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ELECTROMAGNETIC COMPATIBILITY AND ELECTRICAL NOISE CONTROL FOR THE DOE HANFORD SITE

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Abstract: This document was written by MDM Corp., Richland, WA to provide recommended electromagnetic interference and electromagnetic compatibility for double shell tank and waste feed delivery project requirements. Minimally aceptable requirements for facility design are suggested.

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PREFACE

This document was written by MDM Services Corp. for the EQE International Corp., Richland, WA to provide recommended guidelines for electromagnetic interference and electromagnetic compatibility for double shell tank farms and waste feed delivery project requirements.

CH2M HILL engineering does not endorse all of the recommendations (e.g., the need for an Electromagnetic Compatibility Plan) in the document, but considers it to be a potential aid in the design of tank farm systems. Also, background information resources and references are expected to be helpful in the production of tank farm design requirement documents.

PLG-1360

Electromagnetic Compatibility And Electrical Noise Control For The DOE Hanford Site

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ELECTROMAGNETIC COMPATIBILITY AND ELECTRICAL NOISE CONTROL FOR THE DOE HANFORD SITE

1.0 INTRODUCTION

This document provides the recommended requirements in the areas of electromagnetic interference (EMI) and electromagnetic compatibility (EMC) for the CH2M-Hill Double Shell Tank and Waste Feed Delivery Project. This standard provides minimally acceptable requirements for facility design in this area, following the requirements of DOE 6430.1A, U.S. DOE General Design Criteria, dated Nov. 1, 1989 (Reference 7.1.0).

2.0 PURPOSE AND SCOPE

The purpose of this standard is to provide a design basis for minimizing the electromagnetic interference and electrical noise susceptibility of typical instrumentation and control systems used in nuclear facilities. It should be used as a guide during development or purchase of new systems, modification to existing systems, and troubleshooting operational systems. This design standard provides the circuit designer with sufficient information to prioritize the noise issues and identify the true problems that must be solved for each circuit. In this way, the critical factors can be attacked aggressively with the available resources while non-critical factors will not consume resources.

This standard also provides information to the maintenance and operating personnel to ensure that noise immunity is not compromised after circuit installation, either by maintenance or surveillance actions, or through aging of electrical components.

The scope of the standard applies generically to all systems of the CH2M Hill Double Shell Tank Farm and Waste Feed Delivery Project. The guidelines are provided based on the system operating characteristics, i.e., signal frequency and voltage level, impedance, function or physical size.

The basic operating characteristics of a system will define whether the system has a high susceptibility to electrical noise and is a potential victim, or whether the system can be a generator of electrical noise and, therefore, is an aggressor. All systems are considered as installed in the facility and include interconnecting cabling, grounding, shielding and physical relationships to noise generators.

This standard places special emphasis on the design considerations for sensitive analog systems and digital systems. Electrical noise is defined in practical terms and key issues are emphasized. Only fundamental circuit analysis techniques are used within the standard so that electrical noise problems can be understood and respected by non-electrical engineers. Detailed analyses and calculations are left to references identified within the text of this standard.

Special importance is placed on evaluating electrical noise as a function of the circuit design specifications, emphasizing grouping circuits by frequency, load and signal level. This standard

stresses the need for integral systems to have an EMI control plan for each system to be examined both as a potential polluter of the environment and as a receiver to the environment.

3.0 QUICK REFERENCE FOR STANDARD

3.1 GENERAL

This design standard provides general design guidelines as a set of tables in Section 4.1.1, while the rest of Section 4.1.1 provides an expansion of the design guidelines. Section 4.1.2 provides similar assistance in dealing with maintenance considerations for electromagnetic compatibility. Section 4.1.0 provides the theoretical background for the standard.

The general design guidelines in Section 4.1.1 provide the do's and don'ts for most design needs, and should all be addressed for a complete EMI free design.

The vast majority of potential electrical noise problems may be eliminated by following a few simple rules described in Section 3.2 as minimal EMI Design Considerations for all circuits. The list of design and installation practices in Section 3.2 is required for all design functions. In addition, an Application Matrix, Section 3.3, has been prepared for basic design tasks involving EMI sensitive circuits, referencing the appropriate section or table in the standard.

3.2 MINIMAL EMI DESIGN CONSIDERATIONS

The following guidelines are provided for circuits which do not require separate design considerations for EMI control. For the most part, these guidelines are meant to prevent the inadvertent creation and coupling of noise to other circuits during normal operation or in case of circuit failure.

3.2.1 INSTRUMENT AND CONTROL CIRCUIT GUIDELINES

- Use twisted pair, shielded cable or equivalent.
- Connect shield to circuit common.
- Ground circuit common directly to station earth ground for safety. (The station earth ground serves two purposes: 1) it provides a return path to earth for lightning, static charge, and power distribution faults and 2) it provides a potential reference point for all circuits/equipment. This ground may be a single point on the station ground mat, a distributed bus(s) tied to the earth ground, or building structural steel tied to the earth ground.)
- For high frequency circuits, ground shields to reference ground plans at both ends and at multiple, random points in between to reduce noise coupling.
- Don't utilize remote power equipment grounds as grounding points for I&C circuits. Tie power equipment grounds and I&C grounds together only at the single point station earth ground.
- Twist exposed circuit leads together as pairs: signal and common.
- When shields must be broken at connectors or penetrations, maintain continuity with a

jumper, twisted with signal leads.

- In multi-conductor cables, connect all unused conductors to shield ground connection.

3.2.2 ELECTRICAL CIRCUIT GUIDELINES

- Use multi-conductor power cable, keeping all conductors twisted in the same cable.
- Keep ground fault return path close to power cable. If necessary, carry ground return with power cable.
- Twist exposed insulated power conductors together to minimize noise coupling.
- Use surge protection on all inductive loads to prevent generation of voltage spikes.
- Use arc suppression on relay/switch contacts.
- Use rigid galvanized steel raceways.

3.3 APPLICATION MATRIX

The following application guide, Table 1, has been provided to assist the design engineer in accessing the most applicable part of the standard for his/her design task. It can also be used as a check list to ensure that EMI is properly addressed during the design process

TABLE 1: DESIGN APPLICATION GUIDE

TASK	DESIGN CONSIDERATIONS	STANDARD REFERENCE	COMMENTS
I. Install new system in plant.	1. Will system be sensitive to EMI in plant or will it generate noise for interference with other system?	Table 3 Typical Noise Emitters and Receivers	Lists typical noise receivers/emitters. Potential problem if located close to unshielded cables with voltage or current sources greater than 10 times the reference system sensitivity. Use of shielded, twisted pairs will extend range to 1000 times the system sensitivity.
	2. If 1, above, is yes, then is manufacturer using good EMI control practices?	Section 4.1.1.2 Resolving Whether System in Emitter or Receiver	Evidence of poor EMI practices or last minute modifications to fix noise problems may be symptoms of marginal performance. In this case, consider developing an EMI control plan with performance tests.
	3. Defining plant shielding and ground connections.	Table 7 Recommended Shielding and Grounding	
	4. Defining separation for interconnecting cables.	Table 6 Separation Between Cables	

TABLE 1: DESIGN APPLICATION GUIDE

TASK	DESIGN CONSIDERATIONS	STANDARD REFERENCE	COMMENTS
	5. Developing an EMI control plan.	Section 4.1.1.5 Preparing an Electromagnetic Compatibility Plan	This reference provides the elements of a plan. Noise levels and test points must be defined for each system and location. MIL-STD- 461C is a good starting point. General susceptibility levels, taken from this standard and modified slightly, are: Radiated 10v/meter, 20KHz to 800 Mhz Conducted • Power frequency into signal input: 1v from 50 ohm, 1 watt source. • Power frequency into shields or grounds: 20 amperes. • Noise pickup: 200v, 10 microsecond trapezoidal pulse at 60 Hz reprate into power line input and into cable shields, etc.

TABLE 1: DESIGN APPLICATION GUIDE

TASK	DESIGN CONSIDERATIONS	STANDARD REFERENCE	COMMENTS
II. Modifying existing system/circuit.	1. If system has history of EMI or unresolved problems, treat like new system.	Refer to references for new design.	This is the time to look at the entire circuit to determine if it might be beneficial to extend the scope of the modifications to improve EMC.
	2. Meeting minimum EMI considerations.	Section 3.2 Minimal EMI Design Considerations	Original designs may not have used any EMI control, especially for emissions. Evaluate all replacement parts to determine if they would meet the current minimum design requirements. Wherever possible, upgrade components such as cables, filters, suppressors, etc.
	3. Increasing signal level sensitivity.	Table 6 Separation Between Cables. Table 7 Recommended Shielding and Grounding.	Increasing signal level sensitivity at any point in the circuit may require additional shielding or isolation from noise sources.
	4. Changing operating frequency characteristics. Verify proper shielding and grounding design and proper connections.	Table 7 Recommended Shielding and Grounding. Table 5 Cable Shielding Effectiveness.	Increasing the pass band or adding digital components will make a system sensitive to high frequency noise. If shields and ground connections cannot be otherwise guaranteed to be as good as new, they should be remade.

TABLE 1: DESIGN APPLICATION GUIDE

TASK	DESIGN CONSIDERATIONS	STANDARD REFERENCE	COMMENTS
III. Performing corrective maintenance on system/circuit.	1. Finding source of electrical noise/EMI problem.	Section 4.1.2 Maintenance EMI Considerations.	This flow chart leads the engineer through a logical sequence to pinpoint the source of an EMI problem.
	2. Shielding a noisy system/ circuit.	Table 7 Recommended Shielding and Grounding.	
	3. Adding noise suppression to a coil.	Figure 2 Surge Suppression.	Coils and inductive loads are a major source of electrical noise transients. This figure gives different ways to eliminate the surge noise.
	4. Verifying proper ground.	Section 4.1.0.3.6 Principles of Grounding.	Improper low frequency grounds may contribute to the electrical noise problem. The key is that the shield should be tied to circuit common which should be tied from only one point to the earth ground.
	5. Separating cables to reduce EMI.	Table 6 Separation Between Cables.	If it becomes necessary to install new cables, maintain adequate separation between noisy and sensitive cables.

