IEEE Guide for Instrumentation Control Equipment Grounding in Generating Stations

Sponsor

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

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IEEE Standards Board

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

Keywords: control equipment, generating stations, grounding, instrumentation

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Introduction

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

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

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

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

This guide was prepared by a task force of the Grounding Practices Working Group, which is a part of the Station Design Subcommittee of the IEEE Power Engineering Society. Task force members are as follows:

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IEEE Guide for Instrumentation and Control Equipment Grounding in Generating Stations

1. Overview

1.1 Scope

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

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

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

1.2 Purpose

The typical environment in a generating station provides many sources of electrical noise, such as the switching of large inductive loads, high fault currents, static switching, and high-energy, high-frequency transients associated with switching at the generator or transmission voltage level. The increasing use of solid-state equipment, computer- or microprocessor-based control, and signal multiplexing systems in these applications introduces a number of specific concerns with respect to electrical noise control. This guide discusses methods for the grounding of I & C equipment and their associated circuits in generating stations.

It is intended to provide guidance for the design of grounding systems for I & C equipment specific to the generating station. The low-level electrical signals transmitted from various I & C equipment in a generating station through long cables may undergo signal distortion as they travel to the receiving end. This distortion is typically caused by noise pickup either at the signal source or along the cable run. The level of noise on the received signal can cause errors in measurement and control functions (and in extreme cases, damage to equipment), which in turn may result in costly unit downtime. The use of proper grounding along with proper shielding techniques can solve a large percentage of noise problems. It should be recognized that there are numerous accepted grounding techniques and that the actual installation of a ground system should be made in consultation with I & C equipment manufacturers.

The grounding methods in this guide are intended to minimize degradation of I & C signals in generating stations. By contrast, the station grounding system is mainly oriented toward meeting the requirements of various safety codes that aim to establish a grounding system that will provide a low-impedance path to ground. This low-impedance path helps to ensure that high voltages are not developed on equipment or structures as a consequence of lightning surges, electrical faults, circulating currents, or static charges. This guide is complementary to IEEE Std 665-1995.[1]

2. References

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

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

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

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

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

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

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

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

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

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[1] Information about references can be found in clause 2.

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

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

3. Definitions

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

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

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

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

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

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

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

3.6 cutoff frequency:

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

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

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

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

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

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

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

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

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

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

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

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

3.17 Acronyms

ac	Alternating current
CCVT	Coupling capacitor voltage transformer
CDF	Central distribution frame
CM	Common mode
CT	Current transformer
dc	Direct current
DM	Differential mode
EMC	Electromagnetic compatibility
ESD	Electrostatic discharge
EMI	Electromagnetic interference
GIS	Gas-insulated switchgear
I & C	Instrumentation and control
I_N	Noise current
RF	Radio frequency
RTD	Resistance temperature detector
SE	Shielding effectiveness
SF_6	Sulfur hexafluoride
V_S	Signal voltage
VCM	Common mode voltage
VDM	Differential mode voltage
V_N	Noise voltage
V_T	Voltage transformer
0V RTN	Zero volt return (signal ground reference)

4. Design considerations for electrical noise minimization

4.1 Typical noise sources and their characteristics

Noise sources can be divided into several of the following categories:

a) Natural sources—these happen independently of human activity, but their effects can be controlled.

b) Incidental sources—these are caused by human activity, but they are not intentional.

c) Intentional sources—these are emissions of potentially interfering energy produced for specific purposes unrelated to the equipment or systems under consideration.

4.1.1 Natural sources

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

A typical lightning strike is composed of a downward-stepped leader stroke (usually negatively charged), a first upward positive return stroke, then two or more downward leader strokes, each followed by a positive return stroke. On average, subsequent strokes contain about 40% of the first stroke amplitude.

A continuing current is usually present between stroke sequences. There may be as many as 20 stroke sequences in a typical lightning flash. Characteristics of a typical lightning flash are as follows:

Potential	30 000 000 V
Peak current	34 000 A
Maximum di/dt	40 000 A/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 indicates that it initially behaves as a traveling wave, then subsequently as a dc source.

4.1.2 Incidental sources

Since one of the largest potential sources of electrical noise is a substation located adjacent to the generating station, some of the incidental sources mentioned in these subclauses originate predominantly in the substation environment.

4.1.2.1 High-voltage switching

This is the most frequent source of large transients in electric power systems. Opening or closing a disconnect switch to deenergize or energize a section of bus is accompanied by arcing between the switch contacts, which in turn produces damped oscillatory transients. The transients generated are very steep fronted waves that can be electrostatically or electromagnetically coupled to nearby cables. Typical values are as follows:

Voltage	200% of rated voltage
Oscillation frequency:	
Line disconnect switch	50–300 kHz
Bus disconnect switch	300–600 kHz
Low-voltage switch	300–2000 kHz
Interval between each decaying oscillation	10 μs–16 ms
Duration of string	1 ms–4 s
Decay time	2–4 cycles
Source impedance	5–200 Ω

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

4.1.2.2 Capacitor bank switching

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

a) Those associated with the lumped parameters of the circuit are in the kilohertz frequency range as determined by the equivalent capacitance of the phase capacitors and by the inductance and resistance of the buses, current-limiting reactors, and ground path.

b) Those associated with the distributed parameters of the circuit are in the megahertz frequency range and are the result of the propagation and reflection of the switching step wave along the line.

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

4.1.2.3 Transmission line switching

Transmission line switching is similar to capacitor bank switching, with the difference being the purely distributive nature of the inductance and capacitance of the line. The magnitude of the line-charging current tends to be substantially less than that for capacitor bank switching.

4.1.2.4 Coupling capacitor voltage transformer (CCVT)

The capacitors in these devices along with the inductance of the power system conductors constitute a resonant circuit whose frequency can be in the megahertz range. Any oscillatory high-frequency transients occurring on the high voltage bus can give rise to high-frequency currents that are coupled through the capacitors to the control circuits.

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

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

4.1.2.5 Gas-insulated switchgear (GIS)

During the operation of GIS, the high-voltage gradients caused by restrikes between contacts induce traveling waves that are confined to the inside of the GIS enclosure by skin effect. They travel along the GIS, are divided and reflected at junctions, but are confined by the open circuit breakers or disconnect switches. Only when discontinuities or breaks in the enclosure are encountered do potentials transfer to the exterior enclosure surface and result in noise voltages. The most common enclosure discontinuities are SF_6-to-air terminations, cable potheads (with insulated flanges) and, for some switchgear, current transformers. However, the SF_6-to-air termination represents by far the largest enclosure discontinuity, and hence the largest source of noise voltages in most GIS.

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

Typical values for GIS measured at the bushing:	
Voltage	40–70% of rated voltage
Oscillation frequency	5–50 MHz
Duration at flashover	40 ns
Duration at disconnect operation	170 ms string of pulses

4.1.2.6 Ground voltage differences

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

4.1.2.7 Current transformers (CTs)

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

4.1.2.8 Rotating equipment

Rotating equipment contains many possible internal sources of high-frequency interference. These include the following:

a) Partial discharges (e.g., corona discharge) within the stator winding insulation.
b) Slot discharges between the coil surfaces and the stator iron.
c) Sparking from exciters with brushes.
d) Arcing associated with conductor strands that have fractured from copper fatigue. This arcing is not continuous but is caused by a movement of conductor surfaces as a result of steady-state and transient magnetic forces.
e) Dc machine brushes.

4.1.2.9 Thyristors

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

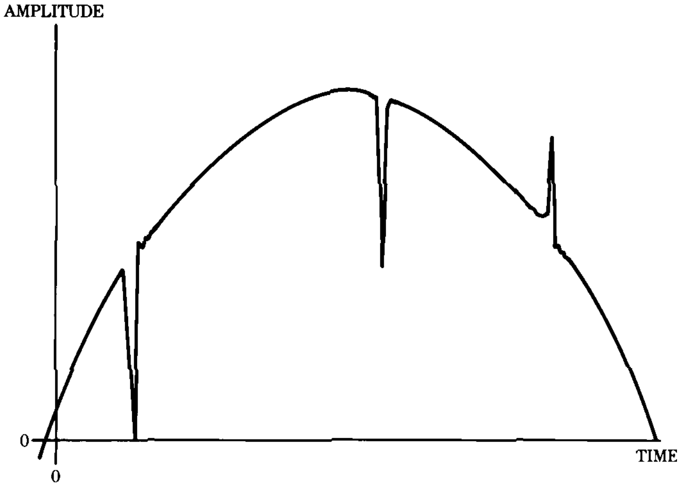


Figure 1—Line notching waveshape

4.1.2.10 Computer systems

The noise generated by microprocessor and memory boards within a computer is dependent primarily upon the computer's clock frequency (300 kHz–10 MHz). The highest noise frequency, however, will be a function of the rise and fall times of the clock pulse. A digital signal with a rise time of 3 ns is roughly equivalent to a 100 MHz sine wave. While this noise is usually well shielded within the computer cabinet, the various computer subsystems and peripheral devices can contribute significantly to the noise generated by the total computer system. The major contributing devices have the following characteristics:

a) *CRT display*. Noise sources are the video circuitry (typical 20–50 V swing at 10–20 MHz) and the horizontal yoke drive circuitry (typical 3 A peak-to-peak amplitude at 10–20 MHz).

b) *Disk drives*. Noise generated by disk drives is dependent on the data processing rate (400 kHz–2 MHz for floppy drives, and 1–10 MHz for hard disk drives).

c) *Switching power supply*. The noise generated by these devices is dependent upon the switching frequency (typical 10–100 kHz) and the switching amplitude.

d) *Printers*. The major noise sources for these devices are the printhead solenoids and the carriage positioning motors along with the associated drivers.

e) *Cabling*. One of the most overlooked sources of noise in a computer system is the interconnect cabling. The noise generated is dependent upon the signal level, the number of conductors within each cable, and the type of shielding provided. This subject will be fully covered in clause 6.

4.1.2.11 DC control circuits

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

4.1.2.12 Mechanical vibration

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

Terminal blocks with loose connections can also produce an arc discharge. When conduit fittings necessary for ground integrity vibrate loose, they also can produce an arc discharge that will radiate high-frequency noise.

4.1.2.13 Chemical contamination

Most plant atmospheres contain suspended chemicals (i.e., oil, coolants, degreasing solutions) that may settle on electrical equipment.

