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IEEE Guide for Instrumentation and Control Equipment Grounding in Generating Stations

IEEE Power Engineering Society

Sponsored by the
Energy Development and Power Generation Committee

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Abstract: 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 generating stations are identified.
Keywords: control, generating stations, grounding, I&C, instrumentation

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Introduction

This introduction in not part of IEEE Std 1050-2004, IEEE Guide for Instrumentation and Control Equipment Grounding in Generating Stations.

The original version of IEEE Std 1050 was 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 on which to write a guide. Experience since 1989 has shown that DCS grounding is essentially no different from the concepts presented in the 1989 version, and would not require a specialized treatment in the guide.

The 1996 revision consisted of three major changes to the document. The first was the incorporation of comments, corrections, and clarifications that have been brought to the attention of the working group. The second change was a significant rearrangement of the document for enhanced user-friendliness. This included a complete redrawing of the significant figures in Clause 5 to more clearly depict the concepts being illustrated. The third change was the reformatting of the document to conform to the latest style manual for IEEE standards.

The revision includes major improvements in terminology consistency along with further elaboration of the various concepts that are introduced. Additional enhancements have been made to Clause 5 and its figures for clarity, including new subclauses on power source grounding and surge protection. Clause 6 on cable shields receives another reformatting to make the topics directly relate to the various types of I&C circuits encountered in generating station design. Results of industry surveys are included to illustrate the prevalence of various cable shield grounding techniques.

This guide was prepared by a Task Force of the Grounding Practices Working Group. The Working Group is part of the Station Design, Operation, and Control Subcommittee and was sponsored by the Energy Development and Power Generation Committee of the IEEE Power Engineering Society.

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Peter Aouad
Aldean Benge
Leslie A. D. Grant
Warren L. Lewis
Richard Meininger
Derek M. Sawyer
Malcolm V. Thaden, Jr.
Gerald L. Vaughn

The following members of the individual balloting committee voted on this standard. Balloters may have voted for approval, disapproval, or abstention.

William Ackerman
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Tommy Cooper
Joseph Deckman
William G. Fossey
Randall Groves
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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 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.

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, the equipment ground and the signal reference ground. The concepts of equipment grounding are well covered in other IEEE standards. The concepts of grounding of instrument chassis, cable shields, signal pairs, and other related instrumentation and control items require special care in order to ensure that both personnel working on equipment are adequately protected from electrical shock and that interference signals are not inadvertently coupled into signal circuits. Although safety takes top priority, the I&C systems must be simultaneously safe and operationally reliable.

The basic theory and guidelines that should be understood before designing I&C grounding are presented in Clause 4. Clause 5 presents various approaches for the grounding of equipment associated with generating station I&C systems. 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, electronic drives, and high-energy, high-frequency transients associated with switching at transmission voltage levels. The increasing use of solid-state equipment and microprocessor-based control 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 their associated circuits in this environment.

The generally low-level electrical signals transmitted from various I&C equipment in a generating station through often lengthy 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 may cause operational errors and in extreme cases, damage to equipment which in turn may result in costly unit downtime. The use of proper grounding and shielding techniques can prevent 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 with reference to the recommendations of the I&C equipment manufacturers since the techniques used to solve one problem may result in the creation of a different problem.

The grounding methods in this guide are intended to minimize degradation of instrumentation and control signals in generating stations. By contrast, the overall station grounding system is designed for safety considerations to establish a grounding system that will provide a low-impedance path for power currents to return to the power reference ground point for rapid fault clearing and to minimize potential differences between electrical equipment and the local equipment grounding structures. The equipment grounding system is intended to reasonably ensure that hazardous voltages are not developed between grounded equipment or structures as a consequence of lightning surges, electrical faults, leakage or circulating currents, or static charges.

2. Normative references

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

Accredited Standards Committee C2-2002, National Electrical Safety Code® (NESC®).[1]

IEC/TS 61312-1:1995, Protection Against Lightning Electromagnetic Pulse (LEMP) Part I: General Principles.[2]

IEEE Std C57.13.3™-1983 (Reaff 1990), IEEE Guide for the Grounding of Instrument Transformer Secondary Circuits and Cases.[3, 4]

IEEE Std C62.23™-1995, IEEE Recommended Practice on Surge voltages in Low-Voltage AC Power Circuits.

IEEE Std C62.43™-1999 IEEE Guide for the Application of Surge Protectors Used in Low-Voltage (Less Than or Equal to 1000 Vrms or 1200 Vdc) Data, Communication, and/or Signaling Circuit Application.

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

IEEE Std 422™-1986, IEEE Guide for the Design and Installation of Cable Systems in Power Generating Stations.

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[1] The NESC is available from the Institute of Electrical and Electronics Engineers, Inc., 445 Hoes Lane, Piscataway, NJ 08854, USA (http://standards.ieee.org/).

[2] IEC publications are available from the Sales Department of the International Electrotechnical Commission, Case Postale 131, 3, rue de Varembé, CH-1211, Genève 20, Switzerland/Suisse (http://www.iec.ch/). IEC publications are also available in the United States from the Sales Department, American National Standards Institute, 25 West 43rd Street, 4th Floor, New York, NY 10036, USA (http://www.ansi.org/).

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IEEE Std 518™-1982 (Reaff 1996), IEEE Guide for the Installation of Electrical Equipment to Minimize Noise Inputs to Controllers from External Sources.

IEEE Std 525™-1992 (Reaff 1999), 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™-1999, IEEE Recommended Practice for Grounding Electronic Equipment (IEEE Emerald Book).

NFPA 70-2002: National Electrical Code® (NEC®).[5]

NFPA-780-2004: Standard for the Installation of Lightning Protection Systems.

3. Definitions and acronyms

3.1 Definitions

This subclause contains key terms as they are used in this guide. An asterisk (*) denotes definitions not included in *The Authoritative Dictionary of IEEE Standards Terms* [B21].[6]

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

3.3 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. For certain systems this technique provides a good functional compromise between the ideal signal grounding methods and ease of installation and troubleshooting.

3.4 common-mode (CM) noise: The generally unwanted noise voltage and current that appears equally and in phase from each victim signal, control, or power circuit conductor to ground, or between grounds or grounding conductors. CM noise is also referred to as longitudinal-mode (LM) noise. Common-mode noise may be caused by one or more of the following:

a) Electrostatic induction (E-field capacitive coupling) via near field effects. With equal capacitance between the set of victim conductors and their immediate surroundings, the noise voltage and current developed will be the same on all victim wires in the same circuit.

b) Magnetic induction (H-field transformer coupling) via near field effects. With the magnetic field linking the set of victim conductors equally, the noise voltage and current developed will be the same on all victim conductors in the same circuit.

c) Electromagnetic wave coupling via far-field effects. Electric dipole (or monopole) antennas and/or magnetic loop antennas inadvertently formed in the victim conductor system can accept electromagnetic wave radiation and cause it to appear as common-mode noise and current on their path.

d) A variation in potential between two or more ground references to which the victim circuit's conductors are connected. An example would be two separate buildings with a metallic signal or power cable routed between them along with a grounded circuit or signal conductor. When a lightning

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[5] The NEC is published by the National Fire Protection Association, Batterymarch Park, Quincy, MA 02269, USA (http://www.nfpa.org). Copies are also available from the Institute of Electrical and Electronics Engineers, Inc., 445 Hoes Lane, Piscataway, NJ 08854, USA (http://standards.ieee.org/).

[6] The numbers in brackets correspond to those of the bibliography in Annex A.

strike or ac system ground-fault occurs at one building a CM noise condition will be produced on all of the conductors of the interconnecting cable. A potential difference is then seen to exist for the duration of the event between the two buildings via the interconnecting cable and a CM current flows between the buildings via the cable. Note that the lightning or fault current that is coupled into the enclosed loop area of the circuit conductors can also produce a CM effect. Direct lightning or fault current contact with the circuit conductors is not required.

3.5 coupling: The mechanism by which a near-field interference source of voltage, current, or both produces directly related interference in a victim circuit without a conductive (galvanic) path being involved in the transfer. In general, coupling occurs via stray or parasitic reactive coupling means. (*See:* **radiation** in The Authoritative Dictionary [B21] for similar far-field effects.)

3.6 crosstalk: The unwanted transfer of signals or electrical noise by near-field coupling mechanisms between electrically separated, but physically adjacent circuit conductors. Crosstalk problems generally vary inversely with the spacing between the involved circuit conductors, and is commonly used in reference to effects within multi-conductor cables.

3.7 cutoff frequency: a) (General) The frequency that is usually identified with the first –3 dB 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 0.

3.8 distributed control system (DCS):* A control system composed of distributed software, hardware, cabling, sensors, activators, and input/output communication capability that is used to control and monitor equipment and processes.

3.9 electromagnetic compatibility (EMC):* The capability of electronic equipment or systems to be operated in the intended operational electromagnetic environment at designed levels of efficiency in all design operating modes. Also, the required ability of items of electrical and electronic equipment to be reliably operated without electrical interference occurring between them.

3.10 electromagnetic interference (EMI):* Impairment of a wanted electromagnetic signal by an electromagnetic disturbance. Also, applied to equipment whose operation is impaired by conducted, coupled, or radiated electrical interference (EMI) of some type

3.11 equipment (safety) ground:* All of the conductive, normally non-current carrying metal parts of equipment, raceways, and other enclosures that are connected to a site's: (1) grounded ac system conductor (the neutral), (2) the related equipment grounding conductors, (3) the related ac grounding electrode conductor and, (4) the related ac system earth grounding electrode itself.

3.12 ground: A conducting connection, whether intentional or accidental, between and electrical circuit or equipment and the earth or to some conducting body that serves in place of the earth (such as a vehicle's frame).

3.13 ground, ac system: The single point at which an ac power system has its common or neutral terminal connected to the power system ground reference.

3.14 immunity: The desirable property of equipment that prevents unintentional operation by a defined intensity of EMI.

3.15 neutral:* The terminal of a single or polyphase electrical power source that carries only the unbalanced or triplen harmonic currents between the connected loads and the power source. On a two-wire, single-phase power source, the term "neutral" is also applied to the common terminal of the ac system. This term is also applied to the circuit conductor(s) that is connected to the power source's neutral terminal. The neutral may be either solidly grounded, resistance grounded, impedance grounded, or ungrounded depending upon the design requirements for the ac system.

3.16 noise (electrical): Any unwanted voltages or currents appearing in a circuit that may or may not simultaneously contain desired signals, electrical power, or both. In this context, “noise” is generally considered to be of a sub-cyclic and impulsive character to differentiate it from relatively steady-state harmonic waveform distortion.

3.17 normal-mode (NM) noise: The noise voltage or current that appears in the same mode as the desired signal or power waveform on the victim circuit. Differential mode (DM) noise is also referred to as transverse noise and normal mode noise. DM noise may be caused by one or more of the following:

a) Any of the previously described common-mode (CM) interference mechanisms that occur on victim signal paths where the induced CM voltage or currant is not carried in equally on circuit conductors.

b) Electrostatic fields linking unequally with the distributed capacitance of the victim signal wires.

c) Magnetic induction linking magnetic fields unequally with the victim signal wires.

d) Electromagnetic wave coupling. Electric dipole (or monopole) antennas and/or magnetic loop antennas inadvertently formed in the signal wiring or cabling can detect electromagnetic wave radiation and cause it to appear as normal mode noise on the circuit conductors.

e) Junction or thermal potentials due to the use of dissimilar metals in the connection system.

f) Common-mode to normal-mode noise conversion in the victim path, particularly via transformer coupling actions.

3.18 signal ground:* That point, bus-bar, or terminal to which signal return conductors and signal cable shields are to be connected and made common to one another. Ultimately, this point is connected to the equipment ground by means of a grounding/bonding jumper, strap, or grounding conductor.

3.19 susceptibility: The degree to which equipment may be operationally affected by a defined intensity of electromagnetic interference (EMI).

3.2 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
EG	equipment ground
EGC	equipment grounding conductor
EMC	electromagnetic compatibility
EMI	electromagnetic interference
ESD	electrostatic discharge
GIS	gas insulated switchgear
I&C	instrumentation and control
I_{cm}	common-mode current
I_N	noise current
LC	inductive/capacitive
LCR	inductive/capacitive/resistive
MOV	metal oxide varistor

Q	quality factor
RC	resistive/capacitive
R	radio frequency
RTD	resistance temperature detector
SCR	silicon controlled rectifier
SDS	separately derived ac system
SE	service entry
SE	shielding effectiveness
SEQ	service equipment
SF_6	Sulfur Hexafluoride
SIS	solidly interconnected ac system
SRS	signal reference structure
TVSS	transient voltage surge suppression
V_S	signal voltage
V_{CM}	common-mode voltage
VDM	differential-mode voltage
VN	noise voltage
VT	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:

a) *Natural sources*—Those that happen independently of human activity; but their effects can be controlled.

b) *Incidental sources*—Those 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 to which any control system will be exposed is lightning. While most electronic control systems will probably fail under a direct lightning strike, even a remote power line strike can cause interference as the lightning-induced surge travels along power lines and is dissipated through leakage, radiation, and power loss in the distribution system.

In addition to the currents created in the power system's conductors by a direct strike, lightning can also create similarly rapidly changing and high current flows through the earth and through numerous grounded metallic systems and items such as cable shields, equipment grounding conductors, building steel, metallic piping systems, conduits, raceways, and metallic equipment enclosures.

Single-point grounding of the above metallic items does not prevent the indicated lightning current from flowing because of the distributed capacitance of the involved items, which completes the current path via stray reactive coupling. In addition, insulation of these items is not always a reliable protection for this problem since the large lightning induced voltages can often arc-over through six-feet of air.

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's 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/μs
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 striking a power line indicates that it initially behaves as a traveling wave and subsequently as a dc source. In cases where the lighting stroke terminates on a tower or lightning terminal, it may be analyzed through circuit analysis.

More information about the magnitudes and effects of lightning surge currents on structures, electrical systems, building wiring, and telecommunications system cables may be obtained by reference to IEEE Std 1100-1999, IEEE Std C62.23-1995, IEEE Std C62.41-1991 (R1995), IEEE Std C62.43-1999, NFPA-780-1997, and IEC/TR 61312-1:1995.

4.1.2 Incidental sources

Since one of the largest potential sources of electrical noise in an electrical generating station is the adjacent high-voltage substation, some of the incidental sources mentioned in the following subclauses originate predominantly in the substation environment. Experience has shown that the electrical noise generated in the power distribution system may reach the generating station I&C systems through the interconnections with the earth grounding system and the I&C cables that run between the substation and the generating station.

4.1.2.1 High-voltage switching

This is the most frequent source of large transients in electric power systems. Opening or closing a set of polyphase contacts (disconnect switch or circuit breaker) to deenergize or energize a section of bus is normally accompanied by arcing between the switch contacts. In addition, on a multipole operator it is virtually impossible to have all three contacts operate in perfect synchronism. As a result, one contact will operate first, a second next, and finally the third. This produces unbalanced switching conditions on the circuit until all three contacts are either fully closed or fully open. The result of this kind of switching is almost always the production of transient damped oscillatory voltage and current disturbances on the distribution path.

The typical transients generated in the above manner are very steep fronted waves near to their point of origination. With distance, these transients are both attenuated and the wavefronts are slowed down by the losses and impedance mismatches of the transmission medium.

The above transients are also capable of being electrostatically (E-Field) or magnetically (H-Field) coupled by near-field action to nearby cables. In far-field fashion they are radiated as an electromagnetic (radio) wave to sensitive systems. 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 µs–16 ms
Duration of string	1 ms–4 s
Decay time	2–4 s
Source impedance	5–200 Ω

4.1.2.2 Capacitor bank switching

Capacitor bank switching can produce severe electrical transients. The transients produced by the direct switching (without the use of pre-charging or pre-insertion resistors) of three-phase capacitor banks consist of two components:

a) Those associated with 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.

b) Those associated with 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. The distributed parameters define the surge or traveling wave impedance of the conductors. These are most severe at points where the electrical distribution wiring is somehow terminated such as at the end of a radial feeder, or at the point of service entry to a building because of the large impedance mismatch. For example, the end of a radial feeder is an open circuit where the reflection from the traveling wave adds to the incoming wave to produce an approximate doubling of the transient voltage. At the building service entry, the impedance mismatch can create reflections that result in an approximate doubling of the transient current. This latter effect also is quite pronounced when a surge protection device goes into operation.

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 initial frequency transition. They also decrease the oscillatory decay (ringing) frequency of the transients since more capacitance is added to the system by their presence. Energy stored in the nearby bank may further contribute to the severity of the transient if its polarity is such that it algebraically adds to that being introduced by the first set of capacitors to be switched.

4.1.2.3 Transmission line switching

Transmission line switching is similar to capacitor bank switching with the difference being the purely distributed nature of the inductance and capacitance of the line. The magnitude of the line-charging current tends to be substantially less than that for power-factor capacitor bank switching, but the system voltages can be very high in comparison and there is a corresponding increase in the amount of energy being rerouted.

4.1.2.4 Coupling capacitor voltage transformer (CCVT)

The measurement of voltages on high-voltage systems must be done by indirect as opposed to direct means such as a resistive voltage divider or typical step-down transformer. In these cases, a CCVT is generally used due to the isolation it provides.

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 are coupled through the capacitors to the signal and control circuits.

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 power ground conductor and the nearby signal cable. Transient potentials of up to 10 kV have been measured in signal cables.

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

4.1.2.5 Gas insulated switchgear (GIS)

Typical GIS equipment often has faster contact operating time than air-insulated equipment and the gas allows the contact's arcs to be more quickly extinguished. This combination of effects produces faster switching transition times, which result in higher frequency disturbances being created than are produced in air-insulated equipment.

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 and are divided and reflected at junctions, but are confined by any open circuit breakers or disconnect switches along the path of propagation. 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 SF_6-to-air terminations, cable potheads (with insulated flanges) and, for some switchgear, current transformers. The SF_6-to-air termination represents by far the largest enclosure discontinuity and hence the largest source of noise voltages in most GIS. This location represents a critical coupling area for control and signal cables.

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 typically lengthy due to the installation height above ground that equipment of this type is often associated with. Therefore, as a result of L(di/dt) effects, they are almost always too inductive to effectively reduce these high-frequency noise voltages. Also, they usually act as efficient radiators or EMI from the corresponding antenna effects when their length is >1/20th of a wavelength at the EMI's fundamental frequency. Two of the best solutions for minimizing electrical noise are to physically distance the sensitive victim instrument and control systems from these areas, and to fully shield the victim equipment and filter all conductors that penetrate the victim equipment's metal enclosures.

4.1.2.6 Vacuum insulated switchgear (VIS)

This equipment is similar to GIS except that the environment for the contacts is a vacuum as opposed to a gas. Therefore, as a result of faster arc extinguishing time during contact bounce or opening, this type of equipment is capable of producing even faster transient voltage and current wavefronts from its operation than equivalent GIS equipment.

4.1.2.7 Earth ground voltage differences

Earth grounding systems that extend over large areas have sufficient point-to-point earth impedance to create a difference in voltage between two points within the system during transient fault events and lightning strike conditions. The conduction of these types of power-system transients through the grounding system is one of the most common causes of large ground potential differences from the related impedance effects. A typical transient represents an ac signal of 1 kHz or greater and the path for the transient current will be parallel to the path of the associated power system conductors.

Earth ground offset voltages may only be minimized by making better connections to the earth when the overall distance between the two points of interest can be viewed under the conditions of circuit analysis. This is generally when the distance is less than 1/20 λ at the frequency of interest. When the distance the current has to travel between points in the earth exceeds 1/20 λ, then transmission and wave theory must be used and there is no practical means to keep all points at or even very near the same potential. Hence, at some critical frequency the earth grounding system cannot be used in any sense as a means of equalizing potentials or minimizing unwanted current flows between points on its surface when they exceed 1/20 λ, no matter how good a connection to earth has been made.

4.1.2.8 Current transformers (CTs)

Saturation of current transformer cores by excessive primary current (dc or ac) can induce very high voltages in the secondary windings and thence onto the conductors attached to them. This phenomenon is repeated for each transition from saturation in one direction to saturation in the other, so it may occur on a cycle-to-cycle basis. AC problems occur simply because of too much primary current for the CT design, while dc problems are typically associated with the effects of lightning. The unwanted transient voltage appearing in the secondary circuit consists of high-magnitude spikes having alternating polarity and persisting for a few milliseconds every half-cycle for the duration of the overcurrent condition.

4.1.2.9 Electro-mechanical equipment

Electro-mechanical equipment and some forms of rotating equipment, such as that containing unshielded windings or fields, centrifugal switches, armature brushes, or slip-rings, contain many possible internal sources of high-frequency interference. These include:

a) Partial (corona) discharges within the stator winding insulation of motors. Note that this can also occur on dry-type transformers.
b) Slot discharges between 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.
f) Centrifugal switch contact operation and arcing.
g) Older types of non metal-enclosed or other inadequately shielded motor-controllers with arcing contacts. These may be of the manual or contactor type. Non-interlocked, manually operated reversing and motor "plugging" types of controls are potential problem sources since they may be operated while the motor is still spinning.
h) Variable frequency or pulse inverter drives. These are also capable of producing both conductive and radiated EMI from the fast transition times associated with SCR, IGBT, or similar motor inverter-driver switching schemes. The largest number of conducted EMI problems involving this type of equipment occur in the range of the first 100 harmonics of the fundamental frequency of the driver circuit.

i) Distributed capacitance. A motor that is being initially energized or in some cases de-energized is capable of coupling a transient current from its winding to its metal frame/enclosure and thence into the associated equipment grounding system for that motor. The coupling mechanism, in this case, is the distributed capacitance from the winding to the case and is proportional to motor size and voltage rating. Large motors operating at medium voltage can produce the greatest EMI effects, particularly since these typically have a large number of associated I&C circuits.

4.1.2.10 Silicon controlled rectifiers (SCRs)

When SCRs are used for switching ac voltage, they generally must have additional circuitry to control the voltage rise time (dv/dt). If the voltage rise time is not controlled, it can even interfere with the operation of the SCR itself. When a pair of SCRs are used for three-phase motor control, an EMI or "noise" condition called "line notching" or "commutation notching" can occur on the voltage waveform as shown in Figure 1.

"Notching" most commonly occurs on polyphase systems and is produced when the SCR is switched-off (commutated) when the current flowing through it falls below the minimum necessary to sustain conduction. On an ac system, the zero-crossing point for the current waveform is the typical point at which this is said to occur. When the load served by a set of SCRs is of the resistive type, the power-factor is unity and both voltage and current are in-phase as applied to the SCRs. However, if there is less than unity power-factor, then there can be a condition where current (lagging) is still flowing in the "on" SCR and voltage (leading) is simultaneously being applied to the "off" SCR. If the "off" SCR has a gate signal present at this time, it will fire and conduct at the same time the "on" SCR is still conducting. Hence, for a brief period at commutation time, both SCRs will be on and fully conducting.

The above unwanted action produces a momentary short-circuit (limited by circuit impedance), which then draws excess current and maximizes any possible voltage drops in the related circuit across its impedances. This action produces the characteristic "notch" on the voltage waveform and a corresponding "spike" on the associated current waveform. The transition times for the notch and spike are typically restricted by the related circuit's time constants (RLC actions). The duration of the notch will typically be dependent upon the amount of phase shift between the voltage and current waveforms (power factor) since this will affect the zero-crossing point for the current on the SCR that is to be gated-off, and for the voltage for the SCR to be gated-on.

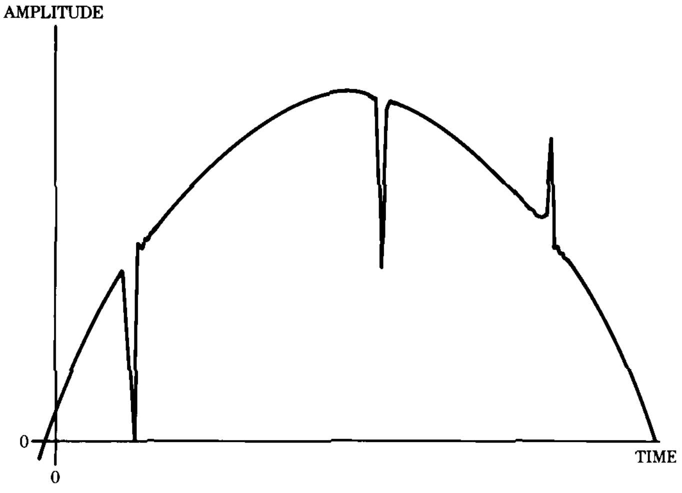


Figure 1—Line-notching waveshape

4.1.2.11 Digital Logic-Based systems (computers, controllers, and related equipment)

The harmonic noise generated by microprocessor and memory boards within an item of equipment such as a computer, is dependent primarily upon its system clock frequency. The highest noise frequency, however, will be a harmonically related function of the rise and fall times of the clock pulse, whichever is faster. For example, a digital signal with a rise time of 3 ns is roughly equivalent to a 100 MHz sine wave.

While the above noise is usually well confined within the properly shielded and filtered equipment's cabinet, which has been compliance tested per the emissions standards of the country of origin, it can escape into the environment by conducted, radiated, or both means if that enclosure is modified or left opened, its power or signal cable port filtering is defeated, or it is penetrated by a foreign, unfiltered conductor of some type such as a field installed signal, power, or grounding conductor. For similar reasons, the various computer subsystems and peripheral devices can contribute significantly to the noise generated by the total computer system, especially via EMI "leakage" from the interconnecting, power, signal, and control connectors and cables. This is especially the case when connectors and cables are field fabricated and have not been formally test certified to be compatible with the original equipment. This is generally not a problem with ac power cables that make connections to factory-provided, field-wiring compartments or associated receptacle/plug style connections that are integral to the compliant equipment.

The major contributing devices to EMI have the following characteristics:

a) *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). Near-field EMI in the form of very low-frequency H-fields up to several tens of kHz from the horizontal yoke itself, are also encountered. This latter condition is a common problem when two or more CRT displays are placed very close to one another and the mutual EMI coupled between them affects the stability of the raster and produces effects such as slowly wavy lines, swimming display, or horizontal bands rolling up or down.

b) *Switching power supply.* The radiated noise generated by these devices is dependent upon the switching frequency (typical 10–100 kHz) and the switching amplitude. These devices also provide large amounts of EMI in the form of conducted harmonic current waveform distortion on the ac power supply wiring up to a few kHz. Most of this conducted EMI will involve odd-ordered harmonics from the ac system's fundamental.

c) *Printers.* The major noise sources for these devices fall into two categories. For impact printers, the EMI is generated from the drivers and collapsing fields of printhead solenoids and the printhead or carriage positioning motors along with the associated internal wiring to and from them. For laser printers, the EMI is generated by the gated SCR or transistor switched power control circuits that are used to control the current for high-intensity drum erasure lamps and the heaters used with toner fuser rolls.

d) *Cabling.* One of the most overlooked sources of radiated EMI 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 their physical orientation (symmetry of twisting or lack thereof), and the type of shielding provided if any. The connectors used at the ends of these cables are also known to be a point of EMI emission if they are not properly shielded and grounded. Crosstalk between different circuits being carried in the same cable is also a common means of EMI propagation on these cables.

4.1.2.12 DC control circuits

One of the major causes of transient overvoltages within a dc control circuit is the energizing of an inductance within a circuit. This induced voltage may be defined as:

$$V = I\frac{L}{C} \tag{1}$$

where

I is the current through the coil,
L is the inductance of the coil,
C is the stray capacitance of the circuit.

The involved inductance may consist of both discrete and distributed circuit elements. The involved capacitance may consist of the distributed wiring or stray capacitance plus any lumped capacitance from connected components. The current of interest is the value of the current at the instant the circuit is deenergized by switching open the power source at any point in the circuit.

EMI impulses in excess of 3 kV can be produced by interrupting the current in highly inductive devices such as a solenoid or a thermal-magnetic circuit breaker's magnetic trip coil. Arcing across the electromechanical contacts will tend to limit the magnitude of the impulses (an increasing air-gap and arc represents increasing impedance). As a general rule and with the exception of lightning-induced impulses, electrostatically or magnetically induced ac voltages or currents from nearby external circuitry and conductors are relatively small in magnitude when compared to the internal inductive impulses induced in dc control circuits on their own wiring.

4.1.2.13 Mechanical vibration

Mechanical vibration and shock can produce arc discharge EMI whenever loose electrical connections are moved or electromechanical switch contacts bounce open or closed 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. Also, many low-voltage circuits can involve the switching of very large amounts of available current. Power supply buses rated at ±5, ±12 Vdc logic and 12, 24, or 48 Vdc control power are commonly rated for several tens of continuous amperes to more than a hundred amperes on larger items of equipment.

Terminal blocks, electrical components with loose connections, or poorly made splices in conductor paths are common points on a wiring system where vibration causes problems to occur. When metallic conduit or other raceway fittings necessary for EMI shielding and equipment ground integrity vibrate loose, they can produce an ineffective shielding connection, an arc discharge that will rapidly change the otherwise stable current flow in the affected path, radiation of high-frequency noise, or combinations of these three problems.

4.1.2.14 Chemical contamination

Most industrial facility atmospheres contain suspended chemicals (such as oil, coolants, or degreasing solutions) that may settle on electrical equipment.

Even though liquid and even gas-tight electrical connections should normally be immune to this method of contamination, vibration and temperature changes may compromise the normally sealed electrical connection. For example, vibration causes normally sealed connections to flex or linearly move in and out of the seal and thereby permit the entrance of chemical contaminants that are riding on the surface of the conductor during its motions. In addition, many electrical connections and their seals are made with mechanically dissimilar materials that have different coefficients of expansion and contraction. Therefore, temperature changes will also cause the conductors passing through the seals in these kinds of connections to both experience changes in the radial clearances and sealing pressure of the seal as well as changes in length, the effects of which can combine and permit contaminants to enter.

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

Any time water or a chemical contaminant can get in between two metal items and especially when they are of dissimilar materials from widely spaced regions on the galvanic series, a semi-conducting joint is created that may also act as a wet-cell battery with a small potential across the joint. Such an unwanted type of joint is created when the contaminant acts as the electrolyte and the two metals assume the role of anode and cathode depending upon where they stand on the galvanic series. By itself, this electrochemical activity becomes a problem is two ways. The first is that the metal may literally be eaten away due to the corrosive action of electrolysis, and the second is that the developed potential may be considered a point-source of EMI.

A third form of EMI problem also exists that may be more of a problem in some cases. In this case, the electrochemical action of the contaminated joint is not usually of concern in the direct creation of the EMI. Instead, it generally takes an externally induced or conducted current to be forced through it in order for the problem to fully emerge. This kind of EMI problem is typically a radiated type (but it can also be conductive on the involved path) and it occurs since the electrochemical joint is a rectifying, semiconducting path. As such, it represents a non-linear impedance to any current flow forced through it. This non-linear impedance creates harmonic current and related voltage waveform distortion of the current's fundamental frequency as it conducts. Thus, a fundamental frequency current passing through such a non-linear conducting joint will suddenly be combined with a number of higher-order, harmonically-related currents, each of which will be both conducted and radiated to whatever degree is possible on the circuit. This is especially a problem when there is a strong source of radio-frequency energy nearby where such a joint can begin unintentionally acting as a part of an antenna circuit. Examples of external sources of exciting current are those created from an intentional radiator such as a transmitter, or from an unintentional one such as nearby arcing contacts, or corona discharge on HV equipment. A natural source of exciting current is nearby lightning.

4.1.2.15 Human interaction via electrostatic discharge (ESD)

The electrostatic discharge (ESD) occurs when an electrostatically charged operator touches and thereby discharges via some part of the victim equipment. For example, external ESD may occur to metallically enclosed equipment, its data or signal cables and connectors, or its exposed controls. This is a known and serious type of EMI problem. Also, a lack of good ESD practices by personnel may cause ESD to occur within victim equipment and directly onto sensitive circuits and components due to careless handling of circuit plug-in cards, connectors, and similar internal components.

