Opto 22 Technical Note

TN9603 Grounding, Shielding, Noise, and Compatibility

Grounding, shielding and the reduction of noise are topics warranting serious consideration, during both the system design and troubleshooting phases of control system building. The three technical notes of the 9603 series address different issues pertaining to these topics. 9603A covers proper grounding and wiring practice to develop highly noise-immune systems. 9603B covers sources of and guidelines for remedying external noise pickup affecting system performance. 9603C provides some general information about electromagnetic compatibility concerns with Opto 22 industrial control equipment.

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TN9603A Grounding and Wiring Practices

One of the best methods to avoid problems with noise and signal interference in electronic control systems is to use proper grounding and shielding practice. Most noise and interference problems can be eliminated through the use of good shielding and the elimination of grounding conflicts. Many industrial environments have a sufficiently low background electronic noise level that secure shielding and "good" wiring are not an issue; there are many environments, however, where good practice in terms of grounding, shielding, and wiring can mean the difference between an excellent and an unacceptable electronic control system.

I. Grounding

Proper grounding in essential to the proper operation of the majority of electrical and electronic equipment, as well as the minimization of equipment generated EMI. Unfortunately, even a ground or grounds that seem secure may not be of sufficient quality to offer optimal performance from a given electronic system.

There are many sources for a ground connection in an industrial environment, ranging from the ground socket on a power receptacle to a cold-water pipe to a panel grounding bus to a copper rod literally buried in the ground. These are all typically secure grounds, meant to reliably source or sink any excess current the grounded device might require. Unfortunately, the quality of a ground can vary greatly, even if it acts ideally as a current source or sink. First, ground potential varies from point to point on the earth's surface. This is especially true when a large amount of current is being sunk or sourced near to or at a grounding point; one example is typical one-phase power, where the neutral and ground conductors are really the same, and may even be connected together at the service panel. I have personally measured differences of several tens of volts on receptacles on different circuits in the same room. The impedance of the wiring between any connected equipment and earth ground, combined with sourced or sunk current, can create a voltage offset between "ground" and the true earth potential of zero. This is not normally a problem for electronic systems linked to a single ground, as the regulators in the power supply float above this ground reference, no matter how imperfect it might be. The problem comes when there is a system with multiple grounds at different potentials.

Multiple grounds at different potentials can cause all sorts of problems with electronic systems. First, power supplies at different grounds will reference these grounds to regulate their voltage. A voltage reference difference can mean that any voltage signal referenced to its source ground sent from one location to another will have a severe offset at the receiving location. This is not a problem for isolated I/O, where the I/O is floated up to a common reference potential. For non-isolated I/O, however, the signal might cease to have any meaning. Worse, if a common line is run between non-isolated I/O at different ground, and hence reference potentials, large currents might begin to flow from one point to another through the common line. At the least, this will alter the power regulation at one or both ends, and possibly cause circuit protection to be tripped or fuses to be blown; more extreme cases could lead to fires or other hazards. Remember that a grounded shield, in this case, is a common line. The moral of this story is that the potential between two different grounding points should be checked before any connection is made between them. Remember that an ideal ground is an ideal current source and sink, hence even a small voltage imbalance could lead to large amounts of current flowing. If at all possible, avoid making connections between non-isolated devices referenced to different grounds. If practical, try to use the same ground reference for all electronic devices in a control system.

II. Wiring

Many noise problems can be addressed by using proper wiring practice when connecting elements of a control system. Control system wiring can carry any number of different types of signals, or even power. The relative difference in signal amplitude between different lines can cause cross talk or other interference problems. Bad wiring layout or practice can accentuate the noises inherent in any wiring.

First, it is important to make sure that low-level signal lines (analog or discrete) are always routed separately from any lines that carry either high voltage, current, or both. Analog and discrete signal lines should also be routed away from each other whenever possible. This is doubly true for discrete lines using 120 VAC for a signal voltage. "Routing separately" in this case means making sure that the conductors are in separate wire bundles, separated by at least a few inches in a panel situation. Different conductor types should be routed in separate conduit for any counduited runs. It's also nice to try to dedicate one side of an installation to high level signals, and the other to low level signals. Where signal or data lines must cross power conductors, they should cross at a right angle to prevent electromagnetic coupling between the lines.