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

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

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

4.1.2.14 Human interaction

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

A typical discharge would be a 5000 V, 5 A current pulse of 200 ns duration. While the energy contained in this pulse is only about 1.25 mJ, this is sufficient to interfere with computer logic levels. An arc discharge does not have to occur for an electrostatic field to interfere with a control circuit. Any object that has picked up a large electrostatic charge can create a voltage shift of several volts when brought in close proximity to a control circuit or cable.

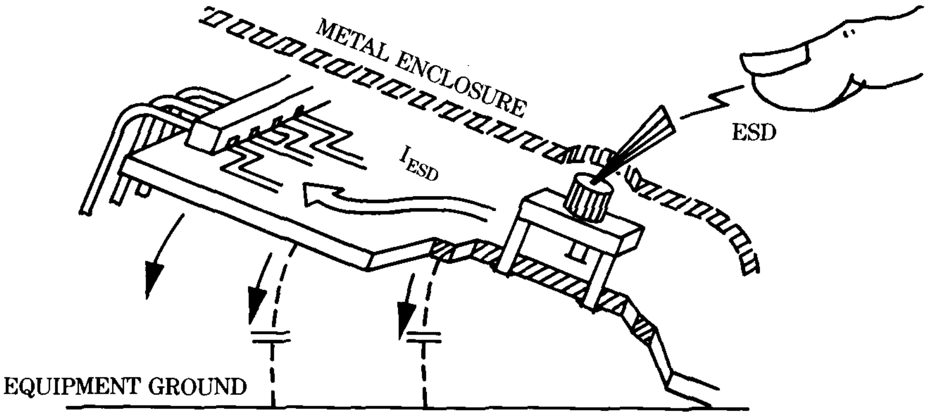


Figure 2—Electrostatic discharge noise generation

4.1.2.15 Cable resonance

Avoiding resonances at radio frequencies has become increasingly important as the clock frequencies of digital circuits have increased beyond the 3–10 MHz range. Resonance is related to the velocity of propagation of electric signals in the conductors and to the repetition rate of a series of signals. Electrical disturbances travel at 299 300 m/s in a vacuum, and slightly slower in conductors.

For example, a voltage wave will travel 30 m in free space during one cycle of a 10 MHz clock signal in a computer. In a cable it may travel only 17 m. If the voltage wave reflects from the cable termination and is in phase with a new wave, resonance will occur and line oscillations will be greatly magnified. If one end of the circuit is grounded, the first resonance at 10 MHz occurs when the conductor is only 6.7 m, or 0.25 wavelengths, long.

At this frequency, a cable 6.7 m long appears to be virtually an open circuit, or at least a very high impedance. It is incapable of equalizing the voltages appearing between its ends. A cable longer than 1/20 of a wavelength cannot be counted upon to equalize voltages between its ends. This amounts to only 1.4 m at 10 MHz. At high frequencies, signal lines are often terminated in their characteristic surge impedance to eliminate most of the reflection and resonance. However, single grounded conductors within a cable can no longer provide a virtual short circuit between one end and the other at the high-frequency portion of a broad frequency range.

4.1.2.16 Other incidental sources

Noise can also be generated by such sources as transformer and motor inrush currents, load tap-changing, flashover of gaps due to overvoltages, ferroresonance, impulse testing, megger testing, low-voltage breakers and contactors, and corona discharge from high-voltage transmission lines. Noise from transmission line corona can occur miles from the point of generation by propagating along the line. The noise generated by these sources will attenuate with increasing distance.

4.1.3 Intentional sources

Many devices intentionally use radio frequency (RF) energy to accomplish their function, such as radios (e.g., security guard transceivers, citizen's band, etc.), RF-stabilized arc welders, induction heaters, and RF drying equipment. These devices produce considerable amounts of RF energy that generally is not contained and therefore can reach control equipment.

4.2 Noise-coupling methods

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

a) Conductive (direct contact)
b) Capacitive (electric)
c) Inductive (magnetic)
d) Radiative (electromagnetic)

Both capacitive and inductive coupling refer primarily to near field coupling. A control circuit or cable is considered to be in the near field of an electromagnetic source when the source to circuit distance is less than 0.167 of the wavelength ($\lambda/2\pi$) of the highest source frequency. Radiative coupling refers to circuits located in the far field of a source where the source's emissions are seen as a true propagating wave.

Each of these coupling methods will be detailed later in this guide.

4.2.1 Characteristics of electromagnetic fields

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

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

4.2.2 Common impedance coupling (conductive)

As is shown in figure 3, when two or more circuits share a wire or junction point, common impedance coupling is a possible noise source. The point of common impedance may be intentional for grounding purposes (ground loop problem), or may be undesired leakage conductance between circuits. Current in one circuit can then cause a noise voltage to appear in another circuit. The level of interference is dependent upon the magnitude of the common impedance.

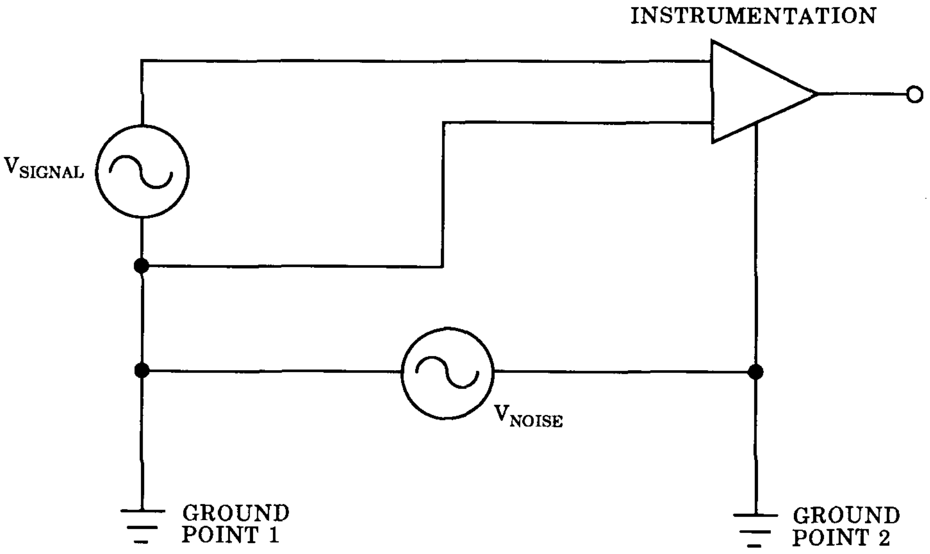


Figure 3—Example of common impedance coupling (ground loop)

4.2.3 Capacitive coupling (electric)

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

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

where:

I is the current flow through the circuit capacitance.
C is the capacitance between the two circuits.
de/dt is the voltage change rate in the first circuit.

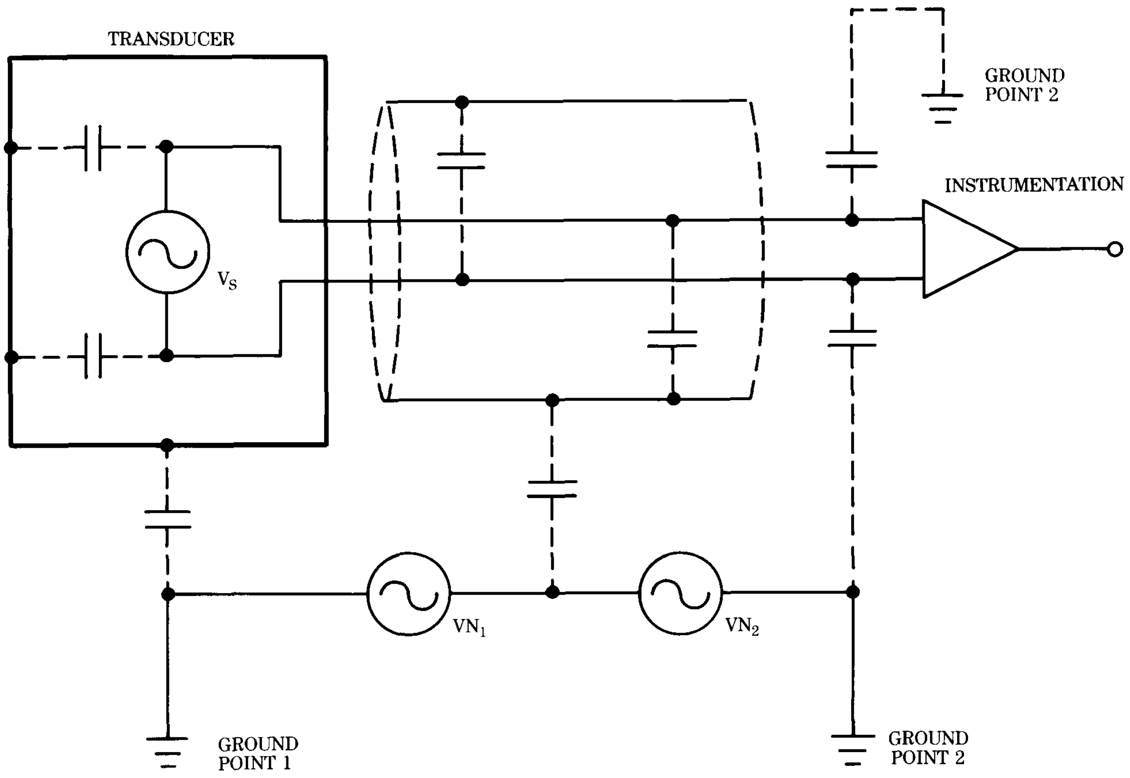


Figure 4—Example of capacitive coupling

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

4.2.4 Inductive coupling (magnetic)

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

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

$$E = M\, di/dt$$

where:

E is the induced voltage in the second circuit.
M is the mutual inductance (amount of flux).
di/dt is the current change rate in the first circuit.