TABLE 1: DESIGN APPLICATION GUIDE

TASK	DESIGN CONSIDERATIONS	STANDARD REFERENCE	COMMENTS
	6. Eliminating noise on high frequency circuits using the reference ground plane.	Section 4.1.0.3.6.	High frequency systems require multiple connections between the signal cable shield and the reference ground plane, especially at amplifiers or shielded enclosures.
	7. General electrical maintenance.	Section 4.1.2 Maintenance EMC Considerations, pg 133.	This section provides guidelines to minimize the possibility of maintenance induced EMI.

4.0 STANDARD

4.1 DISCUSSION

4.1.0 GENERAL DISCUSSION

4.1.0.0 Overview

In measurement and control circuits, electrical noise is a collective term indicating an undesired voltage or current in a circuit that interferes with a desired voltage or current. It has become an established practice to call the electrical noise electromagnetic interference or simply EMI. This standard will use EMI and electrical noise interchangeably, but will emphasize using EMI as a universal expression.

The EMI affecting a circuit has the same basic characteristics as desired signals and in most cases is unavoidably generated by another circuit. Therefore, it cannot be arbitrarily eliminated. This EMI should be considered as a part of the environment of a circuit and must be included in the circuit design in order to insure reliable EMI free operation.

4.1.0.1 COMPONENTS OF ELECTROMAGNETIC INTERFERENCE PROBLEM

(1) The affected circuit, often called the victim circuit or the receiver.

(2) The emitting circuit, often called the aggressor circuit or the transmitter.

(3) The coupling path, providing the mechanism to transfer the undesired electrical energy from the aggressor to the victim.

Figure 1 illustrates a generic EMI problem with a victim circuit being "attacked" by many different aggressors existing in a normal power plant. The design engineer for a new system will generally not be able to modify existing systems, but instead will have to incorporate protection for the existing systems into the design of the new system. An EMI problem will always be beyond the scope of a single design. That is, the design engineer will always have to contend with the balance of the plant as both victims and aggressors and the only design variable will be the coupling path between the new circuit or system and the balance of the plant. The design engineer must insure that the design circuit is neither victim nor aggressor in the intended application and that the new circuit does not become a coupling path to create EMI problems in existing circuits.

Electrical noise can show up in measurement and control circuits as a permanent step change in signal level, as a gain change or calibration error or as modulation of the signal varying from low frequency drift to high frequency spiking.

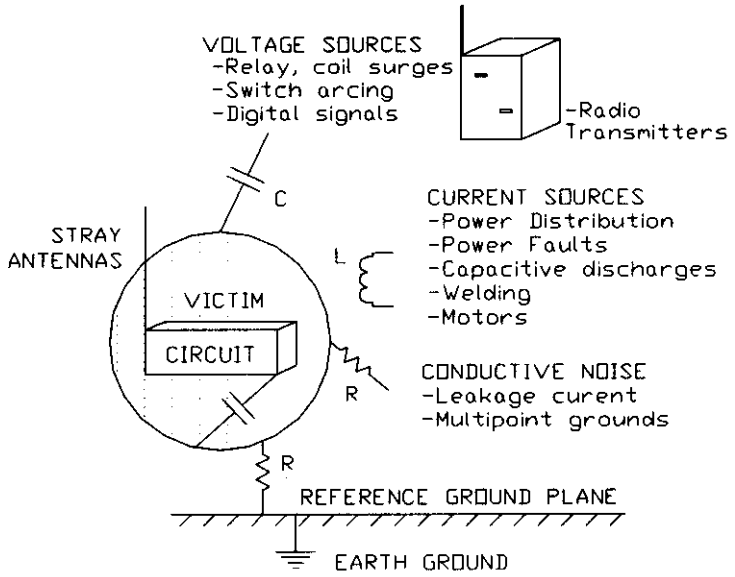

FIGURE 1: ELECTROMAGNETIC ENVIRONMENT

4.1.0.2 Fundamental Concepts of Electromagnetic Compatibility

The fundamental concept of compatibility is that a victim circuit must be able to function in the presence of electrical noise generated by an aggressor circuit. The theoretical treatment of electrical noise is quite complex. The roots are nested in Maxwell's Equations. Early simplifications involved reducing electrical noise to three different problems: DC, electrical and magnetic, and electromagnetic[1]. In the 1960s, military standards emphasized electrical noise as Electromagnetic Interference (EMI) as a wide frequency phenomenon. Recently, the computer industry has reawakened the need to deal with electrical noise differences and has emphasized the need to relate electrical noise to wavelength and compare the dimensions of a circuit to the wavelength of the signal.

EMI can be generated by components internal to a system or it can be generated externally and then coupled to the design circuit. If the circuit designer has knowledge of the EMI environment and the coupling paths, it is possible to calculate the circuit EMI levels and determine if the EMI will interfere with the design objectives of the circuit. For example, in a digital circuit operating at 5 volts, a 2.0 volt EMI pulse would cause errors. However, a 0.2 volt EMI pulse would have no effect on the digital decoding. Conversely, in an analog circuit measuring 0.010 volt pulses from a detector, the same 0.2 volt EMI pulse would be a serious problem.

Predictive modeling techniques exist to determine the EMI contributions to most circuits and the designer should be able to determine the conditions necessary to maintain a high signal-to- noise

[1] Reference 7.2.1, Henney, page 1-90 to 1-94. These are actually defined as steady state (DC), quasi steady state open (electrical), quasi steady state closed (magnetic) and electromagnetic or radiation.

ratio. Unfortunately, this part of the design process is flawed because the operational environment and coupling paths are not well known and assumptions have to be made. This can lead to unrealistically low predictions of the environment and result in no protection from EMI; or, it can lead to fear of everything and result in unrealistic designs that cannot be fully implemented in practice.

While the latter case would appear to be the conservative approach, it could have just as severe an EMI problem as the first case. EMI control is very much related to opening or closing the coupling paths. The difference between closed and open can represent a large isolation factor while the quality of the open or closed path represents a small contribution to the isolation factor. A complex EMI control design may wind up adding components in series, any one of which can fail and couple EMI into the circuit.

Most existing circuits in the power plant have evolved to be EMI resistant, brought about through the competitive process between manufacturers. A designer should have no fear of cloning such a proven circuit so long as the frequency group, load range, and signal level are kept the same. But, if the designer decides to make a slight change to improve performance, such as replacing a section of a DC circuit with a fiber optics link, the circuit should be reexamined for potential EMI problems. In the case of the fiber link, the circuit will now be sensitive to EMI in the spectrum of the digital circuitry associated with the link. The original circuit was insensitive to this EMI. Without an EMI plan, this circuit modification could be a design failure.

4.1.0.3 Fundamental Concepts of EMI and Coupling

The same fundamental concepts must be taken into account in each case of actual or potential EMI. They include the frequency relationship between the aggressor and victim (frequency spectrum), the relative signal levels, and existing or proposed shielding and grounding schemes.

4.1.0.3.1 Frequency Spectrum

Signal and electrical noise frequencies are important because noise coupling is strongly frequency dependent and it is possible to exploit frequency differences to prevent or fix electrical noise problems. Problems can be avoided by designing with system frequencies in mind.

In order to simplify the understanding of power plant electrical noise problems, this standard will present electrical noise in two frequency ranges: low frequencies, including DC, below radio frequency (< < 20 KHz), and radio frequencies (> > 20 KHz)[2]. This simplification emphasizes the principal differences in electrical noise coupling and protection and is based on the differences between radiation theory and circuit theory. The term EMI will be used exclusively for all time varying, radio frequency electrical noise signals, which have wave properties. Often, the term electrical noise will be used for both DC and time varying electrical noise below

[2] Various authors pick break points between 10 and 20 KHz where tests and design analysis change from conductive to radiated. MIL STD 461C has a number of different requirements: The range for conducted susceptibility, power lead is 30 Hz to 50 KHz while the range for radiated susceptibility, electric field is 14 KHz to 10 GHz.

Ref. 7.2.2, Chapter, has a good, brief discussion of the different standards.

20 KHz, where most of the power plant instrumentation and controls function, to emphasize that this is a special case of EMI. A critical factor in designing for electrical noise immunity is to understand that there are very real and distinct differences between dealing with the EMI at radio frequencies and dealing with electrical noise below radio frequencies.

The frequency spectrum may be considered in two very broad dimensions for the purpose of electromagnetic compatibility in the power plant:

a) DC - 20 KHz Power, audio, and low-frequency radio

b) above 20 KHz Radio, television, radar etc.

Only two ranges have been used because, signals in the lower frequency range will, in general, not readily be transmitted or received via radio antenna effects on circuits commonly used in electric power plants, while those frequencies that exhibit radio antenna effects can all be considered as a group.

Frequencies in the higher range will readily be coupled via antenna action in power plant circuits. They will, therefore, require special attention in order to control electromagnetic interference.

4.1.0.3.2 Frequency Wavelength

The coupling of electromagnetic interference through antenna effects is strongly dependent on the correlation between the physical dimensions of the components making up an electrical system and the frequency of the interference. This is because the periodic wave, which defines the frequency, will have a finite length in whatever media it is propagating. This wavelength is defined as:

$$\text{WAVELENGTH} = \frac{\text{VELOCITY OF PROPAGATION}}{\text{FREQUENCY}}$$

In air or space the velocity of propagation is 3×10^8 meters/second.

Some examples of frequency and wavelength are:

FREQUENCY	WAVELENGTH	
(Hertz)	(Meters)	(Feet)
100 KHz	3000	9842
1 MHz	300	984
10 MHz	30	98
100 MHz	3	10

Waves travel slower in cables and the above lengths can be reduced by 50 to 70 percent for typical plant cables. As a rule of thumb, the designer should start worrying about the antenna effects of cables for high frequencies with wavelengths equal to 20 times the electrical length of the cable. This means that a power cable 70 meters long will have an electrical length of 140 meters and will have a sensitivity to a wavelength of 2800 meters or frequencies of 107 KHz and above.