Second, all analog signal and digital data line conductors should be shielded individually. The shield should be connected at one end only, typically on the controller side. It is extremely important that millivolt level signals from devices like load cells and thermocouples be shielded. If a thermocouple is grounded at the sensing end, an isolated input module should be used. Current signals, like 4-20 mA signals, are typically more immune to noise than voltage signals, but conductors carrying these signals should also be shielded. Data lines should also typically be shielded; the exceptions to this are short RS-422/485 runs (less than two meters) using twisted-pair cable, the Pamux parallel bus, and the Mistic Local Bus. In the case of the two buses, adding a shield or ground plane changes the line impedance enough that bus performance over long distances is reduced. Shielded cable is often described in terms of percent shield coverage. Braided shields will offer from 75 to 100% shield coverage, while foil or foil-backed plastic will offer 100% coverage. It is important to note that percent coverage is not an indicator of shielding effectiveness, as this is frequency and radiated-power dependent. A good quality shielded cable should suffice for most industrial purposes, though.

Last, as stated in the previous section, it is best to avoid wiring non-isolated equipment referenced to separate grounds together. It is also important to check the potential difference between two commons before they are wired together. In no case should earth ground beused as a common reference in distributed ground applications. Power supply wiring should be sized appropriately for the largest potential load that the wiring in question will see. Electromechanical equipment and electronics should never share power supplies without adequate line-to-line filtering and regulation installed, as this type of equipment can introduce large amounts of noise into a wiring system. When possible, devices that share a common power supply should be wired in a star configuration. For more information please refer to Opto 22 Application Note 9606, about implementation of power supplies.

Most industrial noise problems can be eliminated by the application of proper practice when it comes to connecting field devices together. For the most part, good wiring practice can be derived from good common sense, though there are some issues that might not necessarily be obvious without some background or experience with the subject. For more information about how to protect an electronic control system from external interference and noise, please see Opto 22 Technical Note 9603B.

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TN9603B Operational Interference and Noise

Electrical noise presents one of the largest obstacles to achieving optimal performance from any electrical or electronic system. Normally, internal noise (that which is generated within the individual system components) is accounted for by the designers of the system. External noise, while also designed for, cannot in all cases be anticipated, and thus may still present severe problems to system operation. This is especially true of external noise at the interfaces into the system, including point-to-point signal wiring, power supply wiring, exposed components and transducers, and equipment ground. Fortunately, external noise can be greatly reduced by applying proper wiring, shielding, and grounding practices. This document will not address the effects of environmental noise on wireless communication links. It also does not address noise generation or compliance by electronic control systems, for more information on this topic, see Opto 22 Application Note 9603C.

It is physically impossible to remove all noise from any given system, as there are three fundamental noise components inherent in any electronic system operating at a temperature above absolute zero. What matters for electronic control and telemetry systems is that the noise level is reduced to the point where it no longer affects system operation. Unfortunately, this reduction is not easily quantifiable, as different system components will show different sensitivity to different forms of noise or interference. The millivolt signal from a thermocouple, for example, will more likely suffer from small amplitude induced voltage noise than the signals from a 5V logic high-speed quadrature counter. The quadrature counter signal, on the other hand, will be more sensitive to mid-to-high frequency large-amplitude noise (generating spurious "signal" pulses) than the thermocouple. The latter is buffered by input filters and its own thermal mass, making it sensitive only to low-frequency voltage noise of relatively small amplitude, while the former has a high "valid signal" threshold but is sensitive to any input above this point, even at high frequencies. Knowing the character of a system component's sensitivity can be extremely useful when determining how to deal with a noise problem. In general, small analog signals are significantly more prone to noise contamination than discrete signals.

I consider there to be three major types of noise sources in the industrial world, grouped more based on methods by which the problems are addressed rather than strictly by physical nature. Noise from each of these source types must be addressed differently, in terms of how to protect a signal. Below are the three major source types and summaries of their characteristics, followed by methods of signal protection.

I. Line to Line Interference

The primary source of line-to-line interference is capacitive and inductive coupling of signals between conductors located close to each other. Typically, this will be seen when a conductor carrying a small, sensitive signal runs parallel to a conductor carrying AC, or switched DC power—they might run in the same conduit. Less commonly, one finds leakage of signal from a small-signal line to another small signal line. The fields created by a signal change (60 Hz for U.S. AC, power on / off for DC) cause sympathetic charge movement or potentials in the small-signal line. If this line drives a high-impedance load, the potential change cause by the electromagnetic coupling (known as "cross talk") can result in a voltage error at the load end ("load end" being where the signal is read). More rarely, such induced currents or potentials can cause instability at the source end, leading to oscillations in the output driver stage of whatever device is generating the signal, leading to severe measurement inaccuracies. The simple solution here is to locate power cables as far from signal cables as possible, and also to locate discrete signal and analog signal conductors apart from each other. This separation of discrete and analog signals is especially important if 120VAC logic is in use. Typically, a few inches of separation between conductor types will suffice, though a greater separation might be required if voltages or currents are high. When sensitive signals must cross power conductors, they should cross at a right angle, but should never in any case form a loop around the current carrying cable by crossing it twice in opposite directions. It also helps if signal carrying conductors, especially ones carrying analog signals, are properly shielded (more later).

