

IEEE Guide for Instrumentation Control Equipment Grounding in Generating Stations

Sponsor

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

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Abstract: Information about grounding methods for generating station instrumentation and control (I & C) equipment is provided. The identification of I & C equipment grounding methods to achieve both a suitable level of protection for personnel and equipment is included, as well as suitable noise immunity for signal ground references in generating stations. Both ideal theoretical methods and accepted practices in the electric utility industry are presented.

Keywords: control equipment, generating stations, grounding, instrumentation

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Introduction

(This introduction is not a part of IEEE Std 1050-1996, IEEE Guide for Instrumentation and Control Equipment Grounding in Generating Stations.)

IEEE Std 1050 was first published in 1989 after a five year development cycle. Specific recommendations for the grounding of distributed control systems (DCS) were intentionally omitted from the 1989 edition, since at the time the document was being written (1984-1987), there was not a large base of installed systems and user experience from which to write a guide. Experience since 1989 has shown that the DCS grounding is essentially no different from the concepts presented in the 1989 version, and would not require a specialized treatment in the guide.

This revision consists of three major changes to the document. The first is the incorporation of comments, corrections, and clarifications that have been brought to the attention of the working group. The second change is a significant rearrangement of the document for enhanced user-friendliness. This includes a complete redrawing of the significant figures in clause 5 to more clearly depict the concepts being discussed. The third change is a reformatting of the document to conform to the editorial conventions presented in the most current edition of the IEEE Style Manual.

With the issue of this revision, the task force will turn its attention to incorporating significant comments and clarifications that were received from interested parties outside of the formal balloting process. These comments were received after the cutoff date in the formal approval process and this has functionally prevented them from being incorporated into this revision. The improvements made by this revision are significant enough that this revision should be issued on schedule, instead of introducing a significant delay to incorporate the new material.

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IEEE Guide for Instrumentation and Control Equipment Grounding in Generating Stations

1. Overview

1.1 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 to provide suitable electric noise immunity for signal ground references in generating stations. Both 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.

This guide is intended to provide information about grounding methods for generating station I & C equipment. Grounding design is normally based on the concept of two separate grounding systems: the equipment ground and the signal reference ground. The grounding of instrument chassis, racks, cable sheaths, or cable shields and signal pairs requires special care to ensure that personnel working on equipment are adequately protected against electrical shock hazards during both normal and abnormal conditions, as well as to ensure that interference signals are not inadvertently coupled into signal circuits.

The basic theory and guidelines to be understood before designing I & C grounding are presented in clause 4. Clause 5 provides guidance for grounding of equipment associated with generating station I & C systems and presents various approaches to providing a signal ground system. Clause 6 presents accepted practices in grounding the shields of I & C cables, while clause 7 covers the testing of I & C grounding systems.

1.2 Purpose

The typical environment in a generating station provides many sources of electrical noise, such as the switching of large inductive loads, high fault currents, static switching, and high-energy, high-frequency transients associated with switching at the generator or transmission voltage level. 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 guide discusses methods for the grounding of I & C equipment and their associated circuits in generating stations.

It is intended to provide guidance for the design of grounding systems for I & C equipment specific to the generating station. The low-level electrical signals transmitted from various I & C equipment in a generating station through long cables may undergo signal distortion as they travel to the receiving end. This distortion is typically 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. 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 I & C signals in generating stations. By contrast, the station grounding system is mainly oriented toward meeting the requirements of various safety codes that aim to establish a grounding system that will provide a low-impedance path to ground. This low-impedance path helps to ensure that high voltages are not developed on equipment or structures as a consequence of lightning surges, electrical faults, circulating currents, or static charges. This guide is complementary to IEEE Std 665-1995.¹

2. References

This guide should be used in conjunction with the following publications. When the following standards are superseded by an approved revision, the revision applies.

Accredited Standards Committee C2-1997, National Electrical Safety Code (NESC®).²

IEEE Std 100-1992, The New IEEE Standard Dictionary of Electrical and Electronics Terms (ANSI).³

IEEE Std 142-1991, IEEE Recommended Practice for Grounding of Industrial and Commercial Power Systems (IEEE Green Book) [ANSI].