While ESD is typically associated with conditions of low relative humidity, the involvement of ESD prone materials (those that are widely spaced on the triboelectric table) as used for clothing articles, shoes, and walking or working surfaces can clearly exacerbate an otherwise harmless problem. Thus, an ESD problem can be experienced over a much wider range of relative humidity conditions than might be expected by a lack of attention to the needed use of ESD resistant materials.

An example of ESD ingress to a victim circuit is shown in Figure 2 where a metallic switch body is mounted on a printed circuit board, but is isolated from the conductive cabinet. The ESD current will create both conducted and radiated noise in the victim equipment as it conductively flows to ground via the printed circuit board's traces and wiring capacitances. Once the ESD current enters the equipment's wiring harness or logic power supply distribution bus system, it is also free to radiate in far-field fashion within the equipment and to near-field couple to adjacent conductors and components. This allows the ESD to produce singular or simultaneous multiple failure symptoms in the equipment, and often over widely spaced areas. Hence, an ESD at one point in the victim equipment may produce its unwanted effects some distance away within the equipment on other circuits.

An ESD that occurs directly to a poorly grounded/bonded metal cabinet's door or side-panel is also a known EMI problem in that the large sheet metal area acts as a plane-wave radiator; therefore, when the ESD strikes the external surface, its wavefront also travels through the thickness of the door or panel and is re-radiated from the inside surface into the enclosure's volume containing the ESD susceptible circuits.

An example of ESD 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.

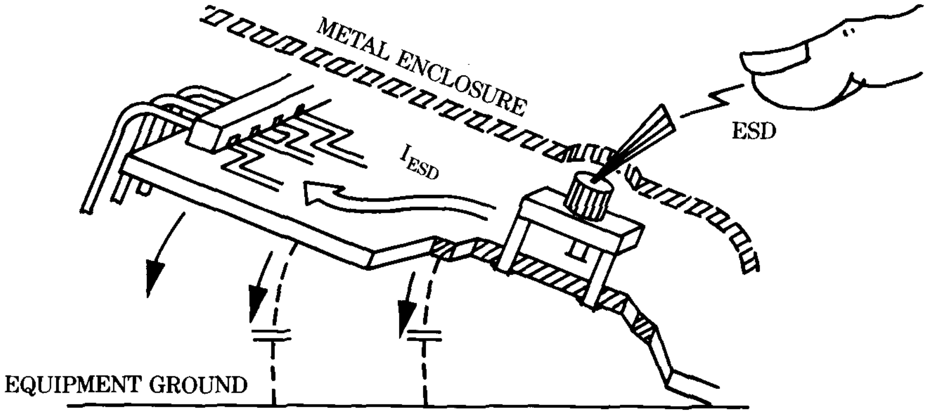


Figure 2—Electrostatic discharge noise generation

4.1.2.16 Cable resonance

Avoiding unwanted resonances in signal and grounding cables from environmental EMI occurring at radio frequencies has become increasingly important. Without proper preventive design measures being taken, signal and grounding cables may become resonant to some frequency of radiated (far-field), coupled (near field), or conducted (galvanic) EMI, and thereby subject the circuits connected to them to unintentionally high currents and/or voltages.

Resonance is related to the LC ratio of the involved conductor and its associated electrical length expressed in terms of wavelength. In general, it is recommended that no conductor be allowed to have an electrical length that exceeds approximately 1/20 λ at the highest frequency of the EMI environment into which it is intended to be operated. This minimizes the effects of EMI on the conductor since it cannot become resonant.

The worst conditions of resonance occur at the first quarter-wave point and succeeding odd-multiples thereof (0.25 λ, 0.75 λ, 1.25 λ, ...). At these points of resonance, the voltage will be maximum at one end of the conductor (with a current minimum), and the current will be maximum at the opposite end of the conductor (with a voltage minimum). As a result, the electrical components and insulation systems are stressed at one end of the path where the voltage is high, and at the opposite end where the peak or rms current carrying ability of the components or conductors is stressed because the current is high. With EMI currents extending into half, full, or multi-cycle durations, the true-rms value of the current is what is of concern, as compared to transients such as lightning and faults where the concern is for the path's current carrying ability and is expressed in terms of I^2t.

Resonances of the first half-wave point and succeeding even-multiples thereof (0.5λ, 1.0λ, 1.5λ, ...) produce essentially identical EMI current and voltage distribution conditions at each end of the affected conductor. The voltage at one end is essentially the same as that at the other end, and the same holds true for the current.

Conductors installed in free-space will have self-resonant points that will normally be somewhat higher in frequency than those installed in close proximity to the earth, or in particular ferrous metal items. This is the result of mutual coupling that exists between the conductor and the earth or ferrous items, and the result is generally that the self-resonant frequency of the conductor is lowered. In addition, depending upon the amount of stray coupling involved, the velocity factor of the path is also generally reduced to values that are less then that of a conductor in free space.

The full-wave, self-resonant frequency of a conductor in free space may be estimated by Equation (2):

$$f = c/l \tag{2}$$

Where c is the speed of propagation in free space, approximately 300 meters per microsecond. Measuring time in microseconds yields a result for f in megahertz.

Equation (2) may be used to approximate the self-resonant conditions of a cable or grounding conductor's path. If the result is divided by 20, the 1/20 λ point may be estimated and used as a recommended limit. Similarly, dividing the result by 4.0 or by 2.0 respectively gives the quarter-wave point and half-wave point estimates. Rearranging the equation allows the estimated length of the conductor to be determined in view of a given amount of EMI frequency.

4.1.2.17 Reflections and traveling waves

Excessively high currents and voltages on EMI affected cables, or grounding conductors may also occur from traveling waves on the path, which encounter a severe impedance mismatch such as an open or shorted-end. In this type of situation, the traveling wave is partially or fully reflected by the impedance mismatch and the reflected portion is instantaneously added to the original wave at the point of reflection. As a result, the current or voltage at such a point may easily be doubled.

In the case of an open-end termination such as at the end of an overhead radial distribution feeder, the impedance is very high (open circuit), so the reflection occurs on the voltage waveform and not the current waveform. There is no current flow in the open circuit, but a very high potential may be created. In the case of a short-circuit termination such as where a surge-arrester is applied on the end of an overhead radial distribution feeder, the impedance is very low (it approaches a short-circuit condition in respect to the traveling wave), so the reflection occurs on the current waveform and not on the voltage waveform. There is little voltage developed across a "short circuit."

EMI conditions at or near the shorted or open-end termination for a traveling wave can be very severe. For example, near-field conditions are worst for H-fields nearest the shorted-termination (highest current, lowest voltage) while E-field conditions are similarly serious nearest the open-termination (highest voltage, lowest current). Radiation of far-field EMI can occur all along the conductor's path once it is subjected to EMI, which forms a traveling wave on it. Hence, unwanted EMI effects are unavoidable under these kinds of conditions if there are any victim power, signal, grounding, or other conductors located near the conductor carrying the traveling wave.

4.1.2.17.1 Velocity factor

Traveling waves move through a conductive medium (such as a wire) at a velocity that may be considerably less than that for the radiated wave in free space or air. The free space velocity factor of 1.0x is approximately 299 m/s for a radiated wave. Velocity factors less than 1.0x always occur when a wave travels through a physical medium such as a wire, and this affects calculations regarding how long a conductor may be in relation to conditions of actual self-resonance vs. equivalent free space electrical length.

For example, the leading edge (first transition) of a radiated wave will travel 30 m in free space during one cycle of a 10 MHz clock signal in a microprocessor. However, within an insulated conductor in a cable, it may travel only 21 m due to a reduced velocity factor, which, in this case, would be 0.7x (21m/30m = 0.7). If the voltage wave reflects from the cable termination where the cable has been terminated "open" or at least in a very high impedance in comparison to the signal cable's characteristic impedance, and is in phase with a new wave, resonance will occur and line oscillations will be greatly magnified. Also, if one end of the circuit is grounded, the first resonance at 10 MHz occurs when the conductor is only 5.25 m or 1/4 wavelength long.

At this frequency, the 5.25 m long cable appears to be virtually an open circuit between ends or at least a very high impedance. It is incapable of equalizing the voltages appearing between its ends. A cable or grounding conductor, longer than 1/20 λ cannot be counted upon to adequately equalize voltages between its ends. This amounts to only 1.5 m of length at 10 MHz, so it should become apparent that the use of long grounding/bonding conductors in a facility that is a part of a "single-point" or similar grounding system will not be effective for high-frequency EMI.

At high frequencies, signal transmission lines are often terminated in their characteristic surge impedance to eliminate most of the reflection and resonance. However, no single-grounded conductor within a cable can provide a virtual short circuit between one end and the other over a very useful portion of a broad frequency range, and not at all once 1/4 λ conditions and odd-multiples thereof, are approached.

4.1.2.18 Power circuit inrush current

Small conductors on higher impedance circuits carrying small amounts of current cannot induce significant transient voltages and currents into larger power conductors on low-impedance circuits. This is the result of the relative impedance of the respective circuits and limits on how fast a large current change can be impressed onto the path. However, the reverse situation is of major concern. Where I&C circuits are placed nearby to power conductors, the likelihood of transient voltages and currents being coupled to the instrumentation and control circuits is very high.

The transients produced by the unwanted near-field coupling can electromagnetically induce voltages that create current transients in the I&C circuits installed near these power cables. This can occur when the power circuit is energized and acts as a primary winding for an air-core transformer with the nearby I&C circuit act as the secondary winding.

4.1.2.19 Other incidental sources

Noise can also be generated by such sources such as transformer and motor inrush currents, load tap-changing, flashover of gaps from overvoltages, ferroresonance, impulse testing, megger testing, low-voltage breaker 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.

Local incidental sources of EMI may also occur as a result of electrostatic filters in HVAC systems, ozone generators used with water purification systems, neon signs, and "bug-zappers." Unfiltered SCR circuits used to phase-control incandescent lighting systems also generate EMI in both radiated and conducted form. High- and low-pressure sodium lighting fixtures contain arcs and can produce EMI if they are not shielded. This also applies to mercury vapor lighting fixtures. Both forms of lighting fixtures may radiate high-frequency EMI unless shielded, and both will conduct low-frequency EMI back onto the ac power system in the form of harmonic current and voltage waveform distortion unless harmonic filtering is provided at the fixture to prevent this.

Electric arc welders also create EMI at the arc, and both conduct it onto the connected ac power system and radiate it into the environment by the loop-antenna (far field) and transformer primary effects (near-field) that the welding cables can create if they are used without tightly twisting them together. Voltages used in the arc-welding process are fairly low, while peak and rms currents may be quite high. Hence, E-field EMI is not as much a problem as is H-field EMI.

4.1.3 Intentional sources

Many devices intentionally use radio frequency (RF) energy to accomplish their function, such as hand-held transceivers (cellular telephones, broadcast transmitters, security guard transceivers, citizen's band radios), RF-stabilized arc welders, induction heaters and RF electrostatic drying equipment. These devices produce considerable amounts of RF energy, which generally is not contained and can therefore reach I&C equipment.

Proximity effects can easily offset the fact that a radiating source of EMI is otherwise "low-power." For example, an 800 MHz cellular phone does not radiate much peak power by itself, but if brought into close proximity to victim circuits such as those within an electronic equipment cabinet with the door open, considerable EMI can be coupled into these circuits. Unlike most two-way radio equipment, cellular telephones radiate even when they are not in actual two-way use by their operator since they must periodically notify the cellular site's computer that they are on and where they are so that incoming calls may be received.

4.2 Noise-coupling methods

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

a) Conductive (common impedance, galvanic, arcing, or direct contact)
b) Capacitive (electric)
c) Inductive (magnetic)
d) Radiation (electromagnetic)

Both capacitive and inductive coupling refer primarily to near-field coupling. This is also often referred to as the reactive field where the energy is stored or as stray (parasitic) reactive 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 l/6 λ of the highest source frequency. Radiation coupling refers to circuits located in the far field of a source where the source's emissions are seen as a true traveling electromagnetic wave. This latter situation involves radio wave transmissions and antennae effects.

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

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 ohms is defined as the ratio of the E-field intensity expressed in V/m to the H-field intensity expressed in A/m. In the reactive or near field, where the energy is stored, the E-field and H-field can be considered independently where the wave impedance does not apply.

E-fields are generated by and most easily interact with high-impedance, voltage-driven circuitry, such as a straight wire or dipole. E-fields are most readily coupled by capacitor action. H-fields are generated by and most readily interact with low-impedance, current-driven circuitry, such as a wire loop. H-fields are most readily coupled by transformer action.

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 (free space) is 377 Ω.

4.2.2 Common impedance coupling

Conductive coupling is also known as common impedance coupling, and can be created by galvanic action or an arc. As shown in Figure 3, when two or more circuits share a wire or conductor as a common section of their signal paths, common impedance coupling is a possible noise source. The point of common impedance may be undesirable for grounding purposes (ground loop problem) or may be undesirable because of leakage conductance between circuits. Current in one circuit can then cause a noise voltage to appear in another circuit as a result of voltage drop or Ldi/dt effects. The level of interference is dependent upon the magnitude of the common impedance and the interfering current. The most common occurrence of this coupling is when two circuits share a common return, such as the ground plane on a PC board or the signal common bus between two PC boards. The illustration is that of a voltage or current divider with the victim circuit being tapped across the impedance, which has current flow in it from the aggressor circuit.

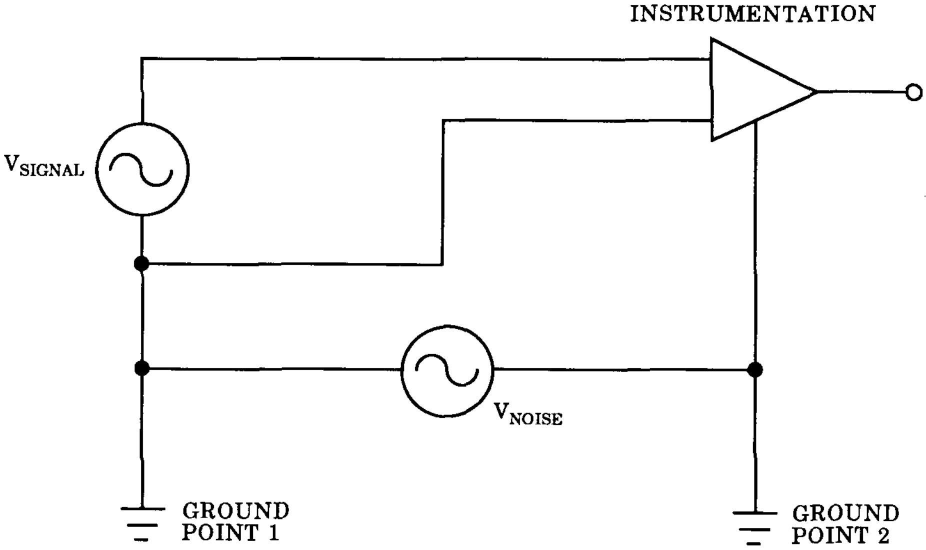


Figure 3—Example of common impedance coupling (ground loop)

4.2.3 Capacitive coupling (electric)

This type of coupling is also known as capacitive coupling. As shown in Figure 4, every portion of an electric system has stray or parasitic capacitance between it and every other portion. Any voltage change, regardless of location, tends to drive a current through these capacitances and produce an equivalent noise current in the victim circuit according to Equation (3):

$$I = C\, de/dt \tag{3}$$

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.

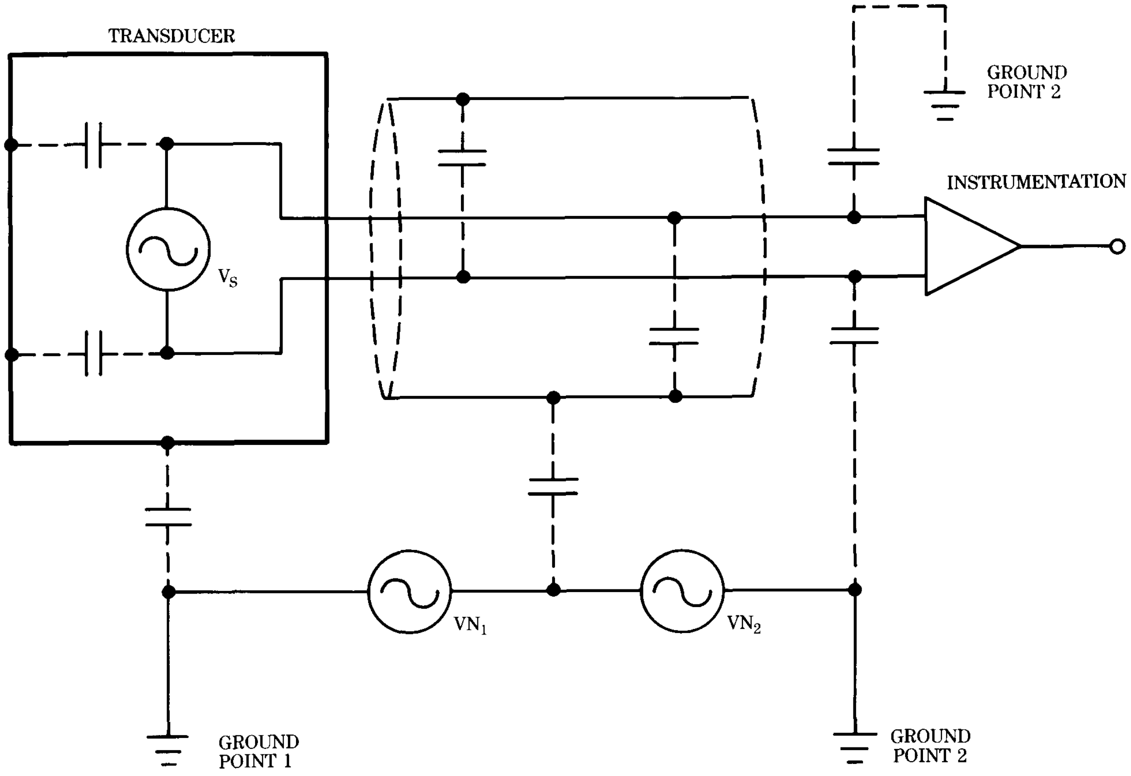


Figure 4—Example of capacitive coupling

For capacitive coupling, the coupling exponentially decreases as the distance between the conductors increases. In the very near field, the coupling varies by the cube and then quickly begins varying by classical square-law. High-impedance circuits are more susceptible to capacitively coupled noise as they are predominately voltage sensitive.

As a result of the higher impedance nature of capacitively coupled circuitry, not much rms current can be sustained over the coupled path. Loading such a circuit quickly collapses its EMI signal.

4.2.4 Inductive coupling

This type of coupling is also known as magnetic coupling. The various circuits of any system ultimately exist as closed loops. These loops have mutual inductances that are directly proportional to the area enclosed by the loops as shown in Figure 5. Interaction between the loops is essentially a transformer action between the aggressor interference source and the sensitive victim circuit. Even dc circuits produce a strongly changing magnetic field when their current is interrupted.

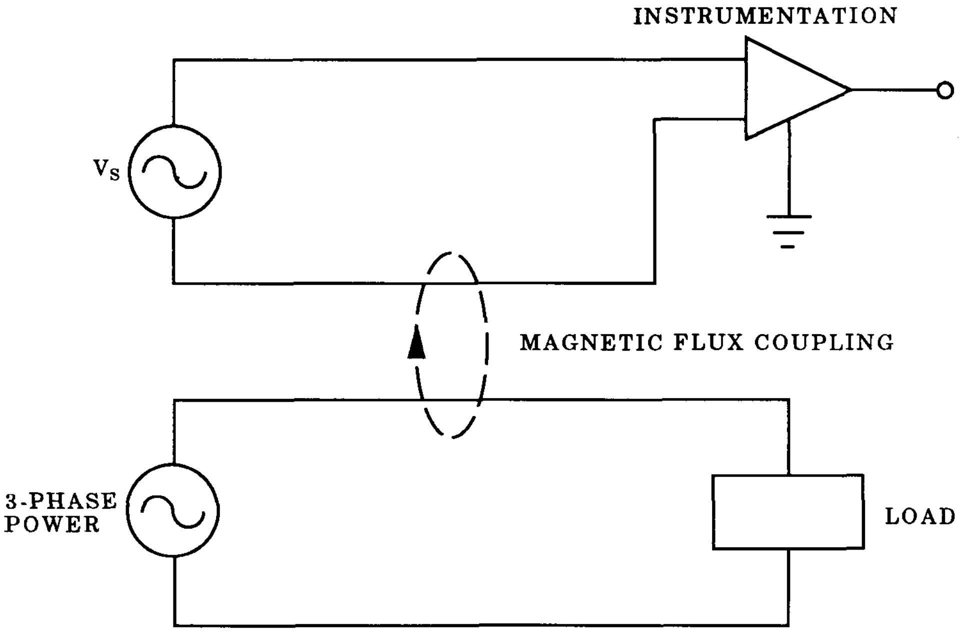


Figure 5—Example of inductive coupling

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 Equation (4):

$$E = M\, di/dt \tag{4}$$

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.

Coupling varies according to the cube in the very near field, and then quickly follows classical square-law thereafter.

Both capacitive and inductive coupling are functions of the time derivative or rate of change of the source field ($d\phi/dt$). Therefore, the interference coupling factor for a fixed coupling loop geometry increases with the higher frequency content of the transient current in the aggressor loop.

4.2.5 Radiation coupling

This type of coupling is also known as electromagnetic or radio wave coupling. High-frequency signals produced by an external source may transfer a significant amount of energy to the control circuit by radiation of an electromagnetic wave and coupling through unintentional antennas. Even though the interference frequencies may be much higher than those to which the control circuit will normally respond, they can become troublesome if they are modulated at the source by switching or by the ac power frequency or its harmonics and then picked up and non-linearly demodulated or rectified by the control circuit. This process of pickup and demodulation can produce additional harmonically related spurious signals in the victim instrument or control circuit. This circuit may then become a local re-radiation source of the EMI at the fundamental or harmonically-related frequency from antenna effects of the victim circuit's wiring.

4.2.6 Interference modes

4.2.6.1 Common-mode interference

This type of interference is also known as longitudinal-mode interference. It is simultaneously introduced into all of the conductors of the signal path, including its grounding conductor if it has one. As a result of the simultaneous nature of the introduction of the CM interference, little, if any, potential difference may be seen between the victim conductors. Instead, significant potential differences are generally seen to exist between all of the victim conductors and the circuits and ground reference for the circuit the victim conductors are terminated. This is illustrated by Figure 6.

CM currents are most commonly caused by equal electrical pickup in a pair of conductors, and in paths of equal impedance will be essentially equal. If the CM current's affected paths are of differing impedance, then the CM current will be inversely proportional to the impedance presented by each victim conductor path forming the loop.

CM interference acts indirectly on the victim receiver. Therefore, a signal error must be preceded by a conversion from common-mode interference to differential-mode (DM) interference. A purely CM surge between separate grounds as shown in Figure 6 will be almost completely rejected by a well-balanced, differential amplifier. Connecting one side of the differential amplifier to ground will produce a differential-mode surge. Transformer coupling without using carefully balanced, center-tapped windings referenced to signal ground will produce DM interference by the CM to DM conversion that takes place as a result of the winding's geometry.

Mismatched impedances of passive components (resistors, capacitors, and inductors) used in the transmission of balanced signals through circuits also contribute to the conversion of CM to DM current or voltage in the victim circuit.

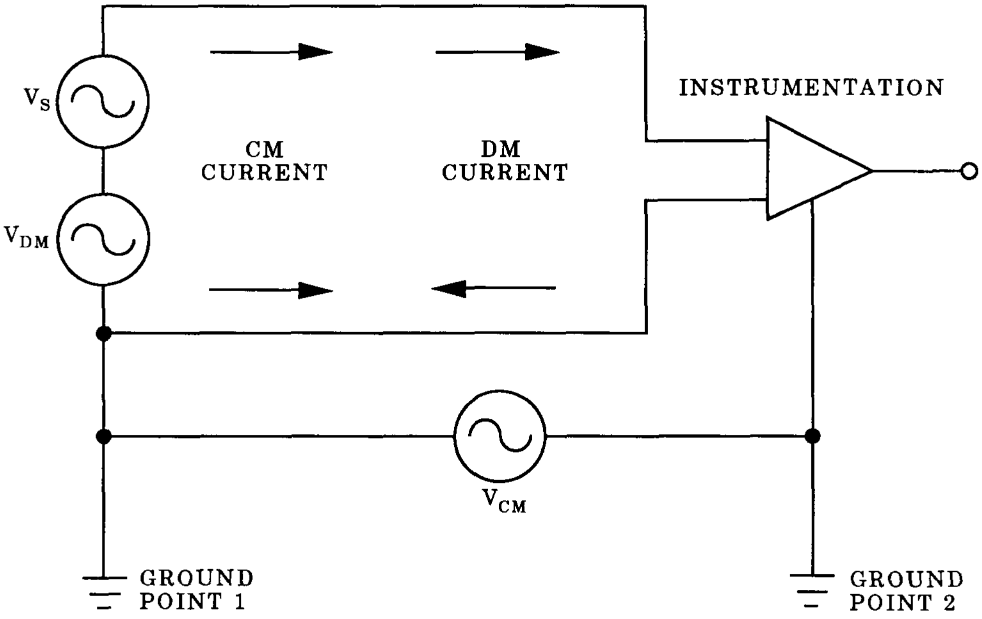


Figure 6—Example of common and differential-mode interference

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.

CM transients are more likely to cause dielectric failure to ground than differential-mode transients. Both types of transients, however, can damage both passive (resistors, capacitors, inductors, etc.) and active components (transistors, integrated circuits) as all have breakdown voltage limits to ground or can be damaged by the effects of excess CM current passing through the component (I^2t effects)

4.2.6.2 Differential-mode (DM) interference

This type of interference is also known as normal or transverse interference. Differential-mode interference looks like a valid signal and can be induced into the signal channel through the same path as the legitimate signal (see Figure 6), where it usually algebraically combines with the desired signal thus producing a composite, corrupted signal. The interfering DM signal can be produced by the conversion of CM current to DM as discussed in 4.2.6.1. The full magnitude of the interference is directly coupled to the victim system using the same paths, mechanisms, and components as are used by the desired signal.

DM interference will often have frequency characteristics that usefully differentiate it from the desired signal. This can sometimes be used to advantage to attenuate it. One example of this is when the DM interference occurs at a frequency widely separated from that of the desired signal. In this case, appropriate filtering can be very effective. If the DM interference occurs too closely to that of the desired signal, the use of a filter would unintentionally affect the desired signal.

In a two-wire system, the normal signal current (DM) in each wire is usually of equal amplitude and opposite in phase. The differential-mode interference current is also equal and opposite, but may have any phase, amplitude, or waveform shape difference.

DM interference is principally conducted on power or signal paths and is typically the result of changes in loading on the affected set of conductors from the effects of multiple, varying or switched loads acting on the commonly shared path impedance that produce IZ drop conditions of rms, instantaneous, or both types.

Whether a CM or DM interference produces greater numbers of problems on a signal circuit is strictly dependent upon the design of the victim circuit; its state at the time of occurrence of the interference; and the amplitude, duration, and rate of change of the CM or DM interference current or voltage.

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 from a combination of both inductive and capacitive coupling, which is termed crosstalk. Both of these coupling methods are directly proportional to the frequency of the signal and the effects vary according to the twist, physical lay, geometry, and symmetry of the conductors involved. The effectiveness of the shielding between adjacent signal conductors also affects crosstalk.

Increasing the amount of impedance in the crosstalk affected paths proportionally increases the effects of the unwanted capacitive coupling existing between them. For inductive coupling, the opposite is true where increasing the impedance inversely decreases the unwanted inductive coupling between them.

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, or to slow down their rate of current or voltage change.

4.3.1.1 Suppression of noise generated by solenoid, relay, or contactor coils

Placing a diode in parallel with a coil is the simplest method of suppression in a dc circuit. This provides a low impedance path in parallel with the circuit stray capacitance and prevents voltage buildup from the energy in the collapsing field of the coil. The diode is back-biased during normal operation and acts as a near short-circuit to the “inductive kick” produced by the collapsing magnetic field of the de-energized inductance. The diode, however, has the disadvantages of:

1) Switch-off delay.
2) Diode failure may short circuit the device.
3) Overvoltage in the reverse direction (possibly caused by spikes from unsuppressed loads) can destroy the diode.
4) Oscillatory, decaying (ringing) transient production on the circuit.

The diode should be properly chosen to have high-reverse overvoltage current characteristics matched to the protected coil current. The 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. It also lowers the “Q” of the LCR circuit and thus reduces the “ringing” when the associated device is de-energized. This technique is illustrated in Figure 7. Variations of this technique can be used with a resistor, capacitor, or resistor plus capacitor (snubber) to suppress the inductive kick on both ac and dc circuits. All have to be properly selected to minimize changes to the characteristics of the overall circuit. An alternative technique can be used to clamp the inductive spike to a fixed level using a metal oxide varistor or back to back zener diodes or Tranzorbs for both ac and dc circuits. These latter techniques will still let through spikes up to the clamping level of the device.

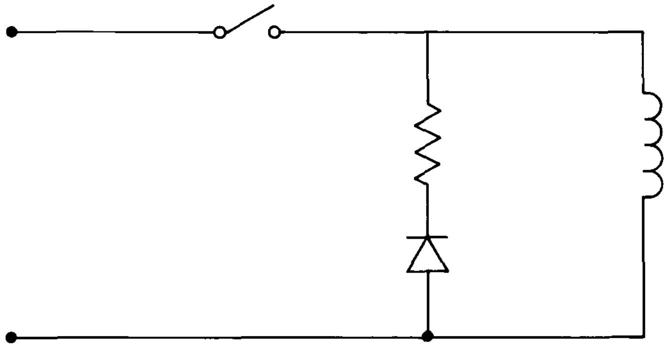


Figure 7—Suppression with a diode and series resistance

Generally the best place to apply this protection is directly across the coil. If the leads to the coil are long, it may be necessary to place additional protection across the initiating contact since the cable inductance could still cause voltage spikes. R-C snubbers are frequently used across switch contacts for this purpose.

4.3.1.2 Suppression of SCRs, dc motor or generator brushes, and alternator slip-rings

Small value capacitors are used to attenuate unwanted high frequencies generated by these devices. This occurs as they represent very low values of reactance at these frequencies when they are applied in parallel to the EMI source. They must also be selected to present a very high reactance to the signal frequencies found on the circuit in order to avoid having the suppression circuit unintentionally affect these desired frequencies. This may be a problem if the frequency of the desired current or voltage is higher than that of the EMI that is to be attenuated.

The suppression capacitors must be placed as close to the interference source as possible to prevent the creation of and emission of RF interference from the intervening inductive wire leads so as to not produce further unwanted EMI from the LC resonant conditions produced by the suppression circuit's own wiring loop.

4.3.1.3 Suppression of input signal noise

It is quite common to place suitable filtering circuits directly onto electronic circuit boards to provide them with an inherent transient immunity. This is not always advisable since it is generally too late to try and effectively attenuate higher levels of EMI at board-level since the EMI is already onto the board's wiring traces and its fields are therefore in close proximity to the circuits on the board that are desired to be protected. Component and PC board trace layout are extremely critical if this approach is to be effective due to the combination of circuit and component density, nearness and quantity of PC wiring traces, and the known effects of near-field coupling under these conditions.

If EMI filtering at board level proves to be inadequate, then it is necessary to provide additional external filtering. R-C and LC filters, zener diodes, Tranzorbs, MOVs, or other non-linear clamping devices such as gas-tubes, and even SCR crowbar clamps can be used as required, but it is necessary to keep lead lengths on these circuits to an absolute minimum so as to prevent these same items from being able to couple back into the same or other PC boards. This latter concern exists since many surge protective devices can operate with very fast di/dt conditions and can generate strong local H-fields near them and their leads.

Cascaded transient or surge protection schemes are a recommended practice. This is where higher level EMI or transient energy is controlled nearest to its point of production or at the point of introduction into an item of equipment, then an intermediate point is similarly protected, but at lower EMI energy. The final attenuation then occurs at the lowest EMI conditions right at the circuit board to be protected. The idea is to handle the largest EMI currents and voltages at the greatest distance from the circuit that can be affected by the EMI, and to handle the clean-up of low-level EMI at board level. This is an important concept and has the greatest practical application when lightning currents or other high-energy level switching transients are involved.

