

IEEE Guide for Instrumentation and Control Equipment Grounding in Generating Stations

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IEEE Guide for Instrumentation and Control Equipment Grounding in Generating Stations

Sponsor

**Energy Development and Power Generation Committee of the
IEEE Power Engineering Society**

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Foreword

(This Foreword is not a part of IEEE Std 1050-1989, Guide for Instrumentation and Control Equipment Grounding in Generating Stations.)

The typical environment in a large generating station provides many sources of electrical noise (eg, static switching, switching of large inductive loads, high fault currents, and high-energy, high-frequency transients associated with switching at the generator or transmission voltage levels). The increasing use of solid-state equipment, computer- or microprocessor-based control and signal multiplexing systems in these applications introduces a number of specific concerns with respect to electrical noise control. This document is a guide that discusses methods for the grounding of instrumentation and control equipment and circuits in this environment.

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IEEE Guide for Instrumentation and Control Equipment Grounding in Generating Stations

1. Scope

This application guide was developed to identify instrumentation and control (I&C) equipment grounding methods to achieve both a suitable level of protection for personnel and equipment, and suitable electric noise immunity for signal ground references in large central generating stations. Both the ideal theoretical methods and accepted practices in the electric utility industry are presented. Special applications relating to advanced energy storage and conversion technologies (photovoltaics, fuel cells, etc) have not been considered.

The purpose of this guide is to provide guidance for the design of grounding systems for instrumentation and control equipment specific to the generating station. It also includes consideration of the requirements for the grounding of systems associated with the interconnection of the station to adjacent substations since these are a large source of electrical noise. It should be recognized that there are numerous accepted grounding techniques and that the actual installation of a ground system should be made in consultation with I&C equipment manufacturers.

The grounding methods in this guide are intended to minimize degradation of instrumentation and control signals in generating stations. By contrast, the station grounding system is mainly oriented toward meeting the safety requirements of various codes, ie, a system which will provide a low-impedance path to ground in order that high voltages cannot exist on equipment or structures due to lightning surges, electrical faults, circulating currents, or static charges. This guide is complementary to ANSI/IEEE Std 518-1982 [B5]¹ and ANSI/IEEE Std 665-1987 [B7].

¹The numbers in brackets correspond to the references listed in Section 8 of this guide.

ANSI/IEEE publications are available from the Institute of Electrical and Electronics Engineers, Service

2. Introduction

The low-level electrical signals transmitted from various instrumentation and control equipment in a generating station through long cables may undergo signal distortion as they travel to the receiving end. This distortion is normally caused by noise pickup either at the signal source or along the cable run.

The level of noise on the received signal can cause errors in measurement and control functions (and in extreme cases, damage to equipment) which in turn may result in costly unit downtime. The use of proper grounding along with proper shielding techniques can solve a large percentage of noise problems.

This guide is intended to give information on grounding methods for generating station instrumentation and control equipment. Grounding design is normally based on the concept of two separate grounding systems:

1. The equipment ground
2. The signal ground or control common ground

The grounding of instrument chassis, racks, cable sheaths, or cable shields and signal pairs requires special care to ensure that

- a. Personnel working on equipment are adequately protected against electrical shock hazards during abnormal conditions.
- b. Interference signals are not inadvertently coupled into signal circuits.
- c. Multiple-signal grounds or inadvertent grounding paths that can give rise to interference on signal conductors are eliminated.

The basic theory and guidelines that should be understood before designing I&C grounding are presented in Section 4. Section 5 provides guidance for grounding of equipment associated with generating station I&C sys-

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tems and presents various approaches to providing a signal ground system. Section 6 presents accepted practices in grounding I&C equipment and circuits in generating stations for various circumstances. General considerations for equipment grounding are discussed in ANSI/IEEE Std 665-1987 [B7]. The signal ground is defined as the zero potential reference point to which electronic hardware and analog loops in a localized area are referenced. ANSI/IEEE Std 518-1982 [B5] provides a general discussion on the application of these two grounding systems in typical industrial environments.

3. Definitions

attenuation. A general term used to denote a decrease in signal magnitude in transmission from one point to another.

central distribution frame grounding.* A type of grounding system where all signal grounds are referenced to a central point rather than at their respective signal sources.

common mode noise (longitudinal). The noise voltage that appears equally and in phase from each signal conductor to ground. Common mode noise may be caused by one or more of the following:

1. *Electrostatic induction.* With equal capacitance between the signal wires and the surroundings, the noise voltage developed will be the same on both signal wires.
2. *Electromagnetic induction.* With the magnetic field linking the signal wires equally, the noise voltage developed will be the same on both signal wires.

coupling. The mechanism by which an interference source produces interference in a signal circuit.

crosstalk. The noise or extraneous signal caused by ac or dc pulse-type signals in adjacent circuits.

* An asterisk denotes definitions not in ANSI/IEEE Std 100-1988, Standard Dictionary of Electrical and Electronics Terms, fourth edition [B3].

cutoff frequency.

1. (General) The frequency that is identified with the transition between a pass-band and an adjacent attenuation band of system or transducer.
2. (Of a waveguide) for a given transmission mode in a nondissipative waveguide, the frequency at which the propagation constant is 0.

distributed control network.* A system comprised of software, hardware, cabling, sensors, and activators, which is used to control and monitor equipment.

electromagnetic compatibility. The capability of electronic equipment or systems to be operated in the intended operational electromagnetic environment at designed levels of efficiency.

electromagnetic interference. Impairment of a wanted electromagnetic signal by an electromagnetic disturbance.

equipment ground.* For the purpose of this guide, shall be the safety ground connection to the conductive, noncurrent-carrying parts of electrical equipment.

ground. A conducting connection, whether intentional or accidental, by which an electric circuit or equipment is connected to the earth, or to some conducting body of relatively large extent that serves in the place of the earth.

neutral. For use with the figures in this guide, the term *neutral* is understood to be the center tap of a three- or four-wire transformer.

Since only single-phase loads are depicted, the other phases of the supply transformer have been omitted for clarity.

noise (electrical). Unwanted electrical signals that produce undesirable effects in circuits of control systems in which they occur.

normal mode noise (transverse or differential). The noise voltage that appears differentially between two signal wires and acts on the signal sensing circuit in the same manner as the desired signal. Normal mode noise may be caused by one or more of the following:

1. Electrostatic induction and differences in distributed capacitance between the signal wires and the surroundings
2. Electromagnetic induction and magnetic fields linking unequally with the signal wires
3. Junction or thermal potentials due to the use of dissimilar metals in the connection system
4. Common mode to normal mode noise conversion

signal ground. For the purpose of this guide, shall be the grounding system to which signals are referenced.

susceptibility. The property of an equipment that describes its capability to function acceptably when subjected to unwanted electromagnetic energy.