IEEE Std 518-1982 (Reaff 1990), IEEE Guide for the Installation of Electrical Equipment to Minimize Noise Inputs to Controllers from External Sources (ANSI).

IEEE Std 525-1992, IEEE Guide for the Design and Installation of Cable Systems in Substations.

IEEE Std 665-1995, IEEE Guide for Generating Station Grounding.

IEEE Std 1100-1992, IEEE Recommended Practice for Powering and Grounding Sensitive Electronic Equipment (IEEE Emerald Book) [ANSI].

IEEE Std C57.13.3-1983, IEEE Guide for the Grounding of Instrument Transformer Secondary Circuits and Cases (ANSI).

¹Information about references can be found in clause 2.

²The NESC® is available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA.

³IEEE publications are available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA.

3. Definitions

This clause contains key terms as they are used in this guide. An asterisk denotes definitions not included in IEEE Std 100-1992.

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

3.2 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.

3.3 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 both of the following:

- a) Electrostatic induction: With equal capacitance between the signal wires and the surroundings, the noise voltage developed will be the same on both signal wires.
- b) Electromagnetic induction: With the magnetic field linking the signal wires equally, the noise voltage developed will be the same on both signal wires.

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

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

3.6 cutoff frequency:

- a) (general) The frequency that is identified with the transition between a passband and an adjacent attenuation band of system or transducer.
- b) (of a waveguide) for a given transmission mode in a nondissipative waveguide, the frequency at which the propagation constant is zero.

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

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

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

3.10 equipment ground*: For the purpose of this guide, the safety ground connection to the conductive, non current-carrying parts of electrical equipment.

3.11 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.

3.12 neutral*: For use with the figures in this guide, the center tap of a grounded three-phase transformer winding. Since only single-phase loads are depicted, the other phases of the supply transformer have been omitted for clarity.

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

3.14 differential mode noise (normal or transverse): The noise voltage that appears differentially between two signal wires and that 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:

- a) Electrostatic induction and differences in distributed capacitance between the signal wires and the surroundings
- b) Electromagnetic induction and magnetic fields linking unequally with the signal wires
- c) Junction or thermal potentials due to the use of dissimilar metals in the connection system
- d) Common mode to normal mode noise conversion

3.15 signal ground*: For the purpose of this guide, the grounding system to which signals are referenced.

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

3.17 Acronyms

ac	Alternating current
CCVT	Coupling capacitor voltage transformer
CDF	Central distribution frame
CM	Common mode
CT	Current transformer
dc	Direct current
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
SE	Shielding effectiveness
SF ₆	Sulfur hexafluoride
V_S	Signal voltage
VCM	Common mode voltage
VDM	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 of the following categories:

- a) Natural sources—these happen independently of human activity, but their effects can be controlled.
- b) Incidental sources—these are caused by human activity, but they are not intentional.
- c) Intentional sources—these are emissions of potentially interfering energy produced for specific purposes unrelated to the equipment or systems under consideration.

4.1.1 Natural sources

Probably the most severe noise source that any control system will ever be exposed to 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 strike is composed of a downward-stepped leader stroke (usually negatively charged), 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% of the first stroke amplitude.

A continuing current is usually present between stroke sequences. There may be as many as 20 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, then 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 these subclauses originate predominantly 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 that can be electrostatically or electromagnetically coupled to nearby cables. Typical values are as follows:

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 s
Decay time	2–4 cycles
Source impedance	5–200 Ω

As a general guideline, for two parallel, multiple-conductor cables separated by 5 cm, up to 0.50 of a transient's magnitude on one cable could 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 the two following components:

- a) Those associated with the lumped parameters of the circuit are in the kilohertz 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.
- b) Those associated with the distributed parameters of the circuit are in the megahertz 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.

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 megahertz range. Any oscillatory high-frequency transients occurring on the high voltage bus can give rise to high-frequency currents that are coupled through the capacitors to the control circuits.