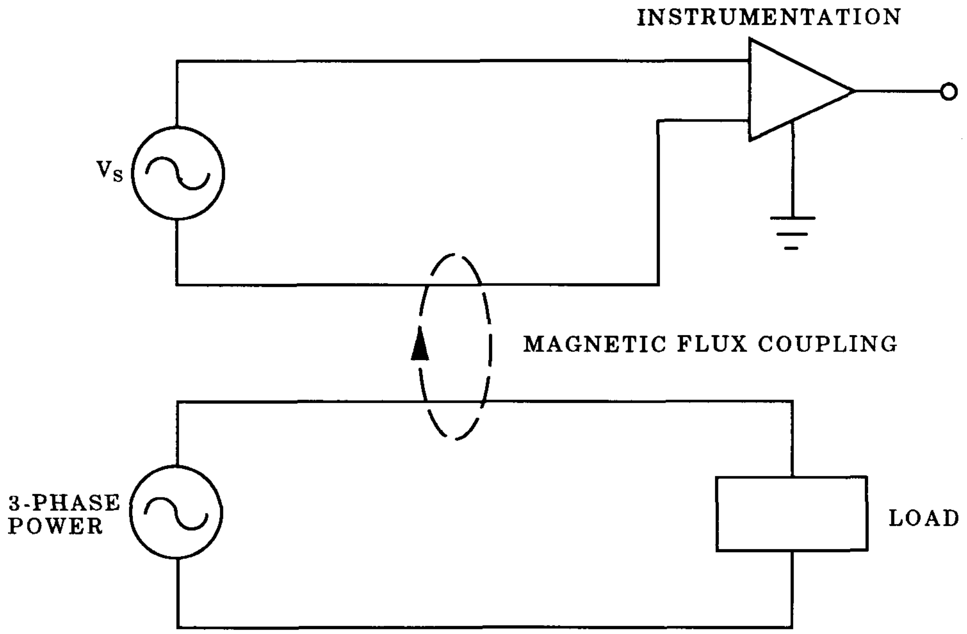


Figure 5—Example of inductive coupling

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

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

4.2.5 Radiative coupling (electromagnetic)

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

4.2.6 Interference modes

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

4.2.6.1 Common mode interference (longitudinal mode)

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

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

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

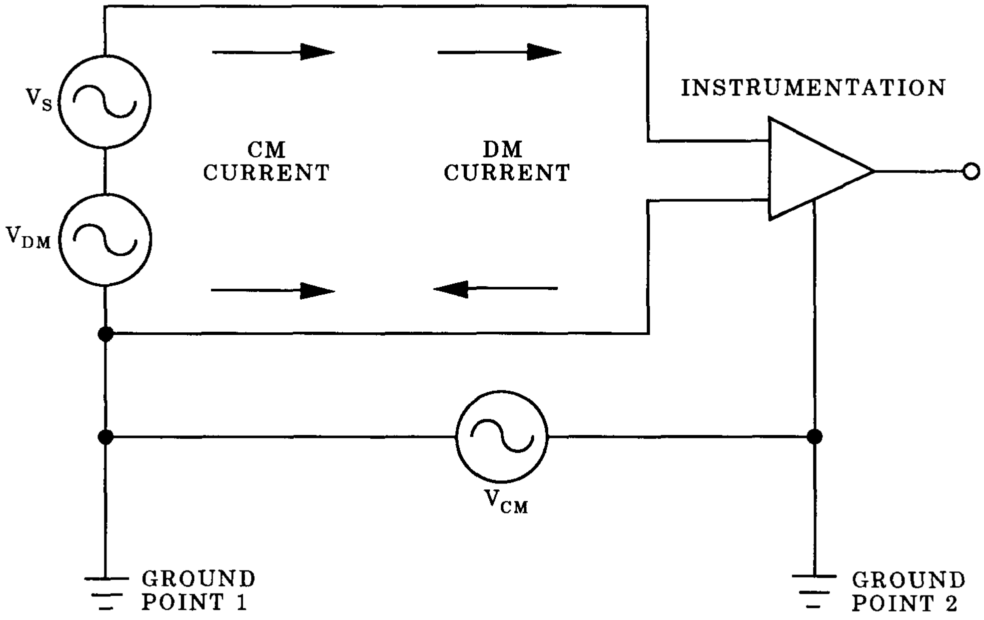


Figure 6—Example of common and differential mode interference

4.2.6.2 Differential mode interference (normal mode, transverse mode)

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

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

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

4.2.6.3 Crosstalk

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

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

4.3 Techniques for electrical noise minimization

4.3.1 Suppression at the source

One of the most effective techniques for reducing transients in a system is to reduce their amplitude at the source.

4.3.1.1 Suppression of noise generated by solenoid-relay coils

Placing a diode in parallel with a magnetic coil is the simplest method of suppression in a dc circuit that prevents the voltage across the coil from exceeding the supply voltage. The diode, however, has the following disadvantages:

a) Switch-off delay
b) Diode failure may short circuit the device
c) Forward overcurrent when the supply is interrupted can destroy the diode
d) Overvoltage in the reverse direction (possibly caused by spikes from unsuppressed loads) can destroy the diode
e) Possiblity of causing additional switching current when “on” or additional leakage current when “off”

The diode should be properly chosen to have high-reverse overvoltage and high-forward overcurrent characteristics. Addition of a series resistance chosen as approximately equal to the coil resistance significantly reduces the switch off delay and eliminates the short circuit if the diode fails. This technique is illustrated in figure 7.

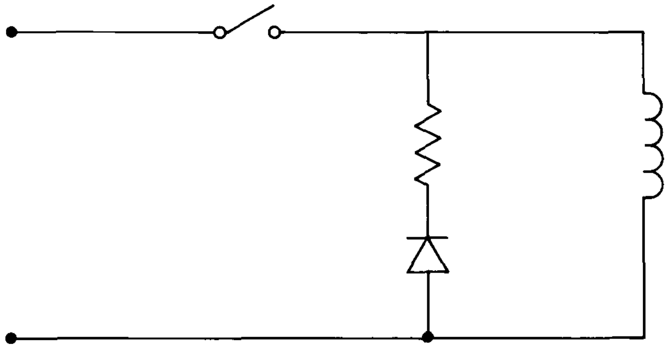


Figure 7—Suppression with a diode and series resistance

Variations of this technique using transorbs or metal oxide varistors can be used. It is still possible, however, that some high-frequency pulses will remain. If this is a problem, an R-C filter can be introduced across the coil. If the leads to the coil are long, it may be necessary to place a second filter across the initiating contact since the cable inductance could cause contact sparking. Back-to-back diodes may be placed across a relay contact to not only suppress the noise, but also to prevent damage to the contacts.

4.3.1.2 Suppression of thyristor rectifiers, motors, and generators

Small capacitors are used to damp high frequencies generated by these devices. They should be placed as close to the interference source as possible to prevent the emission of RF interference.

4.3.1.3 Suppression of input signal noise

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

4.3.2 Positioning and isolating control cables

4.3.2.1 Cable routing

The physical arrangement of the control cables is an important factor affecting surge voltage levels. Techniques for minimizing noise pickup in control circuits include the following:

a) Provide radial routing of control cable. Circuits should not be looped from one piece of equipment to another with the return conductor in another cable. All supply and return conductors should be in a common cable to avoid the large electromagnetic induction that is possible because of the very large flux loops that such an arrangement would produce. This means that both secondary leads of CT's should be in the same cable, both positive and negative dc leads should be in the same cable, and all three phases and neutral of voltage transformer (VT) secondary leads should be in the same cable, etc. If the supply and return signal lines are discrete wires, they should be laid as close to each other as possible within the same raceway to minimize the loop and reduce susceptibility to interference from inductive coupling. If possible, a gentle twisting of the two wires (1 turn/m) can further reduce the magnitude of the induced noise.

b) Orient the control cables at right angles to buswork and power conductors where primary transient currents can exist so as to minimize the coupled length of the cables. Where this is not possible, the separation distance from parallel buses should be maximized.

c) Locate the control room in a centralized location so as to minimize control cable runs.

d) Provide maximum separation between power and control wiring. Both should be routed close to the conductive cabinet or reference ground plane.

e) Avoid inadvertent loops when routing cables.

4.3.2.2 Physical separation

Circuits operating at different voltages (and sometimes different energy levels) should be physically separated. For example, low-energy analog signals should not be run in the same cable as higher energy control signals. Similarly, dc battery and ac control power circuits should not be placed into the same cable and neither circuit should be in the same cable with the station ac service. Likewise, these segregated cables should also be grouped according to function and separated by a reasonable distance. When dissimilar circuits are run parallel to each other in a cable tray for any distance, consideration should be given to separating the two circuit types by a grounded metallic barrier.

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

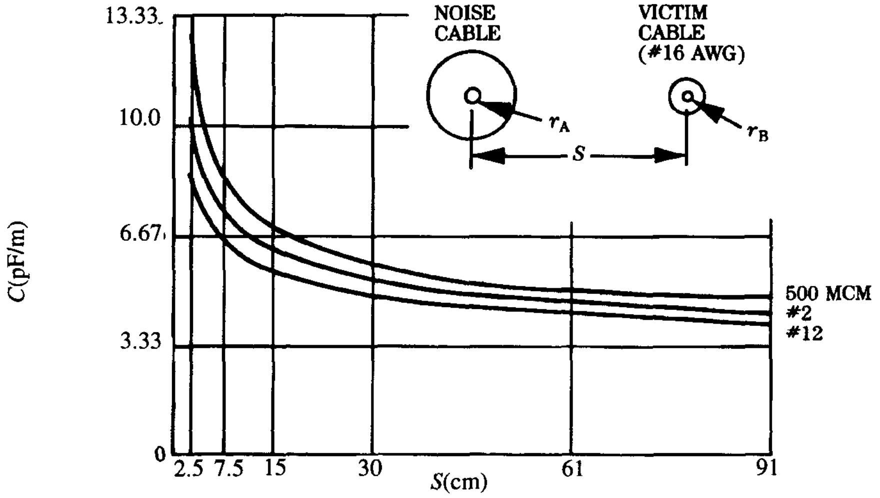


Figure 8—Capacitance versus conductor separation

4.3.3 Shielding

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

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

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

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

How well the shield attenuates an electromagnetic field is referred to as its shielding effectiveness (SE). The standard unit of measure for shielding effectiveness is the decibel. In this application, the decibel is expressed as 20 times the logarithm (base 10) of the ratio of two values of electromagnetic field strength where the field strengths are compared before and after the shield is in place. It is defined as

E-Field, $SE = 20\ log\ E_1/E_2$
H-Field, $SE = 20\ log\ H_1/H_2$

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

In most shielding applications, shielding effectiveness below 20 dB is considered only minimal shielding; 20–80 dB covers the normally acceptable shielding range, and 80–120 dB is above average shielding. Shielding effectiveness above 120 dB is difficult to achieve.