4.3.2 Positioning and isolating control cables

4.3.2.1 Cable routing

The physical arrangement of the I&C cables is an important factor affecting the creation of electrical noise. Techniques for minimizing noise pickup in control circuits include:

a) *Radial routing of I&C cable.* Circuits should not be looped with a single conductor from one piece of equipment to another with the return conductor in another cable. Both supply and return conductors should be in a common cable to minimize loop area and avoid the large magnetic induction possible using separately routed single conductors. 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.

   Any grounding leads associated with any circuit must also be tightly routed with the circuit conductors and also must be carried inside of the same shield, conduit, or other raceway with the associated circuit conductors. This is necessary to keep the impedance of these circuits as low as possible by permitting close interaction of the opposing magnetic fields occurring on them.

   If the supply and return signal lines are discrete wires (as opposed to being part of a factory produced multi-conductor cable), they should be laid as close to each other as possible within the same raceway to minimize the loop area and reduce susceptibility to interference from inductive coupling. The greatest practical amount of symmetrical twisting per unit of length of all signal supply and return conductors along with any dedicated grounding conductor, is desirable. Twisting of conductors during installation must be commensurate with avoiding damage to the conductor's insulation. On power circuits, such tight twisting is not normally feasible, however, the most practical twisting should be applied.

   Do not twist a number of otherwise untwisted pairs of wires going to different circuits together as they can create unwanted crosstalk and a higher impedance for the DM currents in any related pair of signal conductors in such a bundle. However, gently twisting together already twisted signal pairs to form a larger cable is generally advisable if done carefully. There are established rules for doing this such as those promulgated by telecommunications companies, and these rules should be followed. Approximately 1 turn/meter is a generally useful amount of twist to use on multi-pair cables and on power wiring.

b) *Orient the I&C cables at right angles to any conductor that is likely to carry an unbalanced current.* This also applies to conductors that carry a balanced current flow but where one conductor is spaced away from its supply or return path conductors. This mostly applies to separated power bus-bars or any grounding conductors not routed with their associated circuit conductors. Examples of the latter are lightning down and air-terminal conductors, grounding electrode conductors, ac system grounding conductors, and grounding/bonding jumpers. Building steel, metal HVAC ducting, and plumbing or piping systems can also fall into this category. It is often not possible to route the I&C cables at right angles to all items such as this for practical reasons, so the concept of increased spacing to reduce coupling may also be required on the same circuit.

c) *Locate the control room in a centralized location so as to minimize I&C cable runs, or locate it away from areas likely to produce large amounts of EMI and unwanted near-field conditions to the cables used to interface the control room to its external equipment.*

d) *Provide maximum separation between power and control wiring when it is not suitably shielded for operation with close spacing to aggressor circuits.*

e) *Wherever possible, both power and signal types of circuits should be routed close to (right on the surface of) any associated metal parts of an equipment cabinet or other form of cable transport ground plane such as a solid-bottom cable tray, wireway, or other form of signal reference ground grid or plane.* The use of signal transport ground planes, signal reference grids or planes, is a recommended practice wherever they can be used.

f) *Avoid inadvertent loops when routing I&C cables.* For example, do not coil excess cable into a loop instead of cutting it to the exact length needed to make the termination connection. This is a common practice that is well known to cause coupling problems to and from such loops that form single and multi-turn transformer windings. Folding (as opposed to coiling) excess cable back and forth and then tying it in place is a possible way to reduce this effect and to allow excess cable to be dealt with. However, this is not always a good nor a practical solution.

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 IEEE Std 422-1986, and is a clear requirement if all the conductors in the same bundle, conduit, or raceway are not equipped with an insulation system whose rating is equal to or exceeds that of the worst-case example in the same arrangement.

For example, low-energy analog signals should not be run in the same cable as higher energy control signals or with ac power circuits. Similarly, dc battery and ac control power circuits should not be placed into the same cable, conduit, or other raceway, and neither type of circuit should be routed with ac power conductors.

In addition, after segregating cables by voltage level, they may also be separated within these voltage level groups according to function. 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, ferrous barrier to reduce both the capacitive and inductive coupling between the cables. Many types of cable trays and raceways are available from their manufacturers with shielding barriers that can be used for this purpose. Care must be taken during installation to ensure that the desired separation is not compromised. Figure 8 illustrates how rapidly the capacitive coupling is reduced by increasing physical separation.

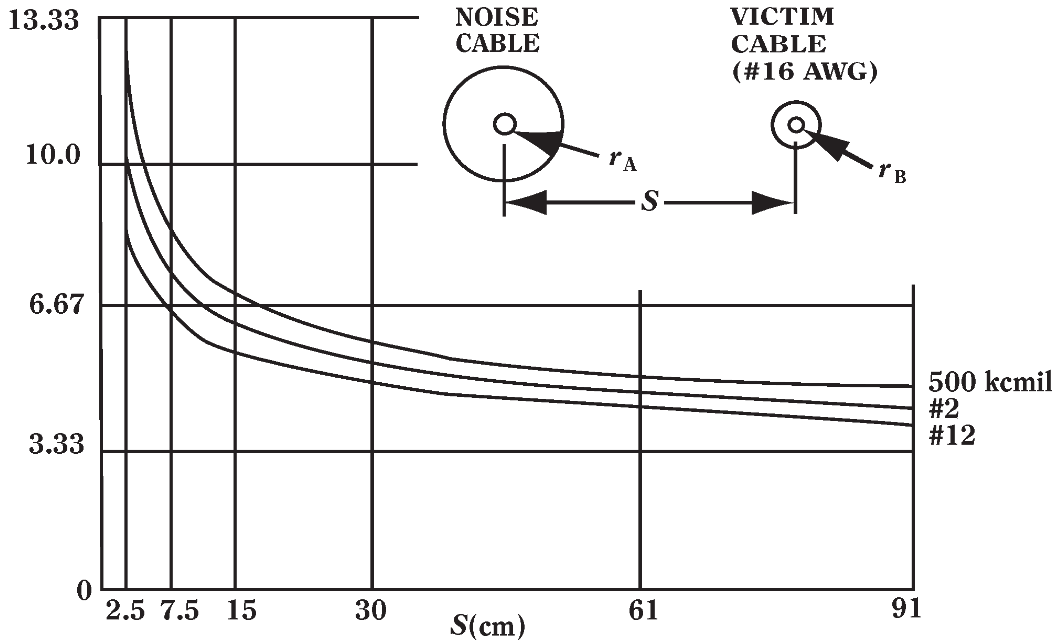


Figure 8—Capacitance vs. conductor separation

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 aggressor source is a low- or high-frequency field, and if it is a near or far-field situation. For cables, a shield may take such forms as enclosing metallic conduit, a cable tray or signal transport ground plane, an overall copper braid, copper tape or aluminized mylar. For components, a shield could be any six-sided, 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 the same reference voltage as the circuit signal common. This is generally done by connecting the shield material to signal common ground. Electrostatic shielding can improve the noise rejection of a high impedance circuit by factors of 100 to 100 000 (–40 dB to –100 dB).

To prevent a very low-frequency or dc magnetic field from reaching the victim conductors or other components, the shield must warp the aggressor magnetic flux lines away from the victim items so that they are not penetrated by them. To shield against dc and extremely low-frequency magnetic fields, the external interfering magnetic flux must be completely or nearly completely diverted from the shielded volume by the shielding material.

To be an effective very low-frequency magnetic shield that diverts magnetic flux, the shielding material must have a low reluctance. Reluctance is inversely proportional to the permeability and the cross-sectional area of the shield. Therefore, to be effective, a very low-frequency magnetic shield must have a high permeability and a large cross-sectional area. This means that very thick walls will be needed in the case of conduits, boxes, and similar forms of shielding. It also means that the material used will need to be specially selected and, for best performance, it cannot be common steel or soft iron. Mu metal is one example of a special material that is used in this application, and special grades of silicon steel may be effective.

Since the permeability of a magnetic material is not constant but depends on the flux density in the shield material, the magnetic flux density must be known in order to estimate the effectiveness of the shield used to warp the magnetic field away from the victim conductors contained within its enclosed volume. If the magnetic flux density is so high that the magnetic shield becomes saturated, then the shield will not be effective above the saturation point.

Effective very low-frequency magnetic field shielding is much more difficult to obtain than electrostatic shielding. For example, the effective magnetic shielding provided by enclosing a 60 Hz power cable in rigid, galvanized, steel conduit may only be a factor of 10 to 100 (–20 dB to –40 dB) for interfering frequencies below 1 kHz. As the noise frequency increases, the effective shielding will increase.

The use of a shield to attenuate H-field interference (a near-field phenomena) on victim conductors in a cable or similar circuit depends upon the shield operating in a fashion other than warping the magnetic flux away from the victim conductors or other component to be protected. In this second case, the magnetic flux lines are allowed to penetrate the enclosing shield and to reach into the victim conductors without much (if any) attenuation. This is achieved by grounding the shield at both ends, with the signal conductors contained inside the shield ground referenced to the same ground point as the shield at each end. The shield will then carry an induced current from the aggressor H-field, and the contained victim conductors will also carry an induced current from the aggressor H-field, with all of the induced currents being 180° out of phase with the aggressor current. Since the impedance of the shield’s closed loop (it is a larger mass of metal that is also grounded at both ends) is much lower than that of the signal conductors contained within (they are smaller and feed into circuitry), this allows more induced current flow to occur in the shield than in the signal conductors contained therein, so the shield’s current also develops its own magnetic field proportional to the current flowing in it, and this is also closely coupled (it is an H-field) to the victim signal conductors along with the originally induced current from the aggressor source. Therefore, the shield’s magnetic field now induces its own current into the victim conductors with another 180° phase, thereby producing two current flows in the victim conductors that are out-of-phase with one another. These two induced currents cancel each other out in the victim conductors, and what is left is the greatly attenuated “noise” on the victim circuit, which cannot be removed without involving efforts with a diminishing rate of return for expended effort.

Note that the foregoing shielding effects are independent of the permeability or reluctance of the material selected for the shield, but do depend upon its conductivity and surface area when skin-effect comes into play in the higher frequency ranges. If there are concerns about grounding the shield at both ends because of low-frequency “ground loop,” then these will need to be addressed by the use of other methods. If there is no shield current induced by the aggressor H-field, then the shield cannot attenuate the EMI being induced into the contained victim conductors. Also, twisting the victim conductors does not affect this situation since the problem is one of induced CM current from the aggressor H-field and not a DM one.

Far-field shielding takes place by a different mechanism. When a high-frequency electromagnetic field impinges on a conductive shield, most of the electromagnetic wave is reflected by the shield material by impedance mismatch. A small portion of the wave is transmitted through the shield material and this is further attenuated as it travels through the thickness of the shield material. Thus, the field incident on the shielded circuit, component or system is lower than the incident electromagnetic field. A highly conductive material such as copper or aluminum, that is sufficiently strong enough to support itself, and encloses an entire circuit, will reduce interference from electromagnetic waves by factors of 10 000 to 1 000 000 (–80 dB to –120 dB).

4.3.3.1 Electronic equipment shielding

Almost any metal cabinet is valued for electric field shielding because it bi-directionally helps prevent the coupling of any electric fields in or out of the cabinet. The steel cabinet is valued for additional bi-directional shielding from magnetic fields that may be generated in adjacent cabinets, or from within the subject cabinet itself.

For both the electric field and magnetic field shielding, cabinet openings or discontinuities may degrade the overall performance, but seldom do they *significantly* alter the shielding performance. However, for electromagnetic wave shielding, it must be remembered that the shield must *totally* enclose the protected circuit. In this case, the need for normal cabinet discontinuities, such as seams, cable penetrations, and apertures may significantly affect the shielding integrity of the cabinet and provide the possibility of electromagnetic coupling both in and out of the cabinet.

The efficiency of the electromagnetic wave 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 $\lambda/20$ will permit electromagnetic energy to pass freely through the opening. 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. For a frequency of 100 MHz, the maximum dimension for a hole will be 0.15 m. For a frequency of 10 MHz, the maximum dimension will be 1.5 m.

Any opening or seam without suitable EMI gasketing or special flange design that promotes capacitive coupling effects, and that is $1/2\ \lambda$ or larger at the EMI's frequency will allow maximum coupling of the EMI in or out of the shielded enclosure. Note that the sides of typical door openings on rack-type cabinets may therefore represent vertically polarized slot-antennae with dimensions approaching two meters in some cases. Therefore, the tops and bottoms of these same doors may also represent similar horizontally polarized slot-antennae with dimensions approaching one meter. A rack or other cabinet in which the door is left open during operation represents a virtually unshielded volume.

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

a) Keeping the longest dimension of apertures in cabinets less than $\lambda/20$. Openings larger than this will require additional protective measures.

b) Where cable must penetrate the cabinet through a hole, shielding can be accomplished by making the hole operate as a waveguide operating beyond cutoff frequency. This can be done by connecting a conductive tube 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 tube should be at least four times the width of the tube.

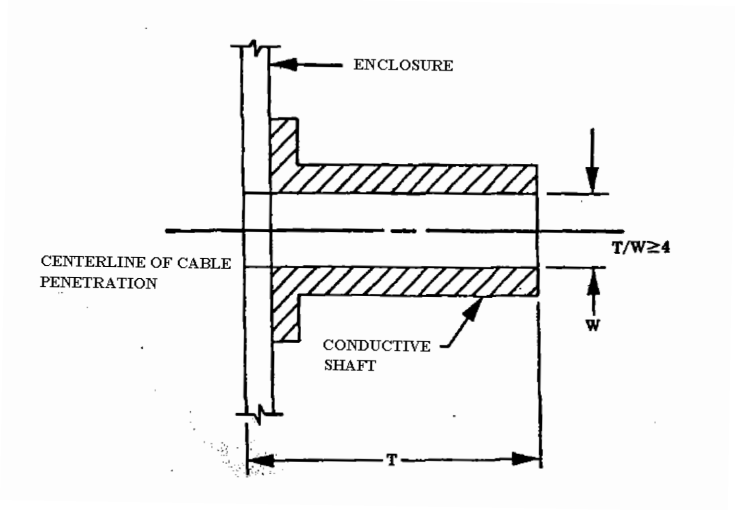


Figure 9—Waveguide beyond cutoff frequency

c) 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.

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

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, but only for cables longer than one wavelength at the interfering frequency.

At high frequencies or for electromagnetic waves, the cable shield should be thought of as a barrier element that connects the barriers formed by the cabinets containing the control circuits as illustrated by Figure 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 as shown by Figure 11.

At low frequencies or for the electric field shielding, the individually shielded conductors or conductor pairs should have their shields connected to ground at the point of maximum capacitance in order to reduce the possibility of a ground loop forming through the capacitance. A low-inductance designed grounding strap or jumper is used to short-out this capacitance. The point of highest capacitance is often the signal source.

Cable shield grounding practices are discussed in Clause 6.

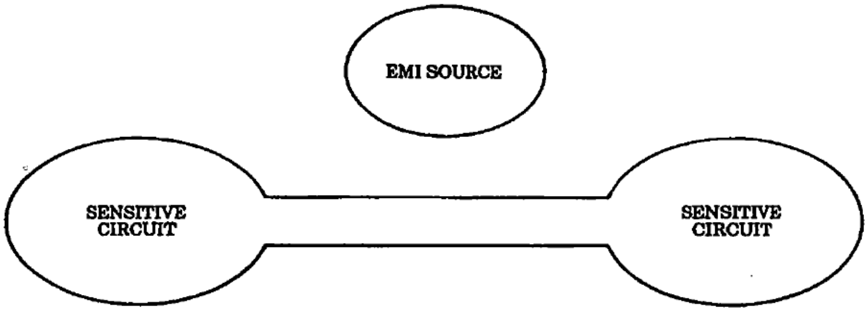


Figure 10—Diagram of a closed EMI barrier

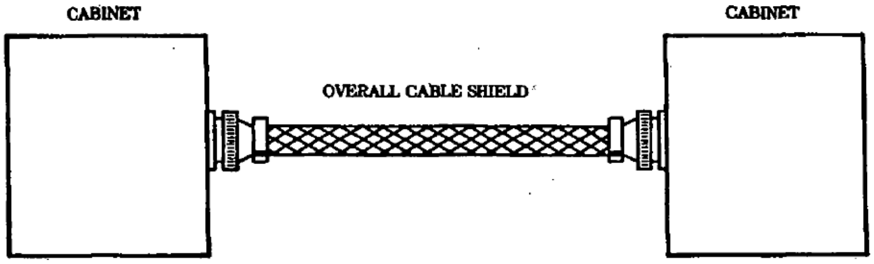


Figure 11—Realization of Figure 10

4.3.4 Grounding

Although grounding is not always required for a shield to be effective, it can become the critical element in determining the effectiveness of certain types of shields such as those for I&C cables. Clause 5 and Clause 6 discuss the various methods for the grounding of I&C systems and cable shields. The following paragraphs, however, discuss certain aspects of grounding that pertain to the shielding recommendations in 4.3.3.

Ideally, no ac power or any other type of grounding conductor should penetrate an equipment cabinet without being appropriately filtered. When conductors do penetrate a cabinet, they can serve as a path along which electromagnetic wave EMI can propagate and effectively reduce the shielding of a cabinet to 0 dB. Because this is a bi-directional situation, EMI from within the cabinet from the processing contained therein, will similarly be allowed to travel along the same conductor and to then EMI contaminate the overall environment. In this latter case the emissions compliance certification of the equipment can be voided. Thus, all power wiring conductors must be interfaced to a cabinet or equipment enclosure via a fully shielded and LC-filtered wiring compartment, which topologically makes the power wiring appear to be on the cabinet's outside surface. Similarly, unless it is filtered, no grounding conductor must be allowed to penetrate the cabinet, but instead should be terminated directly to the outside surface of the cabinet before being allowed to make entrance via a feed-through point. Most importantly, this also applies to cable shields.

At lower frequencies where either the electric field or the magnetic field coupling may be the source of EMI coupling, the physical location of the grounding conductor can cause coupling to the conductors of sensitive circuits. Since cable shields can be expected to pick up EMI, ground connections to this shield should be made away from the conductors for sensitive circuits. The undesirable practice of using pig-tails or jumper wires to ground shields must be avoided for the additional reason that the pig-tails or jumpers provide unwanted coupling points to any victim conductors that may be parallel (or nearly so) oriented to them.

For cables entering or leaving a cabinet, the shields should be fully circumferentially grounded to the outside surface of the cabinet. For cables that run only internal to the cabinet, the shields should be low-inductance grounded to the circuit common inside the cabinet. The use of pig-tails or jumpers should be avoided.

Proper shield grounding techniques will help to eliminate EMI noise radiation and reradiation from both internal and external sources, help to maintain the emissions compliance of the equipment, and help to minimize any fire safety code issues.

4.3.5 Filters

All conductors penetrating an enclosure or cabinet are capable of bi-directionally conducting interference into and out of the enclosure. This includes power conductors, grounding conductors, and any I&C cables and associated cable shields. 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. 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 and therefore out of the bandpass for the desired signal. Otherwise, attempts at filtering the EMI will also effect the desired signal process as well. This will occur for those portions of the signal that overlap in frequency or fall into the "skirt" area of the filter.

The worst case is when an EMI signal becomes impressed onto a digital system's clock circuit since from there it may be routed throughout the system. This kind of EMI is also difficult to find since it makes its presence known by being everywhere at the same time. The second worst case is when EMI enters a low-level amplifier circuit with sufficient bandwidth to amplify the EMI along with the desired signal. This raises the amplitude of the EMI signal to levels far above what it started out, and this allows it to become a stronger source of EMI than it originally was. Proper filtering of circuits is used to generally minimize, if not eliminate, these problems along with others.

Many high-frequency transients can be prevented from entering control enclosures by bypassing each control conductor to the signal/frame ground with a 0.1 microfarad ceramic disk capacitor at the terminal block where the cable enters. This method is most effective if the bypass occurs on the outside surface of the equipment cabinet before any EMI can enter the cabinet's volume. For this method to be effective, the leads of the bypass capacitors should be kept as short as possible. Even better for purposes of bypassing is the use of a coaxial style feed-through capacitor that has its metal case solidly grounded to the equipment's enclosure at the point of penetration. Care should be taken in evaluating if either of these methods will cause an undesirable time delay or waveform distortion of the signal.

LC types of filters achieve their action on the EMI by the following interrelated actions:

1) Reflection via impedance mismatch reflects the EMI back up the same path from which it tried to enter the filter.
2) By circulating the EMI within the filter's elements and creating EMI losses via heat dissipation in the filter's components.
3) By low-impedance shunting action between conductors, and to equipment or signal ground conductors through filter components that are connected line-to-line and line-to-ground.
4) By radiation from the filter's components into the environment (undesired) and to be minimized in a good filter design.
5) By letting the remaining EMI through the filter and out onto the filter's other port.

If the EMI is common mode, the filter must be connected in series between each conductor (including ground conductors and shields) so as to raise the path's impedance to CM current. More impedance equals less current in the path, which results in EMI attenuation. Inductors may also be configured in CM to create a transformer bucking action between the CM current appearing on the conductors.

If the EMI is DM in nature, the filter must be connected between the signal conductors and additionally connected to signal or equipment ground depending upon the circuit being filtered.

Generally a combination filter is used that can attenuate both CM and DM noise. There are many types of filters, but the most common type is a simple combination inductor and capacitor, reactive filter configured for either high pass or low pass and with a characteristic impedance equal to that of the circuit into which it is to be placed at some specified center frequency. For ac power wiring, this is typically 50 Ω at 60 Hz and on telephone type circuits 600 Ω. The center frequency of the latter filter depends upon whether the type of circuit is voice grade or digital.

Filters can range anywhere from simple capacitors and ferrite beads used by themselves, to sophisticated, multi-stage and physically large bandpass filters. The configuration of the filter will naturally depend upon the characteristics of the noise to be filtered, and the rms and peak currents of the signal to be passed through the filter in unattenuated fashion. Since different filter configurations will affect signal parameters such as pulse rise time and waveshapes of both digital and analog circuits, both the positive and negative effects must be considered when applying filters. Supplemental filters have also been known to cause detrimental ringing of digital circuits.

4.3.5.1 AC power filters

AC 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:

a) The filter should optimally be mounted in the bulkhead of the cabinet to protect against input-output lead parasitic capacitance coupling at high frequencies. This is a serious problem that is often overlooked.
b) If the filter cannot be mounted on the bulkhead, isolate the unfiltered power leads to avoid recoupling EMI to the nonfiltered power leads or to signal cabling.
c) Select a power line filter either with a high input impedance or to specifically match the load impedance to avoid changing the overall electrical characteristics of the power distribution system.
d) The power line filter should be rated for the appropriate line-to-line and line-to-ground working voltage and the number of phases on the circuit (including neutral if used).
e) The power line filter should be rated to handle the continuous rms current of the load, and any peak currents that the load may require.

f) The power line filter should be able to handle the harmonic currents from non-linear loads in addition to the fundamental current from the load.

4.3.5.2 Filtering of grounding conductors

Since the equipment grounding conductor is also the conductor that the typical power entry low-pass LC filter for electronic load equipment will be referenced to on an ac power system, its impedance must always be kept as low as possible. This allows the filter to successfully return EMI that it has shunted into the equipment ground to be effectively returned to the ac source. A beneficial EMI loop exists between the LC filter and the ac power source via the interconnecting equipment grounding conductor. Hence, a maximized EMI current in this path may be viewed as beneficial if it is part of the LC filter's operating mode. Accordingly, any actions taken to raise the impedance of this equipment grounding conductor path will have undesirable results.

For example, if an inductance ("choke") is placed into the equipment grounding conductor path for equipment that is attempting to use the path for LC filter return current, the action will reduce the effectiveness of the LC filter to the point that it will simply pass the EMI into the equipment it was intended to keep it out of. Placing an inductance into the path has the equivalent effect of adding it in series with the LC filter's shunt capacitors, which is a known poor practice.

However, if an inductance is inserted into the equipment grounding path for the LC filter, the indications will be that the equipment ground path is "quieter," but that there is now an "unexplained" increase in the amount of CM EMI "noise" current that can be detected in the interconnecting cables from the victim equipment to other items of the overall system. What has happened is that the LC filter's return current "noise" has not been reduced, it has been unknowingly rerouted. Accordingly, the equipment grounding conductor path between equipment and the ac power source must always be configured to offer the lowest amount of impedance across the widest range of frequency possible if reliable operation of the system is to be expected.

4.3.5.3 CM filtering

The appropriate place to apply CM chokes to decouple CM noise current paths, is on the actual data, signal, control, or other interface cable itself. Or, if a large enough choke can be obtained, it may be applied around all of the ac power conductors (line, neutral, and equipment ground) along with the involved conduit or raceway. These kinds of placements of a choke increase the CM impedance of the path and allow a concurrent reduction in CM current, which is usually a beneficial situation.

At high-frequencies, the physical point at which a CM choke is placed onto a conductor is critical. Inductors require current to operate, not voltage. Hence, the chosen point must be a point of significant current flow in order to obtain the needed H-field flux to excite the inductor and get a back-emf action. This means that the wavelength of any CW type of EMI needs to be considered and the choke placed at points on the standing wave that are current maximums, and not minimums. Traveling waves will intersect the choke no matter where it is placed.

Since CM chokes are inductors, they become very unwieldy and expensive as they are designed for lower frequency use. Hence, they are most practical in the high-frequency range. When applied to ac power system conductors of any kind, they may also experience core saturation if the circuit is producing flux at dc, power system fundamental, or harmonic frequencies. This means special care must be taken in the design of the choke's core to avoid this kind of problem, or the use of very large cores.

4.3.6 Other noise minimization techniques

4.3.6.1 Signal Isolation transformers

Isolation transformers can be used to block common-mode interference and dc signals. When both ends of a signal wire pair are fed by signal isolation transformers, the wires become isolated from dc and low-frequency ground potential differences in the terminal equipment. In practice, signal isolation transformers normally are configured as solidly grounded, center-tapped devices so as to present a differentially balanced impedance to ground and to enhance safety. Electrostatic shielding in the signal isolation transformer is important as an additional means of reducing CM currents and a subsequent CM to DM current conversion.

4.3.6.2 Power isolation transformers

An isolation transformer is defined as any transformer consisting of a separate primary and secondary winding where they are not interconnected to form an autotransformer connection. Whether or not the isolation transformer is grounded is not a part of the definition. In this context, a power isolation transformer is still an “isolation” transformer when its secondary winding is solidly grounded to the equipment grounding conductor, equipment frame/enclosure, and any earth grounding electrode system.

When an isolation transformer is introduced into the electrical distribution system and its secondary is grounded, it is referred to as a separately derived ac system. If, instead of grounding the secondary of an isolation transformer, it is interconnected with another solidly grounded ac system via a common neutral conductor run, the arrangement is correctly called a solidly interconnected ac system.

Since all ac systems in a facility should be solidly interconnected via a common equipment grounding conductor system and earth grounding electrode system, a power isolation transformer cannot provide an “isolated” ground to any equipment connected to their secondary. Instead, a power isolation transformer used to create a separately derived ac system can provide a new and local ac system and equipment ground point that is local to the isolation transformer and its served loads without the necessity to use only the service grounding point, which may be quite distant. It is important to note that a power isolation transformer is not used to form a truly “isolated” ground point.

Power isolation transformers may also be provided with electrostatic shields between the primary and secondary windings for enhanced shielding effectiveness.

4.3.6.3 Ground current neutralizing transformers

Ground current neutralizing transformers can be used to eliminate the effects of inductive coupling or ground potential rise associated with cables entering a generating station or run in parallel with the power transmission lines. The inductive coupling will cause ground currents to flow when the I&C cables have multiple connections to ground, either intentionally or unintentionally, from the stray capacitance between the cables and ground.

To implement this method, all incoming I&C 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 same induced potential rise as the cables. To achieve this, one end of the primary circuit may be connected to the station ground and the conductor is run along the same path as the I&C cables with the other end 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 incoming cables and these circuit. This cancellation voltage can also be generated separately.

4.3.6.4 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 various attenuation schemes.

4.3.6.5 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. Narrowing the bandwidth of a circuit is another way to affect the signal-to-noise ratio without changing its impedance.

4.3.6.6 Optically-coupled circuits

Signal circuits that use metallic paths for signal transport can be spot-converted to optically isolated circuits in order to reduce the effects of CM potentials and currents on the circuits. This is accomplished by introducing an appropriate converter into the path (usually at both ends), which includes a dielectric barrier that is bridged by a light beam that is generated by an LED and received on the opposite side by a photo-sensitive transistor. Such circuits are called *optically-coupled* and may have dielectric withstand characteristics of several kV at dc. As the signal frequency increases, the input-to-output reactive coupling may negate the attempted isolation.

Opto-couplers need to be shielded to protect their internal circuits from the effects of nearby EMI.

4.3.6.7 Fiber optic cables

Fiber optic cables are immune to the interference sources that plague standard current-carrying I&C cables. The input and output circuits of the fiber optic links are sensitive to EMI and typically need shielding from local sources of EMI.

Fiber optic cables are often metal-clad to provide mechanical protection of the cable itself. Such a conductive sheath can introduce EMI and especially lightning currents into equipment if the sheath is not solidly grounded prior to its being interfaced to the terminating equipment at the cable’s ends. Ungrounded metal sheaths represent both a fire and shock hazard, particularly when they are routed between buildings or over long vertical or horizontal distances in the same building. The safety concerns are for both lightning and ac system ground-fault conditions.

Metallic fiber optic cable sheaths cannot be effectively insulated in order to avoid solidly grounding them.

4.3.6.8 Surge arresters

4.3.6.8.1 AC power circuits 400 volts and above

Surge arresters are a specially listed and defined class of devices intended to protect electrical circuits from the effects of conducted surge current. The most commonly available form of surge arrester is one that is connected in shunt with the ac power conductors and equipment ground. These designs non-linearly clamp the voltage across their terminals in line-to-line and line-to neutral/equipment ground according to how much current is passed through them and what their wiring configuration has been chosen to be. If there is a sufficient potential difference between the line(s) and equipment ground, they will then divert surge current into the grounding path.

Surge arresters with typically not operate until several kV have appeared across their terminals and after operation they may limit surge voltage to the downstream wiring system to some lesser value, but still one in the kV range. The let-through voltage and its associated current is also dependent upon the surge current being conducted by the arrester and is generally a non-linear relationship. the let-through characteristics of the surge arrester are determined b both its design characteristics and its installation method.

Modern surge arresters typically are of the solid-state variety and do not contain and air-gaps. Air-gap designs are not desirable since they represent an operating variable that is affected by environmental conditions and manufacturing tolerances to a very great degree. Such gaps also tend to experience large changes in performance with each succeeding use as the gap erodes.

Gas-filled and gapped arresters are not desirable since they represent a near short-circuit to the ac power current once they have ionized. In some cases, the ionization may continue for several cycles and large amounts of ac power will be faulted through the device. This places great electro-magnetic stresses on all parts of the involved path and may lead to related electrical equipment failure. SCR based “crowbar” types of surge arresters pose similar problems and are therefore not generally useful in this application.

Since the surge arrester can carry large amounts of surge current with fast rates of current change, for arresters provided in equipment it is advisable to route its conductors adjacent to the equipment enclosure. All surge arrester conductors should be routed to keep them away from any EMI susceptible conductors. This especially applies to the surge arrester’s earth grounding electrode conductors.

4.3.6.8.2 AC power circuits below 400 V

Transient Voltage Surge Suppressors (TVSS) are devices intended to be applied on the building wiring ac power distribution system by attachment to switchboards, panelboards, and branch circuit outlet ends. They can be provided integral with equipment. The ratings of the TVSS must be commensurate with their point of installation on the wiring system. See IEEE Std C64.41.

The most commonly available form of TVSS is one that is connected in shunt with the ac power conductors and equipment ground. These designs non-linearly clamp the voltage across their terminals in line-to-line and line-to-neutral/equipment ground according to how much current is passed through them and what their wiring configuration has been chosen to be. If there is a sufficient potential difference between the line(s) and equipment ground, they will then divert surge current into the grounding path; otherwise, they will not.