3.1 Acronym List

CCVT—Coupling Capacitor Voltage Transformer
 CDF—Central Distribution Frame
 CM—Common Mode
 CT—Current Transformer
 DM—Differential Mode
 EMC—Electromagnetic Compatibility
 ESD—Electrostatic Discharge
 EMI—Electromagnetic Interference
 GIS—Gas Insulated Switchgear
 I&C—Instrumentation and Control
 I_N —Noise Current
 RF—Radio Frequency
 RTD—Resistance Temperature Detector
 SF₆—Sulfur Hexafluoride
 V_S—Signal Voltage
 V_{CM}—Common Mode Voltage
 V_{DM}—Differential Mode Voltage
 V_N—Noise Voltage
 V_T—Voltage Transformer
 0V RTN—Zero Volt Return (Signal Ground Reference)

4. Design Considerations for Electrical Noise Minimization

4.1 Typical Noise Sources and Their Characteristics. Noise sources can be divided into several categories:

1. *Natural sources*—These happen independently of human activity; but their effects can be controlled.

2. *Incidental sources*—These are caused by human activity; but they are not intentional.
3. *Intentional sources*—These are emissions of potentially interfering energy produced for other purposes.

4.1.1 Natural Sources. Probably the most severe noise source to which any control system will ever be exposed is lightning. While most electronic control systems will probably fail under a direct lightning strike, even a remote strike can cause interference as the lightning-induced surge travels along power lines and is dissipated by the power distribution grounding system.

A typical lightning flash is comprised of a downward-stepped leader stroke, usually negative, a first upward positive return stroke, then two or more downward leader strokes, each followed by a positive return stroke. On average, subsequent strokes contain about 40 percent of the first stroke amplitude.

A continuing current is usually present between stroke sequences. There may be as many as twenty stroke sequences in a typical lightning flash. Characteristics of a typical lightning flash are as follows:

Potential	30 000 000 V
Peak current	34 000 A
Maximum di/dt	40 000 A/ μ s
Time interval between strokes	30 ms
Continuing current	140 A
Continuing current duration	150 ms

Analysis of the continuing current component of the lightning flash indicates that it initially behaves as a traveling wave and subsequently as a dc source.

4.1.2 Incidental Sources. Since one of the largest potential sources of electrical noise is a substation located adjacent to the generating station, some of the incidental sources mentioned in this section originate predominately in the substation environment.

4.1.2.1 High-Voltage Switching. This is the most frequent source of large transients in electric power systems. Opening or closing a disconnect switch to deenergize or energize a section of bus is accompanied by arcing between the switch contacts which in turn produces damped oscillatory transients. The transients generated are very steep fronted waves which can be electrostatically or

electromagnetically coupled to nearby cables. Typical values are:

Voltage	200% of Rated Voltage
Oscillation Frequency	
Line disconnect switch	50–300 kHz
Bus disconnect switch	300–600 kHz
Low-voltage switch	300–2000 kHz
Interval between each decaying oscillation	10 μ s–16 ms
Duration of string	1 ms–4 sec
Decay time	2–4 c
Source impedance	5–200 Ω

As a general rule of thumb, for two parallel, multiple-conductor cables separated by 2 in, up to 50 percent of a transient's magnitude on one cable may be transferred to the adjacent cable.

4.1.2.2 Capacitor Bank Switching. Although not the most prevalent source of noise in electric power systems, capacitor bank switching produces the most severe transients. The transients produced by the switching of three-phase capacitor banks consist of two components:

1. Those due to the lumped parameters of the circuit are in the kHz frequency range as determined by the equivalent capacitance of the phase capacitors and by the inductance and resistance of the buses, current-limiting reactors, and ground path.
2. Those due to the distributed parameters of the circuit are in the MHz frequency range and are the result of the propagation and reflection of the switching step wave along the line.

If other nearby capacitor banks are connected to the same line, they lower the impedance seen by the switched capacitor bank, thereby increasing the magnitude and frequency of the transients. Energy stored in the nearby bank may further contribute to the severity of the transient.

4.1.2.3 Transmission Line Switching. Transmission line switching is similar to capacitor bank switching with the difference being the purely distributive nature of the inductance and capacitance of the line. The magnitude of the line-charging current tends to be substantially less than that for capacitor bank switching. The frequency of the transient is inversely proportional to line length.

4.1.2.4 Coupling Capacitor Voltage Transformer (CCVT). The capacitors in these devices along with the inductance of the power

system conductors constitute a resonant circuit whose frequency can be in the MHz range. Any oscillatory high frequency transients occurring on the high voltage bus can give rise to high-frequency currents that flow down through the coupling capacitors via the connection to the station ground grid.

The transformer located in the base of the CCVT contains a distributed stray capacitance of a few hundred pF between the secondary winding and the core and the Faraday shield. This capacitance is the circuit element closing a loop which in turn links the transient magnetic flux between the ground conductor and the signal cable. Transient potentials of up to 10 kV have been measured in signal cables.

Almost identical problems are present in current transformers having wound capacitance bushings.

4.1.2.5 Gas Insulated Switchgear (GIS). During the operation of GIS, the high-voltage gradients caused by restrikes between contacts induce traveling waves that are confined to the inside of the GIS enclosure by skin effect. They travel along the GIS, are divided and reflected at junctions, but are confined by the open circuit breakers or disconnect switches. Only when discontinuities or breaks in the enclosure are encountered do potentials transfer to the exterior enclosure surface and result in noise voltages. The most common enclosure discontinuities are SF₆-to-air terminations, cable potheads (with insulated flanges) and, for some switchgear, current transformers. However, the SF₆-to-air termination represents by far the largest enclosure discontinuity and hence the largest source of noise voltages in most GIS.

Typical values for GIS measured at the bushing:

Voltage:	40%–70% of rated voltage
Oscillation Frequency:	5–50 MHz
Duration at Flashover:	40 ns
Duration at Disconnect Operation:	170 ms string of pulses

The GIS ground connections are often too inductive to effectively reduce these high-frequency noise voltages.

4.1.2.6 Ground Potential Differences. Both electromagnetic coupling and conduction can contribute to substantial ground potential differences, particularly during high-frequency transients and fault conditions. Ground grids that extend over large areas

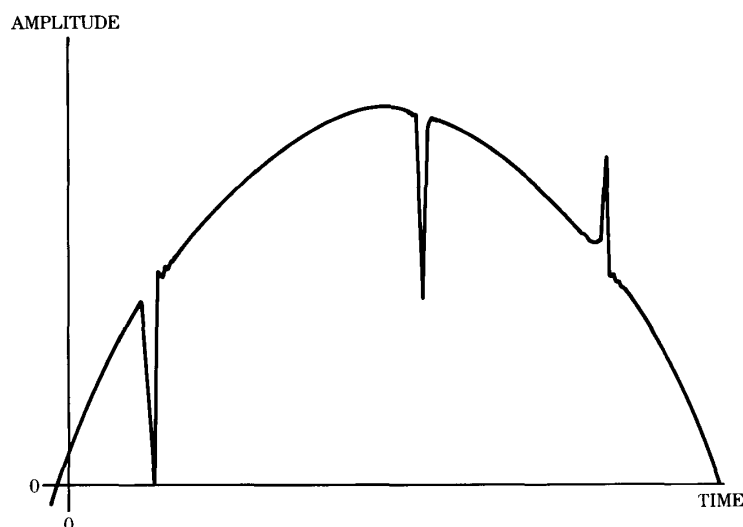


Fig 1
Line-Notching Waveshape

have sufficient inductance to cause high potential differences. Electromagnetic coupling to the ground grid is directly proportional to the rate of change of flux, the length and orientation of the current-carrying conductor, and inversely proportional to the height of the conductor above the ground grid. Conduction of power system transients to the ground grid is typically provided through metallic grounding of transformer neutrals and capacitive paths such as bushings and coupling capacitors. These are low-impedance, high-energy sources that can induce common mode voltage on control circuits.