4.1.0.3.3 Frequency Content of Transient Pulses

Noise which is periodic contains energy only at frequencies which are integer multiples of the fundamental frequency f_o.

$$f_o = \frac{(1)}{T} \text{ Hertz}$$

T = period, seconds

Non-periodic noise contains energy at all frequencies. The energy will, however, be concentrated in a frequency band whose width and center-frequency is determined by the shape of the non-periodic noise.

The frequency content of both periodic and non-periodic noise may readily be determined using Fast Fourier Transform (FFT) analysis.

Knowledge of frequency content can provide information about the probable source and type of coupling of the noise, as well as offering the possibility of its suppression using frequency selective filters.

As an example of the frequency content of a non-periodic noise pulse consider a lightning pulse having a rise time of 1.2 microseconds and a half-amplitude width of 50 microseconds. The shape is that of a critically damped exponential whose frequency content is similar to that of a trapezoidal pulse.[3]

The single lightning pulse contains energy at frequencies from DC to an upper limit usually described as

$$f_{Hi} = \frac{1}{2\pi}\left(\frac{1}{t_r} + \frac{1}{t_d}\right) \text{Hertz}$$

where t_r = leading edge rise time, seconds
t_d = trailing edge decay time, seconds

The above lightning pulse then generates noise in a frequency bandwidth of DC to 135.8 KHz.

[3] See reference 7.2.2 pages 20, 21.

4.1.0.3.4 Signal Level Versus Noise Level

The relative levels of the desired signals and the potential electrical noise sources are important in order to determine whether or not an EMI problem exists. As a conservative approach, the design engineer should always seek to insure that any electrical noise picked up is less than 1% of the smallest expected signal.

Both signals and electrical noise are usually measured in decibels. Decibel measurement normally describes the ratio between two power levels. The numbers involved are small, convenient, and convey a good sense of the physical quantities involved.

In many cases a signal is compared with a standard reference power of one milliwatt. Compare the output of a 1000 MW power plant with a one-milliwatt reference using

$$db = 10\log\left(\frac{P_A}{P_B}\right)$$

where P_A and P_B are two powers we wish to compare.

$$\text{Plant output in dbm} = 10 \log \frac{(1000\text{x}10^6 \text{ watts})}{0.001 \text{ watt}} = 120 \text{ dbm}$$

where dbm means the ratio to 1 milliwatt.

A ratio of voltages may also be expressed in decibels, by relating power to the square of the voltage so that:

$$\text{db volts} = 20 \log \left(\frac{V_A}{V_B} \right)$$

In many I&C systems a typical signal level is one milliwatt. It is prudent to require that noise power be smaller by a factor of 100 dbm, or 0.00001 watt.

EXAMPLE

If a nearby circuit breaker opens with an initial arc power of five megawatts, this signal must be attenuated by

$$db = 10 \log\left(\frac{0.00001 \text{ watt}}{5\text{x}10^6 \text{ watt}} \right) = -117 \text{ db}$$

The design engineer can achieve the required attenuation by physical separation, shielding, or both.

Consider also a 10 microvolt signal from a nuclear event detector. The cable carrying this signal is in a tray with cables energized at 120 VAC. The attenuation required to reduce the electrical noise (the AC signal) to a magnitude equal to the NIS signal is:

$$\text{db voltage} = 20 \log \frac{(10\text{x}10^{-6} \text{ volts})}{120 \text{ volts}} = -141 \text{ db}$$

This is an enormous attenuation. Therefore in many cases both double shielding and physical separation will be required.

4.1.0.0.3.5 Shielding

Shielding is a method of preventing coupling of electric or magnetic fields between aggressors and victims. At low frequencies, the shielding must be considered separately for the electric and magnetic fields, since low frequency circuits will tend to generate either mostly-magnetic fields, or mostly-electric fields. At high frequencies, the fields combine and radiate as plane waves and the shielding is considered as a single problem.

The low frequency electric field may be shielded by installing a conductive plate between the two circuits, and grounding the plate to the circuit ground. The plate acts as a ground plane and does not have to be continuous. A conductive foil enclosing the conductors is generally used.

Shielding magnetic fields at low frequencies is difficult. Non-ferrous materials are not effective because they are transparent to the magnetic flux. Ferrous materials work by concentrating the flux lines away from the victim circuit. The effective shielding value is relatively small when compared to the effective shielding for electric fields at low frequencies. Attenuation of magnetic fields is generally accomplished by minimizing the loop area of both the aggressor and victim. This is done by using twisted pair conductors. Ferrous conduit may be used in addition to the twisting to further attenuate the magnetic fields.

At high frequencies, the plane waves are truly shielded by placing a metal shield completely surrounding the problem circuit. Any seam or penetration into the shield must be treated as a possible noise "leak" and be given special filtering or other treatment.

Shield attenuation for plane waves occurs because part of the wave impinging on the shield is reflected. The portion of the wave that enters the shield suffers losses in the shield material. These losses vary with shield material and thickness, as well as frequency.

In general, shielding is relatively easy for noise which is either mostly electric or plane waves, but more difficult for mostly magnetic waves.

4.1.0.3.6 Grounding

The general definition for ground is: "a conducting connection by which an electric circuit or equipment is connected to the earth, or to some conducting body of relatively large extent that serves in place of earth. It is used for establishing and maintaining the potential of the earth (or large body), or approximately that potential on conductors connected to it, and for conducting body current to and from earth (or the large body)".[4]

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[4] Taken from IEEE Std 100-1988. In this same Standard Dictionary, there are over 90 definitions of terms compounded with ground.

This definition reflects a major safety consideration for both personnel and equipment to insure that potential differences do not exist between equipments that could cause damage to anything connected between the equipments. The definition for ground is sometimes stated more simply as a connection of zero voltage difference, which oftentimes gets misunderstood as a point of zero voltage.[5] This small mistake leads many people to believe that ground will absorb or sink any electrical noise source connected to it.

IN FACT, EARTH GROUND WILL ACT AS A SINK ONLY IF THE ELECTRICAL SOURCE IS REFERENCED TO THE SAME POINT.

The principal objectives of the plant earth ground system are as follows:[6]

1. Maintain safe voltages across the plant during high voltage system transients.
2. Minimize the effects of lightning surges.
3. Provide a low impedance ground fault return path.
4. Provide a low impedance leakage path to dissipate static charge.
5. Minimize noise interferences in instrumentation by providing common reference planes of low relative impedance between devices, circuits, and complete systems.[7]

Connections to the earth ground system are not meant to eliminate electrical noise. The connections are basically for safety. Improper connections can create electrical noise problems. Further, there are distinct differences between the ground induced noise problem for low-frequency circuits and those for high-frequency circuits. Low-frequency circuits require a single point ground connection to prevent electrical noise. High-frequency circuits are effectively isolated from earth by the inductance of long ground leads, but need multiple "ground connections to a reference plane" to prevent electrical noise interference.

The design engineer can provide effective instrument and control grounding only if the system, its signal and potential electrical noise paths, and the physical principles involved are all understood. No one grounding scheme ensures trouble-free operation in all situations.

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[5] There is no such thing as a point of zero voltage; there can only be zero voltage difference between two points.
[6] Taken from Ref 7.1.2, IEEE Std 1050-1989.

[7] Objectives one through four deal with earth grounds and objective five now introduces a common reference plane. This common reference plane, not the ground to earth, serves to reduce noise.

4.1.0.4 Myths Associated with Electrical Noise

- Earth ground acts as a drain for electrical noise. (Truth: earth ground is required for safety-lightning strikes, static charge, and power faults. It will carry current from plant circuits only if it is actually part of the return path for the circuit.)

- Most common cause of problems in the Nuclear Instrumentation System (NIS) is multiple grounds. (Truth: The NIS is a high frequency system. Since high frequency shields require multiple grounds to a reference plane, multiple shield grounds should be a design practice.)

- Connecting a shield to plant ground at two different points provides a path for rf current flow and will induce a voltage on the conductor internal to the shield, causing electrical noise. (Truth: Single conductors appear as inductive high impedances at rf or high frequencies, inhibiting current flow. This same phenomenon, also known as skin effect, serves to isolate the inside and outside surfaces of the shield at high frequencies.)

- Grounding a circuit means providing a path to earth. (Truth: "Grounding" can have many different meanings. One of the more common meanings is to connect the high side of a circuit directly to the low, or common side to eliminate the possibility of any potential on the circuit. For safety reasons a connection is required between earth and the circuit. "Grounding" the high side of the circuit to earth may suffice; however, it is best to tie all conductors together and to earth.)

- Radio frequency (rf) energy is conducted on single wires. (Truth: Only for distances much shorter than a wavelength. Long distances require two complementary conductors acting as an rf transmission line.)

- Placing a metal barrier between two circuits will shield one from the other. (Truth: The metal barrier will provide a line-of-sight shadow shield for radiating high frequencies. However, it will only provide low frequency shielding if it is grounded to the same point as the noise source for electric fields or if it is a magnetic material for magnetic fields.)

4.1.1 DESIGN CONSIDERATIONS FOR NOISE CONTROL

4.1.1.1 General Design Guidelines

The design variables that must be considered to achieve and maintain electromagnetic compatibility include the following:

1. Installation practices.

   Shielding
   Grounding
   Routing

2. Installation hardware.

   Conduits & cable trays
   Cables
   Enclosures

3. Signal Conditioning.

4. System Design Specifications.

Table 1 provides general design considerations for these variables. The design engineer should use this table as a general checklist to insure that all potential problem areas have been addressed. The design engineer should always remain alert for the differences in EMI protection for low-frequency circuits and high-frequency circuits. If an individual system contains both low-frequency circuits and high-frequency circuits that must be interconnected, it will generally be necessary to use the high-frequency recommended practices.

A general purpose approach to design considerations for EMI control and electromagnetic compatibility follows.