Series connected and hybrid designs must be rated to handle the full rms current on the circuit plus remain undamaged by available fault-current during short-circuits. This latter set of requirements limits the application of the TVSS to smaller ampacity circuits due to the high costs associated with the series or hybrid design.

The most commonly available TVSS is MOV based, but may also contain items such as capacitors and strings of matched avalanche diodes, which are series connected due to voltage breakdown requirements. Gas tube based and SCR “crowbar” types of designs on ac power circuits are generally avoided because of the same kinds of problems as discussed above with surge arresters used on service entries and equipment.

4.3.6.8.3 I&C circuits

TVSS equipment should be attached to I&C circuits that enter/exit a building or defined zone to prevent these circuits from propagating a lightning or fault current hazard into or out of the area.

MOV based TVSS designs are not normally used on data/signaling/telecommunications circuits where the capacitance loading effects of the MOV would affect the waveform of the transmitted current on the circuit. LCR based TVSS designs are more accurately classified as filters and so are not discussed in this subclause.

Most common TVSS designs that are intended to provide maximum amounts of protection for the circuits to which they are attached use hybrid arrangements. These are TVSS designs that incorporate both a (shunt) gas-tube, a series impedance, and a (shunt) Tranzorb connected into each of the circuit conductors and to ground.

The avalanche diode is the first (and sometimes only) protective device to go into operation if the surge is small. However, when the surge is larger, it works against the IZ drop the current develops across the series impedance (usually a resistor). This both limits the current through the avalanche diode and ramps up the voltage across the gas-tube on the impedance's input side. The avalanche diode and resistor continue to operate in unison until the ionization voltage for the gas-tube is reached, at which time the tube fires, and reduces the potential across its terminals to about 15 V. This then relieves the resistor and avalanche diode from the high-current handling task, but the avalanche diode may continue to conduct to some degree.

As a result of problems involved with obtaining an exact ionization and conduction condition in separate gas-tubes, the design has evolved to use a common gas-filled envelope, which contains multiple electrodes that are normally insulated from one another. Thus, when any surge causes any ionization to occur on any electrode, the whole gas-tube operates and with a constant voltage drop across each circuit. This important effect also minimizes the highly unwanted conversion of CM surge current to DM surge current. Most gas-tubes are photo-sensitive and so when installed, should be kept in enclosures designed to exclude light.

Hybrid TVSS designs are available in balanced and unbalanced circuit types and for a wide variety of circuit impedances and protocols.

4.3.7 Summary of EMI minimization techniques classified by coupling mechanism

It should be noted that, in real-world applications, the selected EMI minimization techniques 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

a) Eliminate as many common impedance points between circuits as possible by not using any conductor as part of more than one circuit and by not connecting the circuit signal return to ground from more than one point.

b) Avoid using the equipment ground system as part of the signal return path. Where it is necessary to use the equipment ground system as part of the signal return path, make ground connections as short and of as low an impedance as possible. This typically requires that the I&C conductor and ground system be close together.

c) Do not use the earth as a path for any signals or in an attempt to equalize potential between equipment or signal processes, particularly when ac power system ground-faults or lightning currents could become involved. The earth is too high of an impedance to permit this and the level of its impedance rises with the frequency of the current. Ultimately, it becomes too high to be of any use. This typically occurs below 1 MHz.

   Most earth ground testing occurs at or near dc to 1 kHz and the test results are "corrected" to show equivalent dc ohms. Hence, what appears to be a "good" 1 Ω earth ground is in reality a connection of high ohmic value at just a few kHz. In addition to this, the impedance value of any conductor used to make the connection to the earth ground may be in the kilo- to meg-ohm range at the EMI frequency of interest. This means that even if the earth ground would be a good connection by itself, the impedance exhibited by the conductor used to connect to it could invalidate the design.

d) Use signal reference ground planes or grids to equalize potential between interconnected items of equipment over a very broad range of frequency. Typically these kinds of broad-band signal reference structures (SRS) will be effective from dc to over several tens of MHz. The SRS also functions independently from earth ground, although for safety it must be connected to the facility ground system.

4.3.7.2 Capacitive coupling

a) Reduce the impedance of the sensitive circuit to load-down the capacitive coupling mechanism.

b) Position and connect conductive shields so that capacitively coupled noise currents are returned to the signal common ground without flowing through the signal lines. Capacitive shields should adequately enclose the signal circuits and be constructed of a low-impedance material in order to provide an alternative bypass path for the noise current. Use low inductance techniques in how the shield is connected to the ground reference.

c) Route control circuits to minimize coupling between high level circuits and low level circuits. Otherwise, effectively enclose one or the other, or both of the circuits in a shield that is effective for the kind of EMI being propagated from the aggressor to the victim circuit.

d) Specify transformers that have solidly grounded electrostatic shields provided between the primary and secondary windings.

4.3.7.3 Inductive coupling

a) Increase the impedance of the sensitive circuit so that EMI current flow is reduced.

b) Divert dc and very low-frequency sourced magnetic fields by shielding them, the victim circuits, or both with low reluctance (high permeability), ferrous material. Avoid letting this material become saturated.

c) Route control circuits to minimize coupling and loop area (physical separation, right angle crossing, radial routing, twisting of signal pairs).

d) Increase the rise time of the signal.

4.3.7.4 Radiation coupling

a) Absorb radiated waves by using a lossy dielectric or magnetic shield.

b) Reflect radiated waves by using metallic shields.

c) Separate the emitter and receiver by the maximum possible distance since radiated power strength is inversely proportional to the square of the distance. The E-field component of the radiated signal will be inversely proportional to the linear distance.

d) Design cabinet openings with regard to the techniques presented in 4.3.3.1.

e) Terminate external cable shields and power or signal filter grounds on the external surface of the cabinet via fully circumferential connections. Do not use "pig-tail" type connections or jumpers.

f) Recognize and prevent the pickup of electromagnetic radiation near the emitter by inadvertent antennas/conductors and the propagation of that wave to areas near the receiver where it can be re-radiated.

4.3.7.5 Common-mode rejection techniques

Common-mode noise can be produced by any of the above four coupling methods. Since common-mode noise is often converted into differential-mode noise, common-mode noise is the most frequent source of trouble within I&C circuits. Several techniques that are useful in minimizing common-mode noise are:

a) Make the signal circuit symmetrical by using a balanced transducer and identical signal lines.

b) Minimize the common-mode coupling by increasing the physical separation between the emitter and the receiver and minimizing the number of direct connections to the interference source.

c) Use shielding techniques to prevent the interference from reaching the sensitive circuits.

d) Use common-mode rejection devices such as differential amplifiers, power or signal isolation transformers, optical isolators, and CM chokes.

e) Utilize proper grounding methods.

Below 30 kHz and perhaps to as much as 300 kHz, apply the concepts of single-point grounding and floating logic or signal grounds while avoiding multiple grounding connections to the circuit common. This may be difficult to achieve in an extensive system.

Above 30 kHz and below 300 kHz, multi-point grounding may be beneficial. However, above 300 kHz, multi-point grounding is required and extensive use of ground reference structures such as planes, grids, or both should be made. When processes exist on the same system that employ bandwidths above and below 30, then multi-point grounding must be used in combined, hybrid fashion with single-point grounding.

5. I&C system grounding

5.1 Grounding philosophy

5.1.1 Principal objectives

The principal objectives of generating station grounding practices are to:

a) Maintain safe voltages across the station area during high-voltage system transients (step and touch potentials).

b) Minimize the effects of lightning surges on equipment and structures.

c) Provide a low-impedance, ground fault current return path.

d) Provide a low-impedance leakage path for any static charge that might accumulate on equipment.

e) Minimize noise interferences in I&C systems by providing a broad-band, common signal reference of low relative impedance between devices, circuits, and complete systems.

Grounding circuits often share multiple functions, and it is necessary to design a grounding network so that the conveyance of transient voltages from electrical faults, lightning strikes, etc., does not interfere with the function of minimizing noise and preventing these transients from impinging on circuit elements beyond their limit of transient immunity. All portions of the station ground system, whether for power, lightning, or signal reference, need to be interconnected and should not be isolated from each other for any reason. Isolated grounding elements represent a safety and operational hazard as discussed in 5.2.1.

It is therefore necessary to recognize the following four points: The first is that all points on the earth (even within relatively close proximity) will not be the same or equal potential relative to an arbitrary reference point for all frequencies. The second is that each element of a grounding network has a finite resistance and impedance. The third is that there is an inherent transient susceptibility of discrete circuit elements. Care must therefore be taken to ensure that the environment will not exceed the specific operating limits of the individual circuit elements. The fourth is that as local transients cause ground potentials to reach high values, currents may enter conductively connected cable circuits and may also be capacitively and inductively coupled from grounded cable shields in the affected area into the I&C conductors. These conductors may terminate outside of the transient area and could impress high voltages on any connected equipment, with the possibility of causing equipment damage, personnel hazards, or fire hazards.

5.1.2 Generating station grounding system

In any generating station there are four identifiable grounding systems which are all tied to the station grounding grid. Those for lightning, station service power, and equipment grounding are discussed in the following references:

a) IEEE Std 665-1995

b) IEEE Std 142-1991

c) IEEE Std 1100-1999

Requirements of local safety codes are discussed in Annex B.

The fourth grounding system, discussed in the following subclauses, is the I&C grounding system, which is designed to minimize the generation and transfer of noise voltages.

5.2 Types of signal ground systems

An electronic I&C system may be viewed as a complex hub consisting of one or more microprocessors and numerous I&C circuits interfacing through cables with end devices. Within the hub, the interconnections may be complex and it may be impossible to use individual return paths for each end device. Therefore, a common ground or reference plane may be created that will individually act as a return path for one group of signals. Ideally, this reference plane would offer zero impedance to all of the signals it serves. If this were the case, all of the individual signal currents within this system would return to their respective sources without creating unwanted coupling and interference. It is, however, impractical to achieve zero impedance connections, so care must be exercised in interfacing this system to the rest of the plant grounding systems. Improper grounding may cause the flow of electrical noise currents in these common signal returns and create problems. The majority of signals in generating station I&C systems are dc or low-frequency signals.

A fundamental objective of a separate signal ground system is to achieve the same safety goals as the equipment safety ground system, but to do so while keeping the electrical equipment safety ground conductors separate from I&C ground conductors. The separation is desired in order to minimize EMI coupling from electrical equipment, which may have high levels of EMI that could interfere or damage sensitive I&C equipment. There are three common approaches toward this—single-point grounding, multiple-point grounding, and floating grounds. Each concept has its advantages and disadvantages, and a typical generating station signal ground system may use a combination of all three, but in no case shall a method be implemented in such a manner as to create a personnel or fire hazard.

An important element of determining which type of grounding method to utilize is the operating frequency of the I&C system. While the actual microprocessor frequency within an equipment cabinet would be considered high frequency, the vast majority of I&C circuits that exit the cabinets are dc or low-frequency. The inherent conflicts in grounding philosophies for high- and low-frequency circuits has been a continuing source of confusion in determining the proper grounding techniques for I&C systems. The preponderance of low-frequency circuits in generating station I&C systems generally utilize the single-point grounding techniques, which are often recommended by equipment manufacturers.

Note that Figure 12, Figure 13, Figure 14, and Figure 15 depict an additional local supplementary ground connection to a local grounding system for each cabinet in addition to the equipment grounding conductor provided with the incoming ac power circuit. This additional connection will enhance personnel safety by ensuring near-zero step and touch potential to nearby equipment. For some figures, this local ground conductor has also been shown extended to the station ground grid as this optional connection may be recommended by equipment vendors.

5.2.1 Single-point ground system

The single-point ground system is principally used to reduce the unwanted circulation of both dc and ac power system related fundamental and harmonic ground currents in the signal grounding paths. These currents may cause common-mode noise across the range from 0 Hz to about 6 kHz (the 100^{th} harmonic of 60 Hz). A single-point ground system is implemented by connecting the signal circuit common to the station ground reference from only one point. This grounding method is very effective and adequate when dealing with equipment operating at frequencies below 30 kHz and not exceeding 300 kHz. Various sources place this frequency at anywhere between 100 kHz and 10 MHz. The equipment manufacturer should be consulted for each specific installation.

The signal ground reference point should be tied to the equipment safety ground point within the enclosure or local area and there should be no more than one (preferably filtered) ground lead exiting each equipment enclosure. This lead should be a stranded and insulated conductor sized to minimize the steady-state potential difference between devices (less than 1 V or manufacturer's recommendation), and to meet the required mechanical strength. However, under conditions of high magnetic fields (Ldi/dt) this conductor will not normally be able to meet the previous requirement for potential equalization unless the rate of current change per ampere is quite low. Hence, it is normally not very useful in controlling transient current induced potential differences between its ends.

The I&C ground points of each cabinet should be connected by insulating cables to a common insulated bus. The insulated ground conductors serve not only to galvanically isolate the signal ground from unintentional grounds but also to easily differentiate them from the equipment safety ground conductors. A single insulated connection is then made from the common signal ground to the interconnected generating station grounding system. Use of isolated ground rods as the reference point is a safety hazard because the isolated ground reference does not have a direct connection back to the power system neutral which could prevent protective devices from operating because of the high impedance which is introduced. Equipment misoperation and damage from transients and lightning can also become more likely since the isolated reference will have a much larger voltage difference during the transient event than the other interconnected elements. All parts of the grounding system need to be interconnected at some point. Additional discussion is contained in IEEE Std 142-1991 and IEEE Std 1100-1999.

A separate I&C grounding system should be utilized within the cabinet enclosure and it is advantageous to keep these conductors separate from the power or equipment safety grounding connections. Adjacent cabinets should be bolted or bonded together with a single strap or cable for the group. This connection is in addition to the equipment safety grounding conductor or conduit/raceway provided with the incoming ac power circuit. Cabinets located close together should have the supplementary grounds tied together at a single reference point in the local area.

Single-point grounding design is primarily based on the prevention of dc and very low-frequency ground currents from flowing in the signal common. Because electrical power equipment contributes most of the ground current, it is good practice to keep the grounds for sensitive equipment away from power circuits and their ground return paths where large leakage or fault currents may occur. The equipment ground for a cabinet containing I&C equipment should be recognized as being different from the equipment ground for a 400 or 480 volt motor control center in regards to EMI, but not for safety. It is normally not good practice to tie the signal or cabinet grounds from an I&C cabinet to the same point as the equipment grounds for equipment such as motor control centers because of the higher possible currents during both normal system operation and system transients.

A disadvantage of the single-point grounding system is that it may fail to function as a signal reference and even may be detrimental at high operating or threat frequencies. As equipment dimensions or ground conductor lengths ultimately approach 0.15, the conductor can no longer be considered a low-impedance conductor. In this manner, the signal grounding conductor will not effectively act to equalize potential between its ends and may carry EMI to or from the system and increase any interference problems. Single-point grounding would have few drawbacks if electrical noise current could only enter I&C equipment and cables via conductive means; however, high-frequency coupling mechanisms do exist and their effects should be considered.

Another possible disadvantage is that even an otherwise carefully designed and implemented single-point grounding system may unexpectedly evolve over time into unintentionally large, enclosed, EMI gathering and radiating loop areas once modifications and additions of cabinets and cabling are made that do not conform to the original philosophy.

5.2.1.1 Cabinets in close proximity

Figure 12 illustrates a single-point grounding system for I&C cabinets located in close proximity as is often the case in generating station control rooms, dedicated computer rooms, and cable spreading rooms.

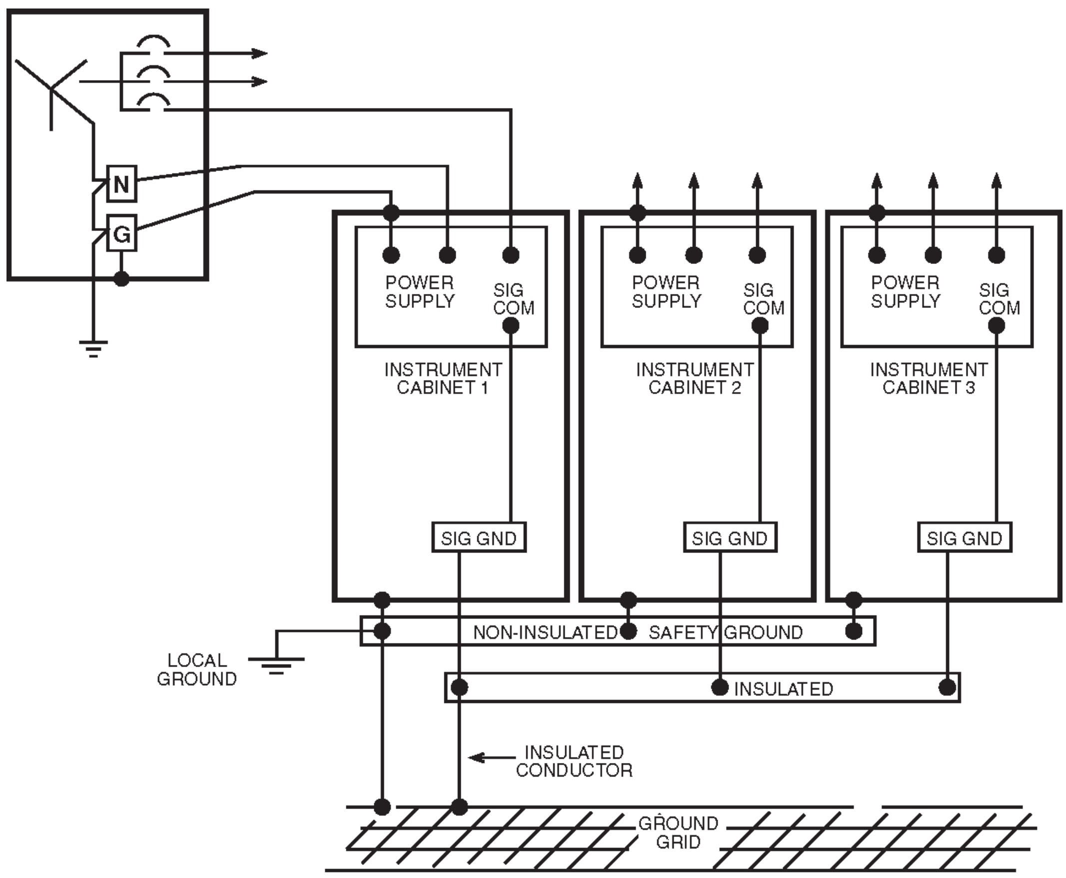


Figure 12—Single-point ground system for low-frequency signals with cabinets in close proximity

I&C equipment manufacturers may tie the I&C and safety grounds together inside of the equipment enclosure. During the installation, these factory connections should not be modified. To do so may create unforeseen EMI problems as well as equipment warranty or service contract difficulties with the OEM unless provisions for doing so are made in the procurement specifications.

5.2.1.2 Cabinets that are widely separated

In a distributed I&C system, the equipment cabinets may be located throughout the generating station and it is impractical or poor practice to implement the single-point grounding arrangement of Figure 12. Physically distributed systems often take the form of a primary control system such as that of Figure 12, with additional remote input/output cabinets from the same manufacturer, as well as interfaces to other control system packages from different manufacturers. An I&C system is considered a distributed system when the individual control station cabinets are separated from each other by a distance long with respect to the wavelength of the interfering signal, but still not at a high enough frequency to create an electromagnetic wave. Separation distances of 30 m between cabinets may be sufficient for them to be electrically "widely separated."

Such as system has special problems since the cabinet ground points will be at relatively different potentials with respect to each other, and unwanted currents may then flow on any ground connection between the cabinets. Figure 13 illustrates an approach to this situation by creating a separate single-point grounding system for each geographic grouping of equipment.

In utilizing multiple, single-point ground systems, the interconnection of low-frequency I&C cables between the separate groupings should be avoided. Connections between widely separated cabinets should be high-frequency data highway cables. The communications circuits between the cabinets must have appropriate protection for the common-mode noise, which is likely to result from the impedance of the long, insulated signal grounds. Standard common-mode protection ratings may not be adequate unless the requirements are built in to the procurement specification. Signals between systems should use either differentially connected signal isolation transformer coupling or ac capacitor coupling with transmitter/receiver circuits having a common-mode withstand voltage that safely exceeds the ground voltage under fault conditions. It may be preferable to eliminate all metallic signal paths between the widely separated cabinets by the use of by fiber optics, optical-coupling means, or by using wireless communications at infra-red or radio frequency.

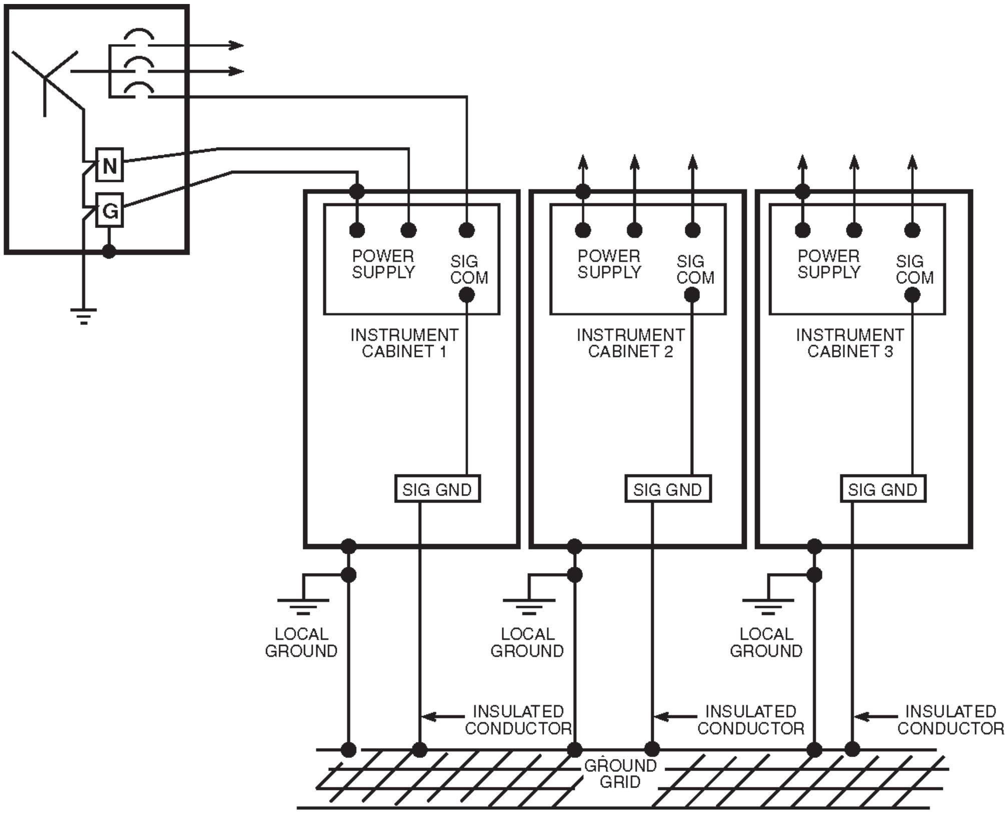


Figure 13—Single-point ground system for low-frequency signals with cabinets widely separated

A multiple-point ground system is an option for low-frequency signals as shown by Figure 13. This configuration accepts the fact that a ground voltage difference will exist between the separate cabinets and that the appropriate degree of protection must be provided for the interconnecting signal cables.

5.2.2 Multiple-point ground system

A multiple-point ground system should be considered for equipment that operates at frequencies above 30 kHz and certainly when operating over 300 kHz. This is also a requirement when electrically long ground cables are used in relation to signal wavelength on the path. Each cabinet is connected to ground at the closest point rather than routing all ground conductors to a single ground point. Within the equipment cabinet, the I&C, power, and equipment ground conductors are each tied to a common point, which is often the equipment frame.

Advantages of this system are that circuit construction is easier, and that standing wave effects in the ground system at high frequencies are avoided.

A disadvantage of a multiple-point ground system is that the system may create multiple low-frequency ground loops that may cause inadvertent common-mode noise in low-frequency circuits. Hybrid forms of grounding can alleviate this problem as can proper design of the signal reference structure (SRS) used to form the commonly shared, multi-point ground reference. Types of SRS include signal reference planes and signal reference grids.This configuration is illustrated by Figure 14.

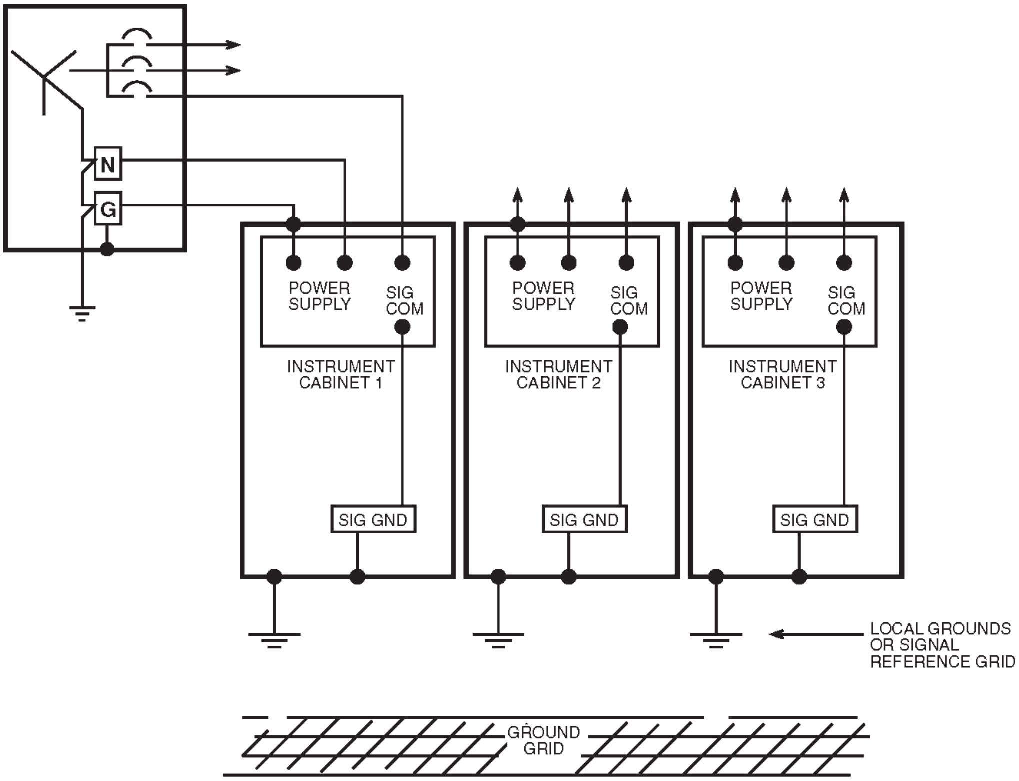


Figure 14—Multiple-point ground system for high-frequency signals

5.2.3 Floating ground system

A true floating ground system is difficult to achieve in practice and will commonly be found only inside otherwise grounded equipment and on physically very small subsystems. It is not a recommended method for grounding generating station I&C systems, but is discussed in this subclause to complete the discussion of other possible grounding methods. An example of its use would be on a printed circuit board within a cabinet, but only on circuits confined to the board's own area.

The floating ground system is used to isolate dc and very low-frequency circuits or equipment electrically from a common ground plane or from common wiring that might introduce circulating currents and produce common-mode noise. This form of design does not afford isolation from higher frequency interference and impulses once they can be adequately coupled by the distributed capacitances and inductances to the circuit. These parasitic high-frequency coupling paths are generally ignored during the design and construction of this type of grounding design, but can be significant sources of EMI problems.

A floating ground system is implemented by electrically interconnecting the signal grounds, yet isolating them from a ground plane (see Figure 15). A hazard of this system is that static charges may accumulate and eventually cause an intermittent disruptive, noise-producing discharge current to flow. It is usually advisable to implement this system with a non-inductive bleeder resistor (500 Ω to 1 000 000 Ω) connected to ground to avoid the buildup of static charges and to help stabilize the voltage to ground. This design is also highly susceptible to dielectric breakdown failures and for transferring breakdown electrical stresses to unexpected points on the system. A floating ground system can also be a difficult design to trouble-shoot.

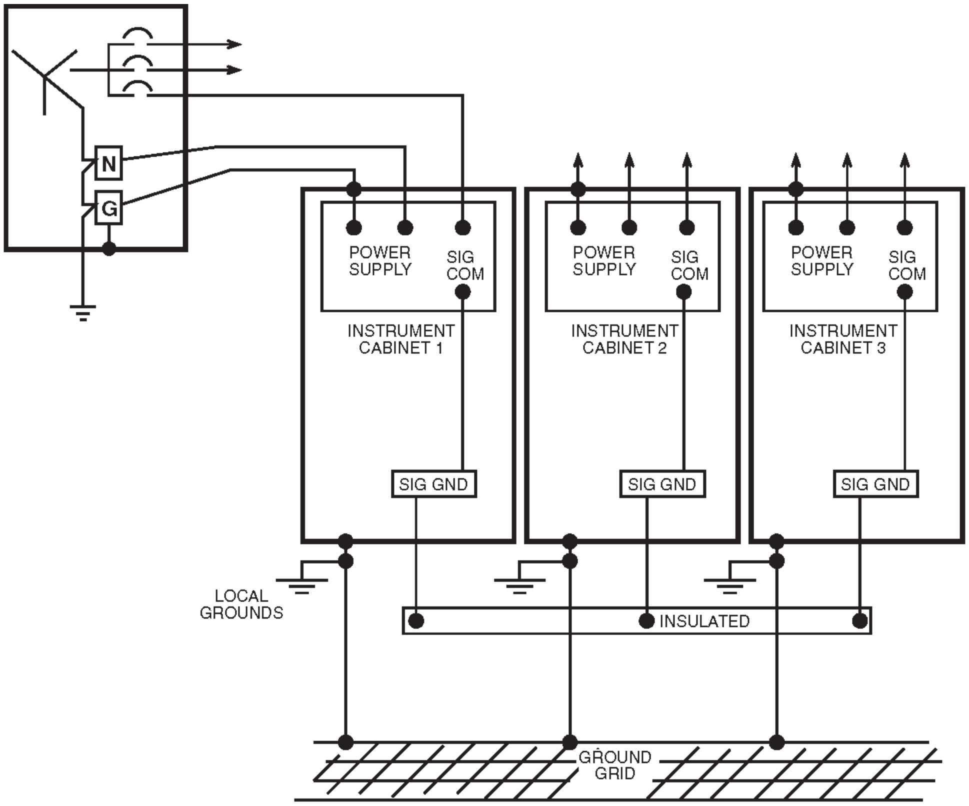


Figure 15—Floating ground system

5.3 Separation criteria for circuits

In order for separation guidelines to be developed for the various types of cables within a generating station, they need to first be classified according to type. A fairly typical grouping is:

M	Medium voltage, single lay cables
P	Low voltage, random lay power cables rated 480–120 Vac, and 125 Vdc
C	Control cables, generally non-shielded for digital inputs and outputs (48–125 V Vdc), and control power (24–125 Vdc and 120 Vac)
L	Instrumentation, generally shielded cables—digital inputs and outputs 24 Vdc and lower, thermocouple, RTD, 4-20 mA and other analog I/O

Circuits are normally run in common raceways, such as cable trays, according to their group classification with no mixing between groups allowed.

In determining the required separation between the cables, the raceway method utilized effects the minimum separation distance. For cables routed in metallic conduits, the separation distances would be less for magnetic conduit than for aluminum conduit. Separation required between metallic conduits will also generally be less than the separation required for cables trays, particularly ladder-type trays with no covers. For cables routed in trays, a separation distance of 50 cm is normally maintained for installation purposes, and this is generally a sufficient distance between categories P and L (with solid bottoms and covers), with 25 cm being required between categories P and C. A distance of 120 cm would be recommended between categories M and L. When trays are installed vertically stacked by group as listed above, the recommended separation distances can often be readily achieved. Barriers within a tray can also be utilized for separation the different cable types.