4.1.2.7 Current Transformers (CT's). Saturation of current transformers by ac can induce very high voltages in the secondary windings. This phenomenon is repeated for each transition from saturation in one direction to saturation in the other. The voltage appearing in the secondary consists of high-magnitude spikes having alternating polarity and persisting for a few milliseconds every half-cycle.

4.1.2.8 Rotating Equipment. Rotating equipment contains many possible internal sources of high-frequency interference. These include

1. Partial discharges (eg, corona discharge) within the stator winding insulation.

2. Slot discharges between coil surfaces and the stator iron.
3. Sparking from exciters with brushes.
4. Arcing associated with conductor strands that have fractured from copper fatigue. This arcing is not continuous but is caused by a movement of conductor surfaces as a result of steady-state and transient magnetic forces.
5. DC machine brushes.

4.1.2.9 Thyristors. When thyristors (sometimes referred to as silicon-controlled rectifiers) are used for switching ac voltage, they generally must have additional circuitry to control the voltage rise time. If the voltage rise time is not controlled, it can even interfere with the operation of the thyristor itself. When a pair of thyristors is used for three-phase motor control, a noise condition called "line notching" can occur (see Fig 1). When the switchover occurs from one power line to another, one thyristor is turning off while the other is turning on. Because of the inductive load, there may be an instant when both are conducting. The resulting short across the two lines produces a notch transient in the power line.

4.1.2.10 Computer Systems. The noise generated by microprocessor and memory boards within a computer is dependent primarily upon their clock frequency (300 kHz–

10 MHz). The highest noise frequency, however, will be a function of the rise and fall times of the clock pulse. A digital signal with a rise time of 5 ns is roughly equivalent to a 100 MHz sine wave. While this noise is usually well shielded within the computer cabinet, the various computer subsystems and peripheral devices can contribute significantly to the noise generated by the total computer system. The major contributing devices have the following characteristics:

1. CRT display. Noise sources within a CRT display are the video circuitry (typical 20–50 V swing at 10–20 MHz) and the horizontal yoke drive circuitry (typical 3 A peak-to-peak amplitude at 10–20 MHz).
2. Disk drives. Noise generated by these devices is dependent upon the data processing rate (400 kHz–2 MHz for floppy drives and 1–10 MHz for hard disk drives).
3. Switching power supply. The noise generated by these devices is dependent upon the switching frequency (typical 10–100 kHz) and the switching amplitude.
4. Printers. The major noise sources for these devices are the printhead solenoids and the carriage positioning motors along with the associated drivers.
5. Cabling. One of the most overlooked sources of noise in a computer system is the interconnect cabling. The noise generated is dependent upon the signal level, the number of conductors within each cable, and the type of shielding provided. This subject will be fully covered in later sections.

4.1.2.11 DC Control Circuits. The internal source of transient overvoltages within a dc control circuit is the energizing and deenergizing of an inductance within the circuit. This induced voltage may be defined as $e = L di/dt$ and is directly proportional to the supply circuit impedance. The inductance may consist of the distributed inductance of the circuit and/or discrete inductive circuit elements. Surges in excess of 3 kV can be produced by interrupting the current in highly inductive devices such as a solenoid or breaker trip coil. As a general rule, 60 Hz ac voltages

induced in dc control circuits are small in magnitude when compared to the internal transients.

4.1.2.12 Mechanical Vibration. Mechanical vibration and shock can produce noise wherever electrical connections are present by causing switch contacts to open or close and produce an arc discharge. This is true even for low-voltage circuits, since voltages as low as 9 V across gold alloy contacts can produce an arc discharge.

Terminal blocks with loose connections can also produce an arc discharge. When conduit fittings necessary for ground integrity vibrate loose, they also can produce an arc discharge and introduce noise into the ground system.

4.1.2.13 Chemical Contamination. Most plant atmospheres contain suspended chemicals; ie, oil, coolants, degreasing solutions, which may settle on electrical equipment.

Even though gas-tight electrical connections should be immune to this method of contamination, vibration and temperature changes may compromise the electrical connection. Vibration causes gas-tight connections to flex and permit the entrance of chemical drops. Since many electrical connections are made with dissimilar materials having different coefficients of expansion, temperature changes will also cause the connection to flex and permit contaminants to enter.

Moisture and chemical droplets in the atmosphere can create unwanted noise from galvanic action. Moisture between connections made with dissimilar metals produces a wet cell, with the result being an unwanted voltage that can become a noise source. Current through the contacts will contribute to the corrosion, causing bad connections and noise.

4.1.2.14 Human Interaction. The Electro-Static Discharge (ESD) that occurs when an operator touches metallic equipment controls during low-humidity conditions is a potential noise source. For example, if (as shown in Fig 2) a metallic switch body is mounted on a printed circuit board but is isolated from the conductive cabinet, the ESD current will create noise as it flows to ground via the printed circuit board and wiring capacitances.

A typical discharge would be a 5000 V, 5 A current pulse of 200 ns duration. While the energy contained in this pulse is only about

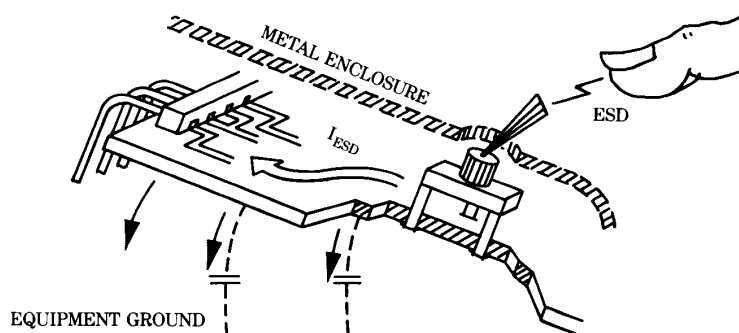


Fig 2
Electrostatic Discharge Noise Generation

1.25 mJ, this is sufficient to interfere with computer logic levels. An arc discharge does not have to occur for an electrostatic field to interfere with a control circuit. Any object that has picked up a large electrostatic charge can create a voltage shift of several volts when brought in close proximity to a control circuit or cable.

4.1.2.15 Cable Resonance. Avoiding resonances at radio frequencies has become increasingly important as the clock frequencies of digital circuits have increased beyond the 3–10 MHz range. Resonance is related to the velocity of propagation of electric signals in the conductors and the repetition rate of a series of signals. Electrical disturbances travel at 186 000 mi/sec in a vacuum, slightly slower in conductors.

For example, a voltage wave will travel 30 m in free space during one cycle of a 10 MHz clock signal in a modern computer. In a grounding conductor, it may travel only 27 m. If a conductor is continuous for only 27 m, the voltage wave will reflect from the open end and arrive back at the beginning at the same instant that another cycle arrives. If the arriving new wave and the reflected wave are in phase, resonance will occur and line oscillations will be greatly magnified. If one end of the conductor is grounded, the first resonance at 10 MHz occurs when the conductor is only 6.7 m or 1/4 wavelength long.

