrumentation from diverse sources that must work together. To achieve a harmonious result, you sometimes need to solve problems with electrical noise. In this case, electrical noise is defined as unwanted signals that prevent proper system operation by disrupting individual system component operation.

The key to signal integrity is first understanding how signals can inadvertently be connected or transmitted from one piece of equipment to another, and then preventing or reducing the unwanted coupling or connection. The sections on power cabling and signal cabling cover the basics and should help you solve problems with electrical noise in vacuum processing systems.

Figure 1 illustrates a common problem that can be corrected by changing the way output power and measurement circuits are connected.

contents

In this circuit, current from the power source flows into the load, where a voltage divider samples the voltage across the load (that is, from the "hot" side of the load to ground) and compares it to a voltage reference. The error amplifier detects any difference and controls the power source through a simple feedback loop. What can go wrong with such a simple circuit? As the circuit is drawn, nothing.

The problem is that the ground symbol represents an ideal that does not actually exist in nature. In reality, the current must flow in a loop with non-zero impedance as shown in Figure 2.

The current flowing in the load causes potential drops across the loop resistances, and this can seriously affect the operation of the circuit. In Figure 2, the voltages dropped by the loop current across R_1 and R_2 cause the measured voltage to differ from the actual voltage across the load. Also, the voltage dropped across R_3 effectively subtracts from the reference voltage. Both effects cause the voltage across the load to decrease as the load current increases, destroying the load regulation of the power supply. None of this is obvious in the original circuit diagram, where the ground symbol hides the circuit loop, its impedance, and the resulting problem.

Figure 3 illustrates a way to resolve the problem.

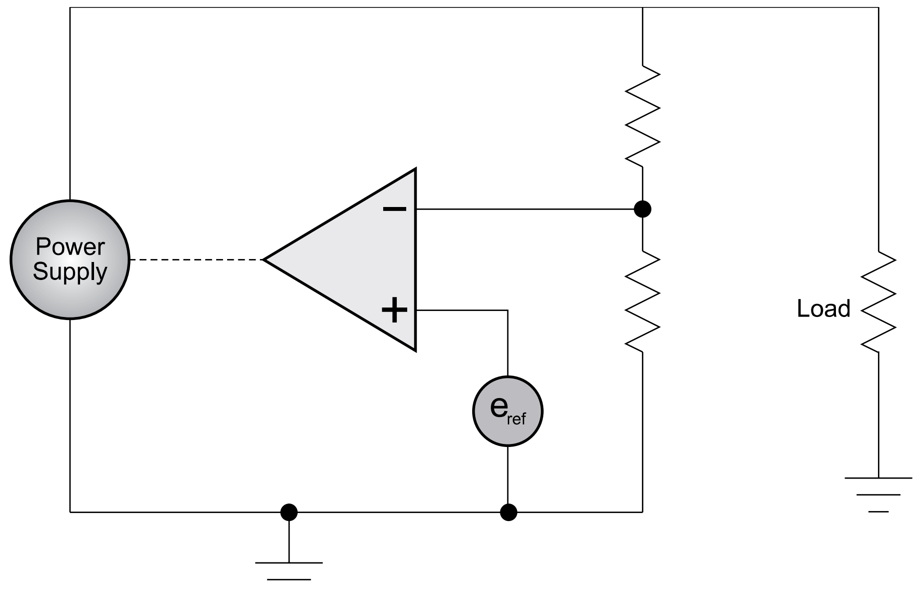

figure 1 regulated power supply (supposed circuit)

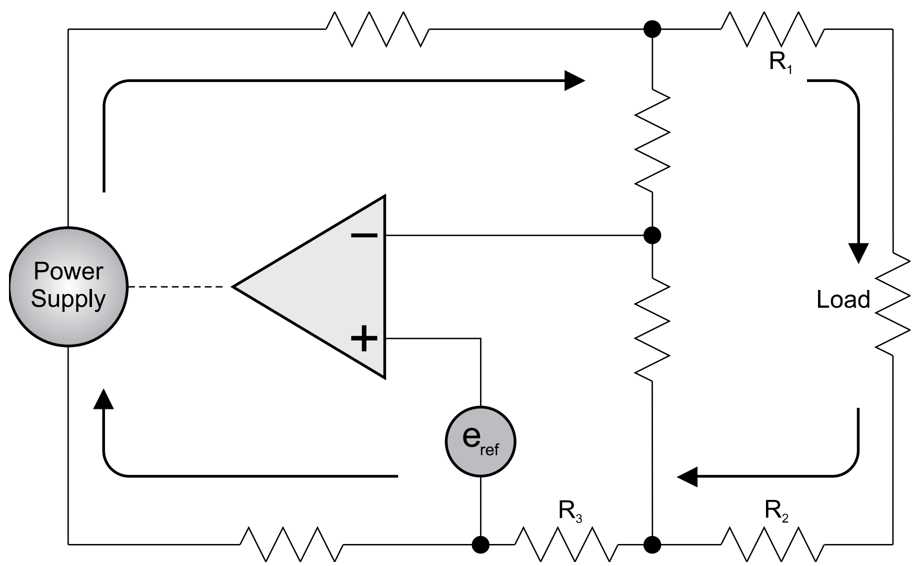

figure 2 regulated power supply (actual circuit)