TABLE 2 GENERAL DESIGN CONSIDERATIONS FOR ELECTROMAGNETIC COMPATIBILITY

Design Area	Guideline	Reference	Purpose
Shielding	Enclose high level/low-frequency current sources in magnetic material shields. At frequency above 10 MHz, any solid conductive shield is effective.	7.2.4	Attenuate magnetic fields in closely coupled areas.
	Enclose high level voltage noise sources in conductive faraday shields.		Isolate/contain electric field.
	Enclose sensitive equipment in shielded enclosures.		Isolate/exclude electromagnetic fields.
	Maintain shielding integrity of enclosures. Use conductive gaskets on doors/covers. -- Eliminate apertures/slots. -- Bond all incoming shields to outside surface. -- Filter or isolate all incoming conductors.		Shielded enclosure can be compromised easily at high frequencies by any one of these items.
	Avoid shield discontinuities such as splices or connectors in high noise environments.		At high frequencies, the discontinuities leak noise into cable.
	Do not allow shielded enclosures to be used as ground points for other circuits.		Avoid ground loops and minimize stray antennas.

TABLE 2 GENERAL DESIGN CONSIDERATIONS FOR ELECTROMAGNETIC COMPATIBILITY

Design Area	Guideline	Reference	Purpose
Grounding	Ground low-frequency circuits at a single point. -- Closest to input for victim -- Closest to source for aggressor	7.2.5, Chapt. 9	Eliminate ground loops.
	Ground high-frequency shields to reference ground plane at multiple random points plus both ends.		Minimize antenna affects of shield. Prevent shield from conducting noise into sensitive areas.
	Ground low-frequency shields to the single point ground for the circuit.		Provide ground return path for capacitively coupled noise.
	Earth ground sensitive analog circuits via ground busses isolated from power grounds.		Minimize ground potential differences caused by leakage currents flowing in power circuits.
	Earth ground high noise circuits with isolated ground or via power ground.		Minimize noise coupling through safety ground system.
	Earth ground digital circuits via ground busses isolated from both power and analog grounds, except at earth point.		Minimize noise coupling through safety ground system.
	Use minimum length, wide ground straps.		Minimize inductance of lead.

TABLE 2 GENERAL DESIGN CONSIDERATIONS FOR ELECTROMAGNETIC COMPATIBILITY

Design Area	Guideline	Reference	Purpose
	Properly bond and protect all ground connections.		Prevent ground path from deteriorating due to corrosion.
Conductor Routing			
	Group conductors in harnesses or raceways according to relative signal levels, keeping ratio of high level to low level signals to less than 10/1 within any group.	7.1.1	Minimize inductive and capacitive signal coupling between conductors.
	Avoid long parallel runs between high current carrying conductors and sensitive circuit conductors. o When necessary to cross other conductors with high current carrying conductors, do so at perpendicular angles.		Minimize inductive coupling to sensitive circuits.
	Keep conductors in raceways or next to reference ground planes formed by structural conductors. Do not suspend conductors in air.	7.2.4	Maintain minimum shield to ground impedance to minimize EMI pickup. Maintain minimum ground loop area in case of fault.
	Keep the signal and return conductor as close together as possible. This includes all phases, neutral and ground, for power circuits.		Minimize inductive loop area, including potential fault path.

TABLE 2 GENERAL DESIGN CONSIDERATIONS FOR ELECTROMAGNETIC COMPATIBILITY

Design Area	Guideline	Reference	Purpose
Conduits and Cable Trays	Instrument cables should not share the same raceway with power cables. o Cables should be grouped in conduits or trays according to signal level, keeping the max/min ratio of signal levels on cables at 10 or less.	7.1.0 7.1.1	This minimizes crosstalk while allowing maximum utilization of raceways.
	Control cables and power cables should not share the same raceway in the vicinity of motor control centers.		Prevent coupling of switching transients from the power cables to control cables. o The transients are high frequencies that are sharply attenuated by the power cable and are principal problem on power cables close to the noise source.
	Cables for lighting branch circuits should not be run in trays.		Noisy cables are best kept by themselves.
	Cables for fire protection system should not be routed through existing raceways.		Noisy cables are best kept by themselves.
	Avoid existing raceways when installing new high sensitivity or high signal level circuit.		Never disturb an electromagnetically compatible environment without good reason.
	Treat conduits just like outer cable shields, maintaining good connections at all joints.	7.3.1	This provides additional shielding and minimizes fault current loop.

TABLE 2 GENERAL DESIGN CONSIDERATIONS FOR ELECTROMAGNETIC COMPATIBILITY

Design Area	Guideline	Reference	Purpose
	Keep all power conductors (hot, neutral and ground) together in same conduit or cable tray.	7.2.4	Minimize inductive coupling with smallest loop area.
	Do not put magnetic material inside the current loop of a power circuit. (Example: Do not put neutral and hot wires in separate RGS conduits.)	7.2.4 7.1.1 7.1.2	Prevent inductive heating of magnetic material.
	Arrange order of cable trays and conduits for most sensitive (lowest power) cables at bottom (on extreme) and least sensitive (highest power) at top (other extreme).	7.1.0 7.1.1 7.1.2	Maintain maximum distance between victim and aggressor circuits, taking advantage of both distance and natural shielding provided by trays and other cables for noise attenuation. Provide maximum cooling configuration for high power cables.
	Use only RGS raceways for current carrying cables.	7.1.0 7.1.1	Maintain maximum magnetic shielding where necessary.
Cables	Use No. 16 AWG twisted and shielded pair for instrumentation (12 twists/ft). • For low-frequency circuits (Max 1MHz) • For differential mode circuits		Minimize inductive coupled noise by minimizing loop area formed by signal and return conductors. Minimize capacitively coupled noise by providing faraday shield around circuit conductors.

TABLE 2 GENERAL DESIGN CONSIDERATIONS FOR ELECTROMAGNETIC COMPATIBILITY

Design Area	Guideline	Reference	Purpose
	Use coaxial cable for high-frequency circuits.	7.2.4	Provide low loss, matched transmission line, as well as minimum loop area and faraday shield.
	Use triaxial or solid shielded coaxial cable for very sensitive high-frequency circuits.		Provide best shielding for electromagnetic radiation.
	Use multiconductor, twisted and shielded cable for special circuits. • Always keep the signal and return conductor twisted together		Adapt to special circuit needs while maintaining best noise control.
Instrument Enclosures	Isolate and filter AC power at input to the enclosure.	7.2.5, Chapt. 12	Eliminate a major source of noise input.
	Shield and physically separate sensitive analog circuits and noise sources.	7.2.6	Design fundamental.
	Use separate ground plane for sensitive analog circuits. (See Mfg. Instructions for guard shield.)		Minimizes common impedance coupling
	Insure that ground connections are permanent. Eliminate accidental or questionable grounds.		Prevent future problems caused by deteriorating or changing grounds.
	Always run signal and return wires together, as twisted pairs, ribbon cable or coaxial cable. Keep single wires as short as possible.		Minimize inductive coupling through loops.

TABLE 2 GENERAL DESIGN CONSIDERATIONS FOR ELECTROMAGNETIC COMPATIBILITY

Design Area	Guideline	Reference	Purpose
	Separate analog, digital, power, and high level noise wires from each other. Use shields around high level noise wires.		Fundamental design.
	Insure that enclosure will maintain its shielding properties throughout its life. • Unless otherwise confirmed, assume that the enclosure provides shielding.		Minimize potential for future problems.
	Ground shields on incoming wires to outside of enclosure. • Watch for inadvertent antennas that may couple to inside enclosure.		Keep noise conducted by shields to outside of enclosure.
	Earth ground enclosure through analog or digital ground system. • Small enclosures may be earth grounded through the instrument cable.		Minimize common impedance coupling through ground system.
	Filter all leads leaving a noise environment.	7.2.4 7.2.0 7.2.5	Prevent noise from polluting other areas.
Signal Conditioning	Use surge damping on inductive loads like relays and coils.		Eliminate a major source of transient noise (shifts noise from high level/high-frequency spike to low level/low-frequency, non-offensive signal)

TABLE 2 GENERAL DESIGN CONSIDERATIONS FOR ELECTROMAGNETIC COMPATIBILITY

Design Area	Guideline	Reference	Purpose
	Keep amplifiers for low signal level systems as close to source as possible.		Minimize the noise that will be picked up and amplified.
	Operate systems below radiating frequency spectrum and use filters to reject all high-frequency noise.		Noise is easier to contend with in low-frequency conduction modes than in high-frequency radiation modes.
	Limit pulse rise times in digital systems.		This limits high-frequency content and minimizes noise interference with other circuits.
	Use differential amplifiers to reduce common mode noise pickup in very sensitive circuits.		Design fundamental.
	Use balanced cable in differential circuits.		Minimize electric field noise pickup.
System Design	Select system operating frequency below or above known problem areas. • Below or above power frequencies • Below radio frequencies	7.2.0 7.2.5	Allow utilization of bandpass filters to sharply reduce major sources of noise.
	Use isolation devices in signal path where cables must connect over long distances in noisy environments.		Minimize potential for low-frequency ground loop problems.

4.1.1.2 Resolving Whether System is Emitter or Receiver

Each new system or modification in the plant needs to be considered as either a noise emitter or a receiver in order to determine where and how EMI protection must be applied.[8]

Tables 3 and 4 give a general list of typical circuits or processes and how they need to be considered. Table 3 covers electromagnetic compatibility between systems, the normal consideration for an operating plant. Table 4 covers electromagnetic compatibility internal to a system, such as the electronics for a measurement system in a drawer or rack. The decision on whether special EMI protection is needed will always be made by comparing emission levels or receiver sensitivity to the general electromagnetic environment in the area.

The analysis as to whether a device or system should be considered an EMI emitter or receiver should include the principal coupling paths, conductive and radiated. Long interconnecting cables will tend to add EMI to a system either by the increase in magnetic or electric field coupling, or by the shared ground resistance. On the other hand, short cables can act as high-frequency antennas and couple considerable high-frequency EMI into a system. A cable shield can act as a receiving antenna in a high radiated EMI area, conduct that EMI on a transmission line formed by the outer shield capacitance to station ground, to a shielded room, and re-radiate that EMI into sensitive circuits. These EMI coupling paths are covered in Section 4.1.0.1, Types of Electrical Noise.