II. Power Supply Interference

Power supplies can represent a major source of interference in electronic control systems, causing noise on the power supply rails. This interference may be generated by the power supply itself, of simply passed through the supply from the AC (or DC) mains. Typically, this noise is caused by load switching, which generates voltage spikes, and by waveform distortion, caused by large numbers of linear or switching power supplies on the same main line. Waveform distortion is usually adequately addressed by the voltage regulator in whatever power supply is being used. The other main problems on power rails are voltage spikes and transients; they are quick enough phenomena that most power regulators cannot track them. This spurious signal can find its way into the logic supply, and cause problems from random hardware resets to physical damage of the controllers. The best way to address these transient problems is first to use separate power supplies for logic and electromechanical devices. Second, electromagnetic devices like motors and solenoids should have appropriate surge reduction devices attached; R-C snubbers and / or varistors for AC loads and commutating diodes for DC loads. As a last resort, zener diodes or metal oxide varistors can be added across the line on the DC side of the power supply, though they must be sized as not to interfere with the normal regulation of the line (having breakdown / conduction voltages higher than the normal operating range of the supply).

Sometimes, the power supply itself can be a source of noise. A poorly filtered switching supply, for example, might leak artifacts from its high-speed switch into its output, resulting in a noise signal at the switching frequency and its even harmonics, normally in the tens of kilohertz and higher. The switching circuits in these supplies sometimes also cause random RFI and EMI problems with low-level signals routed nearby. Switching supplies can cause quite severe problems on data bus lines (Pamux)-- especially if the bus clock frequency is a harmonic of the switch frequency. Linear power supplies can cause noise problems associated with their power transformers; mainly large alternating magnetic fields at line frequency. A linear supply, especially one of the "brute force" variety will also typically exhibit a very large current inrush when it is switched on. This inrush can affect other equipment on the same supply circuit.

The method a power supply is attached to the system it powers plays a major part in the amount of interference that will pass through it, and in the potential sources of interference. As stated earlier, it is important that independent supplies be used to power the logic and electromechanical elements of the system. Also, it is important to remember that the common terminal on the power supply is not the same as earth ground; treating it or connecting it as such might open up a system to common-mode problems, ground loops, or other problems associated with non-ideal earth grounds. Please see Opto 22 data sheet form #1271 for more information regarding power supplies.

III. Radio Frequency and Electromagnetic Interference

RFI and EMI normally present much less of a noise threat to an electronic control system than conducted or close-coupled interference as described in the previous sections. When a system has been properly designed with respect to line filtration and layout, RFI and EMI will become the major sources of external interference to a control system. Unfortunately, these two types of interference (actually, RFI is a subset of EMI) can be the most difficult to protect a system against. Fortunately, there are few locations and environments where electronic industrial control systems are used that have sufficiently powerful RF and EM noise energy sources to cause problems. Exceptions to this include environments where high electrical currents are present and switched (arc welding), environments with large rotating or changing magnetic fields (large AC or DC motors, close proximity to large solenoids), or environments close to RF emitters (broadcasting towers, radar systems).

RFI and EMI typically enter electronic systems through various interconnecting conductors, which act as antennae. These unintentional antennae take the form of power supply and signal leads, circuit board traces, and data lines. The noise currents generated in the lines by the interference are typically very small, as the radiated power absorbed by a line is minimal. Unfortunately, a interconnect of the proper dimensions can be made to resonate, effectively increasing the power received by large amounts. This noise, even amplified, is still normally not a problem for most electronic control systems because there is insufficient current available to drive the recipient device. Devices with extremely high input impedances like MOSFETs, though, will allow sufficient voltage buildup from a small current signal to cause problems. This is why a data line or circuit board trace driving a transistor gate might present more of an RFI or EMI receptor problem than a control line driving a device that needs a larger amount of current to operate, like the LED in an Optocoupler.