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

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

4.3.3.1 Electronic equipment shielding

Electrostatic coupling can be significant when lines do not have a metallic shield connected to the circuit ground reference. The magnitude of the induced voltage depends on the relative values of capacitances between the noise source conductors and the signal circuit conductors. E-field coupling increases with increasing frequency and proximity and predominates over magnetic coupling when the victim circuit has a high impedance. Figure 8 (on the preceding page) illustrates the model for E-field coupling and provides calculated capacitance/cm between common-size power conductors and 16 AWG instrumentation conductors versus separation distance.

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

An opening larger than the wavelength (*l*) divided by 20 (*l*/20) will permit electromagnetic energy to pass freely through the opening without being attenuated. Therefore, openings larger than *l*/20 should be avoided. Since most EMI coupling problems are broad band in nature, the wavelength should be that of the highest interference frequency.

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

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

b) Where cable penetrations occur in a cabinet, shielding can be accomplished by using waveguides operating beyond cutoff frequency. This can be done by connecting a conductive shaft to the inside of the cabinet as shown in figure 9. Since the cutoff frequency of a waveguide is a function of twice the maximum width of the waveguide, the length of the conductive shaft should be at least four times the width of the cable penetration.

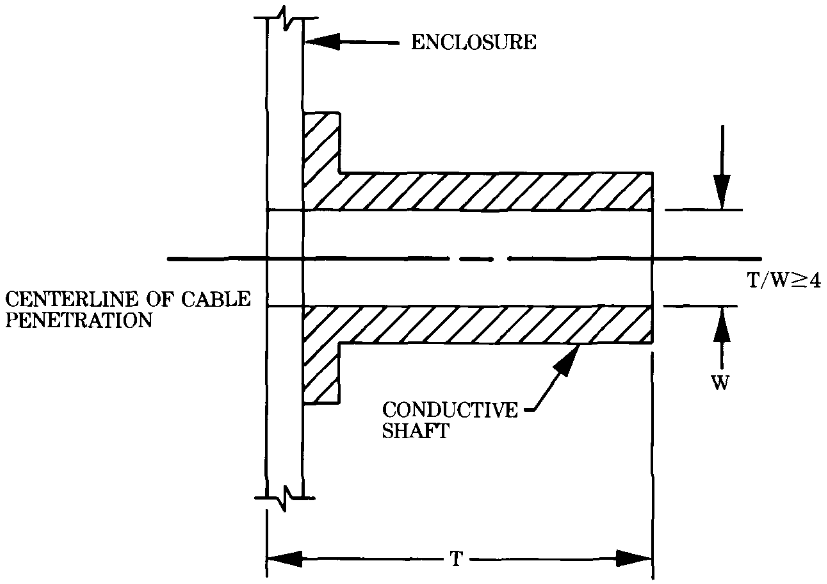


Figure 9—Waveguide beyond cutoff frequency

c) Electronic systems that are packaged in cabinets of plastic or other non conductive materials should have their cases treated with a conductive material to provide shielding. The most frequently used technique is to spray the inside of the cabinet with a special conductive paint containing metal particles.

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

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

4.3.3.2 Cable shielding

For most multiconductor cables, only a single overall shield or individually shielded conductor pairs are used, since the capacitance per unit length greatly increases when both are used. For example, digital signals commonly use only an overall shield. Generalized cable shielding practices are contained in 5.4.

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

The cable shield should be thought of as a barrier element that connects the barriers formed by the cabinets containing the control circuits (see 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 should be closed to protect the internal circuits from wideband external interference (see figure 11). In general, 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. The point of highest capacitance is often the signal source.

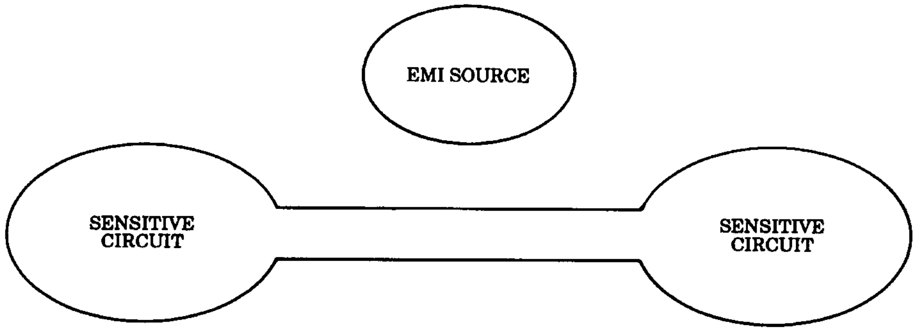
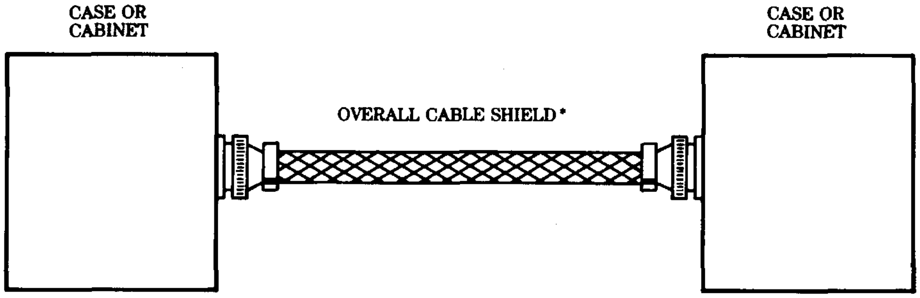


Figure 10—Diagram of a closed EMI barrier



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

Figure 11—Realization of figure 10

4.3.4 Grounding

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

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

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

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

4.3.5 Filters

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

Filters can range anywhere from simple capacitors and ferrite beads to sophisticated bandpass filters. The configuration of the filter will naturally depend upon the characteristics of the noise to be filtered. Since different filter configurations will affect signal parameters, such as pulse rise time and waveshapes of both digital and analog circuits, both the positive and negative effects should be considered when applying filters. Filters have also been known to cause detrimental ringing of digital circuits.

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

a) Keep the unfiltered portion of the power cord that is inside of the equipment as short as possible. The filter should optimally be mounted in the bulkhead of the cabinet to protect against input-output parasitic capacitance coupling at high frequencies.
b) Avoid recoupling of the filtered and nonfiltered power leads due to routing the filtered leads close to the incoming unfiltered leads.
c) Avoid coupling of the power leads with signal/logic cabling.

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

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

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

4.3.6 Other noise minimization techniques

The following are other noise minimization techniques that are available.

4.3.6.1 Isolation transformers

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

4.3.6.2 Neutralizing transformers

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

4.3.6.3 Differential amplifiers

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

4.3.6.4 Increase the signal-to-noise ratio

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

4.3.6.5 Fiber optic cables

Fiber optic cables are immune to the interference sources that plague standard current-carrying control cables. The input and output circuits of the fiber optic links are sensitive to EMI.

4.3.6.6 Surge suppression

Surge arresters, diodes, crystal filters, capacitors or pre-ionized spark gaps can be applied. Their connections should be close to the equipment terminals.

4.3.7 Summary of minimization techniques classified by coupling mechanism

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

4.3.7.1 Common impedance coupling

Minimization techniques for common impedance coupling are as follows:

a) Eliminate as many common impedance points between circuits as possible by not using any conductor as part of more than one circuit.
b) Make ground connections as short as possible. For high frequencies, short is on the order of 1 m and the connection would be made to the signal reference ground. For low frequencies, short is on the order of 100 m and would be made to the single-point earth ground.
c) Reduce the resistance and impedance of ground conductors. For high-frequency circuits, the impedance is of importance only when it is a part of the circuit.

4.3.7.2 Capacitive coupling

Minimization techniques for capacitive coupling are as follows:

a) Reduce the impedance of the sensitive circuit.
b) Position and connect conductive shields so that capacitively coupled noise currents are returned to 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.
c) Route control circuits to minimize coupling (e.g., physical separation and right angle crossings).
d) Specify transformers that have capacitive shields provided between primary and secondary windings.

4.3.7.3 Inductive coupling

Minimization techniques for inductive coupling are as follows:

a) Increase the impedance of the sensitive circuit.
b) Divert magnetic fields by shielding with low reluctance material.
c) Repel magnetic fields by shielding with high permeability material.
d) Route control circuits to minimize coupling and loop area (e.g., physical separation, right angle crossing, radial routing, twisting of signal pairs).
e) In areas of high-frequency interference, use longitudinally shielded cables.
f) Increase the rise time of the signal.

4.3.7.4 Radiative coupling

Minimization techniques for radiative coupling are as follows:

a) Absorb radiated fields by using a lossy dielectric or magnetic shield.
b) Reflect radiated fields by using metallic shields.
c) Separate the emitter and receiver by the maximum possible distance since field strength is inversely proportional to the square of the distance.
d) Design cabinet openings with regard to the techniques presented in 4.3.3.1.

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 control circuits. Several techniques that are useful in minimizing common mode noise are as follows:

a) Make the signal circuit symmetrical by using a balanced transducer and identical signal lines.
b) Maximize the common mode coupling impedances by:
    1) Increasing the physical separation between the emitter and the receiver.
    2) 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, i.e.,
    1) Differential amplifiers
    2) Isolation transformers
    3) Optical isolators
e) Apply the concepts of single-point grounding and floating grounds while avoiding multiple-point grounding schemes. This may be difficult to achieve in an extensive system.

5. I & C system grounding

5.1 Grounding philosophy

This subclause describes the general requirements for grounding and how the specifics of I & C system grounding relate to the entire grounding system.

5.1.1 Principal objectives

The principal objectives of station grounding practices are as follows:

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 instrumentation systems by providing a common signal reference of low relative impedance between devices, circuits, and complete systems.

Grounding circuits often share multiple functions. It is necessary to design a grounding network so that the conveyance of transient voltages due to electrical faults, lightning strikes, etc., does not interfere with the function of minimizing noise, or permit these transients to impinge on circuit elements beyond their limit of transient immunity.