In evaluating now designs, examine first the design on an internal compatibility basis (Table 3, Intra-System Evaluation) and then on an external compatibility basis (Table 4, Inter-System Evaluation). A 12-volt transformer located next to a 100 microampere bridge circuit inside an instrument drawer may create just as much relative interference as a 4 Kv transformer next to a 4-20 milliampere flow transmitter out in the plant.

In evaluating internal compatibility, look for the following signs of good EMI control practices:

- Wiring is separated by function.[9]
- Return wire is always carried with signal wire.

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[8] For a complete design, this will be a three step process: first, make the determination that the system is either an emitter or a receiver; second, determine the coupling paths under system control; and third, determine the amount of protection (isolation) necessary to reduce the coupling to an accepted level. Generally it is desirable to have a factor of 100 safety margin between signal sensitivity and noise levels. The signal-to-noise safety margins must be provided by the system manufacturer or designer. This standard will consider only the need and approach to establishing electromagnetic compatibility.

[9] Reference 7.2.0 suggests separating wiring into six groups: AC power, chassis grounds, and high level audio signals; DC power and susceptible audio signals; digital signals; interfering RF signals; susceptible RF signals; and antenna signals.

- Signal/return wire loop area is minimized.

- Wires entering system enclosures are controlled with shields
- grounded or filters used to eliminate EMI coupling into
- enclosure.

- Ground plane is used on PC boards.

- Minimum wire size is used.

- Sensitive circuits have electrostatic shields.

- AC input power is isolated and filtered.

- Circuit ground points are clearly identified and connections
- are made securely.

- Single point circuit ground is used.

- Very high current circuits are isolated or magnetically shielded from the rest of the system.

In evaluating external electromagnetic compatibility, look for the following signs of good EMI control practices:

- Noisy equipments or systems are isolated and/or shielded from balance of plant.

- Equipments/systems are earth grounded through their respective ground buss (power, analog, digital)

- All metal is grounded

- All connections for signals, power, grounds, shields, conduits, etc., are well made and protected from corrosion

- Inadvertent antennas are not allowed to enter sensitive systems or to exit noisy systems.

- Low frequency systems maintain a single point circuit ground; high frequency systems may have multiple ground points.

- RGS raceways are used for low frequency systems; either RGS or non-magnetic, conductive raceways may be used for high frequency systems.

- Both aggressor and sensitive systems utilize isolated AC power.

TABLE 3: TYPICAL NOISE EMITTER AND RECEIVER; INTRA-SYSTEM EVALUATION

RECEIVER		EMITTERS	
LOW FREQUENCY	HIGH FREQUENCY	LOW FREQUENCY	HIGH FREQUENCY
Amplifiers	Digital logic	Transformers	Power supplies
Current measurement circuits	Amplifiers	Servo systems	Clock circuits
DC power supplies	Wire harness	Motors	Digital line driver
AC power regulation and isolation	Circuit board wiring	Power wiring	Solenoids
	DC power supplies	Amplifiers	Relays
	Panel controls		Oscillators
	Test leads		Antenna feeding from outside enclosure
	AC power regulation and isolation		Digital interconnecting wires
			Inverters
			Rectifiers
			Non-functioning Suppressors

TABLE 4: TYPICAL NOISE EMITTER AND RECEIVERS;
INTER-SYSTEM EVALUATION

RECEIVER		EMITTERS	
LOW FREQUENCY	HIGH FREQUENCY	LOW FREQUENCY	HIGH FREQUENCY
Process Control 4-20 ma loops Thermocouples RTD's 10-50 ma loops	Analog Circuits >>10kHz Rad monitors Nuclear Inst. Systems	Power/leads Start/stall currents Run currents	Portable radios
Audio Communications Systems	Digital Logic	Insulation leakage to ground	Power switching Breakers Commutators Relays Solid state switches Line breakdowns
Analog circuits >>10kHz	Communications circuits	Ground Faults	Digital circuits
Recorders	Amplifiers Rectification in low frequency logic	Lightning currents	Carriers for AC meas. circuits
AC power isolation	Annunciators	Transformers	Fluorescent lights
	Computers	Coils	Mismatched cables - Poor connections
	AC power isolation	Single conductor current loops	Radio, television, microwave transmitters
			Static discharges
			Partial discharge in insulation
			Corona on high voltage conductors

4.1.1.3 Preventing EMI Emission

The power plant has few restrictions on the generation of EMI internal to the plant. Many of the instrument and control systems that are used are not covered by emission standards currently being imposed by the FCC on consumer electronics. This doesn't mitigate the need to MINIMIZE NOISE GENERATION at all times. The victim circuit will fail by itself if not properly protected. The aggressor circuit can cause many other circuits to fail.

4.1.1.3.1 Eliminate the Cause of Noise

In seeking to minimize the generation of EMI in the power plant, set the following priorities:

1. Don't generate radiating signals unintentionally because once generated they are out of control.

2. Minimize the voltage and current levels being used so that conducted interference can be controlled at minimum cost.

3. Include the fault path in the EMI analysis.

4.1.1.3.2 Guarding Against the Unintentional Radiating Signal

In a power plant, this is principally caused by switching transients. Switching voltage creates a traveling wave whose high frequency content is proportional to the rise time and low frequency content is proportional to the width of the pulse.[10] Similar transients are generated by brushes in motors, as well as opening and closing any type of switch from high voltage ac power transfer down to 5 Vdc relay contacts. Arcing of switch or breaker contacts will increase the high frequency content of the wave and the number of waves.

The best method for eliminating this type of radiation is to confine the high frequency content by limiting the rise time from potential EMI sources. This can be accomplished by adding series inductance to the circuit or by shunting the high frequencies to ground with capacitance. Many types of combination filters are available commercially.[11,12] When using filters in logic circuits, be certain to consider the effect of the reduced rise time on the response time of the logic. The filtering will be effective only if placed close to the source.[13]

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[10] A lightning pulse with a 1.2 microsecond rise time and a 50 microsecond fall time will contain energy in the spectrum from 10 KHz to 265 KHz. While much of the energy is in the low-frequency spectrum and can be conducted back to earth, the high frequencies will radiate along rf transmission lines to inadvertent antennas and can cause damage to sensitive systems such as computers.

[11] Reference 7.2.2 has a good discussion on filters.

[12] Cleaning up an ac power distribution system by shortening runs will reduce the circuit inductance, a natural filter, and can create high-frequency noise problems.

[13] If filtering is located farther than 1/20th of a wavelength at the highest frequency generated, you can expect some radiation.

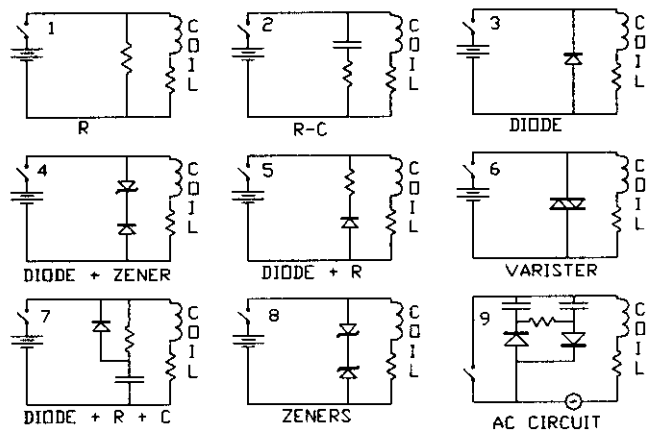
Another source of energy for unintentional radiation is the inductive surge generated by closing or opening a coil or relay. Closing can double the applied voltage; opening can create a wave front a hundred times the applied voltage.[14] All relays or coils that are used in association with high frequency equipment should have some type of surge protection. The protection generally consists of providing a path to dissipate the energy stored in the inductor. Figure 2 illustrates different methods of surge suppression and lists the important features of each. The choice will depend upon the application of the coil. However, the voltage limiting device may not eliminate the radiation threat. Relays and coils are available with built-in protection, or may have the protection added separately.

Still another unintentional source of high frequency radiation is the selection of circuit operating specifications above the needs of the application. Choosing the fastest operating device, whether it is a microprocessor chip or a relay contact, only complicates the design by creating the high frequencies. Then those high frequencies can couple into circuits that have a real need for fast switching capabilities and commensurate sensitivity. To avoid problems, operate a system at the lowest frequency and select components that are matched in switching speed. Be especially cautious about retrofitting high speed microprocessor or logic modules into low speed systems.

[14] Reference 7.2.4. Amplitude is a function of the rate of change of the current. The faster the switching action, the higher the amplitude. Also, the faster the switching action, the higher the frequency content.

4.1.1.3.3 Minimize the Operating Voltage and Current

This is a fundamental design guideline. In an operating plant the design engineer will seldom have much flexibility in this area; nevertheless, he should always consider the possibility of reducing the current requirements in a low impedance loop and the voltage in a high impedance loop.



1. Register – return path for current from collapsing magnetic field of coil. Keeps voltage from building up. Consumes DC power Causes longer release time.
2. Resister/capacitor network – Does not consume DC power but still causes longer release time. Need large capacitor.
3. Diode – excellent suppressor. Polarity, sensitive. Increases release time.
4. Diode plus zener – excellent suppressor. Polarity, sensitive. Does not affect release time or coil life.
5. Diode plus resister - register can adjust release time.
6. Varister – excellent suppression. Draws small DC current normally. Conducts on surge voltage. Proper selection does not offset release time.
7. Resister plus capacitor plus diode - can be excellent suppression without affecting release time. Must be selected for coil.
8. Back to back zener – excellent suppression. Not polarity sensitive. Does not affect release time.
9. AC coil network.

Ref. Engineer's Relay Handbook, Third edition. National Association at Relay Manufacturers, Elikart, Indiana.