Radio-Frequency Interference, spanning the EM spectrum from about 100 kHz to 100 GHz, is the most common form of electromagnetic interference found on Earth, especially in industrialized nations. Noise sources include everything from broadcast radio stations to satellite uplinks to military and civilian radar. The majority of RFI noise problems can be eliminated by ensuring that the susceptible devices are well shielded. Grounded (conductive) metal cases and braid or foil shielded interconnection cables are normally sufficient. Please see Opto 22 Application Note 9603A for information on shielding practice. Sometimes shielding a data line is not enough; some RFI is powerful enough given a large enough antenna to break through a shield by either capacitive coupling to the lines from the shield or by shield saturation. If this is the case, a fiber-optic data link may be required. Typically, the logic boards and associated circuitry for an electronic control system is compact enough to place in an enclosure with enough shielding to deal with any RFI problem.

EMI, as stated before, actually contains RFI as a component. For the purposes of this document, EMI will refer to electromagnetic interference at relatively low frequencies, those below about 100 kHz. Extremely high frequency electromagnetic radiation can also damage electronic equipment; anything above about 10^{16} Hz certainly has the potential not only to penetrate a conventional shield, but to erase EPROMS, damage microcircuitry, and the like. As this sort of EMI is found in large quantities only in space and in specialized facilities, this document will not address it. Low frequency EMI, especially EMI at line frequencies (to 400 Hz) associated with AC power transformers, as well as that generated by switching power supplies and boost converters ("flyback" converters in CRTs), is of greater concern in industrial environments. The magnetic fields generated by these devices can induce an EMF in nearby conductors that can get large enough to cause problems with electronic equipment.

Unfortunately, it is extremely difficult to shield equipment from low-frequency magnetic fields, as these fields will permeate non-magnetic conductors like copper and aluminum, as well as thin layers (thin being several inches, in some cases) of nominally magnetic materials like steel. Shielding materials (mu-metal, ferrite, amorphous alloys, permalloy) are available, but the design of magnetically shielded enclosures is complex, and is probably best addressed as a last resort. Often, it is easier to simply move the source of the EMI away from the electronic controls, or vice-versa. Use of low-leakage (toroidial) or shielded transformers is also an option. Completion of an open magnetic circuit (some autotransformers, some electromechanical actuators, non-toroidial inductors) by providing a high-mu path for the field flux will also significantly reduce EMI in nearby devices. Keeping conductors orthogonal to existing magnetic fields (in the plane perpendicular to the winding axis) will also help to minimize pickup of EMI. In no case should a sensitive signal line be allowed to run parallel with the winding axis of a magnetic device.

Overall, electronic noise of various sorts can be a major cause of undesirable behavior in electronic control systems. Fortunately, this noise is easily addressed by common and proper practices in system design and implementation. For the most part, electronic industrial control hardware is designed with typical environmental electronic noise in mind. Implementation of the hardware can also play a major role in the noise susceptibility of the overall system, but by following good design and installation practice, this susceptibility can be greatly reduced. If noise is still an issue, more extreme measures can be taken to protect the system, the methodology depending on what the source of the interference is.

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TN9603C Interference Generation and Compatibility

Until fairly recently, the primary concern of electronic control system designers when addressing EMI was how to protect their system from being adversely affected by it. More recently, there has been a major movement by the electronics industry toward minimizing the EMI emissions from their equipment. This move has been triggered by the creation and more strict enforcement of compliance standards in several parts of the world, including the United States, Canada, and Europe. American standards, such as the FCC CFR Title 47, Part 15 and MIL-STD-461C, have been in effect for several years now in their current form. The European standard, IEC 801, is newer, and is applicable to most anything electronic which is to be used in Europe. Certain European nations have their own guidelines that may apply in addition to IEC 801; the German VDE standards are an example. Most other industrialized nations also have compatibility standards. Opto 22 publishes lists of all of its products pre-qualified under most major national and international compatibility standards. These lists are available from Opto 22's Product Support Department, at (800) 835-6786. This Application Note is intended only to provide some background and some general design guidelines to a person who is not entirely familiar with compatibility issues. It is not intended to be used as a recipe for compatibility compliance for electronic control systems. Each and every application has its own specific design requirements for meeting compatibility standards, and must be considered individually. It is helpful (but not necessary) that the readers of this document have a basic familiarity with Maxwell's equations (interaction between electrical and magnetic fields), as well as Fourier series and transforms as applied to the analysis of waveforms.