It is therefore necessary to recognize the following four points. The first is that all points on Earth (even within relatively close proximity) are not at equal or zero potential. 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 immunity capability of discrete circuit elements. Care should 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 galvanically connected cable circuits and may also be coupled capacitively and inductively from grounded cable shields in the affected area into the signal conductors. These conductors may terminate outside of the transient area and could impress high voltages on any connected equipment.

5.1.2 Generating station grounding system

In any generating station there are four identifiable grounding systems that are all tied to the grounding grid. Those for lightning, station service power, and equipment are discussed in IEEE Std 665-1987. The I & C grounding system is designed to minimize the generation and transfer of noise voltages.

5.1.3 Equipment grounding for electrical safety

For design requirements for electrical safety refer to the following references as appropriate:

- IEEE Std 665-1995
- IEEE Std 142-1991
- IEEE Std 518-1982
- IEEE Std 1100-1992
- ANSI C2-1997, NESC®
- The specific codes and requirements of the jurisdiction where the equipment is to be installed

5.2 Other grounding considerations

This clause contains other grounding considerations that can affect I & C system grounding.

5.2.1 Safety grounds (mechanical, frame, or ac grounds)

The equipment in this context is the exterior housings of I & C systems. Specifically, it refers to non current-carrying enclosures, such as cabinets, frames, and racks. The objective of the safety ground is to prevent hazardous potentials from developing between adjacent equipment grounds in order to protect personnel and equipment against hazards posed by electrical power faults.

Requirements for the design and installation of a safety ground include the following:

a) Ensure that all enclosures are constructed with special provisions, such as a designated ac ground bus for terminating the equipment ground cable that is run from the station ground mat. This connection is in addition to the grounding conductor/raceway provided with the incoming power conductors.

b) Connect the safety ground cable to the designated equipment ground bus. Use only one connection between the enclosure and the ground. This connection is in addition to the grounding conductor/raceway provided with the incoming power cables.

c) The safety ground cable should be a 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.

d) Connect all individual chassis within the enclosure (particularly electrically operable sliding chassis) that are not integrated into the panel structure to the mechanical structure by either braided, insulated straps, or another form of intentional ground.

e) Tie individual safety ground points of closely located, mechanically unintegrated, cabinets to a single common ground point that is connected to the station ground mat.

5.2.2 Ground conductor lengths

At MHz signal frequencies, the impedance of a long ground cable can become high enough that the conductor no longer provides an effective low-impedance current signal reference. For example, a conductor that at 60 Hz represents an impedance of less than 0.3 Ω represents over 40 000 Ω at 10 MHz.

5.2.3 Generating station-to-substation interconnect

In general, conductors equal in size to the ground grid conductors should be installed near the upper interior sides of the interconnecting cable trenches. These cables should be bonded to both the generating station and substation ground mats. They should also be bonded together and to driven ground rods at closely spaced intermediate points. Buried counterpoise conductors underneath the transmission circuits between substation and plant will provide additional ties between the separate mats.

Since these conductors provide a lower impedance path than the cable shields, the fault or ground currents are diverted from the instrument cables. These conductors also help to limit the ground potential differences between the two mats during fault conditions.

5.2.4 CT, VT, and CCVT grounding

Much has been written and standardized about the proper techniques to use when grounding these devices [B41]. 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.

5.2.5 Gas-insulated switchgear

Because GIS generates a high degree of EMI, the control circuits installed close to the GIS (basically those installed in the same building) should be completely shielded, as is described in the following:

a) All devices installed directly on the GIS (e.g., gas density relays, disconnect switch auxiliary switches, interlocks and drives, circuit breaker controls, CT and VT secondary connections) should be completely metal-enclosed and should 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 corrugated metal shield. This shield 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 the design considerations of 4.3.3.1 should also be taken into account.

d) When equipment with low-transient immunity levels (such as 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.

5.2.6 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 conduits should be connected to the facility ground system regardless of whether 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 should positively penetrate all paint or other nonconductive finishes.

e) All joints not inherently continuous should be bonded 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.

g) All conduit brackets and hangers should be securely bonded to the conduit and the structural members to which they are attached.

h) All cable tray systems should be electrically continuous. This includes support brackets or hangers.

5.3 Signal ground systems

The fundamental objective of a signal ground system is to create a reference ground plane to which the electronic hardware in a localized area is connected. There are three common approaches toward this objective: single-point grounding, multiple-point grounding, and floating grounds. A description of each of these systems is contained in 5.31, 5.3.1.1, 5.3.1.2, 5.3.2, and 5.3.3.

5.3.1 Single-point ground system

The single-point ground system is used to eliminate circulation of ground currents that cause common mode noise. This is the most commonly used system in an industrial environment. It is implemented by connecting the signal circuit to the station ground at only one point. This grounding method is very effective and is adequate when dealing with equipment operating at frequencies below 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.)

A disadvantage of the system is that it is ineffective at high frequencies where signal wavelengths approach the equipment enclosure dimensions or the ground cable length. As equipment dimensions or ground cable lengths approach 0.15 of the signal wavelength, the cable can no longer be considered a low-impedance ground. Single-point reference grounds should be differentiated from signal return conductors, which do carry current under normal conditions.

The purpose of the signal ground is to reference all control signals within a system to a single point. The single ground reference point should have no more than one lead exiting each equipment enclosure. This lead should be a stranded and insulated conductor sized to minimize the potential difference between devices (less than 1 V, or manufacturer's recommendation), and to meet the required mechanical strength. The insulated cable serves not only to isolate the signal ground from unintentional ground connections, but also to easily differentiate it from the equipment ground. A separate signal grounding system should be utilized within the cabinet enclosure. The separate signal grounding system of each cabinet should then be tied together at a single reference point.

The following considerations should be taken into account when designing the grounding system for a centralized I & C system:

- Power into a computer and multiplexed system should come from one source only (that is, one main power transformer).
- Power into the power distribution chassis should bring along a ground wire that grounds the chassis and references it to the power source.
- Power should be distributed from the power distribution chassis to all cabinets in the system through individual circuit breakers or fuses.
- Each cabinet should have a signal ground system separate from its equipment ground.
- The signal ground systems of each cabinet should be connected to a single point that has a single connection to the ground grid.
- If high-frequency interference (above 300 kHz) is a concern then a reference ground plane should be provided (see figure 15).

Single-point grounding design should be based on two distinct considerations: the equipment ground and the signal ground. To obtain maximum noise rejection, these grounds should be completely separated from each other all the way to the ground mat, where they are jointly connected to the station ground.

5.3.1.1 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 cable spreading rooms.

The type of single-point grounding depicted by figure 12 is ideally suited for low-frequency signals, particularly dc control circuits. It is less applicable for a control system with high processing frequencies.

Equipment suppliers often tie signal and safety grounds together inside or outside the equipment enclosure. It may be necessary to separate this common ground connection when integrating a piece of equipment into a grounding system. The requirement for separate signal and safety grounds should be included in the procurement specification.

Note that figures 12, 13, 14, 15, 16, and 17 depict an additional local safety ground for each cabinet in addition to the equipment grounding conductor provided with the incoming power cables. When provided, this additional connection will enhance personnel safety by providing an additional low impedance path to ground. Additionally, the bus bars illustrated by figures 12, 13 and 17 are shown schematically for clarity. They are typically located within a master control cabinet, rather than provided as separate, external buses.

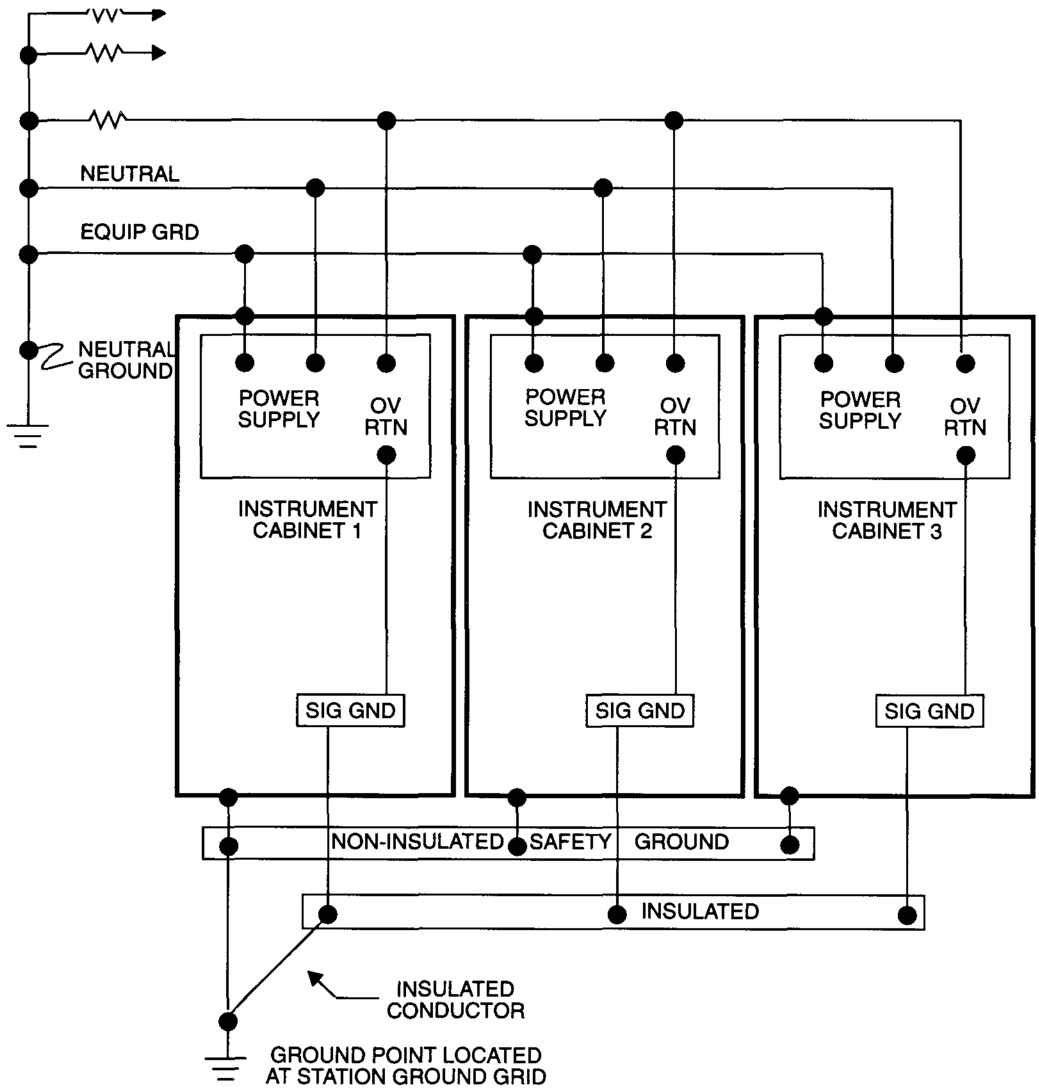


Figure 12—Single-point ground system for low-frequency signals with cabinets in close proximity

5.3.1.2 Cabinets that are widely separated

In a distributed control system the equipment may be widely scattered throughout the station, and it is impractical to implement the single-point grounding arrangement of figure 12. An I & C system is considered a distributed system when the individual control station cabinets are widely separated from each other. Such a system has special problems since the impedance in the signal reference conductors will result in a ground potential difference between the cabinets. Figure 13 illustrates an approach to providing a single-point ground system for this condition. The communications circuits between the cabinets should have appropriate protection for the common mode noise that is likely to result from the impedance of the long, insulated signal grounds.