The transformer located in the base of the CCVT contains a distributed stray capacitance of a few hundred picofarads 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.

Nearly 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.

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

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

4.1.2.6 Ground voltage differences

Grounding systems grids that extend over large areas have sufficient impedance to create a difference in voltage between two points within the system. Conduction of power system transients through the grounding system is one of the most common causes of large ground potential differences.

4.1.2.7 Current transformers (CTs)

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 windings 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 the following:

- a) Partial discharges (e.g., corona discharge) within the stator winding insulation.
- b) Slot discharges between the coil surfaces and the stator iron.
- c) Sparking from exciters with brushes.
- d) 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.
- e) 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 have additional circuitry to control the voltage rise time. If the voltage rise time is not controlled, it can 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 figure 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.

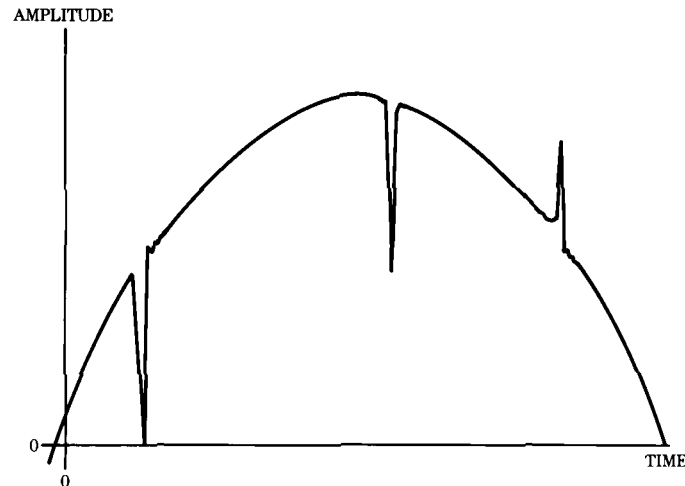


Figure 1—Line notching waveshape

4.1.2.10 Computer systems

The noise generated by microprocessor and memory boards within a computer is dependent primarily upon the computer's 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 3 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:

- a) *CRT display.* Noise sources 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).
- b) *Disk drives.* Noise generated by disk drives is dependent on the data processing rate (400 kHz–2 MHz for floppy drives, and 1–10 MHz for hard disk drives).
- c) *Switching power supply.* The noise generated by these devices is dependent upon the switching frequency (typical 10–100 kHz) and the switching amplitude.
- d) *Printers.* The major noise sources for these devices are the printhead solenoids and the carriage positioning motors along with the associated drivers.
- e) *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 clause 6.

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 that will radiate high-frequency noise.

4.1.2.13 Chemical contamination

Most plant atmospheres contain suspended chemicals (i.e., oil, coolants, degreasing solutions) that 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 connection. Vibration causes gas-tight connections to flex and permit the entrance of chemical droplets. Since many electrical connections are made with dissimilar materials having different coefficients of expansion, temperature changes will also cause the connection to flex and will 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.

Human hands can also introduce chemical contamination during the assembly of system components. Connections should be cleaned of all contamination before mechanical bonding or sealing takes place.

4.1.2.14 Human interaction

The electrostatic discharge (ESD) that occurs when an operator touches metallic equipment controls during low-humidity conditions is a potential noise source. For example, if a metallic switch body is mounted on a printed circuit board but is isolated from the conductive cabinet, as is shown in figure 2, 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 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.