In general, compatibility standards set reference emission spectrums that emissions from a compliant device or system must not exceed during normal operation. Often, there are different classes of equipment ratings with different maximum emissions spectrums, tailored

to the environment where the equipment is designed to be used. A personal microcomputer meant for general household or office use probably does not need to have as tightly controlled of an emissions spectrum as a computer installed in the navigation system of a jetliner, for example. When evaluating compatibility compliance for a system, it is important to know exactly what environments the equipment might conceivably be used in, and thus what emissions standards the equipment must meet. It is also extremely helpful to become familiar with the recommended testing procedures laid out in each standard, as using other procedures will render any data gathered invalid. Last, it is important to understand the various potential sources of EMI in a piece of equipment, the discussion of which is part of the focus of this document.

There are two forms of electronic emissions addressed by compatibility standards; radiated emissions and conducted emissions, or RE and CE (not the same as the European Community's "CE" standards, which refer to IEC 801). These two forms of emissions have mostly self-explanatory titles. RE takes the form of radio-frequency emission and electromagnetic field generation in free space (or air). CE refers to voltage and current surges, spikes, and other electronic emissions leaving the system in question through interconnecting conductors. It can also refer to magnetic flux leakage through a high-permeability path out of the system in question. While all forms of unintentional energy leakage from a system are of concern when compatibility is an issue, compatibility standards tend to focus on RFI and "more electrical" CE. From Maxwell, all dynamic electronic phenomena are also magnetic in nature, so when I say "more electrical" CE, I am referring to voltage spikes, current surges, and power waveform distortion that typically affect equipment in the electrical domain. Most of the time, limiting the generation of interference by a piece of equipment, or one of its components, is a very straightforward process. Knowing exactly what sort of emissions, how "strong" they are, their nature, and the compliance requirements for the use-environment of the equipment, will help greatly in determining how to reduce them to acceptable levels. It is unreasonable to expect that a given form of emission can be completely eliminated; often this is not required, nor is it cost-effective.

Conducted emissions, as stated earlier, are any undesirable signals passing out of the pre-determined boundaries of a system on through electronic or magnetic conduction. The most common form of CE is noise radiated onto the power supply lines to a system, be they AC or DC. On AC power lines, major sources of CE include the switching circuits in switching type supplies, and the filter capacitors in linear supplies. In a switching power supply, large line currents are drawn whenever the load switch is closed; typical switching supplies have operational frequencies from 5 kHz through 80 kHz. Because the current demand on the line swings from zero to "full" load and back for the power supply at the switching frequency, a voltage sag (switch on) followed by a short spike (switch off, inductive kick) is seen on the AC supply line, superimposed on the normal waveform. On a 'scope, this interference will cause the AC supply wave to look somewhat stepped, instead of smooth like it should be. Switching supplies typically must have line side filtration and isolation installed to avoid causing severe problems on the line; sometimes this filtering is not sufficient to allow a given device to meet compatibility standards. Linear power supplies, especially the brute force type, tend to "top off" the energy stored in their filter capacitors when line voltage is at a positive or negative maximum. This has a tendency to create miniature inrush surges into the supply, causing flattening (clipping) of the power supply wave form. The flattening of the input waveform (stepping for switchers, clipping for linears) is harmonic interference on the supply waveform. Typically, this interference is composed of even-order harmonics of the power supply frequency and two other frequencies (time-complementary pair), which are dependent on either the degree of clipping or the power supply switch frequency.

Conducted magnetic interference is relatively rare. Typically, the source of such interference will be from a magnetic circuit that is not properly closed, or "shorted" through an unintentional high m path. The most likely source of such interference is actually RE (see below), where a free-space field is using a magnetic conductor outside of the designated system boundary as part of its flux return path. In theory, a poorly designed, poorly mounted transformer or solenoid could cause magnetic CE. Magnetic CE will not typically interfere with most electronics unless those electronics have circuit layouts or contain components that make them especially sensitive to such interference.

Radiated emissions consist of any energy unintentionally leaving the boundaries of a given system through non-conductive media. Typically, RE consists of radio frequency energy being emitted from a system. RE can also describe any free-space magnetic field phenomena generated within a system, but influencing areas outside of the system, such as might be found near an "open" magnetic circuit. An example of the RFI type of RE might be the high-kHz range noise burst emitted by a spark from an opening contact. A typical magnetodynamic loudspeaker provides a good example of a system containing an "open" magnetic circuit; if the reader has ever placed an unshielded speaker near a television set, they will know what I mean.