Here, a separate ground path is created in which the load current flows. If the resistance in this separate ground path (represented by $R_4 + R_5$) is small compared to the resistance represented by R_1, R_2, and R_3 and the dotted resistors, most of the load current will bypass R_1, R_2, and R_3, thereby minimizing the voltage. Note that if you remove the connection represented by the dotted resistors, Figures 2 and 3 become identical ($R_{1\text{-}3}$ are small compared to the voltage divider resistance and can be ignored). In this case, the error is entirely removed, as no current can flow in the middle loop.

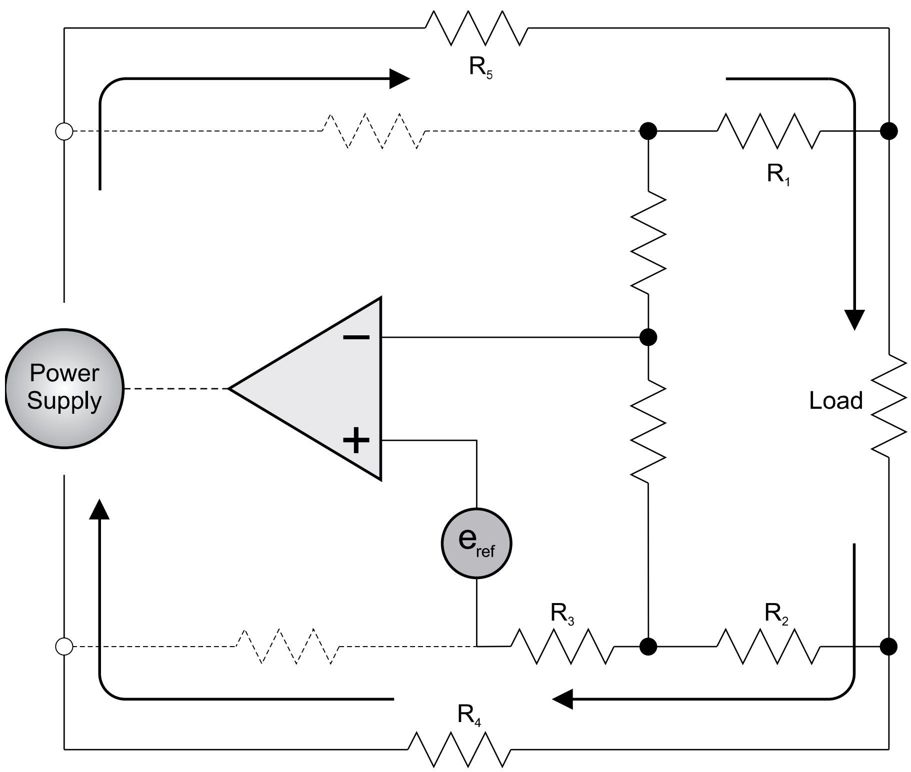

figure 3 regulated power supply with separate load current path

The important thing to realize is that the problem and solutions become obvious once the circuit is drawn as it actually exists, without the use of the ground symbol.

This raises a central point in grounding: knowledge of the current paths is the most powerful tool in understanding how to reduce interference and errors. In general, you need to know where the currents are flowing so that you can control the paths. The best way to control the paths is to ensure that the main power current flows in a single path.

Once the separate current path of Figure 3 is created, it is clearly best to eliminate the dotted connections, so the load current is forced into the outside path where you can control it. This becomes obvious only if you draw the entire circuit without the use of the ground symbol but with the resistors for any path in which load current flows. Do this, and the source and solutions of many mysterious problems related to "system noise" will suddenly become evident.

signal cabling

In this document, *signal cabling* refers to the cables that are used to send control signals to and from the unit.

shielding

For the purposes here, shielding is the process of minimizing signal interference through dielectric materials. How to best shield your circuits depends on how the interference is coupled. *Capacitive* coupling is electric-field coupling. *Inductive* coupling is magnetic-field coupling.

shielding against capacitive coupling

Capacitive coupling occurs when interfering signals pass through stray capacitances. Capacitive coupling to your body, for example, is what might cause an oscillator to change its frequency when you reach your hand over the circuit. In a digital system, cross talk in multi-wire cables is the principal cause of capacitive coupling. To block capacitive coupling, enclose the circuit or conductor you want to protect in a metal shield. This creates an electrostatic, or faraday, shield that breaks capacitive coupling between a noisy circuit and a victim circuit, as shown in Figure 4.