The following considerations should be taken into account when designing the grounding system for a distributed I & C system:

a) An effort should be made to power the distributed system from a single power source.
b) Each individual system should be grounded in accordance with 5.3.1.

c) Instead of one overall safety ground, each cluster of instrumentation cabinets will have its own local equipment ground.

d) Signals between systems should use either transformer coupling or dc coupling, with transmitter/receiver circuits having a common mode withstand voltage that exceeds the ground voltage under fault conditions. The use of one or more isolated ground rods as the signal reference ground is a safety hazard and is not recommended.

e) One system should be used as a master station where both the signal and equipment grounds for the local stations are collected as described in 5.3.1 and the other systems should be treated as remote nodes. At the remote node, the signal ground is left floating from the local ground and is referenced back to the signal ground of the master station through the use of a heavy-gauge insulated wire running along with the lower-gauge signal wires between both locations (in the same conduit but not the same cable).

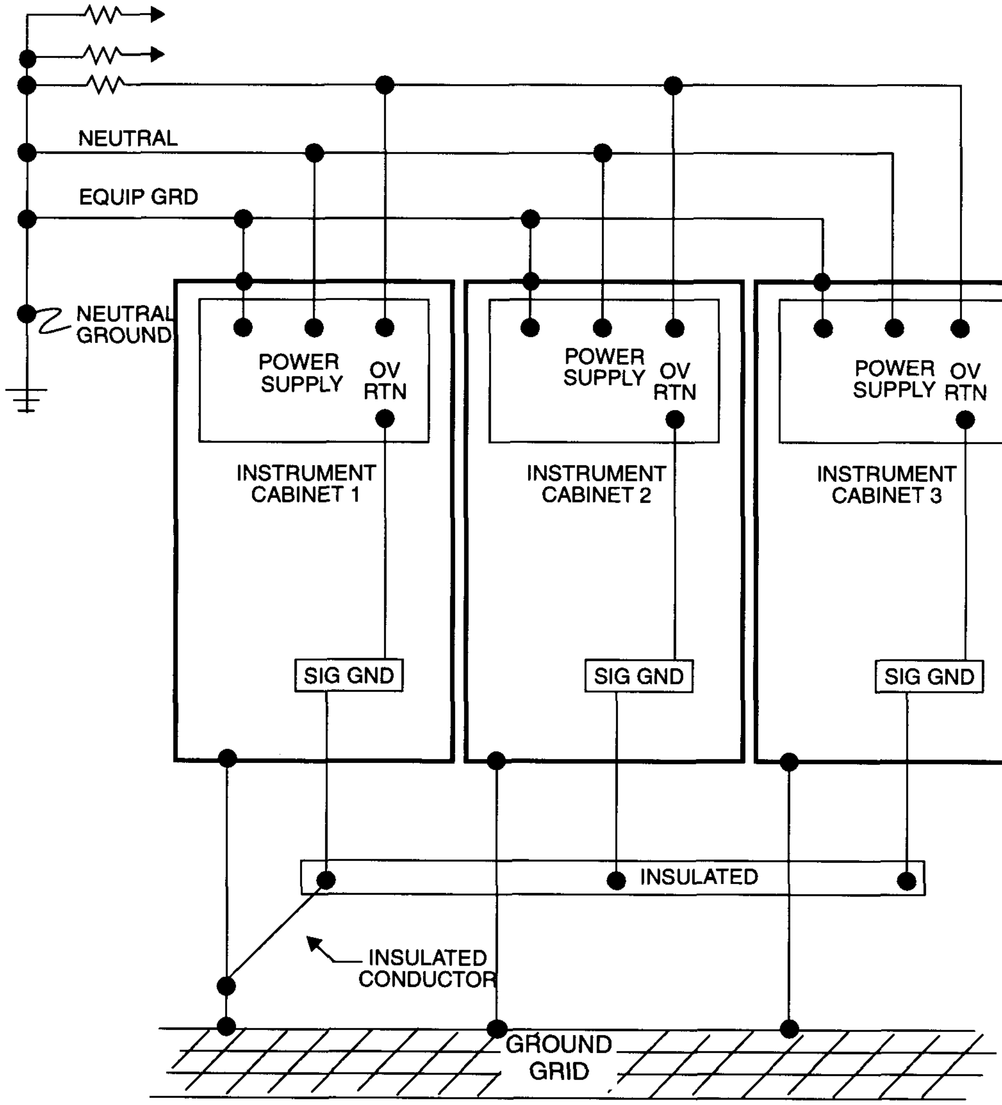


Figure 13—Single-point ground system for low-frequency signals with cabinets widely separated

For safety reasons a door switch may be used on the remote cabinet to tie the signal and local equipment grounds together when the door is opened (see figure 14). This protects maintenance personnel while troubleshooting the equipment at the remote site. Thus, the risk to personnel is minimized when the door is opened at the price of damaging the transmitter/receiver circuits if a ground imbalance due to large currents in the ground grid happens at the same time as maintenance is scheduled for the remote site. A case-by-case analysis of each installation will need to be performed in order to determine whether this approach is appropriate for the equipment configuration.

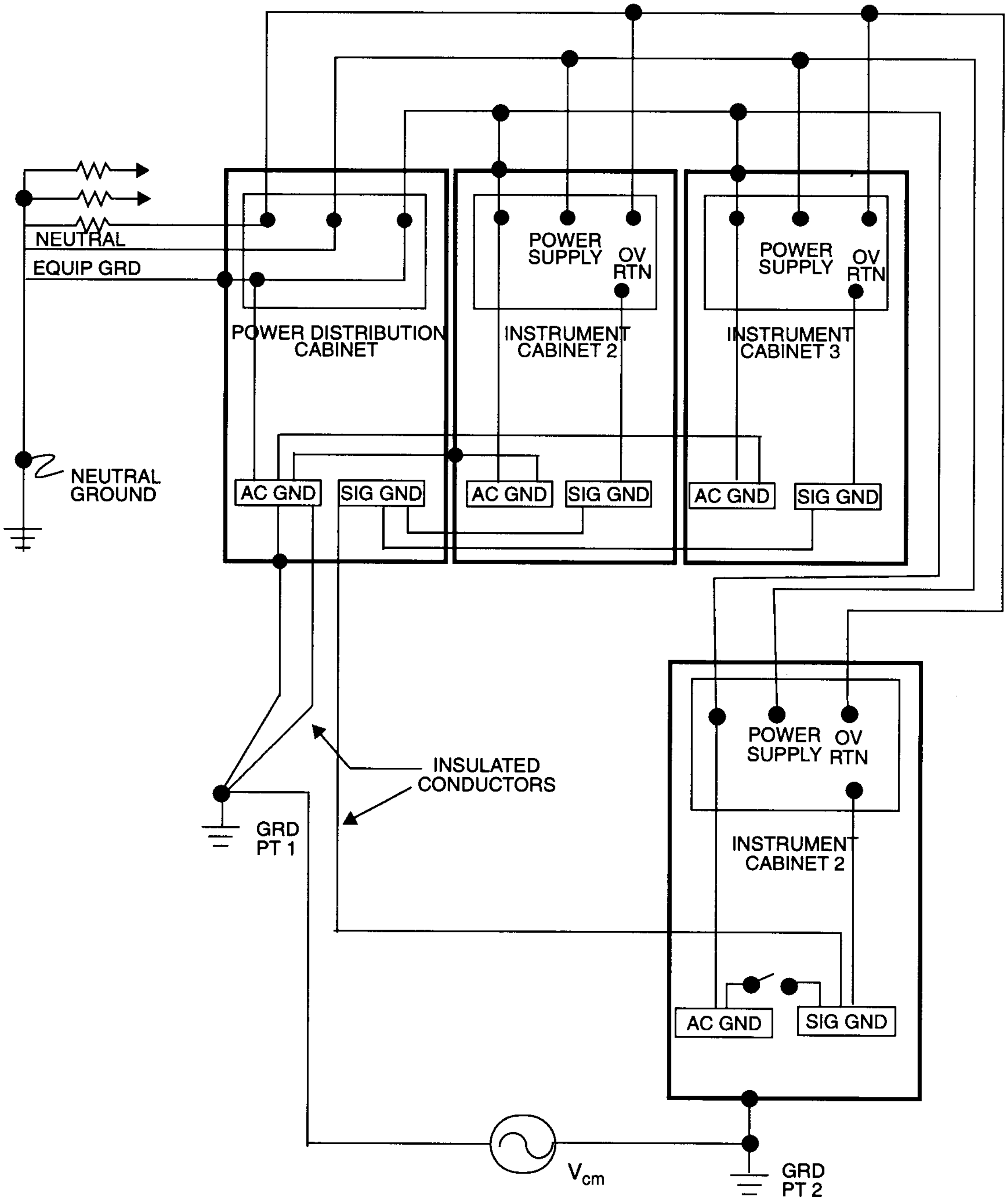


Figure 14—Single-point ground system for low-frequency signals with cabinets widely separated showing safety door switch

5.3.2 Multiple-point ground system

A multiple-point ground system should be considered when grounding equipment that operates at frequencies over 300 kHz, or when long ground cables are used (see figure 15). Each circuit is connected to ground at the closest point rather than routing all ground conductors to a single ground point. The advantages of this system are that circuit construction is easier, and that standing wave effects in the ground system at high frequencies are avoided. However, the system needs to be well maintained to overcome the effects of corrosion, vibration, and temperature change. Another disadvantage is that the system may create multiple ground loops that may cause inadvertent common mode noise.