Radio-frequency electromagnetic radiation is generated whenever there is a distinct current change in a given conductor. The base emission frequency, then, will become the frequency at which the current in a conductor (antenna, now) changes in magnitude or direction. This effect can be heightened greatly when the length of the conductor (antenna) in question is near to an even-order fraction ($1/2^n$) of the free-space wavelength of the given frequency of emission ($l=c/f$). Such tuning of a conductor (intentional for an antenna) can increase the radiated power several times over what it would be without the tuning characteristics. In modern electronics, the signals running on circuit board traces and over communications lines provide ample opportunity for the generation of RFI. After all, a square-wave logic signal typically causes the changes in current required to generate electromagnetic waves. Typically, the emissions from a given circuit will be a fractions and multiples of the circuit clock frequency. Remember also that a square wave implies sine waves at the fundamental frequency, plus several higher frequency sine wave components of varying magnitude (Fourier transform). RFI at these higher harmonics can also potentially be seen coming out of a given system.

Magnetic RE may be found close to any source of a magnetic field. Basically, any field-generating dipole will exhibit field flux lines from one pole to the other. In a device like a transformer, where there is a magnetically conductive circuit made of a material with a high permeability, the flux will be mostly contained within the magnetic material. A circuit of this type would constitute a "closed" magnetic circuit, the flux having a good path between poles. A device with no intentional magnetic circuit, like an electromagnet, relies on flux through free space to complete its circuit. In fact, the reason that an electromagnet is able to operate is that whatever it attaches itself to while energized provides a "lower impedance" return path for the field flux—the path of least resistance. Keep in mind that a solenoid is a fancy name for an electromagnet, though most solenoids are designed to allow a close magnetic circuit when they reach their steady "on" state. These are examples of what might be termed "open" magnetic circuits, where the field flux needs to traverse at least some "free" space. When the flux is traversing this free space, it becomes a sort of RE. The magnetic field around an open magnetic circuit can affect the external environment in many ways, ranging from disturbing other magnetic fields, and thus the operation of whatever devices they are associated with, to causing unintentional currents in nearby conductors. For the most part, the world's compatibility standards focus on radio-frequency RE, as opposed to magnetic fields. The primary reason for this is that magnetic fields are relatively short-range phenomena, while radio waves have the ability to affect more distant systems.

There are three primary methods by which EMI can be reduced or controlled with reference to a specific system. First, proper **Grounding** can reduce both radiated and conductive emissions. Second, **Shielding** is often applicable to the reduction of radiated emissions, most specifically medium to high frequency components (RFI) and magnetic fields. Last, **Filtering** added to conductors leaving a system can significantly reduce conductive emissions, and may also address radiated emissions in a secondary manner. All three of these methods are very closely interrelated; shields must be grounded to be fully effective, filters generally either damp out noise frequencies, or shunt them to ground, and a shield is a filter, in a way.

Grounding is fundamental to almost every electronic system. Unfortunately, grounding is not as simple as tying everything that should be grounded to a pipe stuck in the ground somewhere. For a discussion on grounding practice, please refer to Opto 22 Application Note 9607B. Technically, grounding is a method by which a low-impedance (ideally zero) conductive path is established between two or more points in a system, and possibly also the world external to the system. Additionally, a good ground should be able to act as an ideal current source or sink for short periods of time, and maintain a specific potential with respect to the grounded system, as the ground is often used as the voltage reference for a system. There are three grounding techniques in use, which individually or as a group encompass all possible ground systems. These three types are the floating ground, single point ground, and multipoint ground.

A floating ground is used when an element of a system must be isolated from its local reference for some reason. Often, this sort of ground is used to interface a signal with a high common mode offset relative to the reference ground to a system referenced to the reference ground, thereby preventing ground loops and common-mode conduction problems. This is typically accomplished through the use of transformer isolation on the floating devices' power supply rails, and by optical or transformer isolation of any signal paths from the device into the greater system. The Opto 22 T- and G4-series analog I/O modules are a good example of devices that utilize what amounts to a floating ground. Floating grounds are very useful for limiting DC and low-frequency CE, but nearly useless for addressing mid- to high-frequency CE, as these can couple through the transformers, and also through capacitive coupling between nearby conductors. Because most RE are typically of mid- to high-frequency in nature, isolated grounding can do little to combat RE problems. Additionally, isolated grounds may present an interference and safely hazard due to the buildup of static electricity. Typically, a high-impedance path to earth ground (bleeder resistor) will be installed to combat this buildup without opening the system to ground loop problems.

The single point ground is mostly self-explanatory. A system that is single-point grounded has all component devices linked through a user-supplied low impedance path (okay, a big wire) to a single reference point. An example of this sort of grounding would be a control system with all local components, tied to a common ground bus in a panel. The ground bus, in turn, is connected to earth reference at a single point, perhaps through a purpose-built grounding rod, or a braided strap bonded to a buried cold-water pipe. Here, the ground bus represents the low impedance link between separate components. A properly implemented single-point ground will help reduce CE, and possibly also RE, across the entire spectrum.