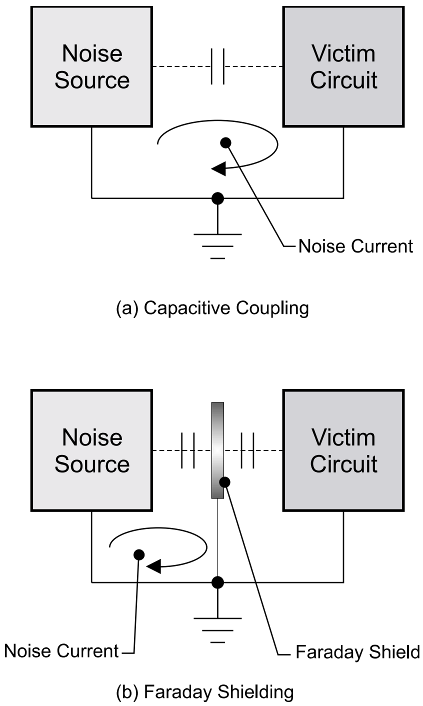

figure 4 capacitive coupling and faraday shielding

Figure 4a shows two circuits coupled through the stray capacitance between them. In Figure 4b, a grounded faraday shield intercepts the stray capacitance so that interference currents flow to ground. You may, for example, insert a ground plane between printed circuit boards (PCB) to eliminate capacitive coupling among them. Similarly, you might ground every other lead in a ribbon cable to reduce cross talk between the remaining leads. Note that in this case the *shield coverage* is not nearly 100 percent, but, often, the ground reduces the interference to adequately low levels. If the capacitance between the shield and the noise source is high enough, the diverted current will be large; therefore, for the shield to be effective, ensure the connection between the shield and the ground has low inductance.

shielding against inductive coupling

With inductive coupling, a time-varying magnetic field links with a victim circuit and generates a voltage, causing eddy currents to flow in the victim circuit and cancel magnetic fields. Several techniques can reduce inductive coupling. One approach is to minimize the offensive fields at their source. You can, for example, minimize the area of the current loop to promote field cancellation. Another approach is to minimize the area of the receiving loop, and thereby the inductive pickup in the victim circuit, since the induced voltage is proportional to this area.

In Figure 5, a time-varying magnetic field induces currents in the nearby shield, a conducting plane of metal. These currents reduce the field; that is, the field that the eddy currents in the shield generate is opposite to the inducing field, near to the plane. The result is a conducting plane that produces electrostatic shielding and magnetic shielding.

Two other factors are also important in creating effective magnetic shielding: properly configuring seams, joints, and holes in the physical structure of the enclosure and selecting the appropriate shielding material.

It is important to allow the eddy currents in the shield to flow freely. If the currents have to detour around slots and holes, or flow across gaps, the shield loses much of its effectiveness. The natural gap at the joint (between the folded back of the enclosure and the side) prevents eddy currents from flowing over the corner joint and provides imperfect

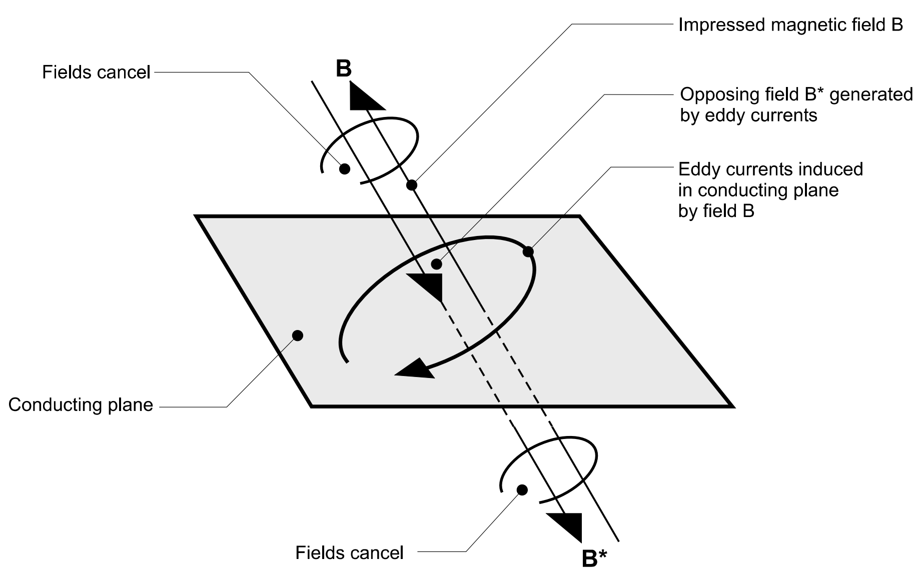

figure 5 time-varying magnetic field inducing currents magnetic shielding. To ensure that the currents can flow easily over all joints, weld joints in enclosures for high frequencies and equipment sensitive to magnetic interference.

