Opto 22 Technical Note

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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