A multi-point ground is a grounding system where different system components are tied to different reference potentials or ground planes. This type of grounding scheme is seen in distributed applications, where the distances between various components make single point grounding impractical. Multipoint grounding has the same effectiveness in reducing CE, and potentially RE, as single-point grounding when properly applied. When using a multi-point ground, it is important to make sure that no components or grounds are tied directly together, unless they are designed to tolerate this (RS-485 is) or the ground potentials at the various ground points in the system are identical (making the system functionally equivalent to a single point ground). Isolation between different system areas is typically achieved using optocouplers or transformers. Thus, care is taken to prevent ground loop problems.

The type of grounding scheme to use is a function of several things. First, the grounding requirements of the system must be assessed from both a compatibility and a safety standpoint. Knowing the grounding requirements of a system will go a long way in determining what sort of scheme, or combination of schemes, should be used with a given system. Second, the practicality issue must be addressed. A system's grounding requirements might seem to require single-point grounding, but be spread enough that multi-point grounding with component isolation is the only option. It makes no sense to specify a grounding scheme that will not address the system requirements. From a EMI compatibility standpoint, there are a few basic rules of thumb that will normally yield good results. First, use a single-point ground for systems whose maximum dimensions do not exceed 3% of the free-space wavelength (l_0 , $l_0 = c/f$) of the highest frequency emission to be addressed. For example, a single point ground would be used in a system generating 10 MHz CE if the overall system dimensions were less than about 30 meters. For systems over 15% l_0 in size, a multi-point grounding scheme is normally called for, not to mention more practical. For broadband systems and systems between 3% and 15% l_0 the ideal type of grounding scheme to be applied might be either single- or multi-point, or a hybrid of both; it will vary from system to system. In general, isolated grounding should be avoided unless the application specifically calls for it.

Isolation might be necessary, for example, on the conductors connecting a multi-point grounded system with different ground potentials at each point. All grounding should be implemented using the shortest paths possible.

Shielding is the second method by which systems can be made to be compatible from an electromagnetic emissions standpoint. More people are familiar with the use of shielding is a tool to reduce the effects of external interference on a system. Some care must be taken here, because designing a shield to reduce EMI emission is not quite the same as designing a shield to reduce EMI pickup. The primary reason behind this is that most EMI "picked up" by a system comes from a relatively distant source, and thus has had a chance to disperse its energy across a larger portion of space. Remember that for electric fields and magnetic fields, influence from one body to another falls of as $1/r^2$, and the magnitude of the Poynting Vector of a plane wave (vector representation for wave energy) also falls off as $1/r^2$ given a spherical radiation pattern from a given source. Unless an intentional radiator is directed at the system in question, the amount of interference energy that must be dealt with by the shield is normally quite small. When the shield is meant to contain EMI, the EMI typically comes from a close source, just inside the shield. This presents an even greater problem when high-strength magnetic fields are the object of attenuation.

Shields typically consist of one or more good conductors layered in some manner around the device or system to be shielded. A shield attenuates EMI through three primary mechanisms. First, because the shield is a good conductor, radio frequency EMI (radio waves) will convert their energy to set up sympathetic currents in the shield like they would in an antenna, but then will simply route this current signal to ground. Second, because the shield is typically surrounded by a material with a high-dielectric constant (air), EMI in the higher plane-wave region (microwaves and above) is reflected away from the shield, as the interface between two media with highly disparate dielectric constants provides a boundary where photons with a specific energy level will be reflected. The same principle applies to the aluminum or silver to glass boundary of a bathroom mirror, but a physical explanation is far beyond the scope of this document. Last, when the shield is designed correctly, it will attenuate magnetic fields by providing a high-m path to close an open "magnetic circuit." Extremely energetic plane wave radiation (X-rays and above) will not be attenuated by most shields, as such radiation is sufficiently energetic to effectively ignore dielectric boundaries achievable with today's materials and technologies, or even tomorrow's theory. Such waves typically require some sort of nuclear interaction between the shield material and the impinging photons to be at all attenuated. This is how lead shielding stops X-rays. As one can see, a shield acts like a filter in the RE domain by whatever applicable mechanism, serving the same sort of function that a more typical CE domain filter would by routing spurious signals to ground, or creating an impedance barrier sufficient to cause the reflection of a higher-frequency signal back into the originating system.