Any holes in the enclosure must be either small or be made in such a way to take into account the presence of the currents. Figure 6a shows an intact wall with its current distribution; in 6b a hole has been punched in the wall, reducing the shield's effectiveness.

Appropriate shielding material is also important. At lower frequencies, the enclosure itself must consist of magnetic permeable and conductive material that provides a conducting path for eddy currents. At higher frequencies, the conductivity is important as well in order to gain the most benefit from eddy currents. Therefore, aluminum or copper materials are the best choice. Choosing magnetic materials involves a compromise in conductivity and in electrostatic shielding effectiveness. For some applications, it may be necessary to use a shield within a shield, one magnetic permeable and the other non-magnetic.

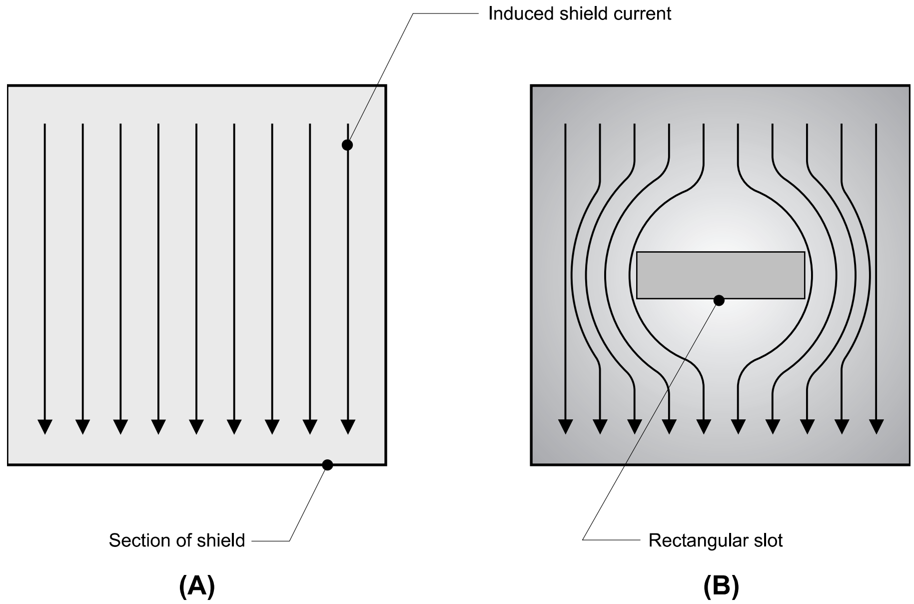

figure 6 current distribution with and without a hole

avoiding ground loops

Using the ground symbol can lure the designer into another trap: ignoring currents that may flow along ground wires, created by small differences in potential across the very low resistance of ground connections. A typical situation is shown in Figure 7.

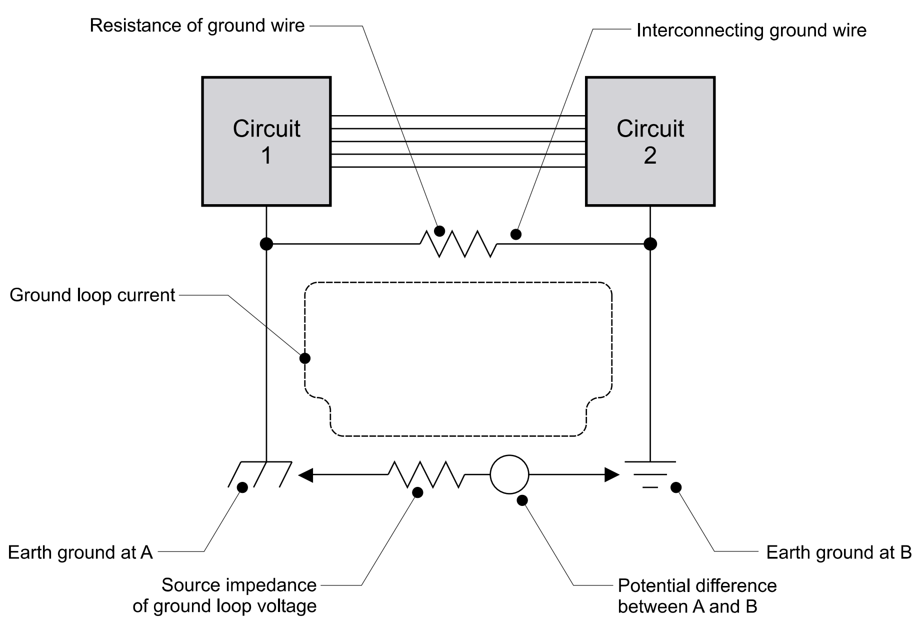

figure 7 ground loops

Here, circuit 1 is tied to earth ground at position A, and circuit 2 is tied to earth ground at position B. If these two positions are physically close together, and there is no high power equipment for some distance, you can assume that the earth grounds (whether actual rods buried in the earth, or a green or green/yellow "PE" ground wire, is immaterial) are at the same potential.