At this frequency, a ground conductor 6.7 m long appears to be virtually an open circuit or at least a very high impedance. It is incapable of equalizing the voltages appearing between its ends. A conductor longer than 1/20 of a wavelength cannot be counted upon to equalize

voltages between its ends. This amounts to only 1.4 m at 10 MHz. At high frequencies, signal lines are often terminated in their characteristic surge impedance to kill most of the reflection and resonance. However, single ground conductors can no longer provide a virtual short circuit between one end and the other at the high-frequency portion of a broad frequency range.

4.1.2.16 Other Incidental Sources. Noise can also be generated by such sources as transformer and motor inrush currents, load tap-changing, flashover of gaps due to over-voltages, ferroresonance, impulse testing, megger testing, low-voltage breakers and contactors, and corona discharge from high-voltage transmission lines. Noise from transmission line corona can occur miles from the point of generation by propagating along the line.

4.1.3 Intentional Sources. Many devices intentionally use Radio Frequency (RF) energy to accomplish their function, such as radios (eg, security guard transceivers, CB's, etc), RF-stabilized arc welders, induction heaters and RF drying equipment. These devices produce considerable amounts of RF energy, which generally is not contained and, therefore, can reach control equipment.

4.2 Noise-Coupling Methods. Noise can be coupled into (or transmitted from) control circuits by any one of four different methods:

1. Conductive (direct contact)
2. Capacitive (electric)
3. Inductive (magnetic)
4. Radiative (electromagnetic)

Both capacitive and inductive coupling refer primarily to near field coupling. A control circuit or cable is considered to be in the near field of an electromagnetic source when the source to circuit distance is less than one-sixth the wavelength ($\lambda/2\pi$) of the highest source frequency. Radiative coupling refers to circuits located in the far field of a source where the source's emissions are seen as a true propagating wave.

Each of these coupling methods will be detailed in a following section.

4.2.1 Characteristics of Electromagnetic Fields. Electromagnetic waves consist of two oscillating fields at right angles to one another: the electric field (E-field) and the magnetic field (H-field). The electromagnetic wave impedance (Z_w) in Ω is defined as the ratio of the E-field intensity expressed in V/m to the H-field intensity expressed in A/m. E-fields are generated by and most easily interact with high-impedance, voltage-driven circuitry, such as a straight wire or dipole. H-fields are generated by and most readily interact with low-impedance, current-driven circuitry, such as a wire loop.

Both the electric and magnetic fields are perpendicular to the direction of propagation of the electromagnetic wave. The value of Z_w for a plane wave propagating through air is 377 Ω .

4.2.2 Common Impedance Coupling (Conductive). As shown in Fig 3, when two or more

circuits share a wire or junction point, common impedance coupling is a potential noise source. The point of common impedance may be intentional for grounding purposes (ground loop problem) or may be undesired leakage conductance between circuits. Current in one circuit can then cause a noise voltage to appear in another circuit. The level of interference is dependent upon the magnitude of the common impedance.

4.2.3 Capacitive Coupling (Electric). As shown in Fig 4, every portion of an electric system has capacitance between it and every other portion. Any voltage change, regardless of location, tends to drive a current through these capacitances and produce noise according to the following formula:

$$I = C \, de/dt$$

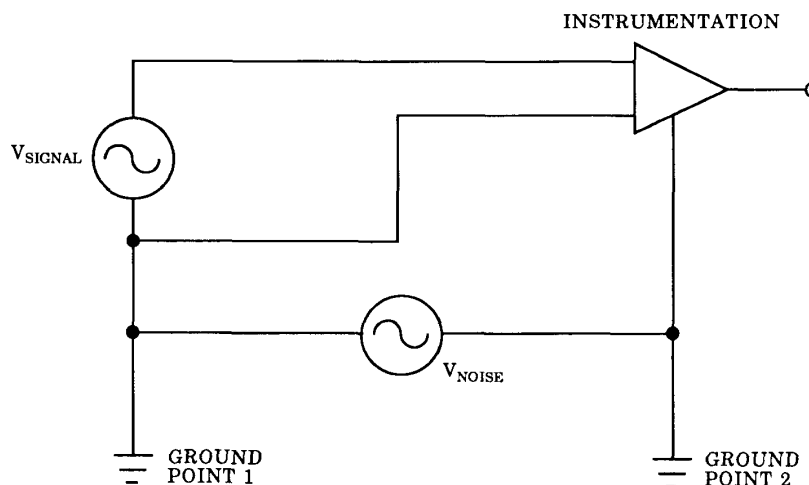
where: I is the current flow through the circuit capacitance.

C is the capacitance between the two circuits.

de/dt is the voltage change rate in the first circuit.

For capacitive coupling, the coupling decreases as the distance between the conductors increases. High-impedance circuits are more susceptible to capacitively coupled noise.

Fig 3
Example of Common Impedance Coupling (Ground Loop)



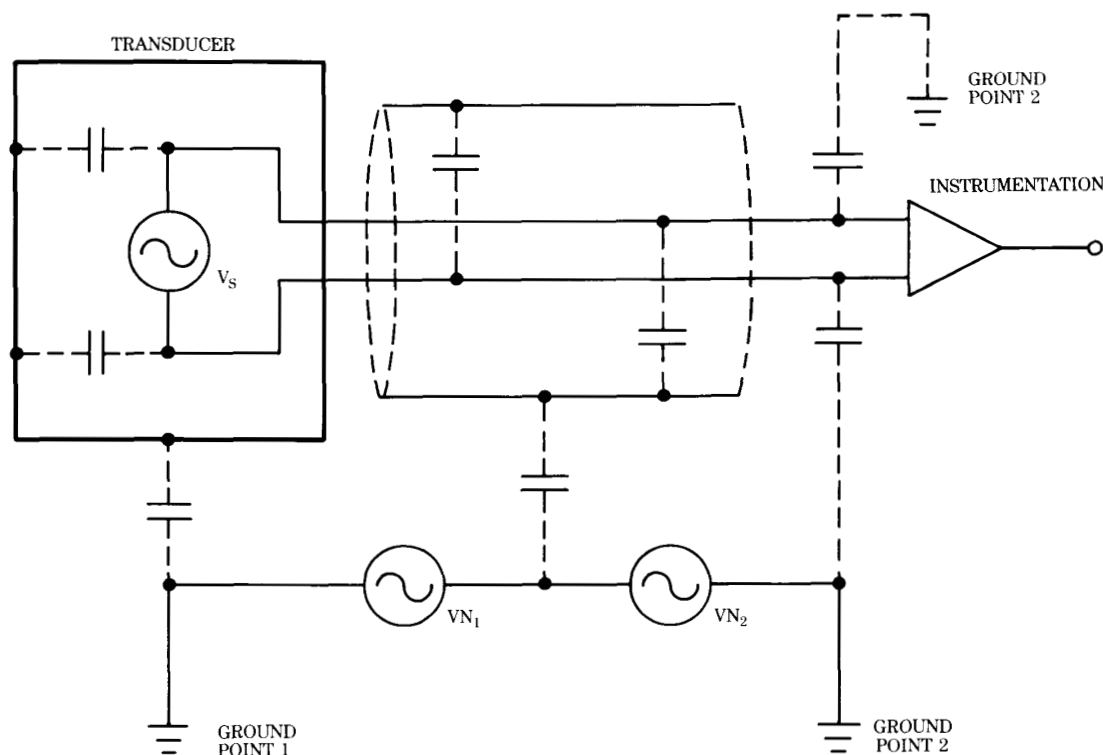


Fig 4
Example of Capacitive Coupling

4.2.4 Inductive Coupling (Magnetic). The various circuits of any system exist as closed loops. These loops have mutual inductances that are directly proportional to the area enclosed by the loops (see Fig 5). Interaction between the loops is essentially a transformer action between the interference source and the sensitive circuit. Even dc circuits produce a changing magnetic field when their current is periodically or intermittently interrupted.