FIGURE 2: SURGE SUPPRESSION

4.1.1.3.4 Consider the Fault Path

This is also a fundamental design guideline. The basic operating design for the power plant provides redundant controls so that no single failure can impair the safe operation of the plant. In evaluating a design for EMI generation, consider the probable fault scenarios and how they might generate EMI which could cause other circuits to fail or give erroneous data that could scram the plant. An obvious potential problem could be a power cable fault to ground that would create a loop thousands of times larger than the operating loop. Add that to a current that might also be 10 to a hundred times higher than the normal operating level and you have the potential to disturb even normally insensitive circuits. The solution, of course, is to carry the ground return

with the power cable or to insure that the raceway provides a substantial ground return path. This will minimize the loop area for the ground fault.

4.1.1.3.5 Isolate the Source of the Noise

When the system design necessitates generation of signals that will exceed the general EMI levels in the area, it will be necessary to isolate the source of the EMI. This must be done in one of two ways:

4.1.1.3.5.1 Shielding

Shielding is straightforward, although not necessarily practical. For electric fields at low frequencies it requires only a conductive enclosure. For magnetic fields at low frequencies it requires a magnetic material. For electromagnetic fields at high frequencies conductive, non-magnetic enclosure can be effective.[15] Remember that for shielding against traveling waves, the shield must fully enclose the protected system and all wires or cables entering or exiting the shield must be prevented from carrying EMI past the shield.

One area with potential need for shielding that is frequently overlooked is the extra current loop formed at connectors or splices in congested areas with mixed signals such as in an instrument rack. Splices are worse than connectors since the individual wires must be separated, enlarging the loop. Magnetic tape is commercially available to wrap these areas and negate the coupling effects of the added loop.[16]

Table 5 provides a summary of the relative shielding effectiveness at different frequencies for common shielding materials used in cables.

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[15] Reference 7.2.4. Above 10 MHz, any solid shield thick enough to be practical provides more than adequate shielding for most applications.
[16] Reference 7.2.4.

TABLE 5: CABLE SHIELDING EFFECTIVENESS

CABLE TYPE	SHIELD DESCRIPTION	ATTENUATION (db*) LOW FREQUENCY ELECTRIC	LOW FREQUENCY MAGNETIC	PLANE WAVE
Insulated pair, No twist	None	0	0	0
Insulated pair, 12 twists per foot	None	0	40	0
Insulated twisted shielded pair	Aluminum foil	70-80	40	60
Coaxial	Tinned copper braid, single shield	60	60	60
Coaxial	Tinned copper braid, two shields, touching	60	60	80-90
Triaxial	Tinned copper braid, two shields insulated from each other	80	60	80-100

TABLE 5: CABLE SHIELDING EFFECTIVENESS

		ATTENUATION (db*)		
CABLE TYPE	SHIELD DESCRIPTION	LOW FREQUENCY ELECTRIC	LOW FREQUENCY MAGNETIC	PLANE WAVE
Coaxial	Solid copper	60-80	60	100-120
Twinaxial	Tinned copper braid, twisted conductors	80-100	40-60	80-100
Twinaxial	Solid copper twisted conductors	80-100	40-60	100-140

*NOTE:
THESE VALUES ARE GIVEN FOR RELATIVE ATTENUATION BY CABLE TYPE. ACTUAL VALUES WILL DEPEND GREATLY ON QUALITY OF CONNECTIONS, INSTALLATION PRACTICES, AND FREQUENCY.

4.1.1.3.5.2 Physical Isolation

Physical isolation can be accomplished by moving the source away from the area. The distance required for EMI reduction will depend on the frequency of the EMI and whether it is electric field, magnetic field, or electromagnetic plane wave.[17]

If physical isolation is required, shielding should also be included as a remedy to minimize the potential for future problems. Since coupling between cables is a major source of EMI in a plant, recommended cable separations are included in Table 6.

[17] For a predominant electric field case, the electric field falls off at $1/r^3$, the magnetic field falls off at $1/r^2$, and the plane wave falls of at $1/r$.

TABLE 6: SEPARATION BETWEEN CABLES

Read down to find allowable separation between range of signal level.

	SIGNAL LEVEL	1	2	3	4	5	6	7
1	RANGE 1 10 microV to 100mV Nuclear instrumentation. Analog circuits. (triaxial cable)	N 0"						
2	RANGE 2 1.0 mV to 1.0 V Low Frequency. Analog Circuits. Coaxial or twisted, shielded pairs.	T/C 0"	N 0"					
3	RANGE 3 10 mV to 10 V Wideband. Digital and analog circuits. Coaxial or twisted shielded pairs.	C RGS 2' Alum 4' ^{T}RGS 3' Alum 3'	 T-T 1" T-C 1" C-C 1"	N 0"				
4	RANGE 4 1 V to 100 V Analog circuits, switching circuits. Twisted shielded pairs.	C RGS 2' Alum 4' ^{T}RGS 3' Alum 3'	T-T 6" T-C 4" C-C 3"	T-T 6" T-C 4" C-C 3"	N 0"			

TABLE 6: SEPARATION BETWEEN CABLES
Read down to find allowable separation between range of signal level.

	SIGNAL LEVEL	1	2	3	4	5	6	7
5	RANGE 5 50 V to 600 V Control, AC feeder circuits. Twisted multiconductor.	C RGS 2' Alum 4' ^{T}RGS3' Alum 3'	T-T 6" T-C 4" C-C 3"	T-T 6" T-C 4" C-C 3"	T-T 0" T-C 0" C-C 0"	N 0"		
6	RANGE 6 100 V to 1 KV 20-80 A Power circuits. Special cable.	C RGS 2' Alum 4' ^{T}RGS3' Alum 3'	T-T 26" T-C 18" C-C 12"	T-T 18" T-C 12" C-C 9"	T-T 6" T-C 4" C-C 3"	T-T 6" T-C 4" C-C 3"	N 0"	
7	RANGE 7 1 KV to 10 KV Power service. HV cable.	C RGS 2' Alum 4' ^{T}RGS3' Alum 3'	T-T 26" T-C 18" C-C 12"	T-T 26" T-C 18" C-C 12"	T-T 18" T-C 12" C-C 4"	T-T 6" T-C 4" C-C 3"	T-T 0" T-C 0" C-C 0"	N 0"
8	RANGE 8 10 KV to 100 KV Power service. HV cable.	T/C 10'	T-T 60" C-C 30"	T-T 60" C-C 30"	T-T 60" C-C 30"	T-T 26" T-C 18" C-C 12"	T-T 0" T-C 0" C-C 0"	T-T 0" T-C 0" C-C 0"

NOTE: 1) All cables are assumed to be a minimum of twisted shielded, coaxial, or as recommended by system supplier. "N" means no tray or conduit, "T" means installed in separate tray, "C" means installed in separate conduit, and "TC" means both tray and conduit used.

2) This table is based on recommendations given in IEEE std. 518-1982, Paragraph 7.4.3. Added emphasis is given to very low level circuits and digital circuits.

4.1.1.4 Protecting the Victim from Noise

The design system will undoubtedly have numerous interfaces or subsystems which will have to be considered separately for EMI protection. The most critical instance will always be the very sensitive, wide-band amplifier or detector at the heart of a system. Overall protection will have to be considered for this most critical case; in that way, the designer can pick and choose for less sensitive systems. The areas that should be considered for reducing the EMI susceptibility of a circuit are:

Amplifier type

Amplifier sensitivity

Filters

Inadvertent antennas

Shielding and grounding

4.1.1.4.1 Amplifier Type

Differential amplifiers driven by balanced lines are the desired design configuration for very sensitive systems that utilize cables connecting between the amplifier and a signal source. The purpose of this design is to null out any signals that are coupled equally to both the signal and return wires in the cable (the common mode pick up). This is especially important for the low frequency systems where conducted EMI is a major problem. The differential amplifier has both inputs balanced to ground. Frequently, the differential amplifier will incorporate a guard shield.[18] The alternative to the differential amplifier is the single-ended amplifier which has one input connected to the common ground.

High frequency systems normally use coaxial cables and operate as single ended systems. Common mode currents are not supported on this. type of cable at high frequencies and there is no need for the differential amplifier. On the other hand, wide-band systems can gain from differential amplifiers; in these cases, a twinaxial cable may be used for both wide frequency response and balance.

4.1.1.4.2 Amplifier Sensitivity

Amplifiers should be selected in conjunction with the signal sources to operate at reasonable signal to EMI levels without becoming EMI sources. Signal levels for new systems should be

[18] Reference 7.2.4. The guard shield is in the amplifier ground plane, but is not tied to any other ground. This allows the guard to be tied to the same potential as the source and essentially prevents any unbalanced current to ground (ground loop).

compared with levels for similar applications in the same or similar areas. If the design changes levels by a factor of 10, there is a good probability that the new system will either incur EMI problems or create EMI problems, unless appropriate improvements in the EMI control measures are also included in the design.

4.1.1.4.3 Filters

Filters should be used to exclude energy in all frequency ranges other than the desired frequency or band of the operating system. By keeping the pass band narrow, the number of potential aggressor circuits can be minimized. Avoid including future capability such as higher frequency or wider bandpass in a system at the risk of introducing EMI problems. The filters should be integral to the system and should be applied as close as possible to the inputs.

Filter designs will generally be classified as communications wave filters and power line filters.[19] However, there are a number of other filtering techniques that can be employed to reduce high frequency EMI. These include the use of simple capacitors, inductors, ferrite beads, and lossy cables. In addition, waveguide below cutoff techniques may be employed when it is necessary to bring cables into a shielded enclosure and other filtering techniques cannot be tolerated.[20] The actual design of the filters has to be a function of overall system design.

4.1.1.4.4 Inadvertent Antennas

The design system should not have wires or cables installed or capable of being installed that have potential to function as receiving antennas that may conduct EMI into the system, radiating antennas that will conduct EMI into sensitive areas and then radiate, or a combination of the two.

Special attention must be given to surveillance or maintenance procedures that may require making test measurements while the system is operating.[21] If measurements must be made on an operational system, be certain that the system is not sensitive to high frequency EMI and there is no possibility of introducing a ground loop through the test equipment.