On the other hand, if there is power equipment or power loads nearby, or if positions A and B are physically separated by a substantial distance, there may be a difference in potential between the earth ground at points A and B. This could be due to currents flowing in the ground straps, wires, or earth, for example. Generally the source impedance of this difference potential is very low—in the milli-ohm or even micro-ohm regime. This difference in potential will drive a current through any connecting wire between the two circuits, as shown in Figure 7.

The magnitude of the current can be very large, even if the voltage difference is small, because of the extremely low source impedance of the ground loop and the small resistance of the interconnecting ground wire. Currents in such interconnect wires can create interference by radiation or induction and can unexpectedly offset amplifiers and other sensitive electronics.

Clearly, it is desirable to avoid the "double" ground connection that forms the basis for the ground loop. To avoid connecting locally to earth ground or forming a second connection to the earth ground wiring of the power system, use a "star" grounding system wherein each item or circuit to be grounded is separately connected to a single grounding point (the center of the star).

Sometimes, however, this is impossible, because more than one point in the system is irrevocably connected to ground (through a water line, for example). In this case, eliminate the additional ground connection that the separate wire connection forms between the two grounded points. This is called "breaking the ground loop."

There will be occasions when it is impossible to avoid the double ground connection or to break the ground loop. For example, you may need to use a high-power radio frequency cable connected to ground at both ends to connect two points that are irrevocably grounded. Or, the same two points may have a sensitive (low-level) signal cable that you must shield, but grounding the shield at one end provides insufficient electrostatic shielding of the cable.

In these cases, determine if the system could be physically reorganized so that the two points in question are closer together electrically. Alternatively, you may use a double shield, with one shield connected to ground at one end of the cable and the other shield connected to ground at the other end of the cable (of course, the two shields must be electrically isolated from each other). This may work if you use a short cable so that the capacitance between the two shields is small enough to avoid the capacitance itself forming a ground loop current path.

If these techniques are not possible, then inserting an impedance in the ground path may raise the load resistance of the ground connection so that the loop current is sufficiently small. To accomplish this, pass the cable through a ferrite core designed for that purpose. One or more turns may be required.

power cabling

coaxial cable

Coaxial cable helps control impedance over a large range of frequencies and relatively low inductance. Produced in high volume, coaxial cable provides high performance at relatively low cost. Figure 8 illustrates a power source connected to a remote load with a coaxial cable.

The power current flows through the center conductor and back to the source through the outer conductor, or shield (see the "Shielding" section at the beginning of this paper). Because the shield completely surrounds the center conductor, and is also concentric with it, there is no (or only a small) external electric or magnetic field. Generally, the shield connects to ground at both

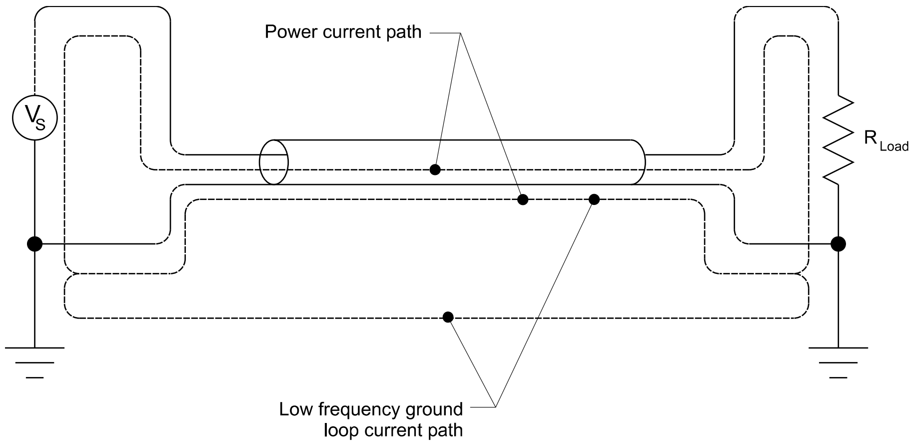

figure 8 power source connected to a remote load with a coaxial cable

ends, in which case a ground loop forms for low-frequency currents to flow. If you are using coaxial cable, ground the cable at both ends. When transmitting low frequencies—below about one megahertz—you can install a common-mode choke to break the ground loop (see the "Multiple Paths in AC Power Systems" section later in this paper).