When a current change occurs in one of these circuits, a changing electromagnetic field through the area of its loop is produced. A voltage will be induced when some of this magnetic flux passes through a second circuit. The amplitude of the induced voltage is directly proportional to the area of the second circuit which encloses the flux from the disturbing circuit. The induced voltage is determined from the following formula:

$$E = M di/dt$$

where: E is the induced voltage in the second circuit.

M is the mutual inductance (amount of flux).

di/dt is the current change rate in the first circuit.

For magnetic coupling the mutual inductance is a direct function of the coupled length of the conductors and an inverse function of the distance between conductors. Low-impedance circuits are more susceptible to inductive coupling.

Both capacitive and inductive coupling are functions of the time derivative or rate of change of the source field. Therefore, the interference coupling factor increases with the higher frequency content of the transient.

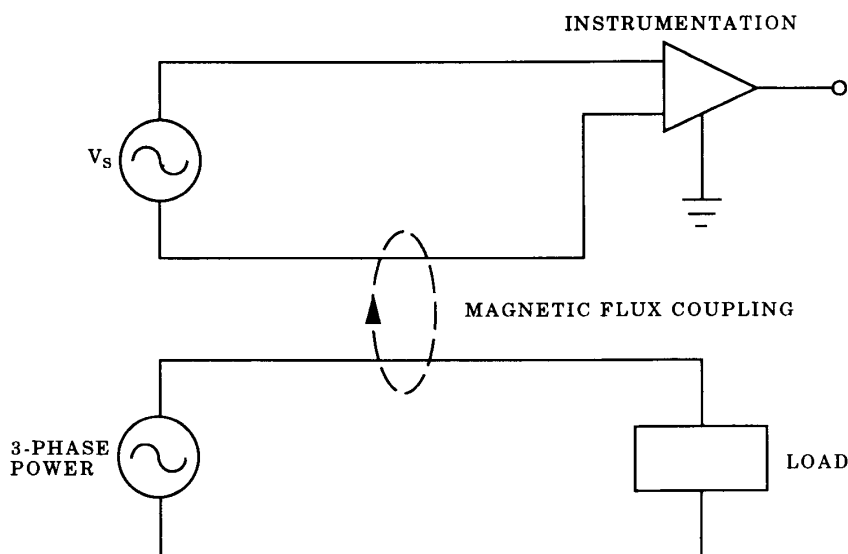


Fig 5
Example of Inductive Coupling

4.2.5 Radiative Coupling (Electromagnetic). High-frequency signals produced by an external source may transfer a significant amount of energy to the control circuit by radiative coupling. Even though the interference frequencies are usually much higher than those to which the control circuit will respond, they can become troublesome if they are modulated by the ac power frequency or its harmonics and then picked up and demodulated by the control circuit. This process of pickup and demodulation can produce spurious signals at the ac power frequency.

4.2.6 Interference Modes.

4.2.6.1 Common Mode Interference (Longitudinal Mode). This type of interference is introduced into the signal channel from a source having at least one terminal that is not part of the legitimate signal channel (see Fig 6). The equipment chassis will always count as one terminal if it is not separated from the circuit network. Common mode currents are most commonly caused by a potential difference between ground points or by electrical pickup in a pair of conductors. Common mode interference acts indirectly on the receiver. Therefore, a signal error must be preceded by a conversion from common mode interference to differential mode interference. A purely common mode surge that is applied to

an unbalanced circuit will produce a differential mode surge.

In a two-wire line, the common mode noise current induced in each wire is more or less of equal amplitude and in phase. The degree of line amplitude balance usually increases with frequency.

Common mode interference originates from sources like licensed transmitters, arc welders, and fluorescent lamps. Common mode transients are more likely to cause dielectric failure than differential mode transients.

4.2.6.2 Differential Mode Interference (Normal Mode, Transverse Mode). This interference is introduced into the signal channel through the same path as the legitimate signal. No current paths exist for the interference current except those of the signal channel itself (see Fig 6). The interference can be produced by the conversion of common mode current to differential mode noise. The full magnitude of the interference is directly coupled to the system. Differential mode interference will often have frequency characteristics that differentiate it from the desired signal.

In a two-wire system, the normal signal current in each wire is usually of equal amplitude and opposite in phase. The differential mode interference current is also equal and opposite.

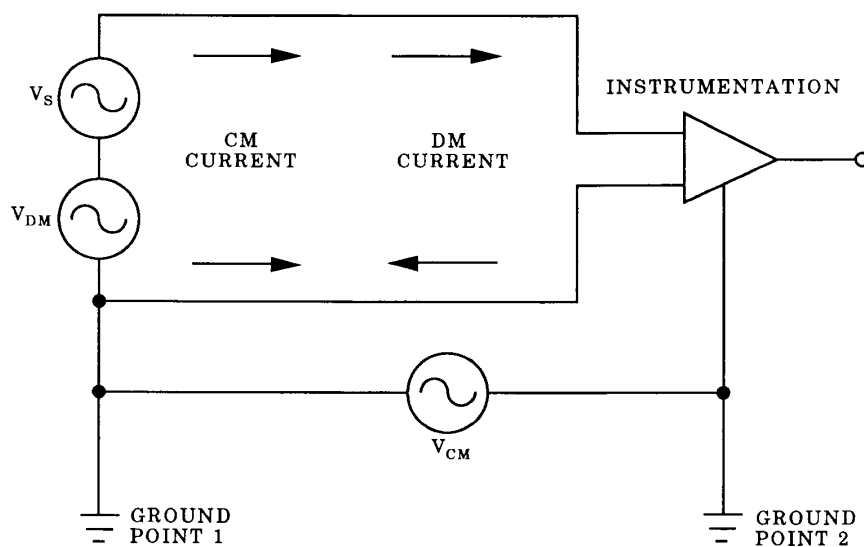


Fig 6
Example of Common and Differential Mode Interference

Differential mode types of interference originate primarily from transients produced by other users on the same power main. Differential mode transients are more likely to produce misoperation of equipment than common mode transients.

4.2.6.3 Crosstalk. When transmitting either an ac or a pulsating dc signal on one pair of a multiple-pair cable, there is a tendency for the signals to be superimposed on signals being carried in adjacent pairs due to a combination of both inductive and capacitive coupling. Both of these coupling methods are directly proportional to the frequency of the signal. By changing the impedance of the signal path, however, the change in the amount of capacitive coupling will be directly proportional, while the change in the amount of inductive coupling will be inversely proportional.

Therefore, the way in which a change of circuit impedance affects the total amount of crosstalk will depend on which factor is greater, capacitive or inductive coupling. If these two quantities are equal, then there will be practically no change in the magnitude of the crosstalk when the impedance is varied.