When conduit is utilized, cables of Group L should normally be run in magnetic conduit to provide optimum shielding. When each of the circuit groups is run in a common underground duct bank where wide separation distances are not feasible, magnetic conduit should continue to be utilized for the circuits of Group L.

Not all of the above grouping will be found in every installation, while other groupings and separations may be required for data communication, fire protection, and telephone cables. Separation criteria can be a relatively simple set of guidelines, or it can be expanded into an elaborate set of tables to cover numerous installation conditions.

Some vendors have specific raceway and separation criteria for the cables associated with their equipment, and these should be incorporated into the overall project separation criteria.

5.4 I&C system power considerations

The following considerations should be taken into account when designing the grounding system for a centralized I&C system similar to that shown in Figure 12.

a) All ac power circuits should come from one locally installed source that is separately derived or solidly interconnected such as a UPS or an isolation transformer.

b) Each ac power circuit should contain an equipment ground conductor that connects to the equipment frame and references it to the power source.

c) AC power should be distributed from the local power source to all local cabinets in the system through individual circuit breakers or fuses. Each circuit should be a dedicated, individual load.

Note that some existing generating stations may use an ungrounded (floating) ac power distribution system for their I&C systems, while other utilize a grounded system. Only the latter design utilizes the equipment ground connection for ac fault protection on the first ground fault to occur. The floating design requires two ground faults to occur before the protective equipment can operate. Floating ac power distribution systems are not recommended unless extensive use is made of ground fault detectors and alarms for the first fault occurrence. Ungrounded systems are also difficult to achieve in practice as many equipment internal power supplies ground one end of the output to the power supply frame, which is in turn solidly connected to the equipment frame and ground.

5.5 Surge protection considerations

5.5.1 Power supply circuits

Experience has shown that the I&C system power source can be a significant source of EMI problems. Surge protection should be provided for all incoming power feeds to critical I&C systems. Many vendors recommend that their equipment be fed from a dedicated local, separately derived power source. Since this is most commonly a UPS or isolation transformer, both of these devices provide some inherent degree of surge protection. Subclause 4.3.5.1 contains recommendations on the use of ac power filters.

5.5.2 Instrumentation and control circuits

Operating experience has shown that, in general, surge protection is not required for I&C circuits located within the main "powerhouse" of traditional steam turbine generating stations and that control circuits that terminate outside of the powerhouse at outlying facilities such as circulating water pumphouses, fuel oil storage, water treatment, etc. may become likely source of surges, which can cause equipment misoperation or damage.

IEC 61312-1:1995 discusses a "zone concept" that elaborates on the empirical findings noted above. Separate geographic "zones" are identified working outwards from the control system, and surge protection should be provided whenever a circuit crosses a zone boundary. The goal is to have high capacity surge protective devices mitigate the surge closest to its point of origin external to the generating station, and then have subsequent surge mitigation with tighter voltage clamping levels and lower energy ratings at each zone boundary heading into the main I&C system processors. Providing surge protection only at either or both ends of a long I&C circuit terminated outside of the main generating station building has been found to be insufficient in some cases. Intermediate surge protection, as discussed by the "zone method," is a logical framework for providing enhanced surge protection. Providing surge protection at boundaries such as exiting a building as meshes well with certain national codes such as discussed in Annex B.

5.6 Other grounding considerations

5.6.1 Equipment safety grounds (mechanical, frame)

The equipment in this context is the exterior housings of I&C systems. Specifically, it refers to normally non-current-carrying metal enclosures, such as cabinets, frames, and racks. The major objective of the equipment safety ground is to prevent hazardous potentials from developing between adjacent grounded equipment in order to protect personnel and equipment against hazards posed by electrical power transients and faults. A desired objective of the equipment safety ground is to provide a low-impedance path for ac system fault currents.

Requirements for the design and installation of an equipment safety ground include:

a) Ensure that all enclosures are constructed with special provisions, such as a designated equipment cabinet ground stud, lug, or bus for terminating the ac equipment grounding conductor that is run with the input power cable from the power distribution system. This connection is in addition to the solid bonding of any metal armor, conduit, or raceway provided with the incoming ac power conductors. A continuous metallic raceway system of sufficient ampacity may serve as the ac equipment grounding conductor. Connect the ac equipment ground conductor and/or continuous metallic raceway system to the designated equipment safety ground bus for the cabinet.

b) Provide a supplementary ground cable connection to the cabinet. The supplementary ground cable is not run with any ac power circuit conductors and will connect to the closest local ground point, ground mat, or reference ground plane if one is available. If multiple enclosures are physically grouped together, first bond them by bolting them to one another and then use only one connection between the enclosure group and the supplementary ground. This singular supplementary ground connection is in addition to the ac equipment grounding conductor and/or continuous metallic raceway system provided with the incoming ac power circuit to each cabinet. The supplementary ground cable should be a flexible, stranded conductor. This conductor should only be insulated if corrosion is a severe hazard. In known corrosive environments, periodic checks should be made as to the integrity of all ground connections.

5.6.2 Ground conductor lengths

At MHz signal frequencies, the impedance of a single conductor can become high enough so that it no longer provides a grounding connection between two points for the purpose of equalizing the relative potential of those points. For example, a conductor that represents an impedance of less than 0.3 Ω at 60 Hz will represent over 40 000 Ω at 10 MHz. Ground conductors longer than 1 m may be viewed as detrimental rather than beneficial for dealing with EMI frequencies in the MHz range.

5.6.3 Generating station-to-substation interconnect

Although not installed for I&C circuit reasons, large diameter ground cables are usually installed along the interconnecting ducts banks and cable trenches between a generating station and its switchyard. In general, conductors equal in size to the ground grid conductors should be installed either along the top corners of a duct bank or near both upper, inner sides of cable trenches. These cables should be bonded to both the generating station and substation ground grids as well as to ground rods at intermediate points. Similarly, buried counterpoise conductors underneath the transmission lines between the substation and generating station will provide additional ties between the grounding systems.

Determining the size of these grounding conductors is related to the required I^2t current handling characteristics and not its impedance at high-frequency for EMI control purposes. Achieving a low impedance requires a focus on surface area and length-to-width ratio rather than on cross-sectional area for fault-current capability and mechanical robustness.

As a result of the coupling actions of the magnetic fields involved between these grounding conductors and the plant’s ac power system conductors that are related to them, they will generally provide a lower impedance path than the I&C cable shields will. Therefore much, but not all, of the ground-fault currents from the ac system may be diverted from the I&C cables. These grounding conductors also help to safely limit the ground step and touch potential differences between the two grids during transients from lightning and faults.

5.6.4 CT, VT, and CCVT grounding

Within IEEE Std C57.13.3-1983, much has been written and standardized about the proper techniques to use when grounding these devices. The general consensus is that the secondary neutrals for these devices should be grounded at the entrance to the relay room rather than at the device.

5.6.5 Gas insulated switchgear (GIS)

Since GIS has been a known source of EMI generation, the I&C circuits installed close to the GIS (generally those installed in the same building) should be completely shielded as follows:

a) All devices installed directly on the GIS (gas density relays, disconnect switch auxiliary switches, interlocks and drives, circuit breaker controls, CT and VT secondary connections) should be completely metal-enclosed and have their housing and covers electrically bonded to the GIS enclosure.
b) All control cables should be shielded. The most effective cable shield is a continuous, cylindrically applied or continuously flow-applied corrugated metal shield as opposed to an interlocked, spiral armor shield. These shields should be grounded in accordance with Clause 6.
c) If control cabinets are installed in the vicinity of the GIS, they should be completely shielded and take into account the design considerations of 4.3.3.1.
d) When equipment with relatively low EMI immunity levels such as non-industrial computers are installed in the same building with the GIS, consideration should be given to the complete shielding (Faraday cage) of the rooms containing this equipment. This may be accomplished using prefabricated copper mesh materials or conductive paint, installed by experienced vendors.

5.6.6 Conduit and cable tray grounding

Conduit and cable tray grounding is discussed in detail in IEEE Std 665-1995. Some important installation considerations are listed here for completeness.

a) All conduit should be connected to the facility ground system regardless of whether or not it is used for enclosing power circuits.
b) All joints between sections of conduit, fittings, and boxes should be electrically continuous.
c) All pipe and locknut threads should be treated with a conductive lubricant before they are engaged and tightened.
d) Grounding locknuts must positively penetrate all paint or other nonconductive finishes.
e) All cable tray systems should be electrically continuous. This includes the support brackets or hangers. All cable tray joints that are not inherently continuous should be bonded across with jumpers adequately sized for the conductors contained in the cable tray.
f) The screws on the cover plates of pull boxes, junction boxes, and outlet boxes should be tight and all should be in place.
g) All raceway brackets and hangers should be securely bonded to the conduit and the structural members to which they are attached.
h) The electromechanical interface between a conduit, a wireway, a cable tray, or similar item should be accomplished by means of direct connection between the two or by appropriate grounding/bonding jumper application.

5.7 Generating station EMI environment

A significant amount of research into characterizing the EMI environment in generating stations has been done by the nuclear power industry since EMI has become a part of the Environmental Qualification for nuclear grade equipment (see [B14], [B15], [B38], [B40]). Although some aspects of nuclear generating stations are different from other types of generating stations, the fundamental generating station similarities of most steam turbine generating stations, regardless of fuel source, makes the research and its conclusions applicable for general applications.

Some findings from this research include:

a) 1–30 MHz is the most common threat frequency for most equipment installed prior to 1995, with 1–80 MHz being the wider threat frequency range for new equipment.
b) Separation criteria for routing of circuits should be utilized. In particular, keep low-level analog signals separate from other circuit types. Having physical distance between circuits of different voltage and current levels is effective in preventing EMI.
c) No significant EMI issues were identified for digital (dry contact) input and output circuits.
d) The most significant EMI threat is hand-held transceivers (e.g.,“walkie-talkies”).
e) Switching mode power supplies can be a significant source of EMI, and separate power supplies fed from the same power source can modulate each other and increase the interference.
f) Modern cellular telephones are not a significant EMI threat.
g) As documented by NUREG/CR3270 [B40], the EMI magnitude can vary by a factor of 10 over a distance of 10 ft.

As a result of this field research, testing requirements have been established that include 8 dB of margin over the worst case threat. Equipment being qualified for nuclear safety-related use is required to meet emissions and susceptibility requirements, while equipment for non-nuclear safety use must meet emissions requirements only. The qualification testing for equipment is quite involved and is done in such a manner as to actually replicate the intended field installation. These qualification tests have been established to clearly define what is required to meet the established EMI limits, including margin. The qualification criteria may not reflect what is necessary in order for the equipment to function properly in its specific environment.

6. Signal cable shield grounding

6.1 Cable shield requirements

Cable shields are grounded for safety and to provide bi-directional attenuation of far-field and near-field EMI on the shielded path. They are also grounded to maintain the shield at the same potential as the circuit common at a specific point in the circuit, usually at one end. The exact physical location of this ground connection(s) will be dependent on the source of significant EMI and the most sensitive part of the circuit. Typically, the most sensitive part of the circuit will be at one of the ends of the cable.

Cable shield grounding practices that are effective for low-frequency interference are not generally effective for high-frequency interference, and practices that are effective for high-frequency interference may create low-frequency problems. Therefore, it is important to understand not only the various sources of EMI to which a circuit will be subjected, but also the advantages and disadvantages of each type shield grounding.

6.2 Analysis of shield grounding practices

In order to properly evaluate shield grounding practices, it is first necessary to understand how the various forms of EMI interact with unshielded circuits. Subclauses 6.2.1 and 6.2.2 will address these noise coupling mechanisms. Some circuit configurations such as those that utilize unbalanced circuits can effectively negate some of the intended protection methods. Selecting a particular type of cable shielding requires that the specific configuration details and functionality of the circuitry being connected is understood. Simply utilizing one type of shielding practice for similar types of circuits connected to equipment from different manufacturers may not produce a similar result.

Electrical noise is normally introduced into the signal circuits through capacitive coupling (4.2.3), inductive coupling (4.2.4), and conductive coupling (4.2.5). Some of the most effective means to reduce these noise signals are shielding and twisting of signal leads, proper grounding, and physical separation of the I&C circuits from the noise source. The purpose of the shield is to reduce the magnitude of the noise coupled into the low-level signal circuits by electrostatic or magnetic coupling. The shield may also be considered an envelope surrounding a circuit so as to reduce this coupling.

6.2.1 Shielding for electrostatic coupling

Figure 16 shows an unshielded circuit without twisted wires subjected to capacitively coupled noise. The external noise source couples the noise into the signal wires through capacitances C_1 and C_2, and the resulting flow of current produces a noise voltage signal across R_L. The noise voltage is proportional to the length of the leads, the impedance of the leads, the amplitude and the frequency of the noise signal, and the relative distance of the leads from the noise source.

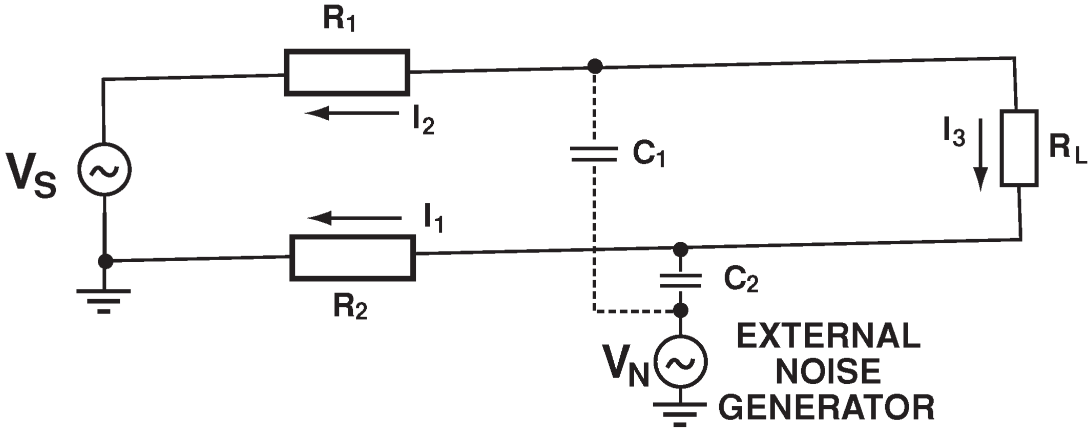


Figure 16—Unshielded, non-twisted control cables subject to capacitively coupled noise

Noise created by electrostatic coupling can be reduced by the use of shielded wire, by separation, and by the twisting of leads. The use of a cable shield is illustrated by Figure 17. The noise-induced currents now flow through the shield and return to ground rather than flowing through the signal conductors. With the shield and signal wire tied to ground at one end, there is no potential difference between the wires and the shield so that no signal current will flow between the conductor and the shield.

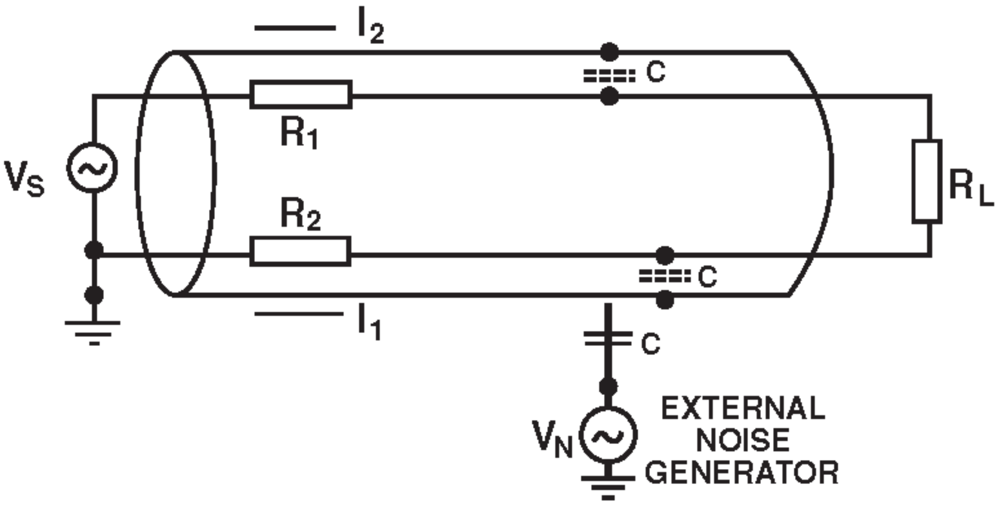


Figure 17—Shielded, non-twisted control cables subject to capacitively coupled noise

Not illustrated in the Figure 17 are the benefits from physical separation and the twisting of leads. Physical separation between the signal conductors and the noise source will reduce the noise coupling. Twisting of the leads provides a balanced capacitive coupling that will also reduce the noise level.

6.2.2 Shielding for inductive coupling

Inductive coupling is the electrical property that exists between two or more conductors, such that when there is a current change in one conductor, there will be a resultant induced voltage in the other conductor. Figure 18 shows a noise source conductor inductively coupling a voltage signal into the signal conductors. The alternating magnetic flux from the disturbing conductor induces a noise voltage in the signal loop that is proportional to the frequency of the disturbing circuit, the magnitude of the disturbing current, and the area enclosed by the signal loop. The noise voltage is inversely proportional to the square of the distance from the disturbing conductor to the signal circuit.

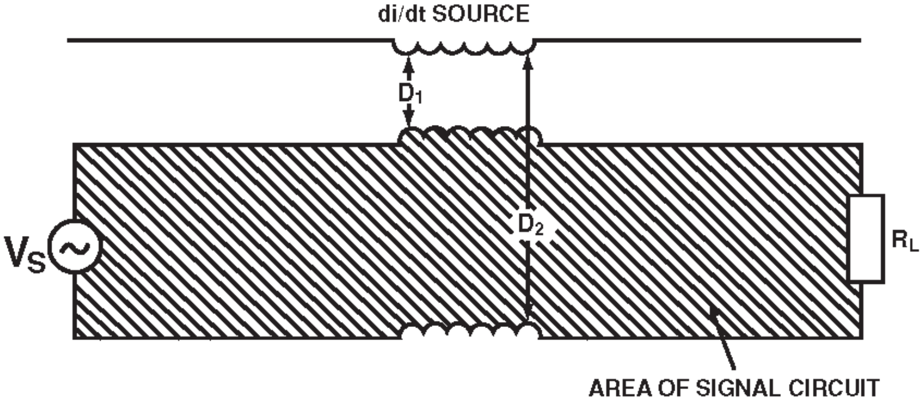


Figure 18—Inductive noise coupling

For low-frequency circuits where ground loops are a known concern, common-mode rejection ratios of up to –60 dB (1000:1) can be achieved by using twisted-pair cables feeding balanced loads. By symmetrically twisting the signal conductors, a series of differential-mode noise canceling adjacent loops are formed in the circuit rather than one large asymmetrical loop that would be formed by using two somewhat parallel conductors. Any changing magnetic field that goes through both loops of the symmetrically twisted-pair cable will tend to be canceled since the currents induced by the magnetic fields into adjacent loops in each wire are in opposite direction.

The shorter the lay (twists per unit length) of the twisted pair, the greater the noise reduction and the higher the frequency at which the twisting may be effective. Since shorter loops are more costly to manufacture, the nature of the known threat and the criticality of the circuits needs to be known in order to achieve a good compromise between shielding effectiveness and installation cost.

Twisted pair cable may be effective in reducing capacitive common-mode coupling to differential-mode amplifiers by insuring that any coupled common-mode noise is also balanced. Protection must still be provided for the residual common-mode noise which results from whatever unequal coupling exists in the cable from asymmetrical twisting, manufacturing tolerances, or method of termination. Twisted pair cable provides no significant benefits in reducing common-mode effects resulting from capacitive coupling to circuits which are grounded or unbalanced. Figure 19 illustrates the benefits of twisted signal conductors.

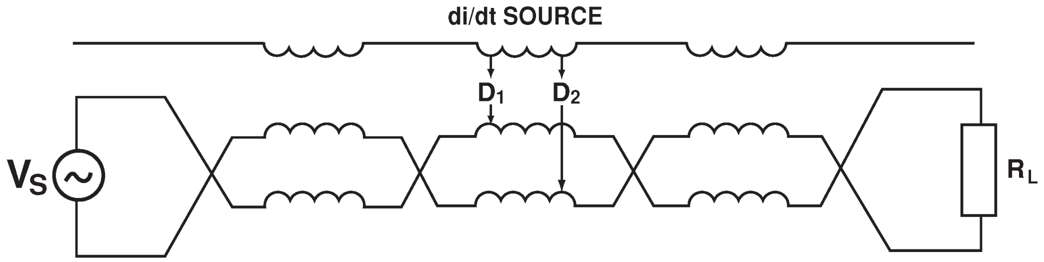


Figure 19—Reduction of inductively-coupled noise by twisting of wires

Inductive coupling can also be reduced by utilizing a shield around the signal wires. The shield becomes effective because the magnetic field produces eddy currents in the shield, which oppose the original magnetic field. The shield can be either magnetic or non-magnetic depending on the type of noise reduction desired as discussed in 4.3.3. Figure 20 illustrates the reduction of magnetic coupling by the use of a shield.

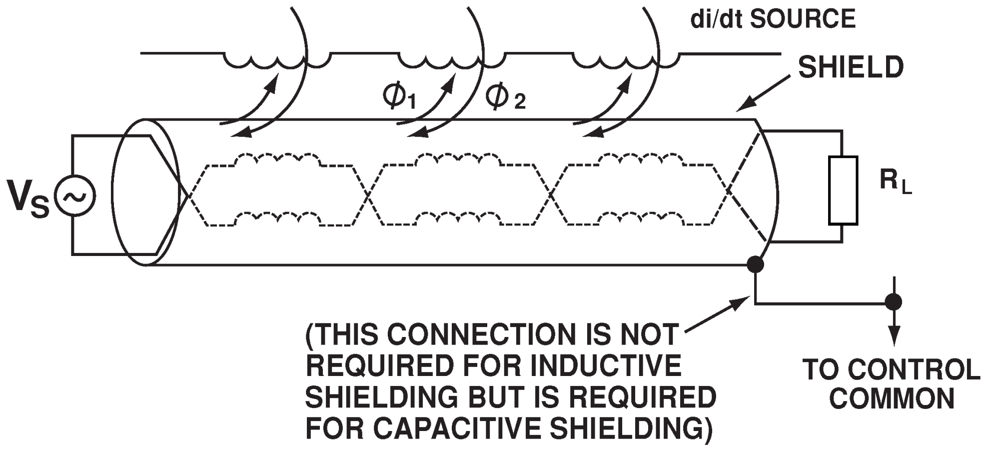


Figure 20—Reduction of inductively-coupled noise coupling by shielding

6.2.3 Unshielded twisted pair circuit grounded at a single point

The previous clauses examined the theoretical improvements that shielding could bring to a circuit in eliminating electrical noise generated by either capacitive or inductive coupling. Figure 21 represents a real-world situation where an unshielded twisted pair circuit is subjected to both inductive and capacitive coupling from an external conductor as well as conductive coupling interference from a ground potential difference of V_N. Capacitive coupling imposes the interference currents I_N from the ground potential difference onto the signal conductors to cause CM noise. Since the signal source is grounded at one end (an unbalanced circuit), the twisted pair circuit will provide little or no protection against capacitive coupling at low frequency since, although there is induced current in each of the conductors pairs, only one of these currents flows through the load resulting in the generation of DM noise V_{DM}. Additional CM noise can be induced in the signal conductors by the inductive coupling from the external conductor. Besides creating differential-mode noise through common-mode noise and unbalanced circuits, the inductive coupling may also cause a differential voltage to be induced directly into the circuit if the conductor pair is untwisted or asymmetrically twisted in areas of high magnetic flux. This can often occur at the cable terminations where the pairs are untwisted.

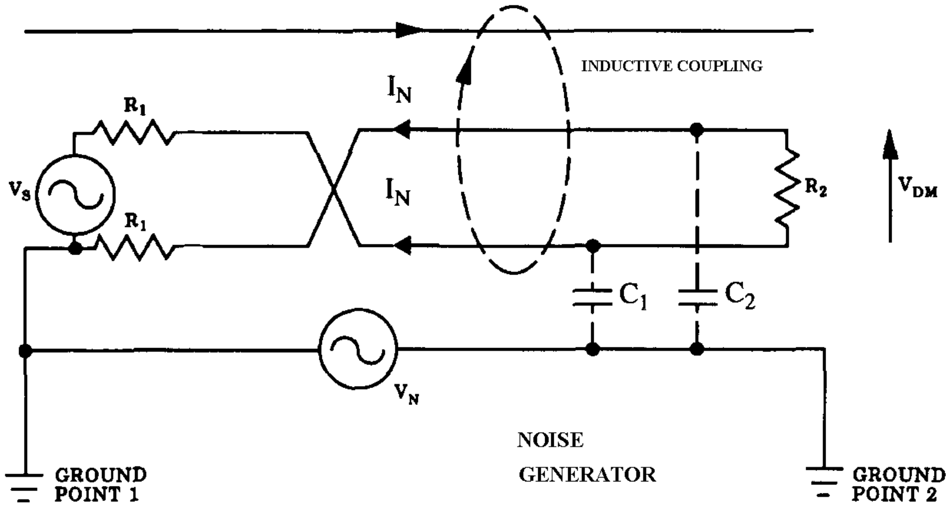


Figure 21—Twisted-pair control cables without shield

6.2.4 Shielded twisted pair circuit grounded at a single point

The arrangement in Figure 22 considerably reduces capacitive coupling for low-frequency circuits. Since the shield is held at the same relative potential as the grounded circuit reference, external voltage sources cannot couple to the shielded circuit. The interference current I_N is conducted along the shield to the common ground point.

Grounding the shield at one end creates a capacitive voltage divider action involving the shield and the distributed capacitance between the shield and the contained conductors. In this case, the externally applied EMI is coupled capacitively to the shield in a distributed fashion. Hence, the low impedance of the shield to the grounded end is a prime factor in determining how well the voltage divider action will perform.

Grounding the shield at one end also eliminates low-frequency ground loop problems, which are a known source of startup and operational problems for control systems. Although effective in eliminating ground loops, it is not effective when high-frequency interference is present. If the circuit length becomes a significant fraction of a wavelength at the EMI frequency, the ability of the shield to beneficially function is defeated since it appears as an extremely high impedance (worst case conditions are at 1/4λ). Shields begin to lose their effectiveness at 1/20λ, and by the time the length reaches the 1/4λ the protection is considered lost.

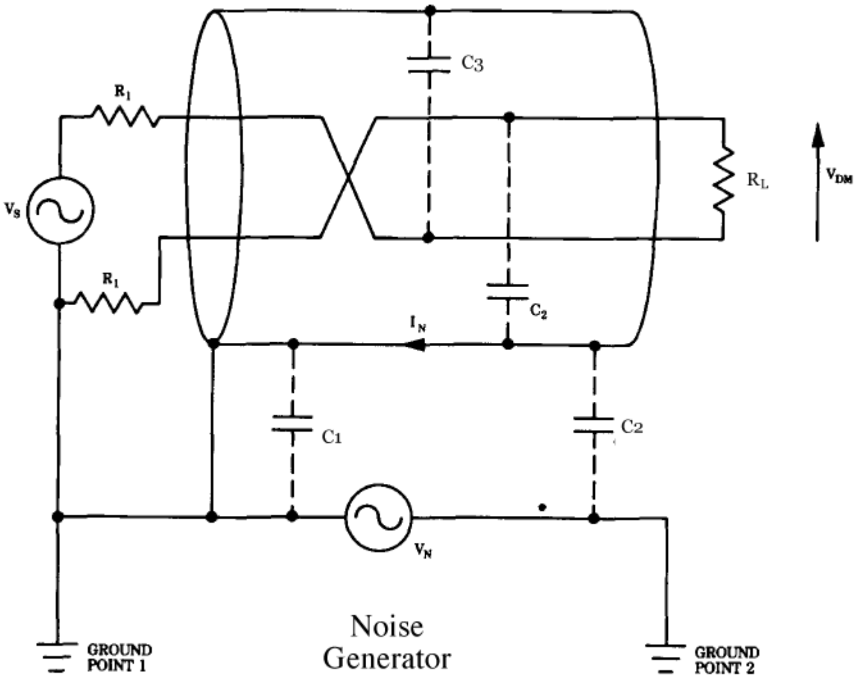


Figure 22—Shielded circuit grounded at one end

The common-mode voltage, as before, is equal to the ground voltage V_N. However, with very high interference frequencies, the inductive properties of the shield must be considered as adding series impedance and noise V_N can directly couple through C_1 and C_2 to the shield and then through C_3 and C_4 to the signal conductors.

Figure 23 shows two examples of single-point grounding. In both cases, the shield is grounded at the signal source point and left floating at the receiving point. This concept of grounding a shield only at the signal source is the ideal method for minimizing low-frequency noise pickup caused by ground currents. Grounding the shield at more than one point will allow ground currents (typically dc, 60 Hz, or lower harmonics of 60 Hz) to flow on the shield and these currents can interfere with intended circuit, as well as possibly other circuits. The shield must be grounded to the circuit common to be effective.

At low frequencies, connecting the cable shield to ground at only one end is sufficient to ensure that both ends are at the same potential as the circuit common. While the location of this specific ground connection is normally not critical and is generally at the signal source, it is preferred to make this connection at the same place where the circuit common is connected to safety ground. If the shield has a high capacitance to ground at some point, this may cause circulating currents to flow at low frequencies. In this case, it is best to make the ground connection at the point of high capacitance.

In general, on long cables there is no way to ensure that both ends of the cable shield are maintained at the same relative potential as circuit common. The ungrounded end of any shielded cable may pose fire and shock safety hazards if the cable should somehow become energized.

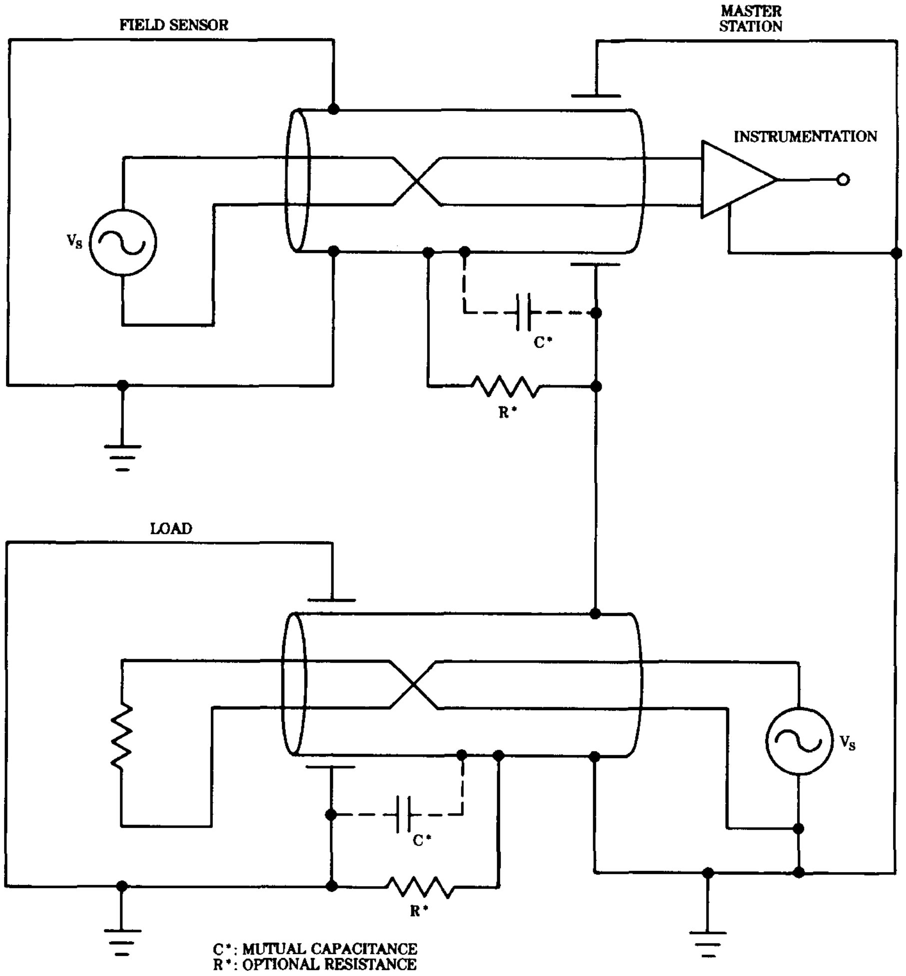


Figure 23—Shield grounded at signal source

6.2.5 Shielded circuit grounded at both ends

The ideal shield ground configuration is shown in Figure 24. For no shield current to flow in this configuration, Location 1 and Location 2 must be at the same relative potential.