Coaxial cable has a power rating for radio frequencies (refer to the cable manufacturers' data sheets) that is dependent upon a number of factors, including dielectric losses in the insulating material. At lower frequencies, the important factor is the I^2R loss in the center conductor. Over time, if the center conductor reaches high temperatures, it can pass through the insulation and contact the shield. Therefore, it is important to ensure the center conductor remains at a safe temperature. For higher currents with the same cable size, use a Teflon® [i]-insulated cable such as RG-393. (Please note that Teflon-insulated cable is much more expensive than polyethylene-insulated cable.)

twisted-pair cable

Twisted-pair cable consists of wires twisted together so that each loops around the other, as shown in Figure 9.

Twisted-pair cable, which you can easily make from available single-conductor wire, is inexpensive and greatly reduces interference. This is because each micro-loop produces an electric dipole field and a magnetic field, opposite to that produced by the adjacent loop. The resulting fields are opposite in sign and cancel one another at a distance from the cable.

Shielding can reduce radiated noise even more, but a shield close to the wiring within it will have currents induced in it by the AC signal in the wires (see the "Shielding" section at the beginning of this paper). This may cause heating in the shield and power loss. Make sure the cable and the shield do not become too hot due to this effect. Heating may also occur in a metal cable tray in which the cable is laid or in the shields of coaxial cables close to the twisted pair. For this reason, run the twisted pair in a separate, insulated cable tray, or space it from metal (especially mild steel) if the cable is carrying high power.

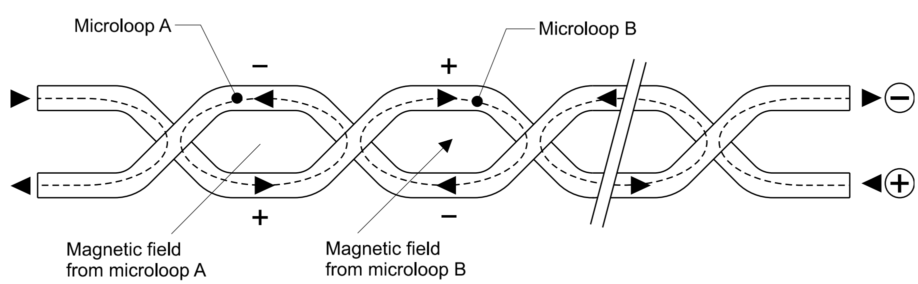

figure 9 twisted-pair cable

quad cable

Alternatively, you can create a quad cable to reduce the stray near field of a twisted pair cable. Such a cable, illustrated in Figure 10, has four conductors twisted together with adjacent wires carrying currents in opposite directions (see the right-hand side of Figure 10). Twisted-quad cable has most of its near field cancelled as well and will not heat nearby conducting planes unless placed in very close contact. Twisted quad is much better than twisted pair for reducing radiated magnetic fields.

other cable forms

The most common alternate cable forms are multiple- twisted-pair, twisted-quad, or coaxial cable, all of which increase current-carrying capability. Useful but less common forms are parallel-plate and multiple-interleaved-parallel-plate transmission lines. These are usually more expensive for the same performance and are used only where their unique characteristics, such as very low impedances, are required.

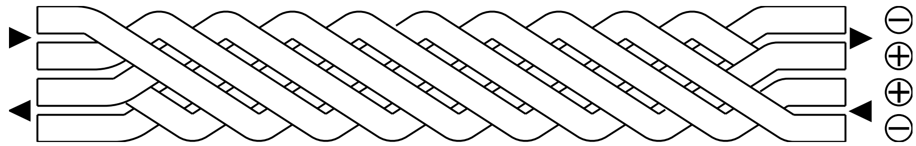

figure 10 twisted-quad cable

interference prevention: multiple current paths

Multiple current paths are a common cause of interference. Knowledge and control of the current paths is the most powerful tool in attacking interference and errors, and the best way to control them is to ensure that the main power current flows in a single, intended path.

multiple paths in dc power systems

Interference problems arise in DC systems because of extraneous connections which “seem reasonable” as the system is connected. Figure 11 illustrates this example.

Here, a connection carries current to a plasma from a DC power supply, consisting of two wires—one to the target from the negative lead of the power supply and another from the system chamber (here serving as the anode) to the positive lead of the power supply. These wires are intended to carry all of the plasma current, as shown in the Figure 11. However, the positive lead is also connected to ground at the power supply, as shown in Figure 11 as the “undesirable connection.” This gives the current another path or set of paths. So the return current from the plasma is divided between the various paths available to it, in proportion to the conductivity of the path. The return current may be conducted on control cable shield, or high-frequency ripple may be coupled into delicate control and measurement circuits in this way. It is even possible to destroy the shield of a control cable by overheating, due to unintended (and often unsuspected) currents.