A multiple-point ground system is an option for low-frequency signals, as shown by figure 16. This configuration accepts that a ground voltage difference will exist between the signal references and that the appropriate degree of protection should be provided for the resulting common mode noise.

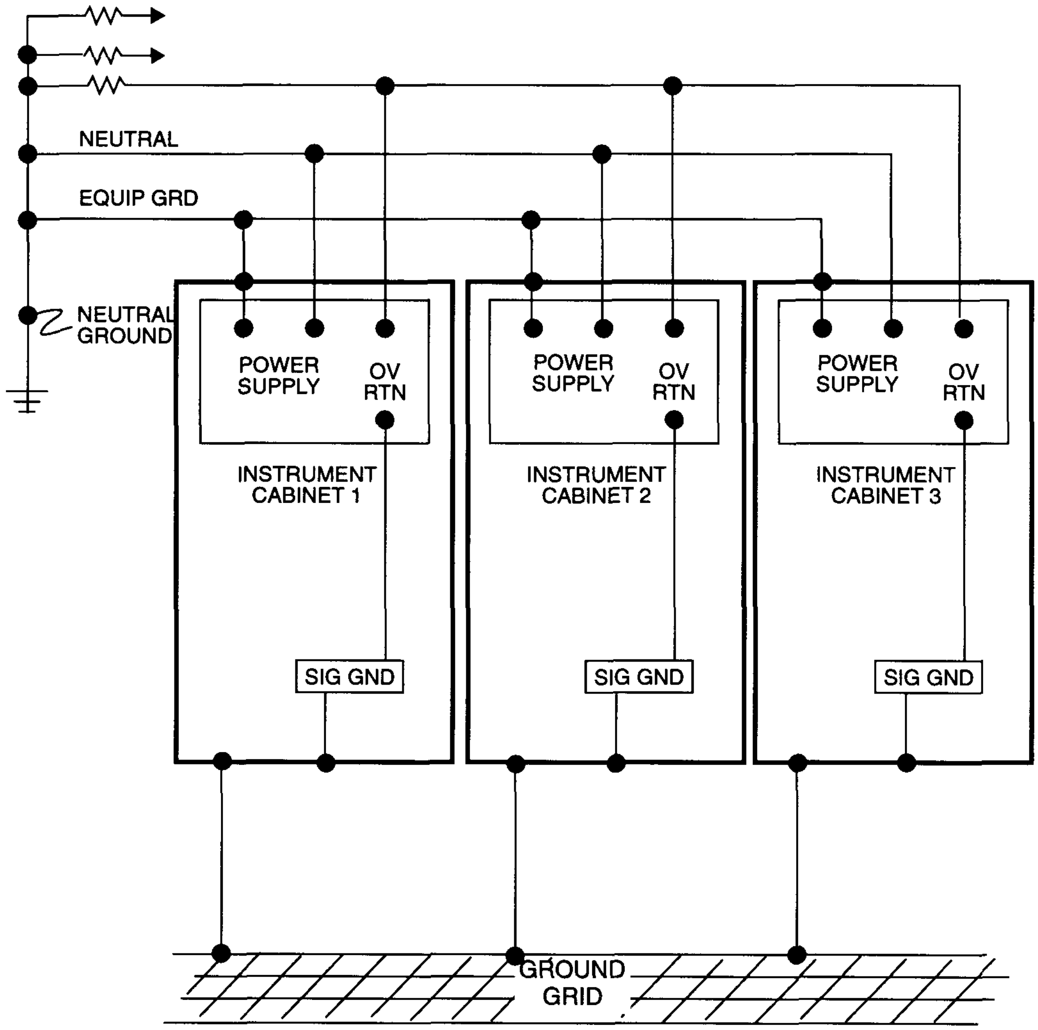


Figure 15—Multiple-point ground system for high-frequency signals

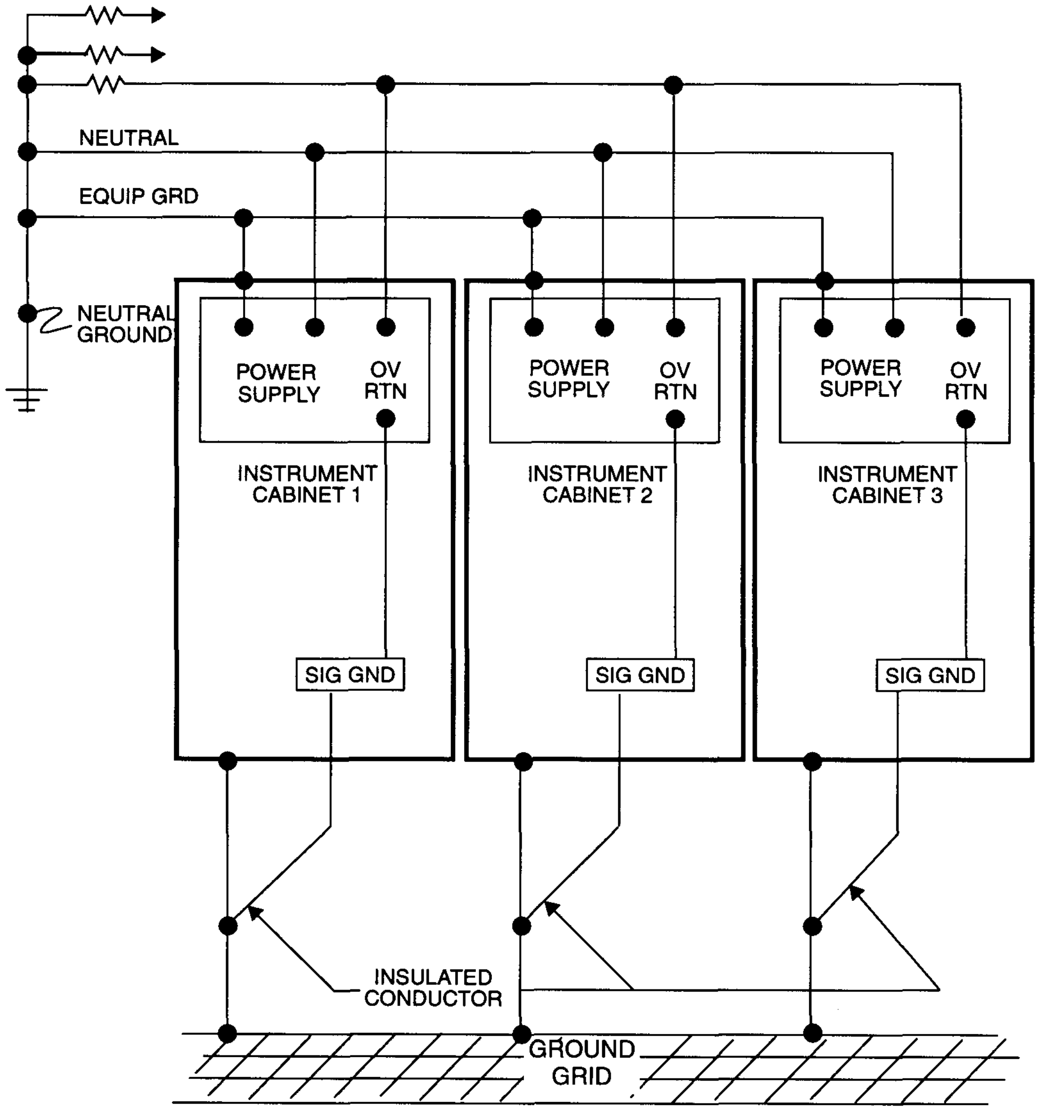


Figure 16—Multiple-point ground system for low-frequency signals with cabinets widely separated

5.3.3 Floating ground system

The floating ground system is used to isolate circuits or equipment electrically from a common ground plane or from common wiring that might introduce circulating currents and produce common mode noise. It is implemented by electrically interconnecting the signal grounds, yet isolating them from a common ground plane (see figure 17). A hazard of this system is that static charges may accumulate and eventually cause a destructive or noise-producing discharge current to flow. It is usually advisable to implement this system with a bleeding resistor connected to ground to avoid the buildup of static charges.