4.1.1.4.5 Shielding and Grounding

Shielding and grounding must be applied as a combination for EMI protection. Further, there are distinct differences between shielding and grounding applications and effects for the low frequency and high frequency conditions. Table 7 provides recommendations for different circuits that will be found in the power plant.

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[19] Reference 7.2.2 has a good discussion on overall filters. Reference 7.2.5 has a good discussion on filter design.
[20] An insulated cable may be run through a hollow tube which will reject rf frequencies below the waveguide cutoff from being conducted on the cable dielectric. May be applicable for very sensitive systems operating above 100 MHz.
[21] A 1-meter test lead will start looking like an antenna at about 3.75 MHz, becoming tuned at 75 MHz.

TABLE 7: Recommended Shielding and Grounding Practices for Instrument and Control Circuits

TYPE CIRCUIT	OPERATING LEVEL	OPERATING FREQUENCY	RECOMMENDED SHIELDING	RECOMMENDED GROUNDING
Analog	10uV – 5mV	20KHz – 100MHz	1) Solid shielded coaxial cable installed in rf tight conduit. Conduit must be continuous. Pull boxes must have rf gaskets.	Conduit must be grounded to Instrument enclosure and reference ground plane at each end. Otherwise, adhere to standard grounding for conduit. If connections are made in pull boxes, ground both mating connectors to pull box.
			2) Triaxial cable installed in rf tight conduit. Conduit must be continuous. Pull boxes must have rf gaskets.	Conduit and outer shield of triaxial cable must be grounded to instrument enclosure and reference ground plane at each end. Otherwise adhere to standard grounding for conduit. If connections are made in pull boxes, ground both mating connectors to pull box.

TABLE 7: Recommended Shielding and Grounding Practices for Instrument and Control Circuits

TYPE CIRCUIT	OPERATING LEVEL	OPERATING FREQUENCY	RECOMMENDED SHIELDING	RECOMMENDED GROUNDING
Analog	5mV – 1000mV	DC – 20KHz	Individual twisted, shielded pairs installed in RGS conduit. (Optional: if RGS conduit is not practical, run in trays and/or keep close to plant structural grounds.)	Single point for shield, signal and earth ground at transmitter. (Optional: shields do not have to be continuous, but must be grounded to circuit common ground. In some cases, signal may be floated.)
		20KHz – 1MHz	Same as above	Single point DC ground for shield, signal and Earth ground at transmitter. Shields must be continuous; it may be necessary to place an AC ground from shield to circuit common at the receiver.

TABLE 7: Recommended Shielding and Grounding Practices for Instrument and Control Circuits

TYPE CIRCUIT	OPERATING LEVEL	OPERATING FREQUENCY	RECOMMENDED SHIELDING	RECOMMENDED GROUNDING
		1MHz – 1000MHz	Coaxial cable enclosed in metallic conduit or in cable trays.	Ground to signal ground reference plane at each end. Transmitter and receiver enclosures should appear to be extensions of cable shield.
	1V – 10V	(Same as requirement for 5mV – 1000mV except that need for RGS conduit is reduced.)		
	4 – 20ma 10 – 50ma	DC – 20KHz	Twisted pairs may be combined in overall shielded cable if circuit sources are similar. Use RGS conduit when within 2 ft of high current carrying conductors.	Ground shield to signal ground at only one end, preferably the signal source.

TABLE 7: Recommended Shielding and Grounding Practices for Instrument and Control Circuits

TYPE CIRCUIT	OPERATING LEVEL	OPERATING FREQUENCY	RECOMMENDED SHIELDING	RECOMMENDED GROUNDING
Digital Digital to Analog Contact/switches	5V – 48V 0 – 10V 5V – 48V	20KHz – 1MHz (rise time greater than 0.3 microseconds)	Short runs (less than 20 meters) individual twisted pairs combined in overall shielded cable.	External shield grounded to reference ground plane at both ends. (Connect circuit ground to digital ground. Optional: ground at only one end.) Better: use optical couplers for total isolation between source and receiver grounds.
			Long runs (greater than 20 meters): individual twisted, shielded pairs.	Same as short runs. Better: use optical couplers.
		10MHz – 100Mhz (rise time less than 0.03 microsecond)	Short runs (less than 2 meters) individual twisted, shielded pairs.	Shield grounded to reference ground plane at each end. Better: use optical couplers.

TABLE 7: Recommended Shielding and Grounding Practices for Instrument and Control Circuits

TYPE CIRCUIT	OPERATING LEVEL	OPERATING FREQUENCY	RECOMMENDED SHIELDING	RECOMMENDED GROUNDING
			Long runs (Greater than 2 meters) Coax or Twinaxial cables	Shield grounded to reference ground plane at each end. (Optional: also ground at each connector.) Better: use fiber optics cable to prevent noise pick up and to isolate between system grounds.

4.1.1.5 Preparing an Electromagnetic Compatibility Plan

The purpose of an EMC Plan is to insure that modifications to the facility or addition of new systems or equipment will operate in the intended electromagnetic environment of the plant and will not create interference with existing systems.
A basic EMC Plan should define the following:

- Objectives.
- Review process.
- Reference documents.
- Description of system.
- EMC requirements.
- Vendor test specifications.
- Plant performance test specifications.

- Objectives.

The objectives must define the methodology of how the EMC Plan will insure the successful operation of plant equipment and controls both during normal operation and during expected equipment failures. The objectives should explain how the remaining sections of the EMC Plan are structured to meet these objectives. The objectives of each EMC Plan should be the same and should be established as a plant standard.

- Review Process.

The review process must establish the management control and technical verification of each EMC Plan. The review process should involve a representative from Construction, Maintenance, Design Engineering, Plant Operations and Station Technical. The review process should consider two levels of review: (1) An administrative review where evidence has been presented that EMC compatibility is assured and no special tests are required by either the vendor or the plant. (2) A formal review for those systems or equipments where EMI may be a problem. This section should also be defined by a plant standard.

- Reference Documents.

These documents must establish the basis for technical requirements and testing. procedures with respect to the plant. This section should also be defined by a plant standard.

- Description of System.

This section must describe the modification to the plant or the addition of new equipment. There must be sufficient detail to identify the types of electrical signals as a function of frequency and voltage or power levels such that a determination can be made as to whether the design could be

either a victim or aggressor. The description should include installation specifics and potential fault modes.

- EMC Requirements.

This section must define the EMI environment for the plant and the allowable EMI that the new systems or equipment may generate. There are currently guidelines in existence that can be adapted to the nuclear power plant. There should be provision within this section to allow for special considerations. This section should define basic shielding and grounding requirements for all systems. The bulk of this section should be established by a plant standard; however, there should be a means within this section for the review process to fine tune the requirements.

This section should provide a means to accept alternate plans or data that has already qualified equipment or modifications for use under similar conditions, without requiring the complete review process.

- Vendor Test Specifications.

This section will uniquely define special tests that the vendor must conduct to insure that the equipment can operate in the intended environment. These requirements should place emphasis on operation of the equipment under typical plant conditions in order to reproduce the EMI coupling conditions of the plant as faithfully as possible. These tests should generally be modeled after the military standards or existing industry standards.

- Plant Test Specifications.

This section should define special tests that should be conducted on the equipment as a part of installation. There should be a major emphasis placed on insuring that the equipment or modifications cannot become an aggressor during its life.

4.1.2 MAINTENANCE EMC CONSIDERATIONS

The performance of the various maintenance functions for required surveillance, preventive maintenance, or corrective maintenance, both for electrical functions and non-electrical functions, has potential for either creating new: aggressor circuits or altering coupling paths. Either case can result in coupling EMI into a critical circuit and scramming the plant.

The basic design criteria for EMC establishes that there are neither aggressors nor victims in the plant and, hence, there are two levels of protection from EMI. Expected equipment failures can turn an EMI resistant circuit into a victim circuit, yet this alone will not disturb normal plant operation. It will still require that an aggressor circuit be created and the EMI be coupled into the victim circuit before the plant operation is affected. Similarly, an EMC circuit can suffer a shielding or grounding failure and start producing EMI and it will not affect plant operation unless it is coupled to a victim circuit. Maintenance functions that either introduce an aggressor circuit or compromise the EMI immunity of a critical circuit simply increase the probability that

EMI will cause a plant scram.

All maintenance functions being performed during plant operation should be conducted in a manner that will not degrade the EMC of the plant. The following sections identify maintenance activities that can degrade the EMC of the plant and should be conducted cautiously during normal plant operation.

4.1.2.1 Keep Noise Out of Critical Areas

Table 8 lists a number of equipment that maintenance might use that could become aggressor circuits and affect sensitive circuits during plant operation. The guidelines are general and conservative and may be applied judiciously. Most of these aggressors turn out to be problems in the higher frequencies and will tend to cause false alarms rather than actual measurement errors. With reasonable precautions, all of this equipment can be used during normal plant operation if the need arises.

TABLE 8 MAINTENANCE AGGRESSOR CIRCUITS

Aggressor Circuit	Type of EMI	Coupling Path	Precautionary Measures
Electric Arc Welding, Plasma Arc Welding	Low Frequency Magnetic Field	Inductive coupling from both AC power and welding cables	1) Minimize loop area of welding conductors and AC power conductors to welder. Use twisted conductors for AC input and for welding hot and return lead. DO NOT USE GROUND FOR RETURN. 2) Keep cables (not in galvanized, steel conduit) at least 1 foot from parallel plant cables for each ½" of insulation separating the cables. 3) Operate welder from non-vital buss AC power source. 4) Keep welding ground connection close to welding point.
	High Frequency Radiation	Inadvertent antennas radiating mainly from arc location.	1) Do not weld within room, building, or line of sight of critical circuits or cables for critical circuits or cables connecting to areas with critical circuits.