The solution is to break the undesirable connection shown in Figure 11 and force all of the return current to flow along the intended return lead. In general, it is best to avoid multiple paths for current flow. When troubleshooting a system with electrical problems, search out possible multiple current paths and eliminate them.

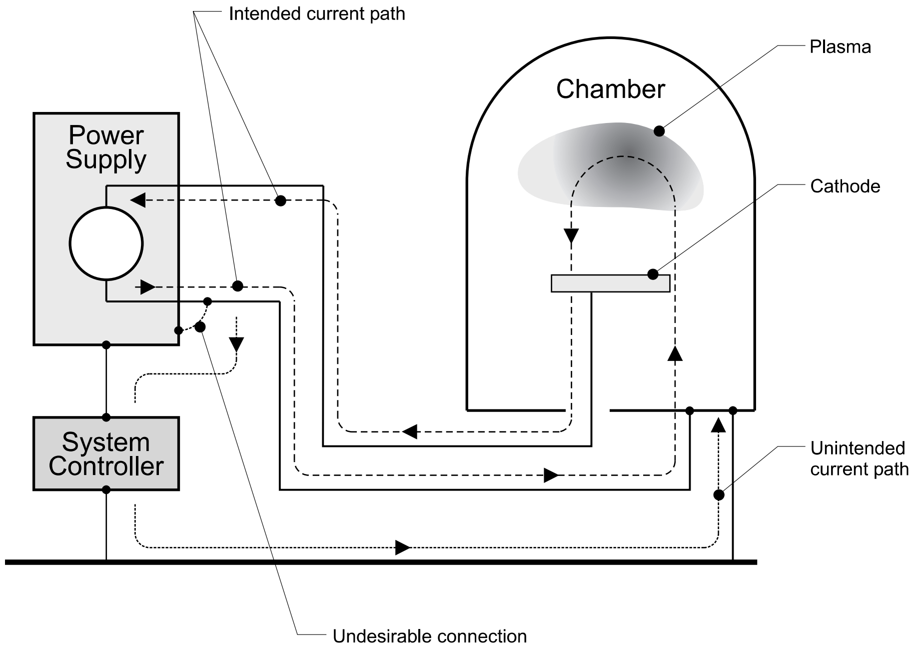

figure 11 multiple current paths in dc power system

multiple paths in ac power systems

With AC power, unavoidable capacitances can also create multiple paths, as illustrated in Figure 12.[ii]

Here it is difficult to break the unintended connection, because it is formed by stray capacitance Cs between the generating circuitry and chassis. In this case, the current must be forced to flow in the desired path by a common-mode choke as shown in Figure 12.

This device resists common-mode current flow (current flowing equally and in the same direction in the two windings) but has little effect on normal-mode current flow (current flowing equally and opposite in the two windings). In Figure 12, the power-supply current in the load is normal-mode current, which produces no voltage across the windings. Flow in the dotted electrical path represents common-mode current, which is resisted by voltages developed across the common-mode choke windings. The presence of the common-mode choke forces the current in the two power leads to be the same—forcing all outbound current to return on the power lines rather than through another, unwanted path. A common-mode choke, then, can effectively break the unwanted current loop of Figure 12, and an illustration of its use is shown in Figure 13.

In Figure 13, a common-mode choke is in the power current path, forcing current to flow in the power circuit loop; a second common-mode choke in the control cable prevents flow of power current in the control cable shield and conductors, blocking an AC ground loop. The common-mode impedance increases as the square of the number of turns, so it is a good idea to wrap the cable several times around the core. Often, however, a single turn (simply slipping a core over the cable) is sufficient.