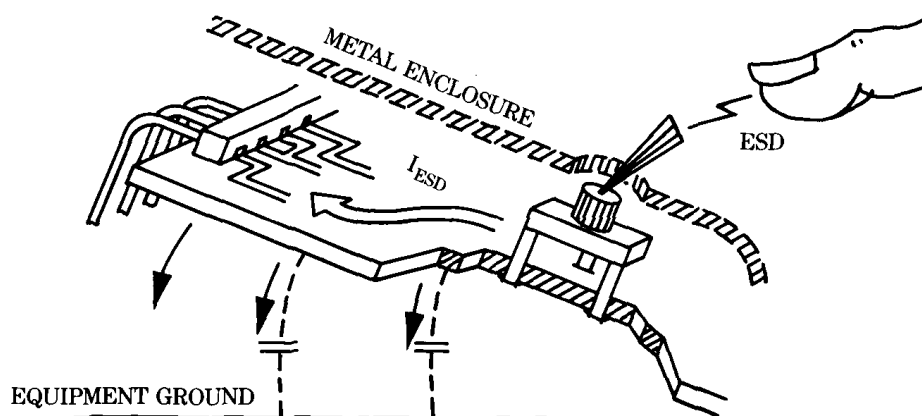


Figure 2—Electrostatic discharge noise generation

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 to the repetition rate of a series of signals. Electrical disturbances travel at 299 300 m/s in a vacuum, and 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 computer. In a cable it may travel only 17 m. If the voltage wave reflects from the cable termination and is in phase with a new wave, resonance will occur and line oscillations will be greatly magnified. If one end of the circuit is grounded, the first resonance at 10 MHz occurs when the conductor is only 6.7 m, or 0.25 wavelengths, long.

At this frequency, a cable 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 cable 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 eliminate most of the reflection and resonance. However, single grounded conductors within a cable 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 overvoltages, 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. The noise generated by these sources will attenuate with increasing distance.

4.1.3 Intentional sources

Many devices intentionally use radio frequency (RF) energy to accomplish their function, such as radios (e.g., security guard transceivers, citizen's band, etc.), RF-stabilized arc welders, induction heaters, and RF drying equipment. These devices produce considerable amounts of RF energy that 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 the following four different methods:

- a) Conductive (direct contact)
- b) Capacitive (electric)
- c) Inductive (magnetic)
- d) 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 0.167 of 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 later in this guide.

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) 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 377Ω .

4.2.2 Common impedance coupling (conductive)

As is shown in figure 3, when two or more circuits share a wire or junction point, common impedance coupling is a possible 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.

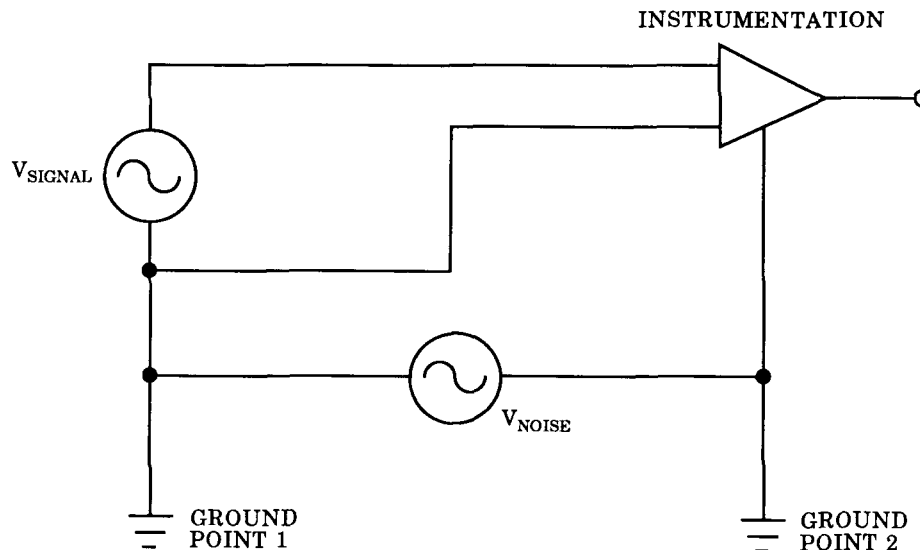


Figure 3—Example of common impedance coupling (ground loop)

4.2.3 Capacitive coupling (electric)

As is shown in figure 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.