In most cases, a grounded metal enclosure surrounding an electronic control system is sufficient to shield the system from external noise, as well as prevent noise leakage from the system. Sometimes, shielding must also be added between various elements of a system already shielded overall, to provide compatibility between individual system components. There are extremely few industrial applications where a control system will need to be shielded against very high energy radiation; the exception to this is in the medical industry, where such control hardware might be used for the control of X-ray equipment, and electron linear accelerators. Shielding design for these sorts of applications will vary on an application basis, but in all cases must be considered very carefully. If shielding design is necessary for a control system, it is most helpful to know exactly what RE frequencies need to be attenuated, as various shielding systems have different levels of effectiveness over the electromagnetic spectrum. Complete attenuation characteristics for most foils, tapes, and coatings sold as shielding materials are available from their respective manufacturers. When designing a shielding system, special attention should be paid to long communications cables, as well as any circuit areas carrying larger currents that are switched often. Also keep in mind that any penetrations in the shield around a given system are potential leak points. In general, the higher the RE frequency, the smaller the allowable penetration in the shield. Doors and access panels which must be removable from the system shield present their own special set of problems. RFI may potentially "leak" around such appurtenances, through reflection through any cracks or gaps in the shield material. It is strongly recommended that special EMI seals be used wherever this could be a problem.

Overall, shielding is probably the biggest "answer" to the question about how to deal with RE compatibility issues. As implied earlier, a simple shield consisting of a grounded, conductive enclosure will adequately address most of the RE compatibility issues raised in typical industrial environments. Such a shield will effectively attenuate radio waves in the most common emissions regions for industrial electronic equipment. Such a shield may or may not help attenuate magnetic fields.

Filtration is a method primarily used to address conducted emissions. It also has a secondary importance in reducing radiated emissions. A typical application of filtration is on an AC line into a system, where an R-C snubber, essentially a first-order shunt style low-pass filter might be added to shunt energy from incoming voltage spikes to the opposite line, and thus away from attached equipment. A low pass filter will work, because the majority of the energy in most line spikes is contained in the higher frequencies, as compared to the relatively low 50 / 60 Hz line frequency. Higher order passive filters are also seen on the line side. Active filtration may also be used on the power supply for a control system; this is virtually always found on the load side of a transformer. Voltage regulators are the most common form of filtration here.

Power supply lines are not the only locations in a control system where filtration is applicable to the reduction of emissions. Often, R-C snubbers and other passive filter components can be found on discrete signal lines. Optical or transformer isolation of both signal and data bus lines are additional types of filtration applied to lines to reduce CE between interconnected systems. Please note that the addition of high-pass or bandpass filters to high-speed data lines is not recommended—adding such filtration will change the physical characteristics of the signals on the line, potentially rendering them illegible to the receiving device or system. Any major filtration required on data lines should be performed in the digital domain when possible.

Unlike shielding, where the application of a generic shield will address most problems, filters must be designed specifically for each line or type of line where CE might be a problem. In general, filtration should be added as close to the source of the emissions as possible; this can cut down on RE and capacitively-coupled CE from the affected line. Active and passive filters may be used, though an active filter directly attached to a power line, without an isolation transformer, is never a good idea. Also keep in mind that active filters are by nature severely band limited by the bandwidth limitations of their component parts. An active filter may not necessarily be able to track a transient signal fast enough to prevent pass-through. Of course, active filters also provide notable advantages over passive filters, namely that they can be "programmed" by design to be very good at addressing certain problems relatively more easily than can simple passive filtration systems. A passive filter will be limited by the number of components, phase shift, and attenuation available in any given configuration. In the majority of cases, active filters are very good for low-speed application, such as regulation of drifting line voltage, or removing line-frequency AC signals superimposed on a DC supply rail. Passive filters tend to be better with "fast" phenomena, such as voltage transients. The physical size an cost of the components needed to create filters for "slow" signal performance is restrictive. Additionally, it is difficult to design passive filtration that has extremely good attenuation (higher than 24 dB / octave), while remaining very frequency selective, or retaining good signal pass-through characteristics in terms of power loss.

Overall, EMC and compatibility are extremely large issues facing the designers of industrial control systems today. Unfortunately, this is such a large and varied topic that this document can do no more than barely scratch the surface of all the nuances involved in design for compatibility. There is one appendix included with this document: Appendix A. It is a list of suggested references for readers interested in learning more about this topic.

Appendix A: Suggested References

AFSC Design Handbook DH1-4, "Electromagnetic Compatability, 4th Edition," United States Air Force, Wright-Patterson AFB, 1991.

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