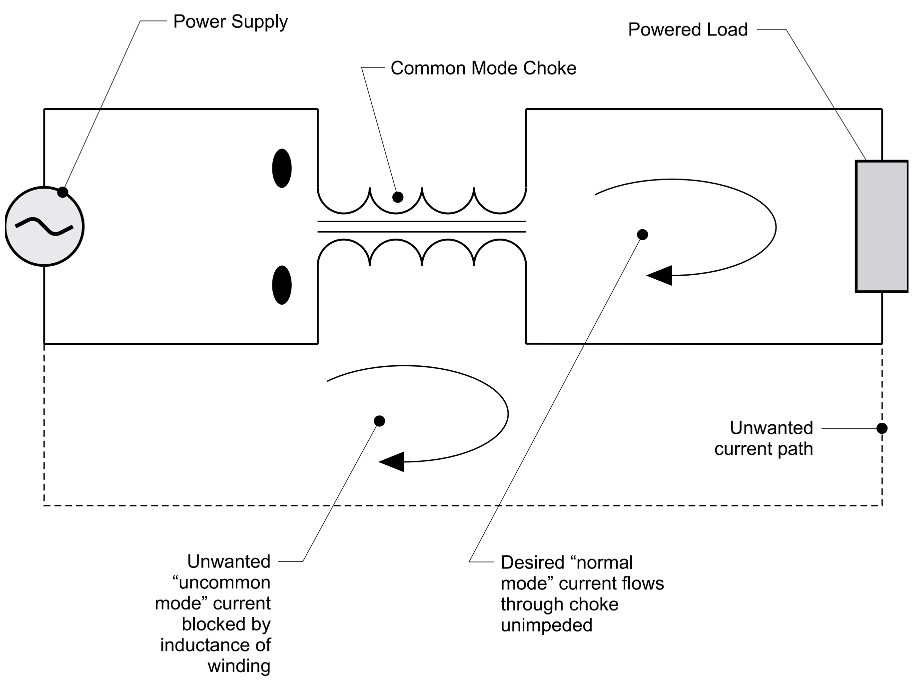

figure 12 multiple paths in ac power system

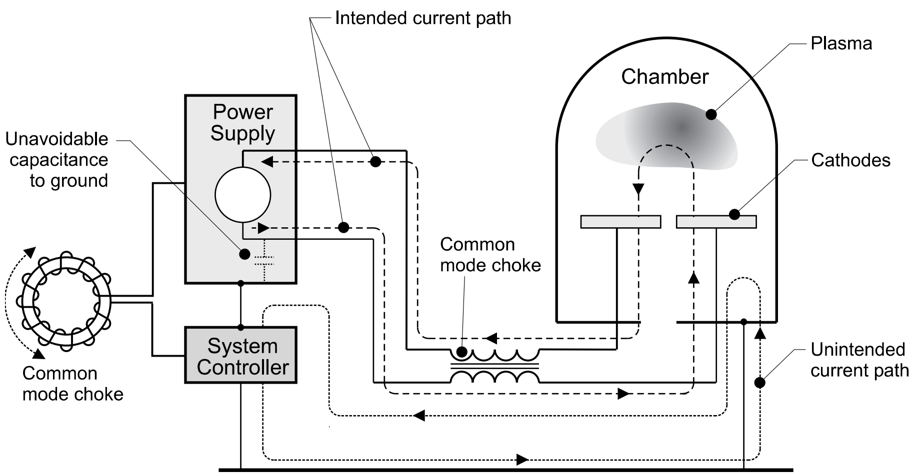

figure 13 common-mode choke

Split cores, with clamps to hold the halves together, are sold as noise-reducing elements for data lines to fit many sizes and shapes of cables, from telephone wire to coaxial cable to ribbon cable.

Often, sensitive instruments will show disturbances from power equipment, despite the best efforts of system and power-supply designers to reduce noise. In this case, isolation by common-mode chokes often solves the problem. You must consider *every* entering cable to the sensitive equipment. For example, a phase-sensitive detector may have a signal input, a phase-reference input, an output to an oscilloscope, another output to a chart recorder, and—don't forget—an AC power line. You should place common-mode chokes in every one of these lines to prevent unwanted currents—noise—from flowing down the cable to form a current loop, which includes the chassis of the sensitive instrument.

bonding

Since the subject of bonding is very broad, this is only a brief introduction. *Bonding* refers to connecting multiple chassis together electrically in order to make the combination less susceptible to noise. This could be two master-slaved power supplies or a power supply and its remote control panel. Local grounding and bonding need to be done with dedicated terminals on the chassis. You should not depend upon rack screws to provide bonding or grounding. Instead, you may connect power units with wire or copper strapping of adequate gauge. When making grounding or bonding connections with nuts and bolts, be sure to provide adequate surface-to-surface contact of the two conductors; don't depend upon the fasteners to conduct the current. It is a also good idea to use external star copper washers for better contact.

If you're not achieving desired results in your vacuum processing system, remember to check the signal integrity. Electrical noise and signal interference are common problems, but, by employing the proper techniques, you will find your individual system components working in concert with one another.

resources

1. Henry W. Ott, Noise Reduction Techniques in Electronic Systems, 2nd Ed., Wiley-Interscience; ISBN 047 185 0683, 1988.

2. Ralph Morrison, Grounding and Shielding Techniques, 4th Ed., Wiley-Interscience, ISBN 047 124 5186, 1998.

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i **Teflon** is a registered trademark of E. I. du Pont de Nemours and Company.

ii This can also cause trouble with DC power supplies, because modern switchmode power systems use high-frequency inverters that can be capacitively coupled to the ground system and insert noise into a ground loop. You can avoid this problem in exactly the same way as that described for AC systems.

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