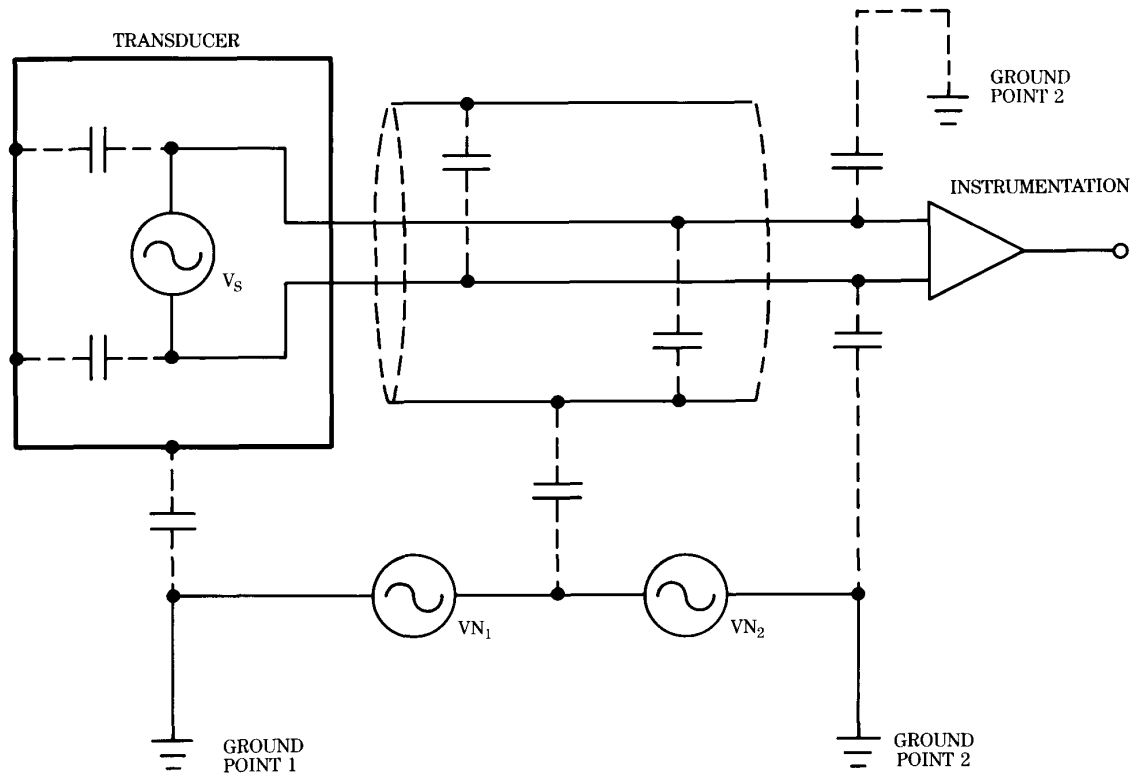


Figure 4—Example of capacitive coupling

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

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 figure 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 that 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.