TABLE 8 MAINTENANCE AGGRESSOR CIRCUITS

Aggressor Circuit	Type of EMI	Coupling Path	Precautionary Measures
			2) If welding is essential, it may be performed inside a temporary shielded enclosure consisting of conductive screen, preferably copper with all seams overlapping at least 6 inches. The welding equipment should also be inside the screened enclosure. No antennas may be allowed to penetrate the shield.
	Low Frequency Electric Fields	Capacitive coupling from AC power Cables	1) AC power cables must be in conduit or at least 5 feet from any unshielded plant cable.
Radio Transmitters	High Frequency Radiation	Inadvertent antennas	1) Do not use portable transmitters within the control room or within rooms containing distribution cabinets for critical circuits, especially

TABLE 8 MAINTENANCE AGGRESSOR CIRCUITS

Aggressor Circuit	Type of EMI	Coupling Path	Precautionary Measures
			microprocessor controlled circuits, nuclear instrumentation, and radiation monitors.
Large Inductive Loads, (such as relays, transformers)	Low & High Frequency E-Fields Low Frequency Magnetic Fields	Capacitive coupling between cables and rf radiation Inductive coupling between cables	1) Do not use or install any new or temporary equipment that requires more than 10 amperes of 115v 60Hz power without first assessing possible noise generation and coupling to nearby circuits, both during operation and in case of a fault.
Motors with Brushes, Drill Motors, Small Appliances, Razors.	High Frequency Radiation	Inadvertent antennas	1) Do not use inside distribution racks containing digital or very sensitive analog, high-frequency equipment such as nuclear instrumentation or radiation monitor. 2) Do not use within the room or general

TABLE 8 MAINTENANCE AGGRESSOR CIRCUITS

Aggressor Circuit	Type of EMI	Coupling Path	Precautionary Measures
			area if the equipment racks are open for surveillance or maintenance.
Charged Capacitors or Open Circuit Cables	Low & High Frequency Magnetic Fields	Inductive coupling between cables, Inadvertent antennas	1) Discharge these circuits with a resistor of approximately 1 to 10. K ohms to minimize the current. Keep discharge leads short and twisted together. 2) When not being used, all cables or capacitive devices should be shorted.
Meggers, High Resistance Testing, High Potting	High Frequency Magnetic Field	Inductive coupling between cables, Inadvertent antennas	1) Long cables or cables attached to capacitors should not be tested for voltage withstand to ground because failure will cause a large current surge. During plant operation,

TABLE 8 MAINTENANCE AGGRESSOR CIRCUITS

Aggressor Circuit	Type of EMI	Coupling Path	Precautionary Measures
			testing should be conducted at voltages equal to or below the operating voltage. Testing of a cable to an enclosed shield and where the cable path is known to be at least 2 feet from any known sensitive circuit may be acceptable up to 1000 volts dc.

5.0 ACRONYMS AND SYMBOLS

Following are abbreviations or acronyms commonly used in this standard.

AC	Alternating current
AWG	American Wire Gage (wire size)
B	Flux density of magnetic fields
C	Capacitor
db	Decibel, logarithmic base 10 ratio of two powers
dbm	Logarithmic power ratio relative to 1 milliwatt
DC	Direct current
E	Electric field
ECAD	Electronic Characterization and Diagnostics instrument system
EMC	Electromagnetic compatibility
EMI	Electromagnetic interference
F	Frequency
f_o	Fundamental frequency
F	Farad - unit of measurement for capacitance
FFT	Fast Fourier Transform
H	Magnetic field
H	Henries - unit of measurement for inductance
Hz	Cycles per second
I	Amperes
K	Kilo
L	Inductor, inductance
m	Milli
ma	Milliamperes
M	mega
M	Mutual inductance
NIS	Nuclear Instrumentation System
rf	Radio frequency
R	Resistor
RGS	Rigid galvanized steel (raceway)
RTD	Resistance temperature detector
SWR	Standing wave ratio
T	Time, period of waveform
T_d	Pulse. decay time
T_r	Pulse rise time
V	volts
Z	Impedance

The following are symbols commonly used in this standard.

ε	Relative permitivity
Φ	Flux (of magnetic field) in Webers
λ	Wavelength
μ	Permeability
π	Pi, (3.1416)
ρ	Coefficient of reflection (on transmission line)
ω	Radian frequency, (2 πf)

6.0 DEFINITIONS

AGGRESSOR -- An electrical circuit that is capable of generating EM emissions in excess of the accepted environment for the area.

BONDING -- 1. (Generating station grounding) The permanent joining of electrical parts to form an electrically conductive path that will ensure electrical continuity and the capacity to conduct safely any current likely to be imposed.

2. (Transmission and distribution) The electrical interconnecting of conductive parts, designed to maintain a common electrical potential.[22]

3. In electrical engineering, the process of connecting together metal parts so that they make low resistance electrical contact for direct current and lower frequency alternating current (NATO).[23]

COUPLING -- The conducted or radiated transfer of EMI from an aggressor to a victim circuit.

CUTOFF FREQUENCY -- The frequency below which electromagnetic energy will not propagate in a wave guide (or transmission line).

EM ... emissions -- Any conducted or radiated emission which causes electromagnetic interference.[23]

EM ... environment -- The electromagnetic field(s) and/or signals existing in a transmission medium.

EM … noise -- An unwanted electromagnetic disturbance that is not of a sinusoidal character.[22]

EMC -- electromagnetic compatibility. The ability of a device to function satisfactorily in its electromagnetic environment without introducing intolerable disturbance to that environment (or to other devices).[22] (Add: when inactive, active or in event of failure).

EMI -- electromagnetic interference. A measure of electromagnetic radiation from equipment.[22]

-- Any electromagnetic energy which interrupts, obstructs, or otherwise degrades or limits the effective performance of telecommunications equipment.[23]

ELECTRICAL FIELD -- A vector field about a charged body. Its strength at any point is the force which would be exerted on a unit positive charge at that point.

ELECTRICAL NOISE -- Unwanted electrical signals, which produce undesirable effects in the circuits of the control systems in which they occur.[23]

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[22] IEEE Standard 100-1988
[23] MIL Standard 463A

ELECTROMAGNETIC WAVE -- A wave characterized by variation of electric and magnetic fields also known as radiowaves, heat rays, light rays.[22]

FFT -- Fast Fourier Transform -- An algorithm for transforming a time domain waveform to the frequency spectrum.

FAR FIELD -- The region of an antenna (conductor) where the electromagnetic energy is radiating and the angular field distribution is essentially independent of a specified point in the antenna region. The Far Field region is commonly taken to be at distances greater than 1/2 pi x wavelength.[22, 23]

-- The region of the field of an antenna where the radiation field predominates and where the angular field distribution is essentially independent of the distance from the antenna.

GROUND -- 1. A conducting connection between two equipments or two points in a circuit for the purpose of establishing a common potential reference.

2. A connection between a circuit or equipment and earth for the purpose of establishing the circuit or equipment common potential reference at the same potential as earth.

3. The electrical connection to earth through an earth electrode system. This connection is extended throughout the facility via the facility ground system, the signal reference network, and the safety ground network.

HIGH FREQUENCY GROUND -- The interconnected metallic network intended to serve as a common reference for currents and voltages at frequencies above 1 MHz. Note 1. Pulse and digital signals with rise and fall times of less than 1 microsecond are classified as high frequency signals. Note 2. High frequency in this sense should not be confused with the broadcast HF band which covers from 3 to 30 MHz.

LOW FREQUENCY GROUND -- A dedicated, single-point network intended to serve as a reference for voltages and currents, whether signal, control or power, from dc up to and including 1 MHz. Pulse and digital signals with rise and fall times greater than 1 microsecond are considered to be low frequency signals.

MAGNETIC FIELD -- A vector field produced by a continuous flow of charge.

MULTIPOINT GROUND -- A scheme of shield grounding in which each shield has multiple physical connections to the reference ground plane. This technique prevents standing waves on the shield at high frequencies and induced voltage on the shield of power cables at low frequencies. If a low frequency circuit is connected to ground at multiple points, noise problems may be created.

NEAR FIELD -- The region of the field immediately surrounding the antenna (conductor) wherein the reactive field predominates.[23]

-- The region of the field immediately surrounding an antenna where the inductive and capacitive fields predominate. In this region the angular distribution of the field varies with distance from the antenna.

PLANE WAVE -- A propagating wave composed of electric and magnetic field vectors whose only spatial dependence of the field vectors is a linear function of position with respect to the direction of propagation.

PROPAGATION -- The travel of waves through or along a medium.[1]

PROPAGATION VELOCITY -- Distance per unit time that a wave will travel in a particular transmission medium. For air, this is 3×10^8 meters per second.

REACTIVE FIELD -- Electric and magnetic fields surrounding an antenna (conductor) and resulting in. the storage of electromagnetic energy rather than in the radiation of electromagnetic energy.[22]

REFERENCE GROUND PLANE -- An interconnecting conductor system approximating earth or a common reference point when viewed with respect to a single conductor or circuit. See HIGH FREQUENCY GROUND.

SHIELD -- A housing, screen, or cover which substantially reduces the coupling of electric and magnetic fields into or out of circuits or prevents the accidental contact of objects or persons with parts or components operating at hazardous voltage levels.

SIGNAL RETURN -- A current-carrying path between a load and the signal source. It is the low side of the closed loop energy transfer circuit between a source-load pair.

SINGLE POINT GROUND -- A scheme of circuit/shield grounding in which each circuit/shield has only one physical connection to ground, ideally at the same point. for a given subsystem. This technique prevents return currents from flowing in the structure.[23]

STANDING WAVES -- A wave, in a transmission medium, in which, for any component of the field, the ratio of its instantaneous value at one point to any other point does not vary with time.

TRANSMISSION LINE -- A system of material boundaries or structures for guiding electromagnetic waves in the TEM (transverse electromagnetic mode). Commonly, a two wire or coaxial system of conductors.[22]

VICTIM -- An electrical circuit which may be susceptible to the general EMI in the area.

WAVE -- A disturbance that is a function of time or space or both.[22]

WAVE LENGTH -- The distance between two points in a periodic wave which have the same

phase.[22]

REFERENCES FOR DEFINITIONS:

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[23] MIL Standard 463A

7.0 REFERENCES

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