4.3 Techniques for Electrical Noise Minimization.

4.3.1 Suppression at the Source. One of the most effective means for reducing transients in a system is to reduce their amplitude at the source.

4.3.1.1 Suppression of Noise Generated by Solenoid-Relay Coils. Placing a diode in parallel with a magnetic coil is the simplest principle of suppression in a dc circuit to prevent the voltage across the coil from exceeding the supply voltage. The diode itself has the disadvantages of:

1. Switch off delay.
2. A diode failure may short circuit the device.
3. Forward overcurrent when the supply is interrupted can destroy the diode.
4. Overvoltage in the reverse direction (possibly caused by spikes from unsuppressed loads) can destroy the diode.
5. It may cause additional switching current when "on" or additional leakage current when "off."

The diode should be properly chosen to have high-reverse overvoltage and high-forward overcurrent characteristics. Addition of a se-

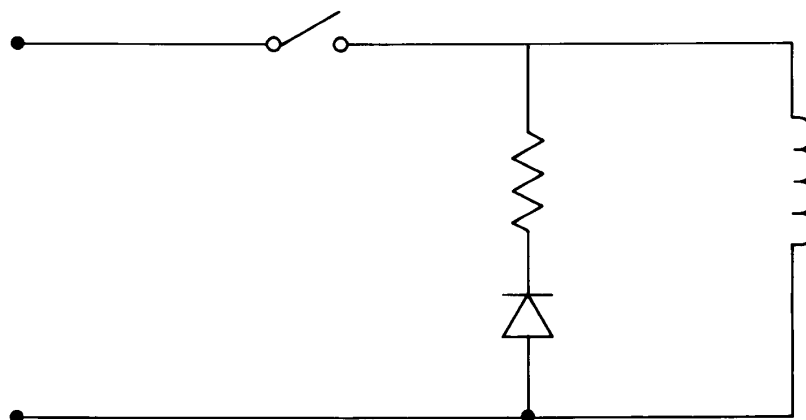


Fig 7

Suppression with a Diode and Series Resistance

ries resistance chosen as approximately equal to the coil resistance significantly reduces the switch off delay and eliminates the short circuit if the diode fails. This technique is illustrated by Fig 7.

Variations of this technique using transorbs or metal oxide varistors can be used. It is still possible, however, that some high-frequency pulses will remain. If this is a problem, an R-C filter is introduced across the coil. If the leads to the coil are long, it may be necessary to place a second filter across the initiating contact since the cable inductance could cause contact sparking.

4.3.1.2 Suppression of Thyristor Rectifiers, Motors, and Generators. Small capacitors are used to damp high frequencies generated by these devices. They must be placed as close to the interference source as possible to prevent the emission of RF interference.

4.3.1.3 Suppression of Input Signal Noise. It is quite normal to arrange suitable filtering circuits directly onto electronic circuit boards to provide them with an inherent transient immunity. (A detailed discussion of this is outside of the scope of this guide.) If this proves to be inadequate, then it is necessary to provide additional external filtering. R-C filters, zeners, and varistors can be used as was recommended for solenoid circuits, but it is necessary to keep lead lengths to an absolute minimum.

4.3.2 Positioning and Isolating Control Cables.

4.3.2.1 Cable Routing. The physical arrangement of the control cables is an impor-

tant factor affecting surge voltage levels. Techniques for minimizing noise pickup in control circuits include:

1. *Radial routing of control cable.* Circuits should not be looped from one piece of equipment to another with the return conductor in another cable. All supply and return conductors should be in a common cable to avoid the large electromagnetic induction possible because of the very large flux loop that such an arrangement would produce. This means that both secondary leads of CT's should be in the same cable, both positive and negative dc leads should be in the same cable, and all three phases and neutral of Voltage Transformer (VT) secondary leads should be in the same cable, etc.

If the supply and return signal lines are discrete wires, they should be laid as close to each other as possible within the cable tray or duct to present a minimum loop for the pickup of interference. If possible, a gentle twisting of the two wires (1 turn/m) can further reduce the magnitude of the induced noise.

2. *Orienting the control cables at right angles to buswork and power conductors* where primary transient currents can exist so as to minimize the coupled length of the cables. Where this is not possible, the separation distance from parallel buses should be maximized.
3. *Locating the control room in a centralized location* so as to minimize control cable runs.

4. *AC power, which enters control cabinets, should be routed as close as possible to the conductive cabinet, while the control cabling should be routed within the interior of the cabinet to minimize any coupling between the two.*

4.3.2.2 Physical Separation. Circuits operating at different voltages (and sometimes different energy levels) should be physically separated. Voltage separation is defined in ANSI/IEEE Std 422-1986 [B4]. For example, low-energy analog signals should not be run in the same cable as higher energy control signals. Similarly, dc battery and ac secondary circuits are not to be placed into the same cable and neither circuit should be in the same cable with the station ac service. Likewise, these segregated cables should also be grouped according to function and separated by a reasonable distance. When dissimilar circuits are run parallel to each other in a cable tray for any distance, consideration may have to be given to separating the two circuit types by a grounded metallic barrier.

Refer to 4.3.3, Fig 8. It is of interest that the knee of the curve for calculated capacitance (and hence shielding effectiveness) is between 150–250 mm separation. Most utilities require 300–450 mm separation between cable trays, chiefly for reasonable installation practice. It is this separation of trays which is of great benefit in a power generation station to reducing noise interference between long runs of cables.

4.3.3 Shielding. Any barrier placed between an emitter and a susceptor that diminishes the strength of the interference can be thought of as an EMI shield. How well the shield attenuates an electromagnetic field is referred to as its Shielding Effectiveness (SE). The standard unit of measure for shielding effectiveness is the decibel (dB). The decibel for this application is expressed as 20 times the logarithm of the ratio of two values of electromagnetic field strength where the field strengths are compared before and after the shield is in place. It is defined as:

$$\begin{aligned}\text{E-Field, SE} &= 20 \log E_1/E_2 \\ \text{H-Field, SE} &= 20 \log H_1/H_2\end{aligned}$$

In most shielding applications, shielding effectiveness below 20 dB is considered only minimal shielding; 20 dB–80 dB covers the normally acceptable shielding range, and

80 dB–120 dB is above average shielding. Shielding effectiveness above 120 dB is difficult to achieve.

SE (dB)	Attenuation Ratio	% Attenuation
20	10:1	90.0
40	10 ² :1	99.0
60	10 ³ :1	99.9
80	10 ⁴ :1	99.99
100	10 ⁵ :1	99.999
120	10 ⁶ :1	99.9999

The loss in field strength due to a shield is a function of the shield material (permeability, conductivity, and thickness), the frequency of the interference and the distance from the EMI source to the shield. At 50–60 Hz, nonmagnetic material of any practical thickness will not provide much shielding against electromagnetic fields.

4.3.3.1 Electronic Equipment Shielding. E-field induction can be significant when lines are not shielded with a grounded metallic shield. The magnitude of the induced voltage depends on the relative values of capacitances between the noise source conductors and the signal circuit conductors. E-field coupling increases with increasing frequency and proximity and predominates over magnetic coupling when the victim circuit has a high impedance. Figure 8 illustrates the model for E-field coupling and provides calculated capacitance/ft between common-size power conductors and no 16 AWG instrumentation conductors versus separation distance.