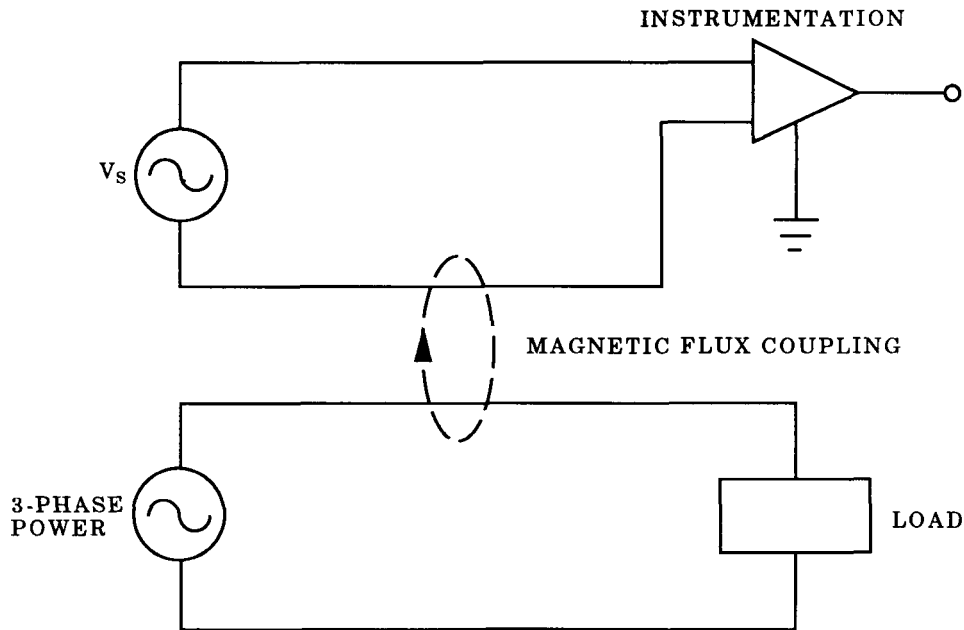


Figure 5—Example of inductive coupling

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.

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 that the control circuit will respond to, 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

This clause describes the various ways that noise will interfere with the intended signals.

4.2.6.1 Common mode interference (longitudinal mode)

Common mode 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 figure 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 will 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 transients are more likely to cause dielectric failure than differential mode transients.

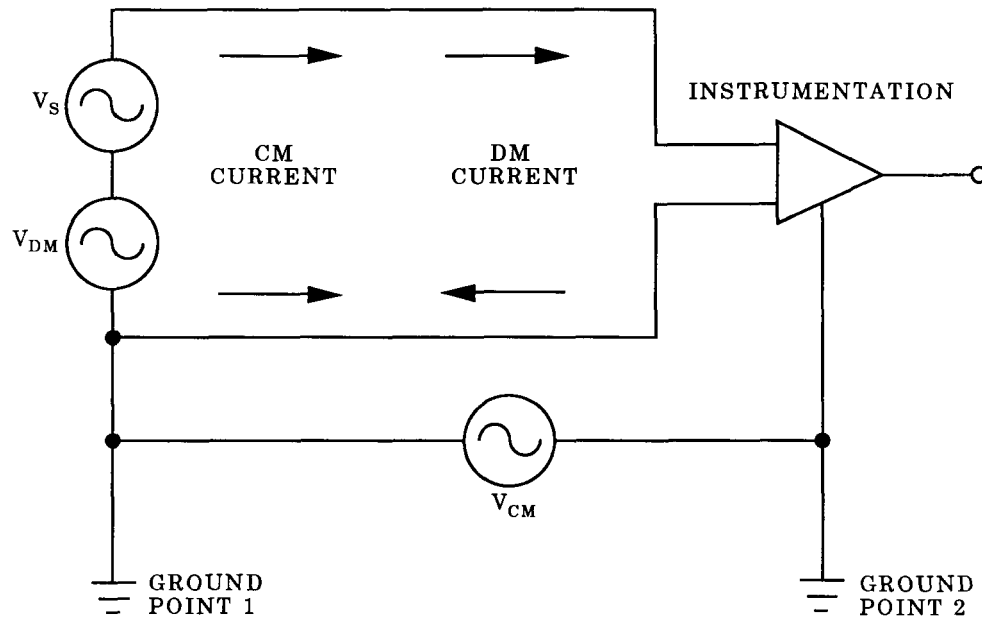


Figure 6—Example of common and differential mode interference

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 figure 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.

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, which is crosstalk. Both of these coupling methods are directly proportional to the frequency of the signal. By changing the impedance of the signal path, 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 techniques 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 method of suppression in a dc circuit that prevents the voltage across the coil from exceeding the supply voltage. The diode, however, has the following disadvantages:

- a) Switch-off delay
- b) Diode failure may short circuit the device
- c) Forward overcurrent when the supply is interrupted can destroy the diode
- d) Overvoltage in the reverse direction (possibly caused by spikes from unsuppressed loads) can destroy the diode
- e) Possibility of causing 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 series 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 in figure 7.