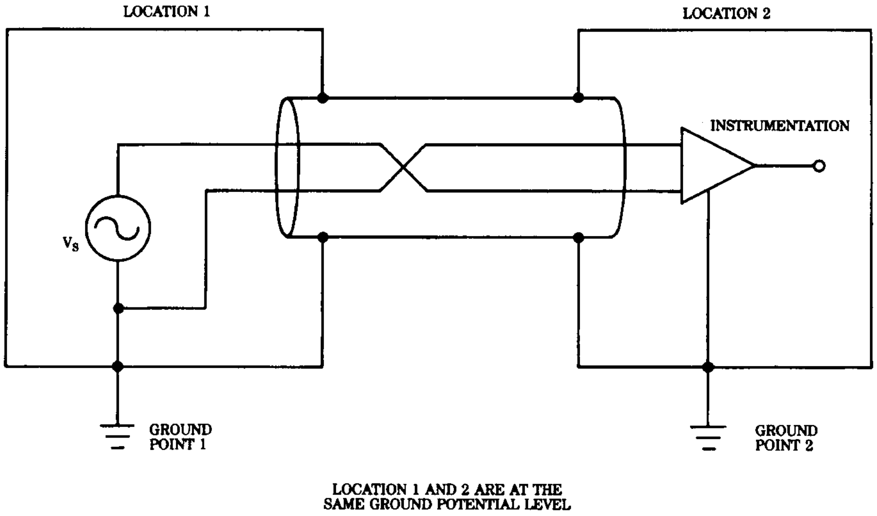


Figure 24—Shield grounded at both ends-ideal

The actual grounding configuration is shown in Figure 25. In this configuration, the voltage difference between Location 1 and Location 2 is a common-mode voltage (V_{CM}), which causes current to flow through the cable shield. At the cable termination points where the signal conductors are outside of the shield, the shield current may also inductively couple to both signal conductors and cause DM noise. Therefore, the input circuits may have to process both the signal voltage and a differential-mode voltage (V_S and V_{DM}). As long as both signal conductors are contained within the cable shield, inductive coupling from the shield current is negligible because the magnetic field within a conductor is zero and the shield looks like a solid conductor due to skin effect.

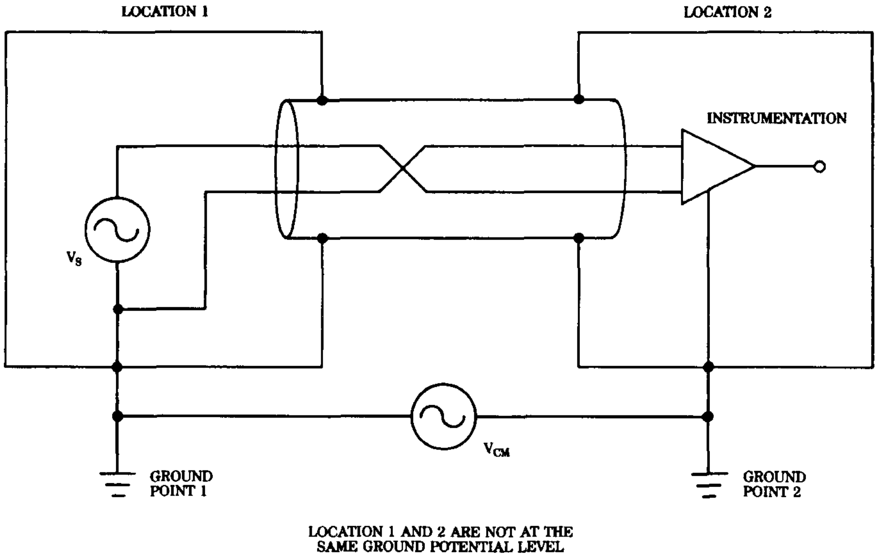


Figure 25—Shield grounded at both ends - actual

A disadvantage of this method is that it can provide a path that creates low-frequency ground loops with corresponding signal degradation.

At high frequencies, the shield may become a relatively efficient antenna, so connecting both ends of the shield to ground will reduce the antenna pickup or emissions. However, connecting the shield to ground at both ends will sometimes allow detrimental dc and low-frequency ground currents to circulate in the shield. Methods to mitigate this are discussed in 6.2.7.

Multiple-conductor cables with individual shields for each twisted pair may have individual shield ground points if they are individually insulated from one another. If a shielded twisted pair is part of a cable bundle that must go through a connector, separate pins should be provided for each shield and the pins should be configured to balance the coupling from the shield to each signal conductor so the net effect is zero. The pin assignments of the shields and signal conductors have a major effect on crosstalk problems. It is poor practice to attempt to combine more than one shield onto the same connector pin since this will increase crosstalk problems and reduce the effectiveness of the shields.

6.2.6 Shielded circuit grounded at multiple points

At high frequencies, connection of the shield to ground at multiple points rather than just at the ends may be required to prevent resonance effects. Although multiple ground points can be effective, grounding a shield at intermediate points increases the possibility of cable damage during installation and may make the cable more susceptible to moisture damage. This may not be a problem, however, if at intermediate points on the cable there are connector sets in place that have been installed to allow cable extension, patching, or splicing because the cable could not be installed in an unbroken length. In this case, one of the connectors may be bulkhead mounted on a grounded plate and this can provide a good means of intermediate cable shield grounding. If installed outdoors or in a hostile industrial environment, such a point on the cable system should be created inside of a suitably rated protective enclosure.

For shielded cables with bi-directional signals where the logical elements are mirror images of one another at opposite ends of the cable, the shield should be grounded at both ends.

In locations where there may be a significant noise source in one area, it is advantageous to make the ground connection as close a possible to this point of maximum noise. In cases where the cable length may be starting to approach $1/20\lambda$ of the EMI frequency, it may be necessary to use additional ac bypass/ground connections along the cable's path to break it up into shorter lengths relative to the EMI's frequency. These may be formed by placing 0.01 to 0.1 microfarad, low inductance capacitors (with low inductance lead lengths) at appropriate points along the cable from the shield to local reference. In such a case, start out by placing the ac ground connection at the control room end and place the dc ground connection at the remote end.

6.2.7 Achieving the advantages of grounding a shield both at only one ends and at both ends

The advantages of grounding a cable shield at one end can be combined with the advantages of grounding the cable shield at both ends. This is done by solidly connecting the cable shield to ground at one end as described above and connecting the other end to ground through a capacitor. At low frequencies, the capacitor behaves as an open circuit, while for higher frequencies the capacitor will behave as a short circuit. This is depicted by Figure 26. Also shown in Figure 26 is the optional connection of surge suppression in parallel with the capacitor.

Typical values to use in this application would be a 0.1 to 0.01 microfarad, low inductance capacitor. This represents a grounding reactance of about 26.5 kΩ at 60 Hz for the 0.1 microfarad capacitor and 265 kΩ for the 0.01 microfarad capacitor. This is essentially an open circuit that maintains the protection against low-frequency ground loops. At 6000 Hz, the 0.1 microfarad capacitor provides a grounding reactance of 265Ω and the 0.01 microfarad capacitor a grounding reactance 2.65 kΩ. However, for EMI at a frequency of

1 MHz the 0.1 microfarad capacitor provides a grounding reactance of 1.59 Ω and the 0.01 microfarad capacitor a grounding reactance of 0.159 Ω. Therefore, it can be seen that high-frequency EMI can be controlled at the same time as dc and low-frequency EMI, and that detrimental shield currents can be essentially reduced to negligible values in practice.

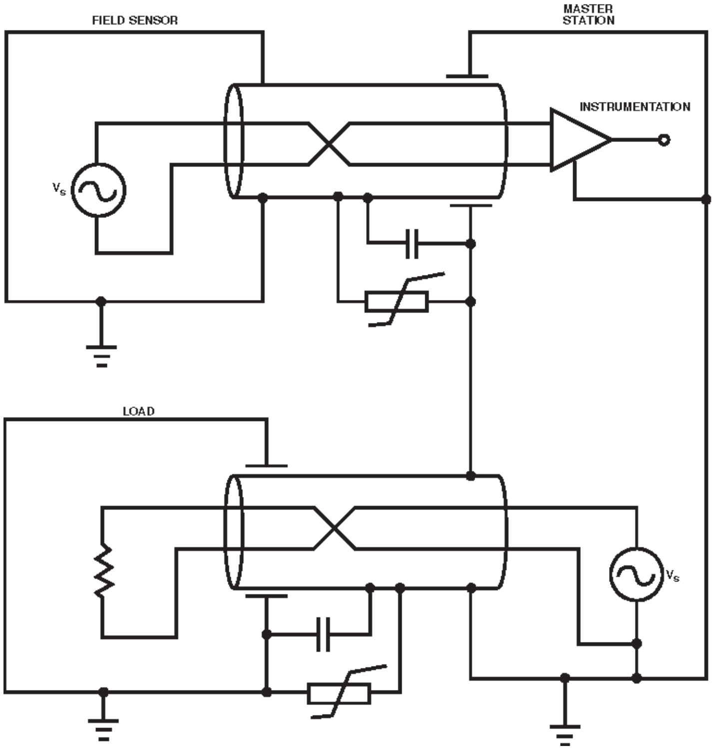


Figure 26—Combination of shield grounding at one and both ends

In the event that surge protection remains a concern even with attempts at correct capacitor value selection, the capacitor providing the best compromise operation may be left installed and then be paralleled with a surge suppression device such as either a stack of back-to-back connected rectifier diodes or a suitable avalanche diode. The number of diodes in the stack are selected to produce a forward voltage drop sufficient to give a stand-off voltage to the EMI on the path while clamping the voltage to a low value once they conduct under high amplitude EMI or surge conditions such as faults or lightning. Gas tubes are not used for this purpose as a result of their high ionizing potential prior to conduction of typically 60–80 V and a relatively high conducting voltage of around 15 V.

6.2.8 Double shielding

Cables with individually shielded pairs and an overall cable shield can utilize both grounding methods for better shielding effectiveness. The individually shielded pairs can have their shield grounded at one end for low-frequency EMI protection while the overall shield can be grounded at both ends to protect the individually shielded pairs from high-frequency interference. Practical disadvantages of this method are additional cable cost and difficulty in ensuring consistent and proper field installation.

In large installations it is common to find combinations of shielded cable types. Large multiconductor cables with individually shielded pairs and an overall shield are routed from the central control system to a field junction box, and then individually shielded pairs are run from the junction box to the end devices.

Rather than utilize cables with multiple sets of shields, an effective overall shield can be installed in the form of a grounded metal conduit/raceway system, which is continuously grounded along its length. Such an installation also provides a generally beneficial and somewhat evenly, distributed capacitive coupling between the shield and equipment ground, which helps to keep resonance problems minimized in most cases. With the raceway grounded along its length and providing an effective shield from external interference, the cable shields can then be grounded at one end. Use of magnetic conduit greatly enhances the shielding from inductive interference.

6.2.9 Balanced circuits

For the common-mode rejection of EMI from ground loops to be effective, the terminal impedance and the pair must both be balanced and symmetrical to ground. This implies that if the circuit is to be grounded, it must be center grounded as shown in Figure 27.

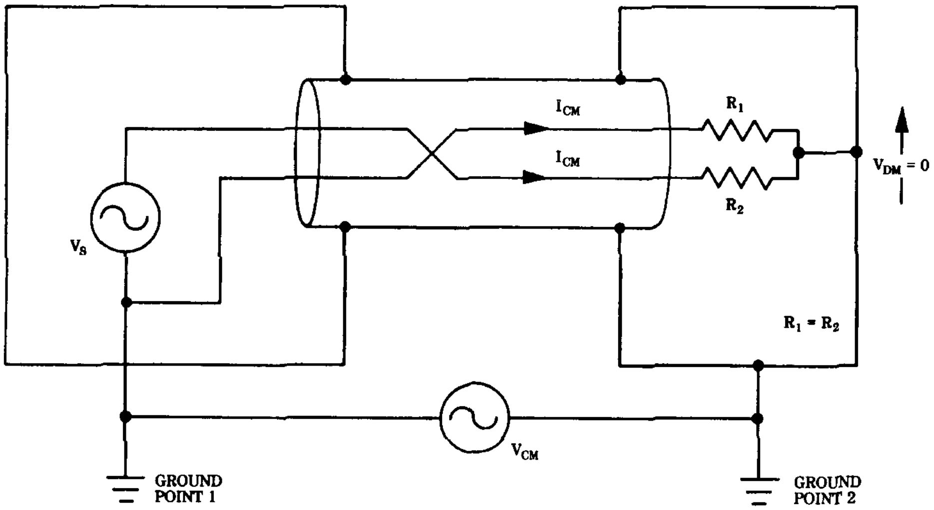


Figure 27—Common-mode rejection with balanced circuit

For a circuit that has been grounded on one side of the twisted-pair, approximately one half of the common-mode current must flow directly through the load while the remaining amount flows in the grounded path. This reduces the common-mode rejection from about –60 dB (1,000:1) to –6 dB (3:1) by the creation of differential-mode noise. There is, therefore, little benefit from using a twisted pair if the circuit is unbalanced by connecting one side to ground as shown in Figure 28. Also, there is still no protection offered by this arrangement to capacitively induced common-mode currents or voltages in the twisted pair. Such common-mode problems can cause poor circuit operation, or possibly voltage or current breakdown of circuit elements at either end of the cable, particularly when subjected to severe transients such as lightning. This emphasizes the need to understand the specific circuit configurations when selecting a cable shield grounding practice. Different I/O cards from the same or different manufacturers may require different shield grounding practices to be utilized.

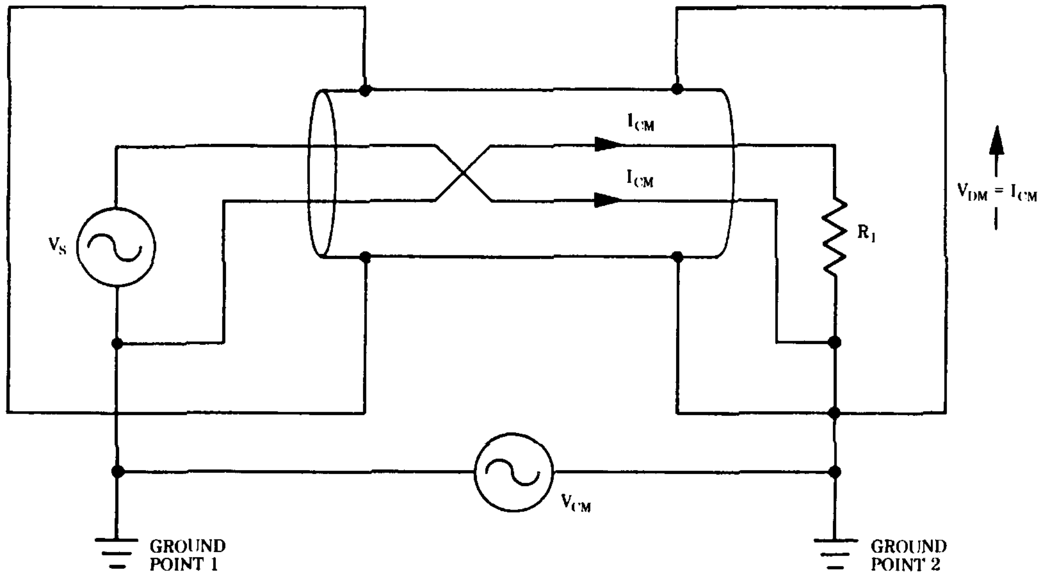


Figure 28—Common-mode rejection nullified by ground

If balanced grounding is not a viable option, it may be better to galvanically float the receiver at its enclosure to increase the ground loop impedance and lower the common-mode current in the twisted pair, This action, however, replaces the galvanic connection with a stray or parasitic capacitance coupling mechanism between the enclosure and the “floated” item(s) inside of it. This can produce new problems that are worse than the existing problem. Floating ground systems are generally not recommended as discussed in 5.2.3.

6.2.10 Coaxial cable

Coaxial cable can be used to transmit signals of all frequencies. It is particularly useful for signals above 300 kHz. Upper limits on frequency are in the range of a few-hundred megahertz where cable losses appear to be the limiting factor. In this type of cable, the inner-surface of the outer conductor (shield) acts as one of the two conductors for the signal. It also provides an EMI path on its outer surface by taking advantage of skin-effects to keep the signal and EMI current separate in the shield’s cross-section. Since the two signal conductors have the same axis (coaxial), the net magnetic flux created external to the cable by the signal process current is zero and likewise the net voltage induced in each conductor due to an external magnetic field is zero.

The particular frequency below which a shield will offer practically no useful attenuation is termed the cut-off frequency and is defined as:

$$f_c = R_s / (2pL_s) \tag{5}$$

where:
R_s = Shield resistance,
L_s = Self-inductance of the shield.

Cutoff frequencies for standard coaxial cables range from 0.5–10 kHz, and this range is directly related to the length of the subject cable as well as its construction characteristics. For example, very short coaxial cable with heavy-wall copper shielding will operate at lower frequency than a longer one with thin-wall shielding.

As the frequency increases above the cutoff frequency, the shield offers increasing attenuation. The improvement in shielding effectiveness results from the reduction in loop area caused by current returning on the shield rather than via the external ground plane established by the site's grounding system, and not by any magnetic shielding properties of the shield itself. At higher frequencies, coaxial cable will begin to look like triaxial cable when the skin depths on the inner and outer surface of the shield do not overlap and the signal process current flows exclusively on the inner surface of the cable's shield. This is the ideal point of operation for coaxial cable.

For coaxial shielding to be effective, the shield must be properly terminated and the center conductor must be kept in the center. The practice of twisting the braid of a coaxial cable and point soldering it to the base of a connector or other termination point will cause currents that were flowing symmetrically on the coaxial outer conductor to become asymmetrical at this point and possibly couple to the signal conductor that was previously centered. This may result in a –20 dB (10:1) or more degradation in the effectiveness of the shield at high frequencies. These "pigtail" terminations also act as antennae and can both radiate and receive EMI in the local area in which they are installed. Finally, such asymmetrical terminations of the cable's end cause an impedance "bump" in the cable, which will cause reflections of the transmitted signal to occur on the signal path with associated standing wave resonance problems, including possible dielectric failures on higher power circuits. This impedance mismatch, therefore, degrades the signal process and may introduce data transfer errors. Accordingly, the braid should be soldered or connector terminated so that it completely and symmetrically encloses the inner conductor at the connection junction and does so with minimum impedance change.

Sharply bending a coaxial cable will displace the center conductor and also cause coupling from the outer conductor to the now displaced center conductor. The maximum possible bend radius should be used when routing coaxial cable. In general, the minimum bend radius should never be less than 10 times the nominal diameter of the cable.

At lower frequencies, if the cable has multiple ground connections, the return current may travel externally between the cable's ends via the site's grounding system rather than through the shield. This unwanted action creates magnetic fields in unknown areas outside the coaxial cable. In the vicinity of the coaxial cable, the signal and return currents are no longer equal and there is now a net magnetic flux created in this area also. A coaxial cable carrying low-frequency signals will not retain its immunity to external fields since any disturbance of the cable's unbalanced fields will now concurrently disturb the contained signal process as well. Also, the circuit will have a second loop through the ground connection, which may have significant induced voltage. Therefore, with low-frequency signals the non-ferrous metal shield of a multiple-grounded coaxial cable offers practically no H-field shielding. This is particularly a problem with audio and video baseband signal processes.

6.3 Other cable shielding considerations

a) Connecting the spare conductors in a cable to ground at both ends has been found to increase the shielding effectiveness of the cable by increasing the amount of grounded metal appearing as a shield, as well as reducing the EMI resulting from parasitic oscillations occurring in the many radiating dipoles that these ungrounded conductors create as a result of the distributed stray LC products. This latter effect is important because of the close proximity of these conductors to the active signal conductors in the same cable. Grounding the spare conductors at each end can also increase low-frequency ground loop problems.

b) If the control cables are being laid in a cable trench, additional low-frequency magnetic shielding of the cables can be provided by running a 4/0 ground grid conductor either inside or on top of the trench. Trenches represent known serious EMI and surge current coupling possibilities. This is generally the result of two often interrelated effects: (1) use of non-metallic conduit or raceway and; (2) tight spacing between the victim and aggressor cables, which results from the need to keep the trenching operation minimized. A known example of this unwanted situation is where a single narrow trench is prepared and then plastic conduit enclosed power conductors to a large motor are buried alongside, above, or below the victim signal circuits, which are also plastic conduit encased. This provides serious EMI and transient voltage or current coupling between the two circuits. Possible solutions are widely separated trenches, and heavy-walled, ferrous metal conduits with anti-corrosion coatings on them.

c) In areas of extremely high voltage such as 230 kV and above, it has sometimes been found necessary to shield not just the I&C circuits, but also all power circuits as well, including lighting and station 120 V service. Operating problems have been caused by high-frequency transients propagating along these paths.

d) Local instrument grounds: Instruments that have grounded connections should have their cable shields connected to the instrument common (ground) as close to the instrument's equipment safety ground as possible. Some trade-offs associated with this recommendation are discussed in 6.5.1.2. Thermocouples (both grounded and floating), RTDs, and other instruments that have grounded inputs should be grounded in this manner. Continuity of the shield should be maintained from the sensor connection to the receiver, and the shield should be isolated from ground except at the point of connection that is usually the signal source (the thermocouple or RTD). This is illustrated in Figure 29.

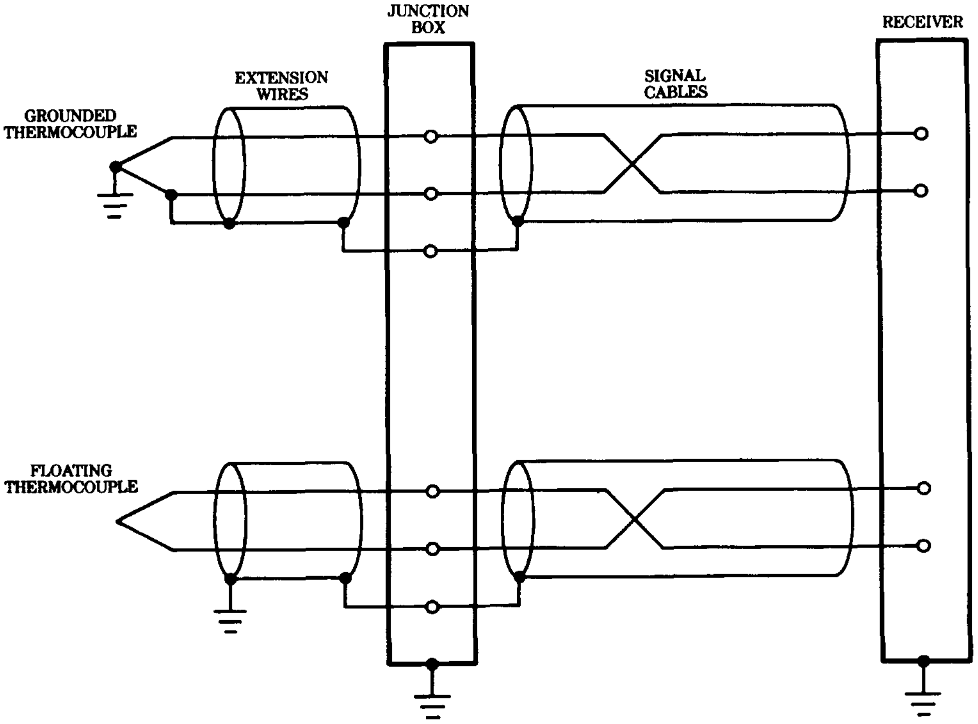


Figure 29—Examples of locally grounded instruments

e) Floating grounds: Signals that are floating (ungrounded) should have their cable shields connected to safety ground as close to the source as possible. Transmitters, isolation amplifiers, and all ungrounded inputs should have their cable shields grounded in this manner. This is depicted by Figure 30.

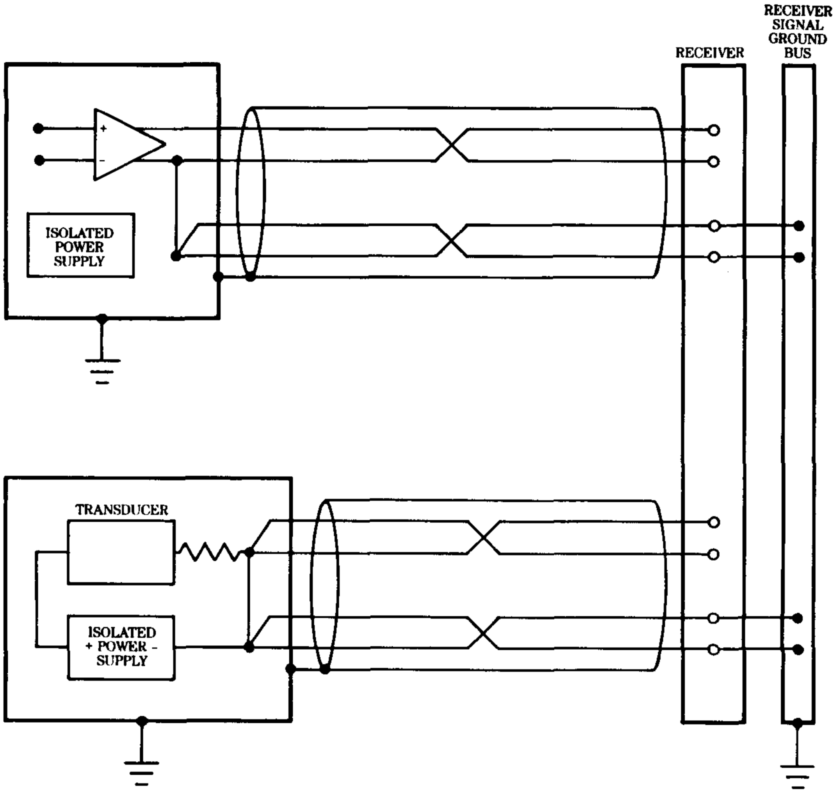


Figure 30—Examples of floating instrumentation loops

f) Differential drivers and receivers: Differential amplifiers, drivers, and receivers may be designed to operate with safety ground connections to separate ground references that may be at different relative potentials. The shield should be permanently connected to equipment ground at the point of maximum capacitance to prevent a capacitively coupled ground loop from forming between the shield connection to ground and the stray capacitance. The point of maximum capacitance is often at the signal source. When both sides are grounded to different reference points, there are two separate shielding enclosures and the differential transmitter and receiver circuits should be rated to withstand the difference in voltage level between both reference points, unless a transformer is the only coupling device used. In this case, one of the grounds may be floated to reduce EMI problems, at the risk of creating a safety problem. A safety switch allows personnel to work on the system without any safely implications.

6.4 Comparison of cable shielding effectiveness

The following table is a comparison of the magnetic and electric shielding effectiveness of various cable systems from Van Doren [B39].

Table 1—Comparison of cable shielding effectiveness

	60 Hz Magnetic field attenuation	100 kHz Electric field attenuation
Cable type	(dB)	(dB)
Parallel wires in air	0 (Ref.)	0 (Ref.)
Twisted pair (9 turns/m)	23	—
Twisted pair (36 turns/m)	43	—
Copper-braided coax (85% coverage)	—	40
Spiral-wrapped copper tape	—	51
Parallel wires in aluminum conduit	3.3	66
Parallel wires in electrical metallic tubing (ferrous)	16.5	70
Parallel wires in rigid galvanized	32	79

6.5 Common practices in shielding cables for distributed control and programmable logic controller circuits

From industry-wide surveys that have been conducted (see [B1] and [B33]), general practices for the grounding of I&C cable shields are evident. It is important to note that there is not universal agreement on every aspect of cable shielding, so the following information must always be utilized after careful consideration for each specific installation. This information is provided to show generally accepted practices utilized by the industry. Even though it is possible that some survey respondents may have reflected practices which predate electronic I&C systems, it is felt that the survey results do reflect appropriate methods for the I&C systems being installed in the mid-1990s. Also note that since over 90% of the cables associated with a typical distributed control system or programmable logic control system carry dc or low-frequency signals, that this is reflected in the following recommendations.

A slight preference in aluminum over copper as the shield material was indicated, with most agreeing that the shield should not be used a signal return path.

The following subclauses discuss the type of signal as well as the source of the power for the signal. Some circuits receive their power directly from a DCS or PLC logic card, while some may receive their power from a separate power supply, which may or may not be located within the DCS or PLC equipment. For many types of DCS and PLC systems, the source of the circuit power is just as important in the type of signal in determining which type of input/output card to utilize. The following subclauses have, therefore, been formatted to group the recommendations into categories that are normally used in the design of DCS and PLC systems.

6.5.1 Analog signals

The vast consensus (over 97%) is that analog circuits must be shielded.

6.5.1.1 Analog inputs powered by a DCS or PLC

For this type of circuit, 46% of industry respondents utilize individually shielded pairs only, 12% utilize an overall shield only, and 39% utilize cables that have individually shielded pairs plus and overall cable shield. No cable shield was recommended by 3% of the respondents. The shield should be grounded at the DCS or PLC according to 90% of the respondents, while 10% would ground the shield at the field device.

6.5.1.2 Analog inputs powered by an external source

For this type of circuit, 46% of industry respondents utilize individually shielded pairs only, 12% utilize an overall shield only, and 39% utilize cables which have individually shielded pairs plus an overall cable shield. No cable shield was recommended by 3% of the respondents. The shield should be grounded at the DCS or PLC according to 79% of the respondents, while 21% would ground the shield at the field device. Compared to the previous item, the difference in where the shield is grounded reflects that a slightly higher percentage are grounding the shield at the field device since this is generally the best location according to theory. That the percentage acting according to ideal theory is not that large appears to reflect the practical difficulties encountered during installation and checkout if cable shields are grounded at different locations on a circuit-by-circuit basis. There are practical advantages for grounding all cable shields at one point, with experience showing that the few circuits that experience difficulties because of a uniform approach can be corrected during startup or early operation.

6.5.1.3 Analog voltage and current transformer inputs

The magnitudes of these signals are generally not directly compatible with the input ratings of DCS or PLC inputs and must be processed with a transducer. These would follow the same recommendations for other analog input signals, depending on whether the transducer is loop-powered or provided with an external power supply.

6.5.1.4 Analog outputs powered by a DCS or PLC

For this type of circuit, all of the respondents recommended utilizing shielded cables, with 45% utilizing individually shielded pairs only, 16%, utilizing an overall shield only, and 39% utilizing cables that have individually shielded pairs plus and overall cable shield. The shield should be grounded at the DCS or PLC according to 90% of the respondents, while 10% would ground the shield at the field device.

6.5.2 Digital (dry contact change of state) signals

Digital (discrete) information in this context refers to the monitoring of a contact change of state, which is typically done with a dc voltage. This should not be confused with high-frequency "digital" communications circuits, which are discussed in 6.5.3. The shielding recommendations for these two types of "digital" circuits are completely different, and the similar nomenclature has undoubtedly caused some confusion in the proper application of cable shield grounding practices.

The survey results show that approximately one-half of the respondents feel that there is no need for the shielding of these circuits. Since these circuits have a high signal-to-noise ratio it was expected that the percentage of respondents not shielding these circuits would be higher. Two items may account for the received response. The first is that the survey did not specifically differentiate the wetting voltage. Respondents who utilize a relatively low-voltage level such as 24 Vdc may feel that shielding is required. The second reason is that it is the practice of some utilities to utilize shielded cable for all DCS and PLC circuits as part of their standard practice since it has the practical benefits of materials standardization and ensures that installation crews recognize the special nature of these circuits. Some of these same utilities also have the practice of not terminating the shields at either end for digital input and output circuits since the circuit susceptibility is low and shielding is not required. One utility has even standardized on separate colored cable for digital inputs, digital outputs, analog inputs, and analog outputs. That way a quick glance can tell whether the circuit has been landed on the appropriate DCS or PLC input/output card. The advantages of this method come with the disadvantages related to consistency of application, material procurement, and warehouse costs.