Most electronic apparatus is housed in conventional steel cabinets. While these cabinets provide some degree of shielding, their shielding effectiveness is compromised by the need for normal cabinet discontinuities, such as seams, cable penetrations, and apertures. Any discontinuity will degrade the shielding integrity of the cabinet and provide the possibility of electromagnetic coupling both in and out of the cabinet. The efficiency of the coupling will depend upon the size of the hole or seam with relation to the wavelength of the interference. Any opening in an enclosure can provide a highly efficient coupling path at some frequency. As an opening increases in size, its coupling efficiency also increases.

An opening larger than the wavelength (λ) divided by 20 ($\lambda/20$) will permit electromagnetic energy to pass freely through the opening

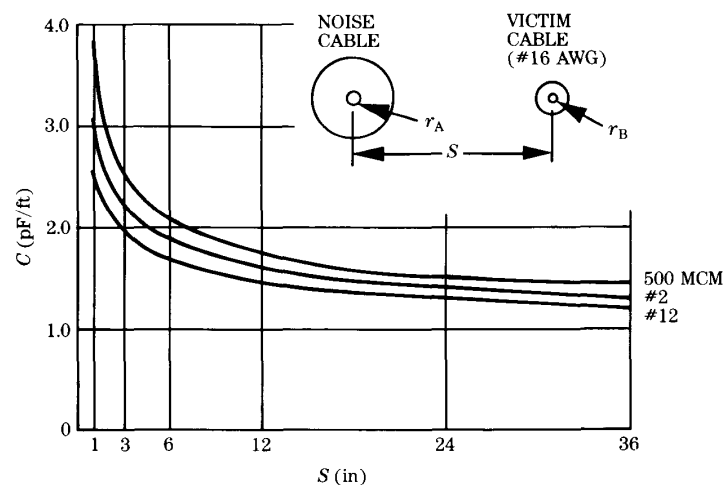


Fig 8
Capacitance versus Conductor Separation

without being attenuated. Therefore, openings larger than $\lambda/20$ should be avoided. Since most EMI coupling problems are broadband in nature, the wavelength must be that of the highest interference frequency.

Whenever an opening must be present in a cabinet, protective measures should be taken to reduce the threat of coupling. These protective measures include

1. Keeping the longest dimension of apertures in cabinets less than $\lambda/20$. Openings larger than this will require additional protective measures.
2. Where cable penetrations occur in a cabinet, shielding can be accomplished by using waveguides operating beyond cut-off frequency. This can be done by connecting a conductive shaft to the inside of the cabinet as shown in Fig 9. Since the cutoff frequency of a waveguide is a function of twice the maximum width of the waveguide, the length of the conductive shaft should be at least four times the width of the cable penetration.
3. Electronic systems that are packaged in cabinets of plastic or other nonconductive materials should have their cases treated with a conductive material to provide shielding. The most frequently used technique is to spray the inside of the cabinet with a special conductive paint containing metal particles.

4. When openings are provided for meters or displays, specially fabricated shielding windows should be used to maintain the conductive barrier of the cabinet. These windows are typically fabricated by applying an optically clear conductive layer to the viewing window or by casting a finely woven wire mesh screen within the window itself.

5. Cabinet seams

- a. All mating surfaces that are electrically conductive should be free from paint, anodization, oxides, grease, etc.
- b. The two surfaces of a seam should overlap. Since the two surfaces of the seam form a capacitor, sufficient capacitive coupling should be provided for the seam to function as an electrical short at high frequencies. Minimum seam width should be five times the maximum expected separation between mating surfaces.
- c. Firm electrical contact should be made at intervals of no greater than $\lambda/20$ along the length of the seam. This contact can be provided by screw fasteners, grounding pads, contact straps across the seam, or conductive gaskets.

4.3.3.2 Cable Shielding. This section will only deal with the special case where there is an overall cable shield provided over individually shielded conductors or conductor pairs.

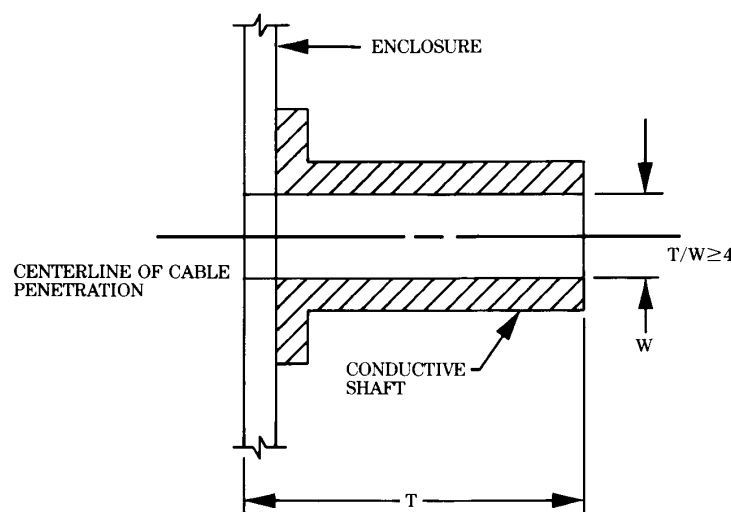


Fig 9
Waveguide Beyond Cutoff Frequency

In most cases, only a single overall shield or individual shields are used, since the capacitance per unit length greatly increases when both are used. For example, digital signals commonly use only an overall shield. Generalized cable shielding practices are contained in 5.4.

The action of an ideal shield conductor can best be illustrated if it is assumed that any magnetic flux, which links the signal conductor, also links the cable shield. The shielding effect is the result of eddy currents set up in the shield by the external magnetic field. These eddy currents set up magnetic fields opposing and counteracting the disturbing magnetic field and will exist regardless of whether or not the shield is connected to ground.