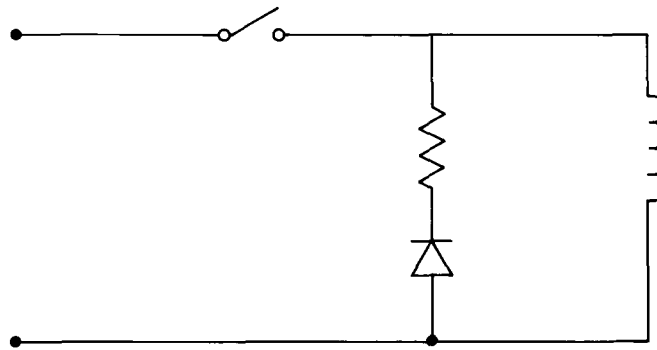


Figure 7—Suppression with a diode and series resistance

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 can be 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. Back-to-back diodes may be placed across a relay contact to not only suppress the noise, but also to prevent damage to the contacts.

4.3.1.2 Suppression of thyristor rectifiers, motors, and generators

Small capacitors are used to damp high frequencies generated by these devices. They should 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 common 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, zener diodes, and varistors can be used as is 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 important factor affecting surge voltage levels. Techniques for minimizing noise pickup in control circuits include the following:

- a) Provide 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 that is possible because of the very large flux loops 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 same raceway to minimize the loop and reduce susceptibility to interference from inductive coupling. If possible, a gentle twisting of the two wires (1 turn/m) can further reduce the magnitude of the induced noise.
- b) Orient 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.
- c) Locate the control room in a centralized location so as to minimize control cable runs.
- d) Provide maximum separation between power and control wiring. Both should be routed close to the conductive cabinet or reference ground plane.
- e) Avoid inadvertent loops when routing cables.

4.3.2.2 Physical separation

Circuits operating at different voltages (and sometimes different energy levels) should be physically separated. For example, low-energy analog signals should not be run in the same cable as higher energy control signals. Similarly, dc battery and ac control power circuits should not 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 should be given to separating the two circuit types by a grounded metallic barrier.

Figure 8 illustrates capacitance versus conductor separation. 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 that is of great benefit to a power generating station in reducing noise interference between long runs of cables.

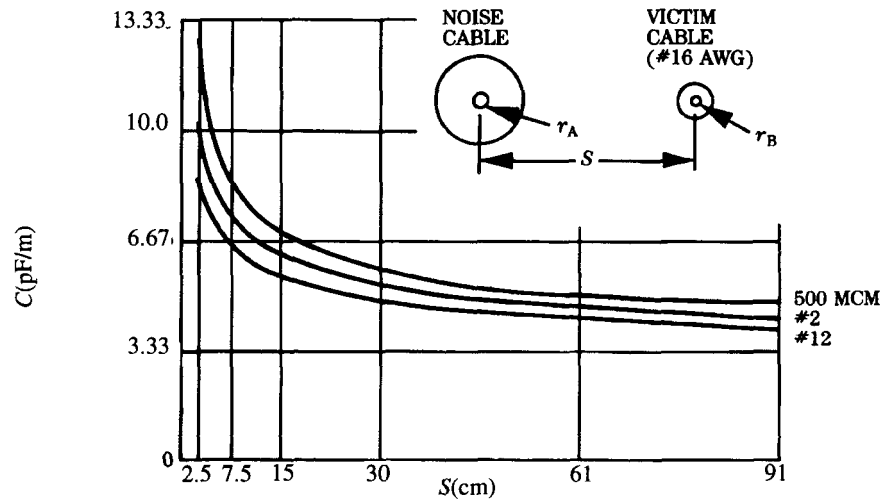


Figure 8—Capacitance versus conductor separation

4.3.3 Shielding

Shielding is used to protect a system, circuit or component from undesirable effects of an external magnetic, electric or electromagnetic field source. The method of shielding may differ depending on whether the external source is a low- or high-frequency field. For cables, a shield may take such forms as metallic conduit, copper braid, copper tape, or aluminized mylar. For components, a shield could be any conductive enclosure.

For dc and low-frequency electrical fields, electrostatic shielding can be easily accomplished by enclosing the sensitive components in a highly conductive material that is held at a constant voltage. This is generally done by connecting the material (shield) to ground.