6.5.2.1 Digital inputs wetted by the DCS or PLC

For this type of circuit, 43% of industry respondents felt that no shielding was required, 29% utilize individually shielded pairs only, 14% utilize an overall shield only, and 14% utilize cables that have individually shielded pairs plus an overall cable shield. The shield should be grounded at the DCS or PLC according to 86% of the respondents, while 14% would ground the shield at the field device.

6.5.2.2 Digital inputs wetted by an external device

For this type of circuit, 58% of industry respondents felt that no shielding was required, 18% utilize individually shielded pairs only, 12% utilize an overall shield only, and 12% utilize cables that have individually shielded pairs plus and overall cable shield. The shield should be grounded at the DCS or PLC according to 83% of the respondents, while 17% would ground the shield at the field device.

6.5.2.3 Digital outputs wetted by the DCS or PLC

For this type of circuit, 56% of industry respondents felt that no shielding was required, 20% utilize individually shielded pairs only, 12% utilize an overall shield only, and 12% utilize cables that have individually shielded pairs plus and overall cable shield. The shield should be grounded at the DCS or PLC according to 88% of the respondents, while 12% would ground the shield at the field device.

6.5.2.4 Digital outputs wetted by an external device

For this type of circuit, 59% of industry respondents felt that no shielding was required, 17% utilize individually shielded pairs only, 12% utilize an overall shield only, and 12% utilize cables that have individually shielded pairs plus and overall cable shield. The shield should be grounded at the DCS or PLC according to 88% of the respondents, while 12% would ground the shield at the field device.

6.5.3 Data highway/digital communication

For these circuits, it is recommended to follow the recommendations of the equipment vendor since each vendor has specific requirements regarding installation methods, cable types, and allowable circuit lengths. Depending on the specific installation, these circuits are typically either shielded twisted pairs, coaxial, or fiber-optic cable.

6.6 Central distribution frame (CDF) grounding practice

In order to minimize the impact of low-frequency EMI on I&C cables, the ideal practice is to ground all cable shields only at the signal source. This would, however, result in a widely distributed grounding system with the following disadvantages.

a) Increased difficulty of controlling shield grounding practices through both the design and construction phases, with experience indicating the likely introduction of numerous ground loops.

b) Substantial increase in commissioning time as a result of locating and remediating ground loop problems.

This CDF grounding approach creates a central grounded reference at, or close to, the plant control room. Combined with other practices of minimizing noise generation in a generating station, this system has been proven to provide protection that minimizes noise coupling to acceptable levels. More sensitive signal and processing systems can be treated separately with the shield grounded at the source end.

The CDF provides an ideal system to permit the termination of trunk cabling systems. It reduces the quantity and length of ground conductors when compared to other grounding practices. These advantages have resulted in substantial cost and schedule advantages in the construction of some commercial nuclear generating stations. It has not been employed in a greenfield generating station design utilizing a modern microprocessor-based distributed control system.

The CDF grounding method is illustrated by Figure C.13.

6.6.1 Principles of CDF grounding

A single large insulated ground conductor is brought directly from the station ground mat (separate from the building distributed ground system) to an insulated copper bus (typical cross section 25 mm × 6 mm) provided on the CDF. This would normally be in a control equipment room immediately adjacent to the main control center.

This bus would form the center of the signal ground and safety ground system for all field signals terminated in the local area and not grounded elsewhere, such as signals connected to the computer or sensitive signals grounded at the other end. Within each CDF area, the signal and equipment grounds may be kept separate up to the point where they should exit the area. Then they are connected together and to the ground mat connection.

An alternative ground bus could be created by applying sheet metal to the wall in the form of a ground-plane and to bring all cables to this point for shield grounding and surge suppression connections. The ground plane is then low-inductance grounded/bonded to the equipment grounding system in the same area; thus, minimizing potential difference between the two. The advantage of this type of ground plane is that it avoids the unintentionally high level of inductance that can result from the CDF cabling method. The cable impedance is not related to cross-sectional area as much as it is surface area, and a ground-plane has a better geometry to take advantage of this fact.

6.6.2 Auxiliary computer CDF grounding

It may be expedient to provide a separate but similar ground bus at the main computer for all field signals directly connected to the computer. This bus would be connected radially by an insulated ground cable from the primary CDF ground bus. This computer CDF would also serve as the central point from which each of the computer cabinet signal ground racks would be referenced.

7. Testing

7.1 General

This clause addresses testing to detect conductive ground loops on I&C circuits that may purposely or inadvertently use the ground system as part of the signal return path. Ground loops are discussed in 4.2.2, 4.3.3, 5.2.2, and 6.2. This clause does not address testing on those high-frequency systems where multiple-point grounding may be used, nor is it intended to be used to test ground systems that are not used for signal returns. Finally, the testing described herein is not full-range testing since it does not account for capacitively or inductively coupled ground loops that respond to changing voltages and currents.

In addition to the above, it must be understood that there are three classes of ground loop: (1) harmful or unwanted, and; (2) benign, in that they appear to have no effects, and; (3) beneficial ground loops such as those that carry surge currents, ac system fault currents, and prevent fires and shocks from occurring. Before embarking on any program to remove or otherwise eliminate any perceived ground loop, it is important to know which of the three types it is, and what will be the total range of effects if it is removed, not just a singular effect. A gain in noise reduction may result in the creation of a safety hazard under certain transient conditions

7.2 Sources of galvanic (conductive) ground loops

The primary sources of conductive ground loops are:

a) More than one ground erroneously placed at different points on a cable shield or signal return.

b) Shield and associated signal wires connected to ground at different locations. A ground loop will be formed through the ground points and the signal wire to shield capacitance.

c) Leakage paths caused by insulation failure, moisture, etc. Leakage paths from moisture normally occur at circuit devices, terminal strips, or connectors.

7.3 Galvanic ground loop prevention and detection

Ground loops are formed whenever two or more connections are made from different points in the circuit to the station ground system. Current flow between the ground points may occur from potential differences between the ground points, but even connections to the same ground point from different points in the circuit can create large loops that will be sensitive to inductive coupling.

Different points on the station grounding system may be at different voltages as a result of current flow through the grounding system. The currents may be the result of power system transients, lightning, or any of the sources listed in 4.1. As a result of these voltage differences in the station grounding system, conductive ground loops may provide a path for current flow through the I&C cable conductors and/or shield via the multiple ground points. This current flow may create CM noise on the signal circuit, and if strong enough, may cause failure of the circuit. It may also cause noise problems if the CM noise is converted to normal mode noise by the circuits and terminations.

The currents of interest in galvanic ground loop problems are most commonly 60 Hz or a harmonic of 60 Hz, with the third harmonic having been historically typical. This has been changing with higher order harmonics causing problems due to the proliferation of non-linear loads that generate higher orders of harmonic energy during their operation. Examples of this are phase-shift fired SCR loads and pulse-width-modulated driven equipment such as variable speed motor drivers.

The loop areas formed by connecting different points in the circuit to the same ground point will be sensitive to current surges flowing in any of the associated grounding wires running to the same grounding point and commonly bundled together.

To avoid ground loops in the initial installation, tests should be conducted to verify that ground loops do not exist. This may be accomplished as follows:

a) Where practical, before grounding shields, signal wires, etc., first make a crude go-no go check for isolation from ground using an ohmmeter. If no unintentional ground points are located, next use some other calibrated device specifically capable of measuring insulation integrity. The resistance between the wire or shield and station ground should be greater than 1 megohm. The substitution of signal generator for the insulation tester will indicate how much of a ground-loop exists as a function of frequency. This can provide a good indication of the importance of non-conductive paths.

b) Where low resistance indicates an improper ground, defective cabling, moisture, etc., the deficiency should be corrected. Only after the deficiency is corrected should the circuit, shield, etc., be connected to ground.

c) After all the equipment and instrument grounds are installed, the overall signal ground system should be checked as described in 7.4.

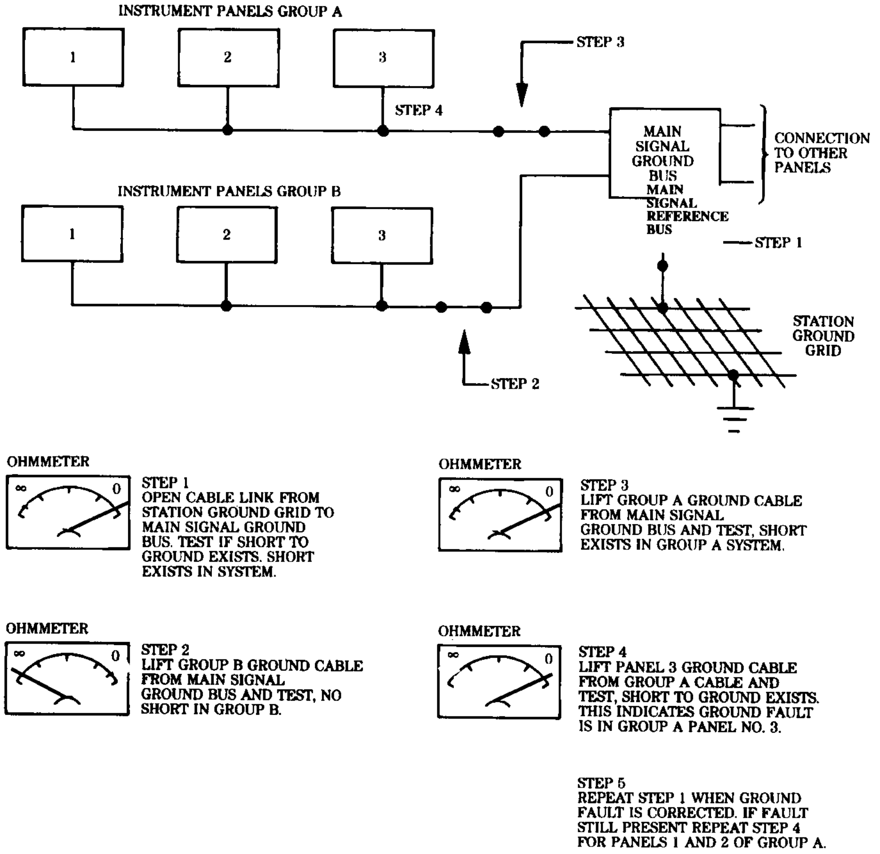
The above test will detect most conductive ground loops, except those formed when long cable shields and the associated I&C circuits are grounded at different locations. The capacitance between these kinds of lengthy shield and the signal wires will permit dc charging current from an ohmmeter and test frequency ac for insulation testers to flow through the cable to ground capacitance. This creates test problems that must be guarded against so that the results are not misinterpreted. The best way to avoid loops formed in this manner is careful design, construction, and field verification of the installation along with the use of experienced cable test personnel.

7.4 Testing for ground loops

Safety considerations.

It is not recommended practice to disconnect the sole equipment grounding conductor or to rely on a questionable equipment ground via a circuitous route during testing when power is still applied to the equipment. For example, in a properly grounded metal conduit containing an equipment grounding conductor, there is not a significant hazard in disconnecting the equipment ground wire or the conduit for testing, but not both at the same. Any disconnecting of grounding connections for the purposes of testing must be done with an understanding of the safety implications of removing a particular connection.

Ground loops formed by multiple direct, inductive (via a choke), or resistive ground connections to the station ground grid can be detected by the procedure described below and illustrated in Figure 31. It will not detect ground loops resulting from incorrect shield grounding as described in 7.2.



STEP 1
OPEN CABLE LINK FROM STATION GROUND GRID TO MAIN SIGNAL GROUND BUS. TEST IF SHORT TO GROUND EXISTS. SHORT EXISTS IN SYSTEM.

STEP 3
LIFT GROUP A GROUND CABLE FROM MAIN SIGNAL GROUND BUS AND TEST, SHORT EXISTS IN GROUP A SYSTEM.

STEP 2
LIFT GROUP B GROUND CABLE FROM MAIN SIGNAL GROUND BUS AND TEST, NO SHORT IN GROUP B.

STEP 4
LIFT PANEL 3 GROUND CABLE FROM GROUP A CABLE AND TEST, SHORT TO GROUND EXISTS. THIS INDICATES GROUND FAULT IS IN GROUP A PANEL NO. 3.

STEP 5
REPEAT STEP 1 WHEN GROUND FAULT IS CORRECTED. IF FAULT STILL PRESENT REPEAT STEP 4 FOR PANELS 1 AND 2 OF GROUP A.

Figure 31—Test for detection of ground loops

If no cabinet or device with low resistance is found, the signal ground cable from the main bus to the cabinet is probably shorted.

Once ohmmeter tests have been completed, the procedure should be repeated with a current limited, no more than 50 Vdc source and a milliammeter to detect high-resistance ground loops. This test should always use a current limited low-voltage source to avoid shock hazards.

Caution should be used in opening any ground circuit. Under certain conditions, dangerous voltages can appear across the open ground circuit. The ground cables should be treated as energized conductors until their potential has been verified by testing. Additionally, opening the ground circuit may change the current distribution in the overall grounding system and cause equipment misoperation. The possible impact on the system should be evaluated before opening any ground circuit.

In the case of operating systems, inadvertent ground loops can sometimes be traced to a particular system, panel, or group of circuits by analyzing the problems caused by noise coupled on the signal circuits. In this case, the test can be simplified to only include those panels or circuits under suspicion.

While the system is first being installed, it is desirable to insert removable links at various points in the ground system to facilitate future testing. If the panel grounds cannot be disconnected as described in the previous procedure and a noise problem exists as a result of ground loops, then some method of measuring noise levels must be utilized. This could involve a procedure as follows:

a) Measure noise current/voltage on I&C ground cables connecting the main signal ground bus to the station grounding system.

b) Measure noise current/voltage on cables connecting panels to the main signal ground bus.

c) Cables with noise current/voltage much higher than other cables may be shorted to ground.

d) Check the noise level on each cable connecting the panel to the faulted ground cable. Panel grounds with high noise levels should be checked.

e) Check the panel thoroughly and correct any inadvertent grounds.

This test is more effective if noise levels at various points are periodically monitored and recorded for future reference. When a problem occurs, the noise levels can then be compared with previously recorded values. However, note that it is normal for some current to flow in a ground system due to capacitive coupling between energized circuit conductors, ground conductors, and cable shields. Thus, the presence of voltage or current on an I&C ground cable does not necessarily mean a problem exists. Additionally, the absence of noise or no incorrect operation of circuits does not indicate the absence of ground loops or potential problems. Problems caused by intermittent noise sources, such as lightning transients and power system ground faults would be virtually impossible to locate during testing since the ground loops would only create a problem when a transient or power system ground fault occurred. Thus, noise measurement tests may not necessarily always be effective in locating unwanted ground loops and potential noise problems.

Noise measurements may, however, be useful in pointing to the cause. The frequency of the major noise components will point to the noise source. The presence of 60 Hz and its principle harmonics would indicate the power ground system as the source. For example, the presence of 180 Hz (the third harmonic of 60 Hz) would indicate a polyphase full-wave rectifier power supply as the probable source. Any relatively continuous high-frequency noise on a data system may be generated by corona discharge, phase-shift fired SCRs, and PWM controlled variable speed motor drives, or within the data system.

7.5 Signal ground system integrity

After initial installation, the following continuity/resistance measurements should be made:

a) Measure and log the resistance between the main signal ground bus and the station grounding system.

b) Measure and log the resistance between each cabinet signal ground point and the main instrument ground bus.

c) Compare the resistances to calculated or specified design goal values. If the resistances are high, check connections and correct any problems found. If resistance remains high, install larger ground cable, if required. Keeping ground conductors as short as possible is always advisable to minimize ground circuit impedance and thus limit noise voltage levels.

7.6 Maintenance of the signal ground system

Periodic inspections should be made of bolted connections to major signal ground buses. This check should include a visual inspection of all connections. Connections should be inspected for tightness and corrosion.

Annex A

(informative)

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Annex B

(informative)

Conformance with local safety codes

In the United States, specific safety codes include:

a) National Electrical Safety Code®, (NESC®) (Accredited Standards Committee C2-2002)
b) National Electrical Code® (NEC)® (NFPA 70-2002)
c) Occupational Safety & Health Act (OSHA), Subpart S
d) The specific codes and requirements of the jurisdiction where the equipment is to be installed.

Significant aspects of these design codes include:

1) The requirements for the equipment grounding system are controlled by the NEC. The full range of NEC requirements are mandatory in each state by legislation and are also required at the Federal level via OSHA Subpart S. Some exceptions for traditional vertically integrated utilities are granted; however, this is generally because it is assumed that the utilities are doing more than the minimum required by the code.
2) The ungrounded end of any shielded cable may pose a fire or shock safety hazard if the cable should somehow become energized. Typically this occurs from lightning or from accidental contact with a conductor from a higher voltage system. The latter situation is common with exterior run cables in industrial environments where electrical power lines are installed overhead. The NEC addresses this issue in detail and requires that no cable shield be permitted to enter a building from the outside without being grounded at the point of penetration. Surge protection of the cable's conductors is also required by the NEC to be applied at this same point which is called the demarcation point.
3) The grounding of all power isolation transformers that are part of a building power system or of unlisted electronic equipment of any kind is strictly controlled by the NEC in article 250, Grounding. In this context, any ac system (such as the one derived from an isolation transformer) that is capable of being solidly grounded so as to limit the available voltage to 150 Vrms or less to ground, are required to be solidly grounded. They may not be resistance grounded, impedance grounded, or ungrounded.
4) Since the NEC requirements are for purposes of protection from electrical fires and shock hazards, there are no exceptions to the requirements that relate to the operation of equipment or for reduction in electrical "noise." Floating any end of a cable and its connected circuitry is an NEC violation and could create a fire or shock hazard.

Additional discussions of installing I&C systems in accordance with the NEC are found in IEEE Std 1100-1999.

Annex C

(informative)

Examples of I&C grounding methods

This annex contains examples of I&C grounding in generating stations. Only a single example is given for each type of circuit and caution should be used in applying the illustrated concept to a similar circuit unless the actual circuit functionality has been carefully examined. Any given end device may be interfaced into a wide variety of circuits ranging from individually isolated input to circuits that share common return paths. Techniques that function well for one type of circuit may not function for other types of circuits.

On many of the following figures, the shields of single twisted-pair cables are shown connected together for clarity. In actuality, each shield would be terminated separately inside the nearest junction box and then jumpered to the shield of the cable on which it continued.