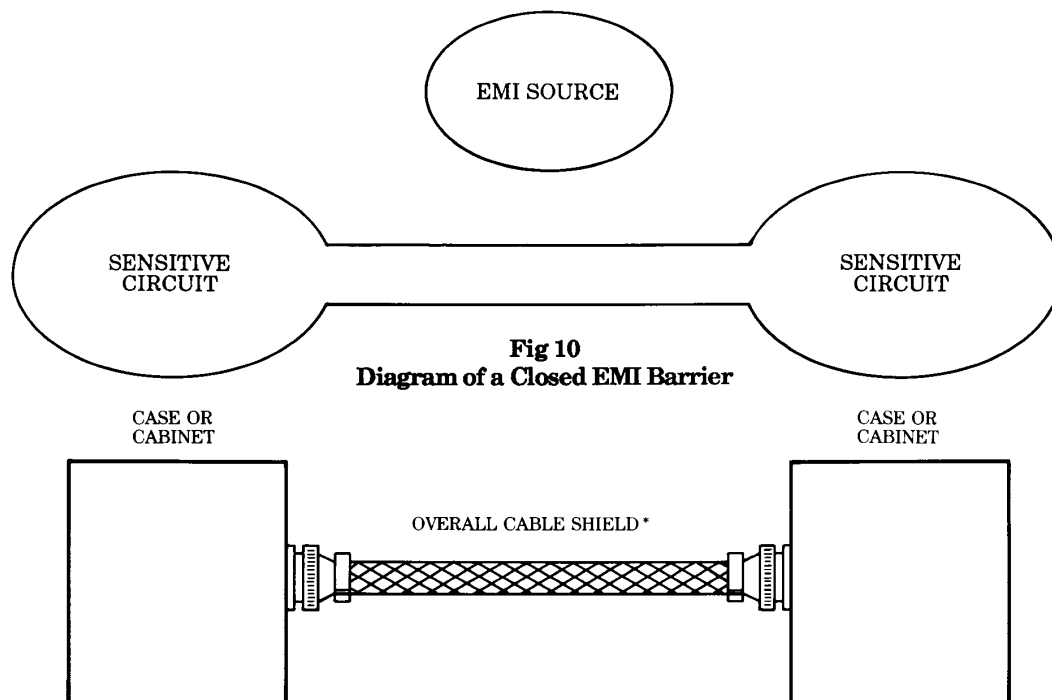
The cable shield should be thought of as a barrier element that connects the barriers formed by the cabinets containing the control circuits (see Fig 10). The shield can take such forms as metallic conduit or ductwork, copper braid, copper tape, or aluminized mylar. Because the cable shield is part of the barrier that protects the interconnected circuits from noise sources outside the barrier, the shield should be made continuous with the cabinets to which it is connected so as to close the barrier. Whether or not the shield is grounded, it must be closed to protect the internal circuits from wideband external interference (see Fig 11). In general, the individually shielded conduc-

tors or conductor pairs should have their shields connected to ground at the signal source. Copper tapes and aluminum foils give a very poor performance in a double-grounded arrangement because of their high resistance. In addition, symmetry of the shield is particularly important, so it is most practical to use longitudinally wrapped copper or aluminum (corrugated) shields.

4.3.4 Grounding. Grounding techniques are covered in detail in Sections 5 and 6. The following paragraphs, however, discuss certain aspects of grounding that pertain to the shielding recommendations in 4.3.3.

Ideally, the ac grounding conductor should not penetrate an equipment cabinet. When ac ground conductors do penetrate a cabinet they can serve as a path along which EMI can propagate and effectively reduce the shielding of a cabinet to 0 dB.

The important thing to remember is that an EMI barrier should be closed, regardless of whether it is connected to ground. An inappropriate grounding technique will probably cause more EMI control problems than it will cure. Cable shields are a prime example of this, since many attempts to ground a cable shield have resulted in opening an EMI barrier. The shielding techniques described in 4.3.3 will provide protection against externally generated interference and will help prevent the escape of internally generated interference.



* Cable contains individually shielded signal pairs that are grounded according to the guidelines presented.

Fig 11
Realization of Fig 10

Proper grounding techniques will help to eliminate noise generation from both internal and external sources.

4.3.5 Filters. All leads are capable of conducting interference into equipment cabinets. This includes power conductors, the ac ground conductor, output leads, and any control or logic lines. Once high-frequency noise enters a sensitive instrument, there is a good chance that some portion of the high-frequency signal will appear as noise in the control circuits. High-frequency noise currents can be kept away from the inside of instruments by draining the currents to a proper ground by filters.

Filters can range anywhere from simple capacitors and ferrite beads to sophisticated bandpass filters. The configuration of the filter will naturally depend upon the characteristics of the noise to be filtered. Since different filter configurations will affect signal pa-

rameters such as pulse rise time and wave-shapes of both digital and analog circuits, both the positive and negative effects must be considered when applying filters. Filters have also been known to cause detrimental ringing of digital circuits.

Power line filters should preferably be of the hybrid common mode/differential mode type in order to combat both types of conducted EMI. Power line filters should be located with regard to the following considerations:

1. Keep the unfiltered portion of the power cord that is inside of the equipment as short as possible.

The filter should optimally be mounted in the bulkhead of the cabinet to protect against input-output parasitic capacitance coupling at high frequencies.

2. Avoid recoupling of the filtered and non-filtered power leads due to routing the

filtered leads close to the incoming unfiltered leads.

3. Avoid coupling of the power leads with signal/logic cabling.

A major source of noise interference involves the ac ground wire. Since this wire is shared by many users, any unwanted current flow generated by these outside sources can be conductively coupled into the control circuits. Separate safety conductors can be used for sensitive equipment; or this conductor can be decoupled by a suitable RF choke. Absorption devices such as ferrite beads can be used to decouple the external field produced by high-frequency common mode interference.

Many high-frequency transients can be prevented from entering control enclosures by bypassing each control conductor to ground with a 0.1 μF capacitor at the terminal block where the cable enters. For this method to be effective, the leads of the bypass capacitors should be kept as short as possible. Care should be taken in evaluation if this method will cause an undesirable time delay of the signal.

In order for a filter to be effective, it is assumed that the interference frequency can be determined to be different than that of the signal frequency.

4.3.6 Other Noise Minimization Techniques.

4.3.6.1 Isolation Transformers. Isolation transformers can be used to balance the signal circuit. When both ends of a wire pair are fed by isolation transformers, the wires become isolated from ground potential differences in the terminal equipment. The use of isolation transformers is only possible for ac signals.

4.3.6.2 Neutralizing Transformers. Neutralizing transformers can be used to eliminate the effects of ground potential rises. All incoming control cables will pass through the neutralizing transformer and become separate secondary windings. The primary winding has the same number of turns as each of the secondaries and is energized by the ground potential rise of the station; one end is connected to the station ground and the other is connected to ground at a sufficient distance not to be affected by station fault currents. Thus, a voltage equal to the ground rise is induced in the control circuits and the ground rise potential is not present between the in-

coming cables and the control circuit. The neutralizing transformer has the advantage because it can be used for both ac and dc signals.

4.3.6.3 Differential Amplifiers. The use of differential amplifiers is an effective means of reducing common mode noise. Even though the common mode tolerance of most integrated circuit differential amplifiers is only a few volts, common mode voltages of up to several thousand volts can be tolerated by using the proper input attenuation scheme.

4.3.6.4 Increase the Signal-to-Noise Ratio. Care must be exercised in using this method for, although it will reduce the induced noise in one region of frequency, it will cause an increase in noise in another region. Changing the circuit impedance to reduce the noise induced by either a primarily inductive or capacitive source is subject to the same warning as increasing the signal-to-noise ratio.

4.3.6.5 Fiber Optic Cables. Use fiber optic cables since they are immune to the interference sources which plague standard current-carrying control cables.

4.3.7 Summary—Minimization Techniques Classified by Coupling Mechanism. It should be noted that, in real world applications, the minimization techniques used will need to be optimized based on the type of interference encountered. Accordingly, some of the techniques that follow are at odds with each other since each is optimized to reduce a specific coupling mechanism.

4.3.7.1 Common Impedance Coupling.

1. Eliminate as many common impedance points between circuits as possible by not using any conductor as part of more than one circuit.
2. Optimize circuit impedances for minimum coupling. Maximum power will be coupled between circuits when the source and load impedances are equal.
3. Make ground connections as short as possible.
4. Reduce the resistance and impedance of ground conductors.

4.3.7.2 Capacitive Coupling.

1. Reduce the impedance of the sensitive circuit.
2. Position and connect conductive shields so that capacitively coupled noise currents are returned to ground without