To shield against dc and low-frequency magnetic fields, the external interfering magnetic flux should be diverted from the shielded space by the shielding material. To be effective, the shielding material should have a low reluctance. Reluctance is inversely proportional to the permeability and the cross sectional area of the shield. Therefore, a magnetic shield should have a high permeability and a large cross-sectional area. Since the permeability of a magnetic material is not constant but depends on the flux density in the shield material, the magnetic flux density needs to be known in order to estimate the effectiveness of the shield. If the magnetic flux density is so high that the magnetic shield becomes saturated, then the shield will not be very effective. Effective magnetic field shielding is much more difficult to obtain than electrostatic shielding.

When a high-frequency electromagnetic field impinges on a conductive shield, part of the electromagnetic wave is reflected by the shield material. The non-reflected portion of the wave is transmitted through the shield material. A portion of the transmitted wave is attenuated as it travels along the shield material. Thus, the field incident on the shielded circuit, component or system is lower than the incident electromagnetic field.

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. In this application, the decibel is expressed as 20 times the logarithm (base 10) 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

$$\text{E-Field, SE} = 20 \log E_1/E_2$$

$$\text{H-Field, SE} = 20 \log H_1/H_2$$

Where E_1 and H_1 are the values prior to shielding and E_2 and H_2 are the values after the shield is in place.

In most shielding applications, shielding effectiveness below 20 dB is considered only minimal shielding; 20–80 dB covers the normally acceptable shielding range, and 80–120 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

Electrostatic coupling can be significant when lines do not have a metallic shield connected to the circuit ground reference. 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 (on the preceding page) illustrates the model for E-field coupling and provides calculated capacitance/cm between common-size power conductors and 16 AWG instrumentation conductors versus separation distance.

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

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

- Keep the longest dimension of apertures in cabinets less than $\lambda/20$. Openings larger than this will require additional protective measures.
- Where cable penetrations occur in a cabinet, shielding can be accomplished by using waveguides operating beyond cutoff frequency. This can be done by connecting a conductive shaft to the inside of the cabinet as shown in figure 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.

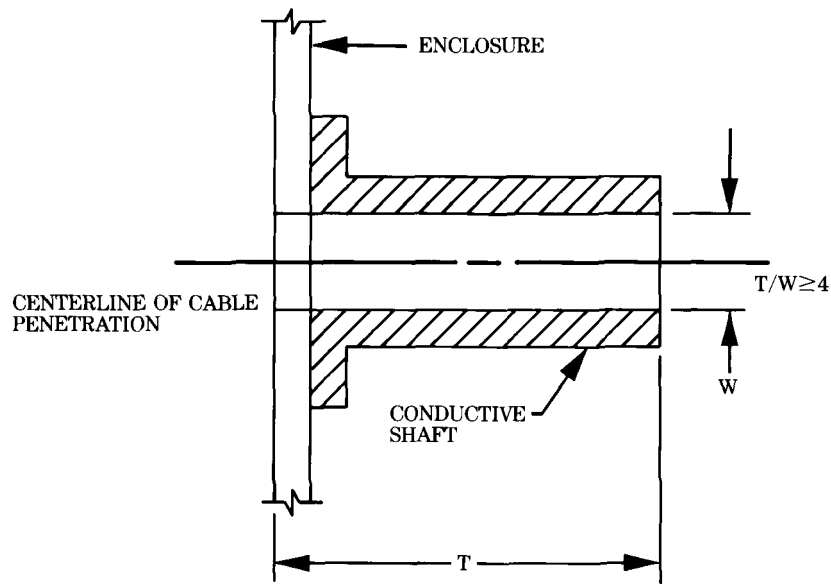


Figure 9—Waveguide beyond cutoff frequency

- c) Electronic systems that are packaged in cabinets of plastic or other non conductive 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.
- d) 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.
- e) Cabinet seams
 - 1) All mating surfaces that are electrically conductive should be free from paint, anodization, oxides, grease, etc.
 - 2) 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.
 - 3) 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

For most multiconductor cables, only a single overall shield or individually shielded conductor pairs 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 that 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 whether or not the shield is connected to ground.