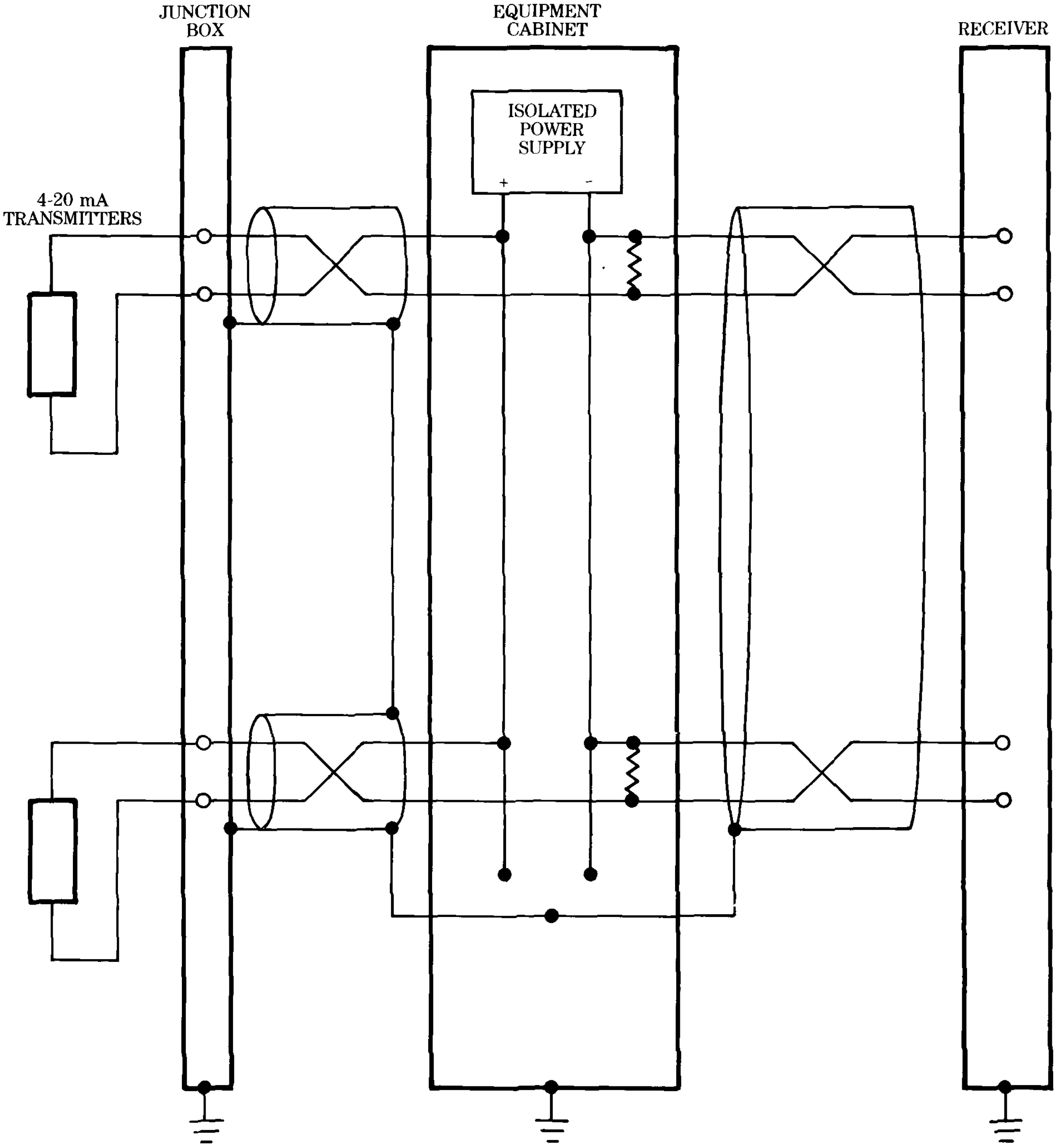

Figure C.1— Analog control loops—ideal

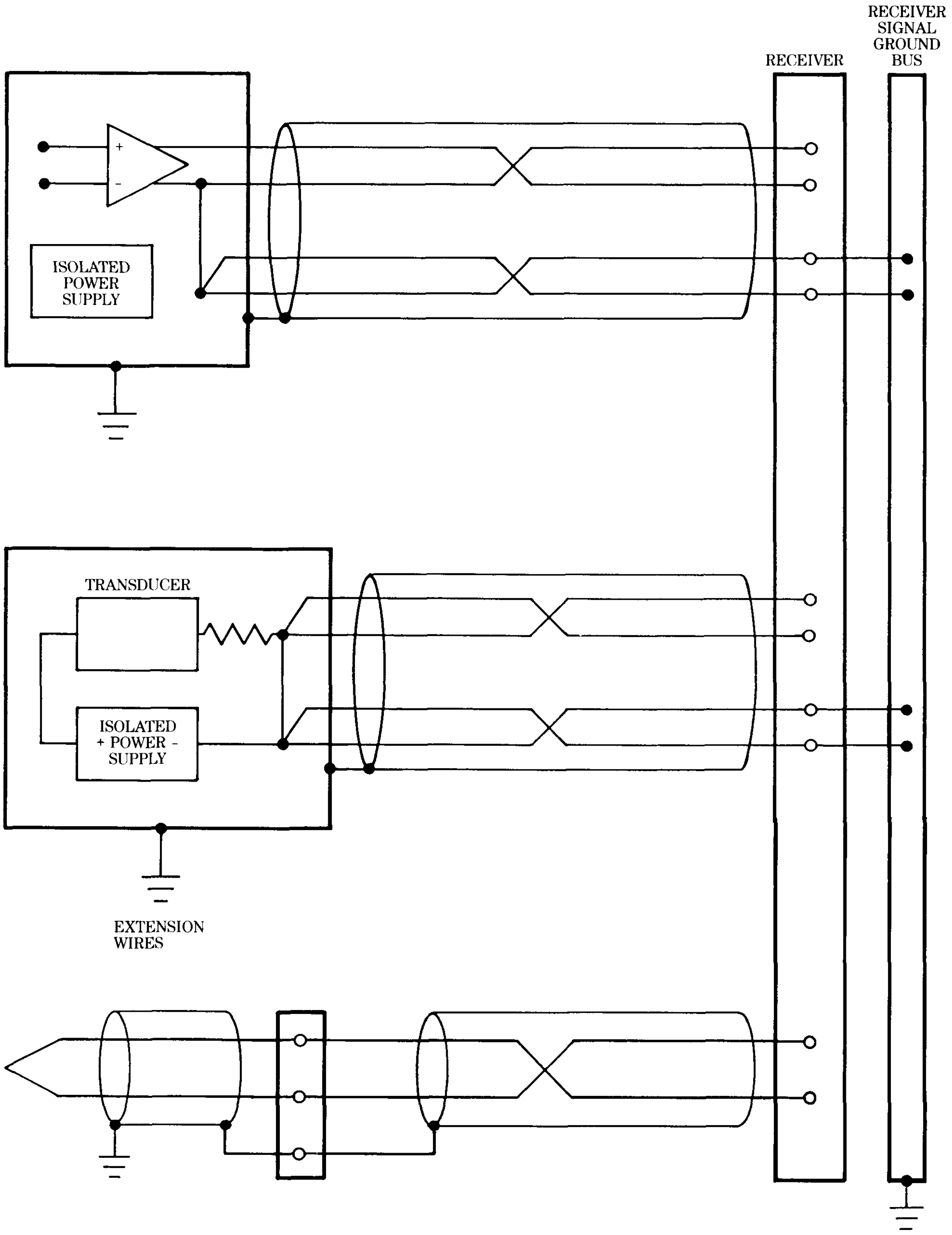

Figure C.2—Floating signal loops—ideal

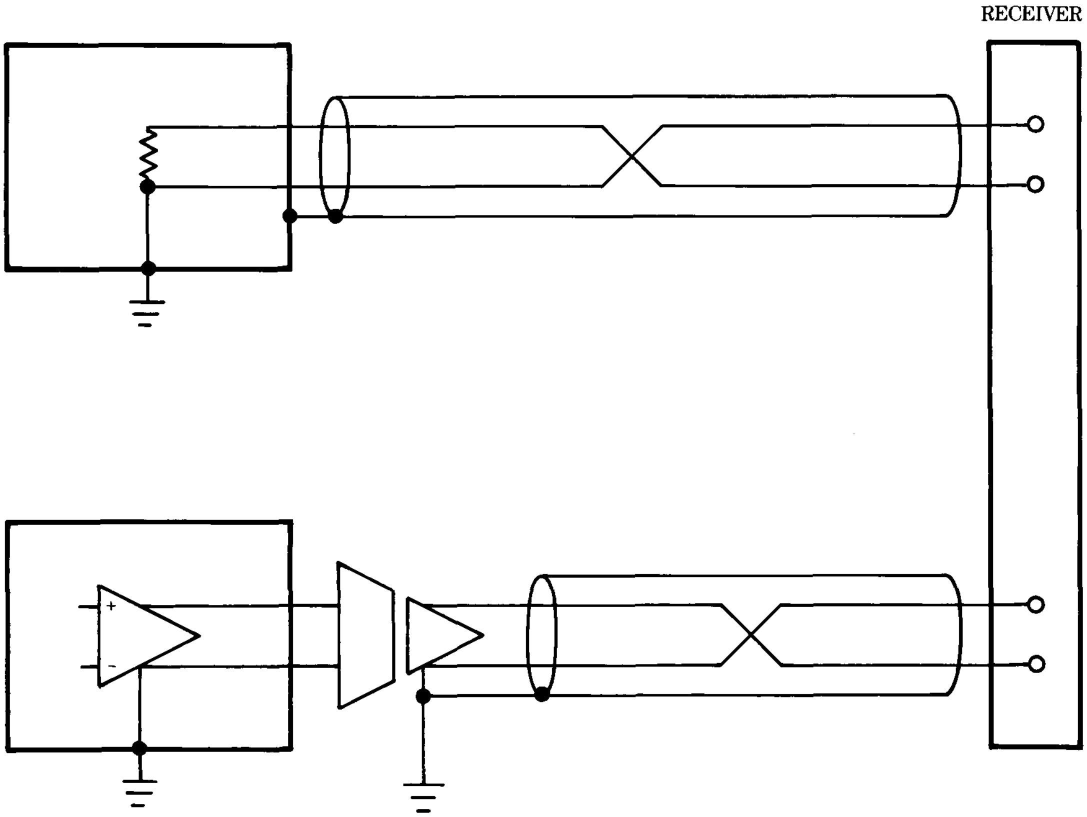

Figure C.3—Grounded signal loops—ideal

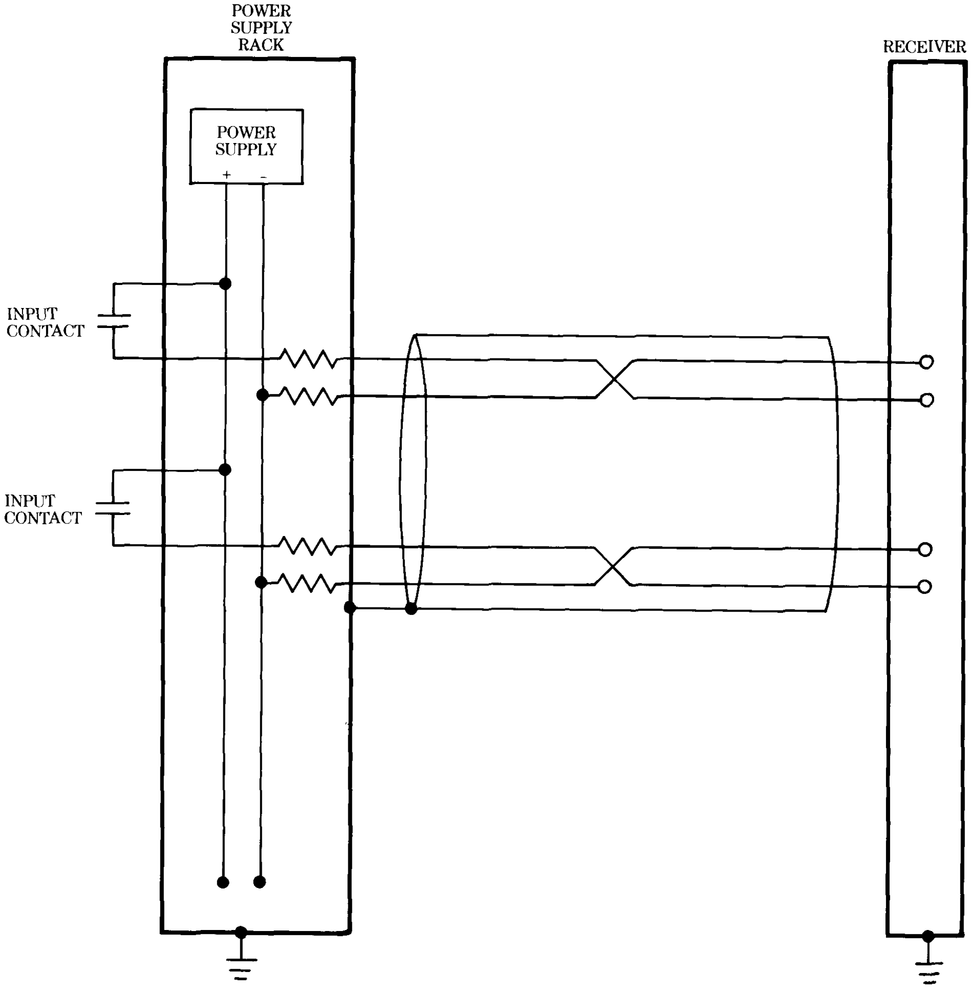

Figure C.4—Digital (dry contact) input—ideal

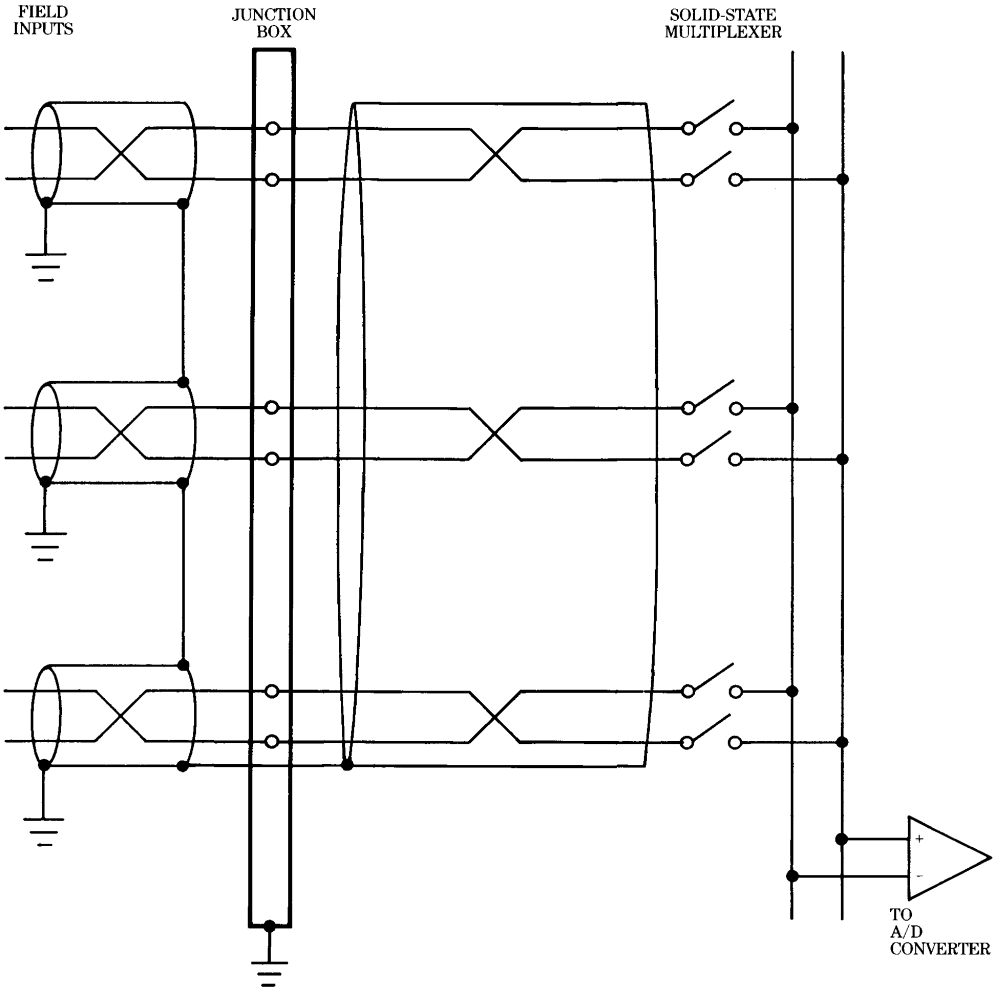

Figure C.5—Computer analog input connections—ideal

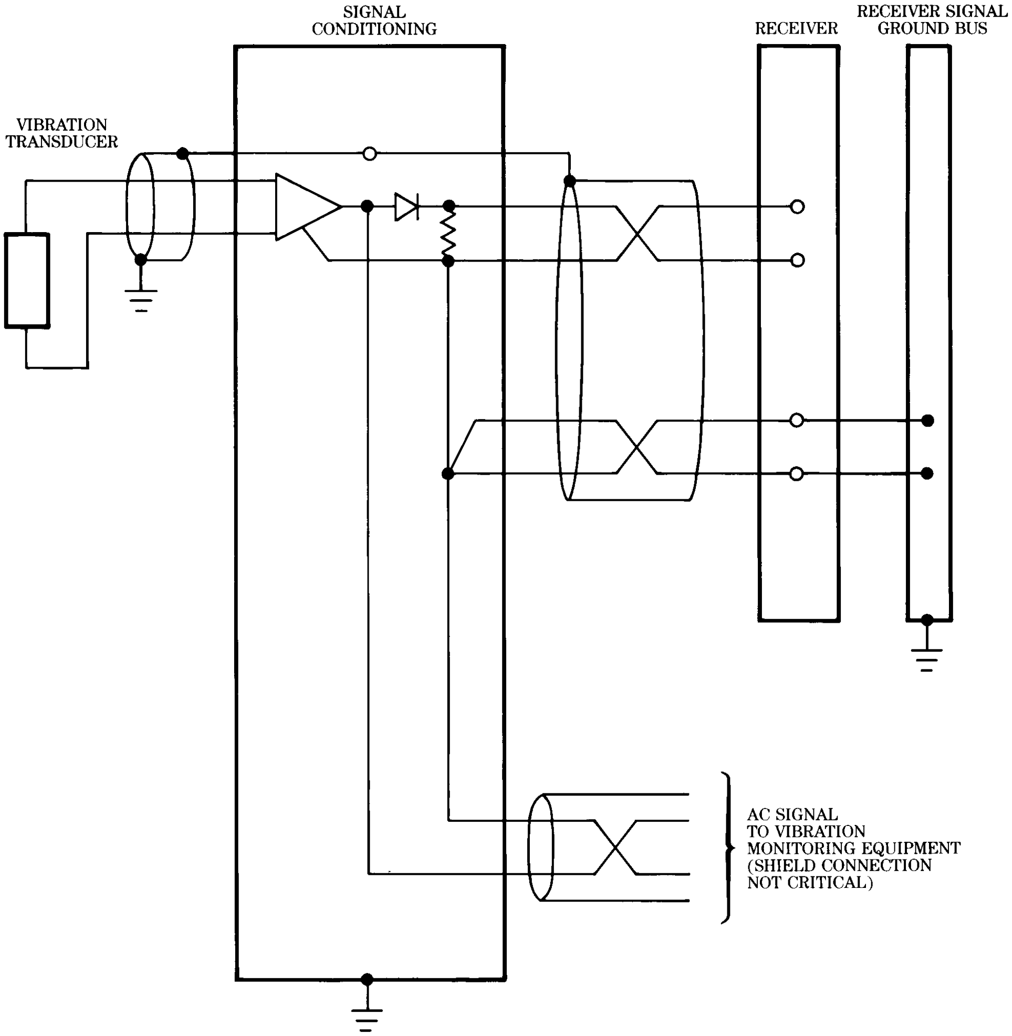

Figure C.6—Vibration signals—ideal

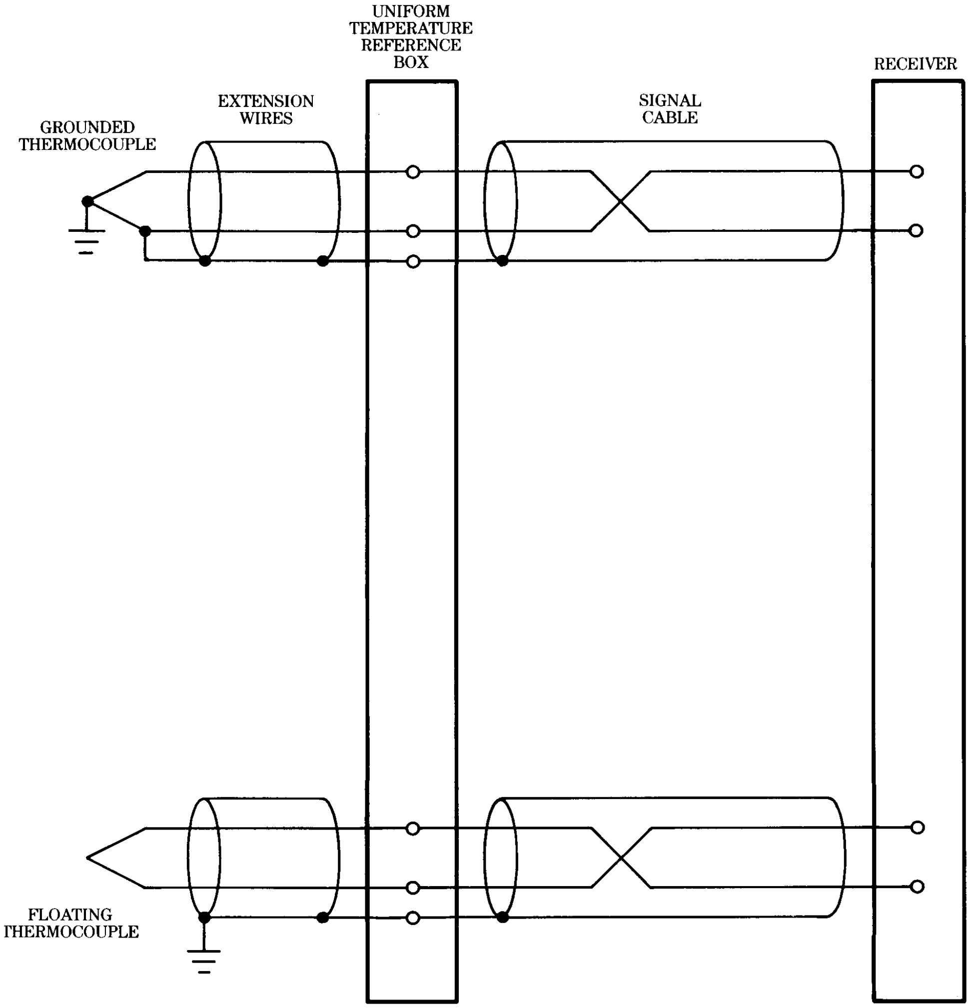

Figure C.7—Thermocouples—ideal

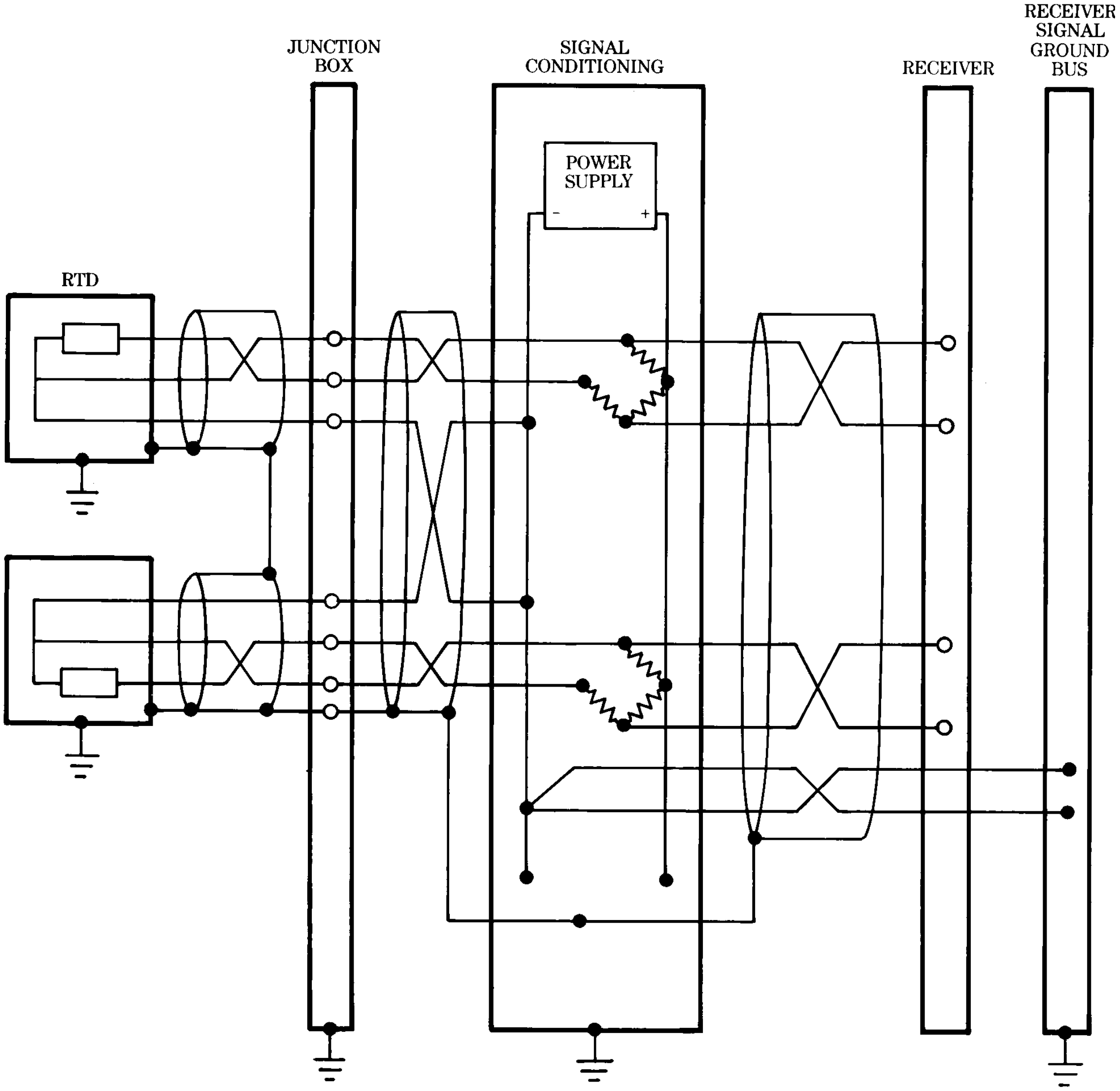

Figure C.8—Grounded RTDs—ideal

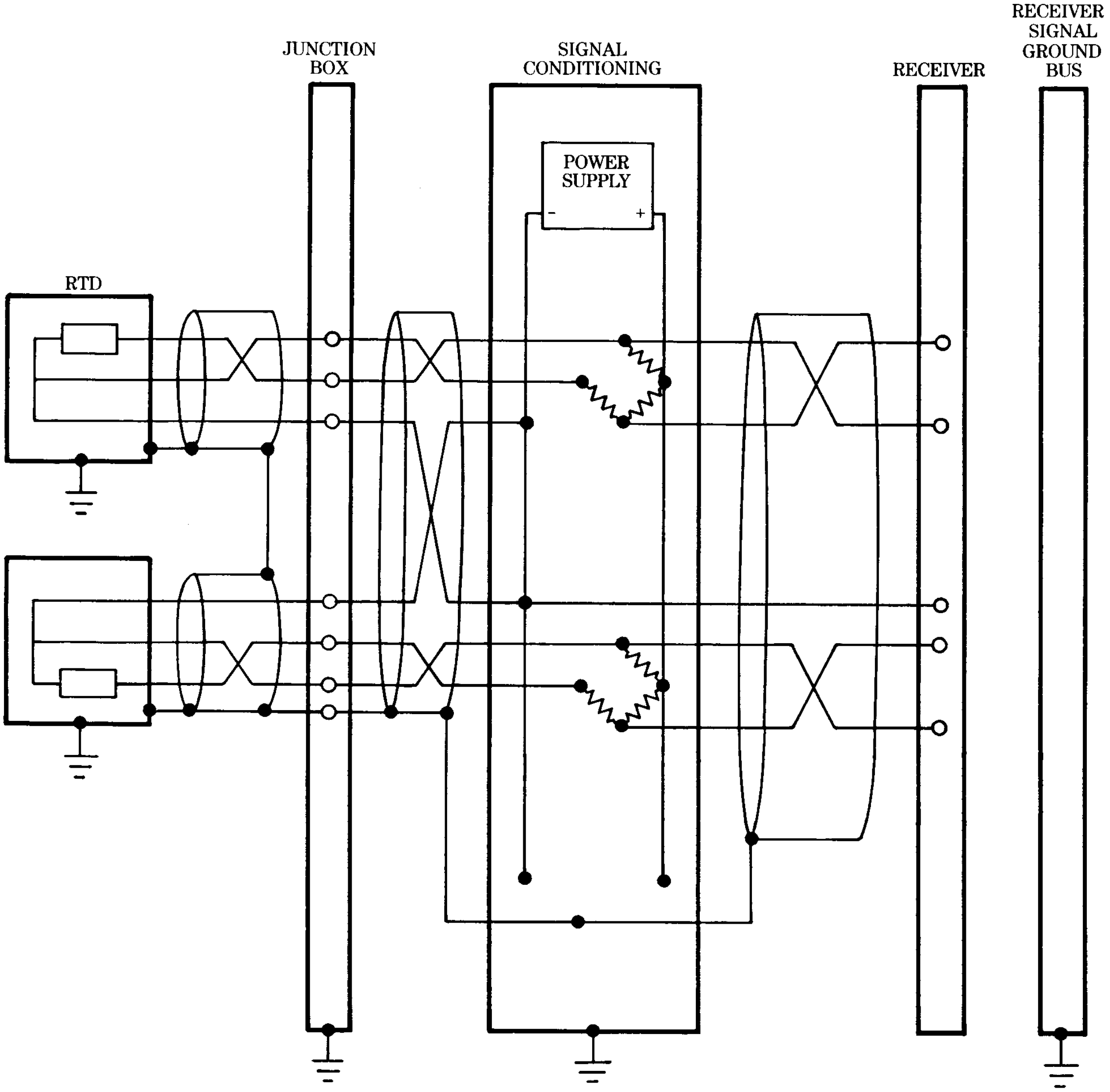

Figure C.9—Ungrounded RTDs—ideal

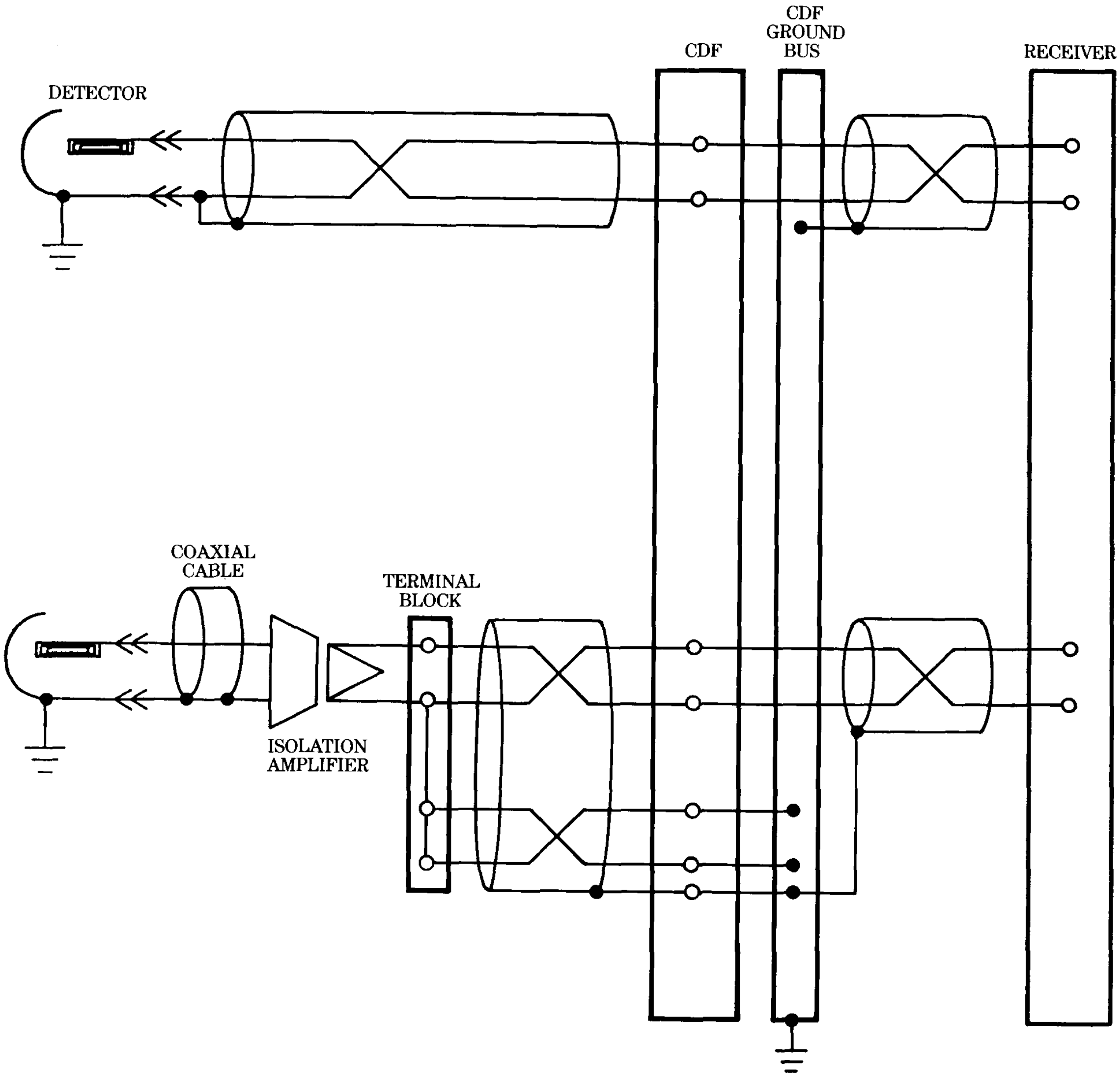

Figure C.10—Core detector—ideal

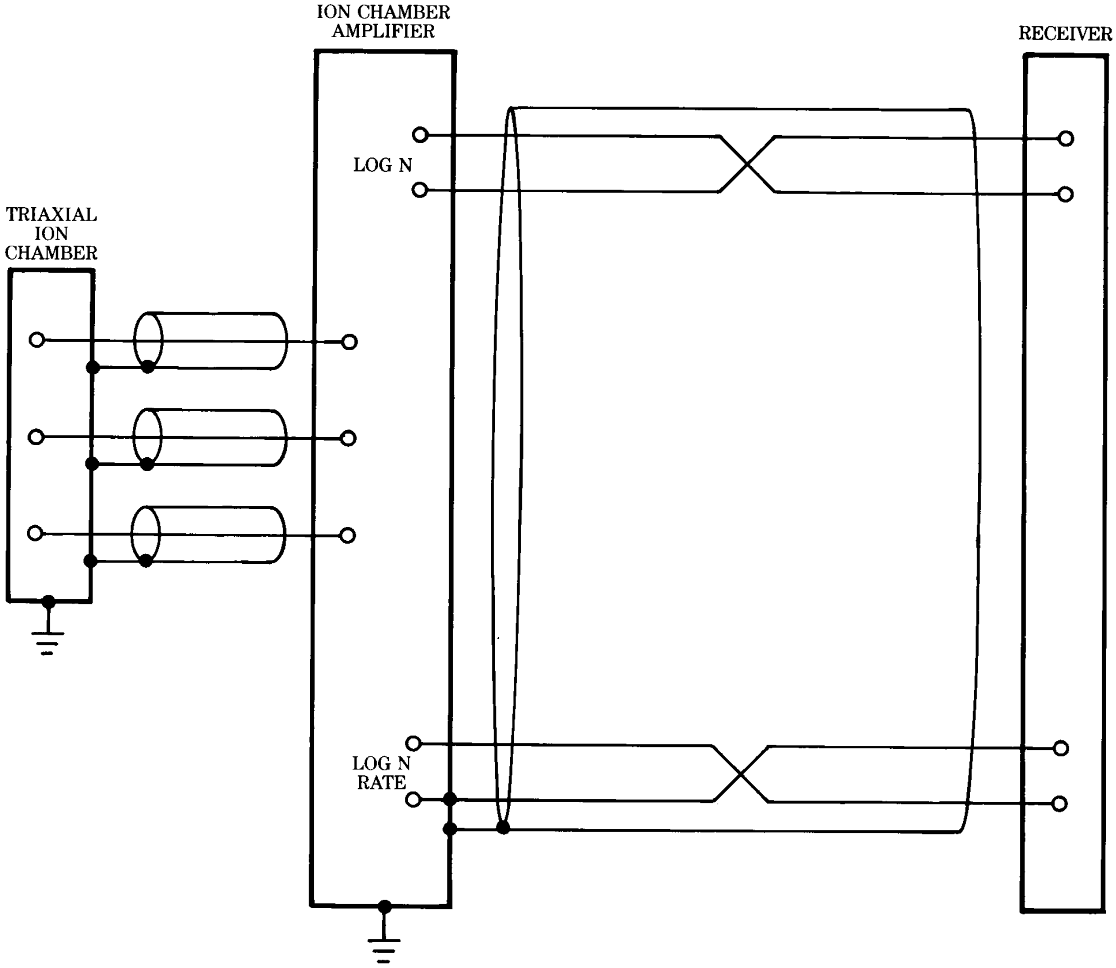

Figure C.11—Ion chamber—ideal

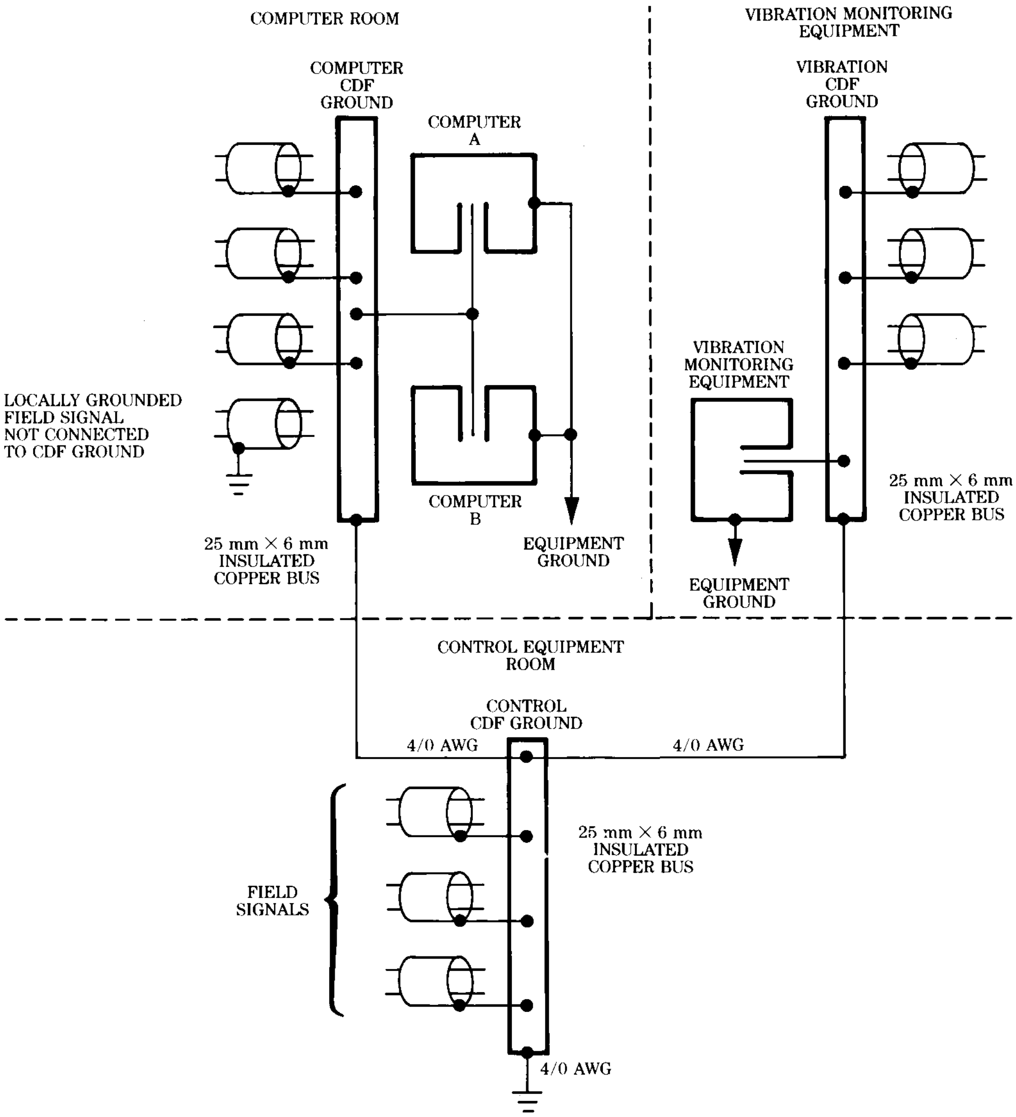

Figure C.12—Installation methods for packaged systems—ideal

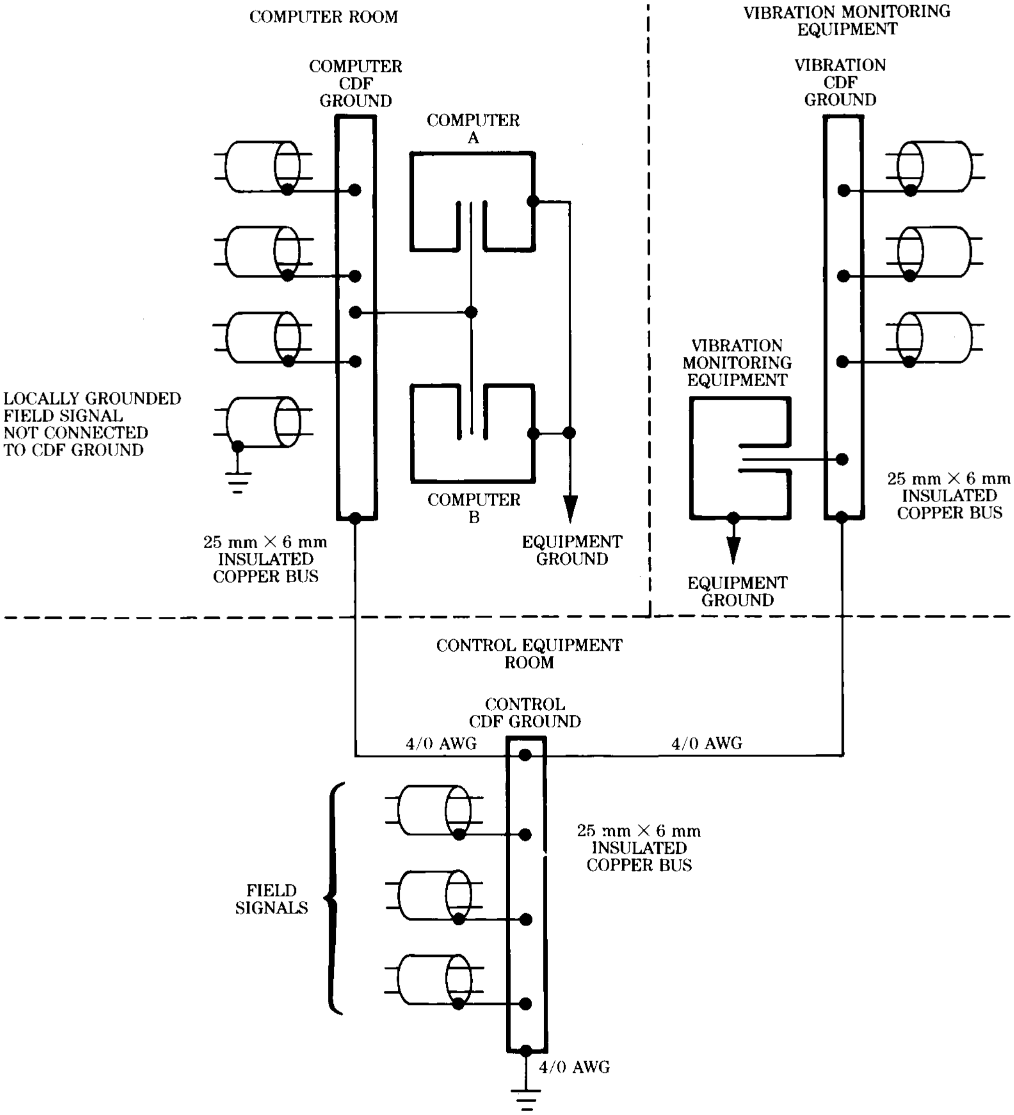

Figure C.13—Example of CDF grounding arrangement