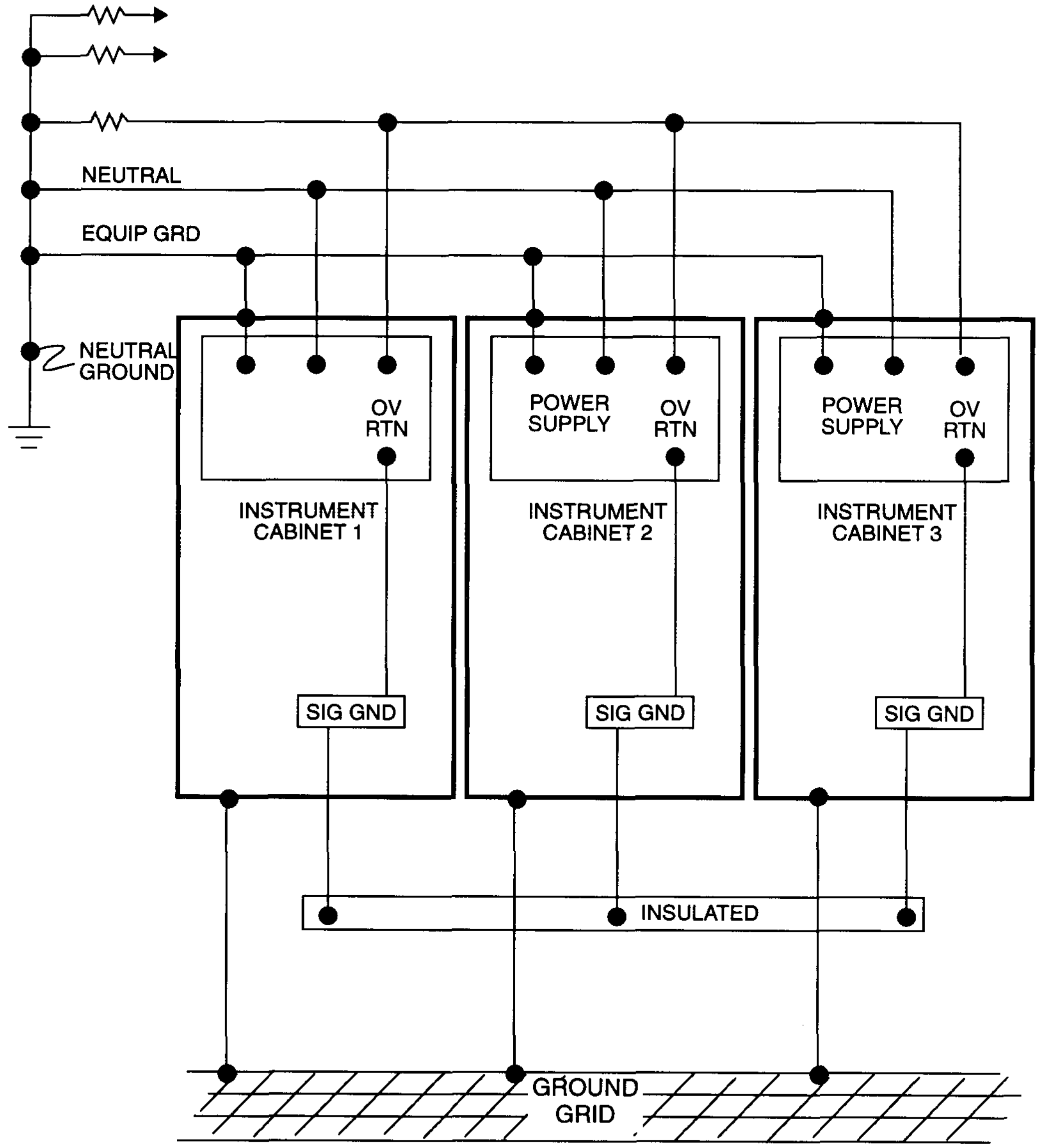


Figure 17—Floating ground system

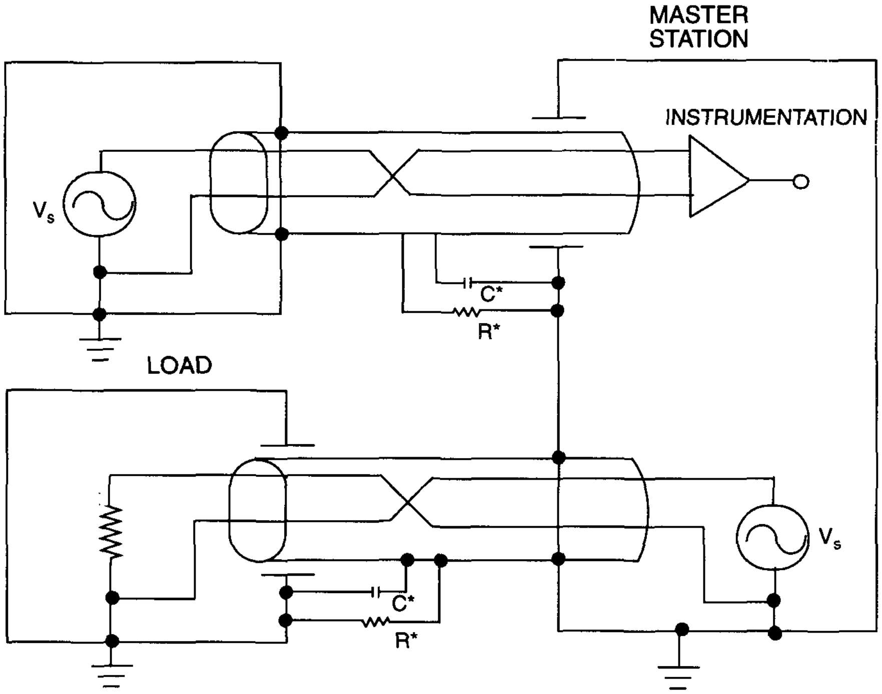
5.4 Grounding of low-frequency control circuits based on susceptibility

5.4.1 Grounding for high-susceptibility control circuits

High-susceptibility control circuits are those circuits with low voltage levels (analog input voltage between 5 mV and 1000 mV, thermocouples being the most common). These circuits are extremely susceptible to noise sources, such as common mode voltages, crosstalk, and electric and magnetic fields. Extension wiring on these circuits should be individually twisted and shielded. Whenever practical, these circuits should be installed in conduit, so that they are not subjected to excessive flexing or bending that might change their characteristics. Figure 18 shows a typical example of how such circuits should be shielded and then grounded at the source end of the shield. Individual shields should be grounded separately.

5.4.2 Grounding for medium-susceptibility control circuits

Medium-susceptibility control circuits are those circuits with medium voltage levels (analog input voltage between 1 V and 10 V). These circuits are likewise susceptible to noise sources such as common mode voltages, crosstalk, and electric and magnetic fields. Extension wiring on these circuits should be individually twisted and shielded. These circuits do not need to be installed in conduit. Figure 18 shows a typical example of how such circuits should be shielded. This illustrates how ideal engineering solutions may introduce the practical disadvantages of creating numerous grounding points distributed throughout the station. Shielding and grounding should be identical to the method described for high-susceptibility control circuits.



C*: CAPACITANCE TO ACT AS SHORT AT HIGH
R*: OPTIONAL RESISTANCE OR SURGE SUPPRESSION DEVICE

Figure 18—General control signal grounding

5.4.3 Grounding for low-susceptibility control circuits

The following is a list of low-susceptibility control circuits:

a) Analog output current (current source): 4 mA < I < 20 mA
b) Analog output voltage (voltage source): 0V < V < 10V
c) Digital output voltage: 5 V, 24 V, 28 V, 48 V
d) Digital output contact: (dry or mercury-wetted contact)
e) Digital input voltage: 5 V, 24 V, 28 V, 48 V
f) Digital input contact: (dry or mercury-wetted contact)

These circuits are less susceptible to the noise sources, such as common mode voltages, crosstalk, and electric and magnetic fields. Extension wiring on these circuits should be individually twisted pairs with an overall shield (one per cable). They need not be installed in conduit. These circuits should be grounded as shown in figure 18. Shielding and grounding should be identical to the method described for high-susceptibility control circuits.

5.5 Grounding for high-frequency signals

High-frequency signals in an I & C system are generally signals with a high susceptibility to noise. These are video signals (e.g., video signals to CRTs) that are transmitted on coaxial cables. The cables can be grounded or floated at either end. Shielded cables for low-frequency signals cannot be used to transfer RF signals.

Isolation transformers are generally used when CRTs are remote and referenced to a grounding point different from the display generator.

6. Signal cable shield grounding requirements

For this clause, all text and illustrations will refer to the cases where a cable contains either individually shielded conductor pairs or a single overall cable shield, since the grounding methods for both cases are identical. The special case where a cable contains both an overall shield and individually shielded conductor pairs is covered in 4.3.3.2.

6.1 Cable shield requirements

In general, cable shields should be connected to ground at both ends when the conductor length to signal wavelength ratio (L/λ) is greater than 0.15). This is a result of the shield becoming a relatively efficient antenna when $L = \lambda/4$ if only one end of the shield is connected to ground. Connecting the cable shield to ground at only one end is effective mainly for low-frequency signals where the cable run is relatively short.

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.

6.2 Analysis of shield grounding practices

6.2.1 Unshielded circuit grounded at a single point

In figure 19, the signal circuit is subjected to magnetic and capacitive interference from an external conductor and also to interference from a ground potential difference of V_N. Capacitive coupling through C_1 and C_2 imposes the interference currents I_N from the ground potential difference onto the signal lines.

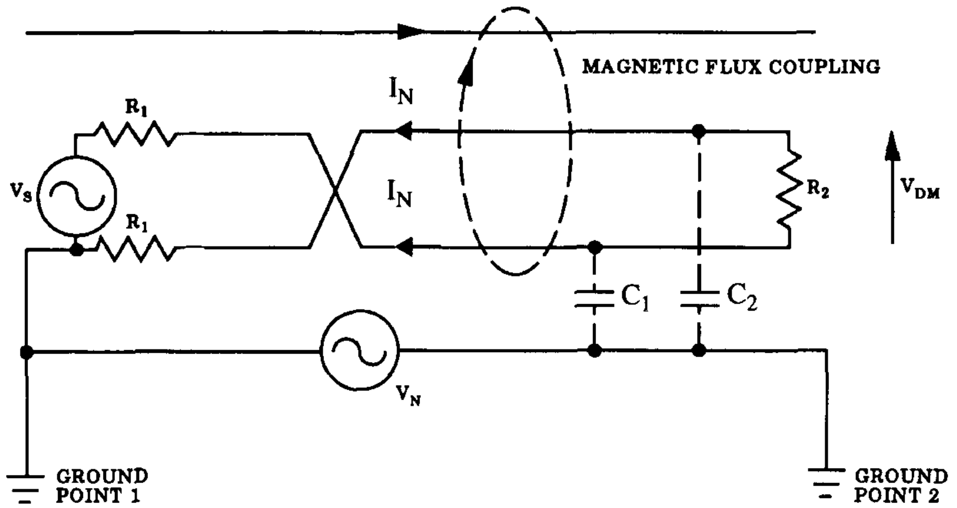


Figure 19—Twisted-pair control cables without shield

If the signal source is grounded (unbalanced circuit), a twisted pair cable will provide no protection against capacitive coupling at low-frequency, since although the induced currents may be equal, the unbalanced circuit will result in differential mode noise.

If the circuit is not connected to ground, it may float at an uncontrolled interference level. The end having the greater capacitance to ground should be grounded. In practice, it is normally the signal source.

The circuit is still subjected to a common mode voltage induced by the magnetic flux caused by the *di*/*dt* in the external conductor. The common mode interference current in the circuit may cause a differential mode voltage V_{DM} if the circuit is not well balanced.

6.2.2 Shielded circuit grounded at one end

The arrangement in figure 20 considerably reduces capacitive interference from other conductors at low frequencies. Since the ground potential is more directly coupled to the shield, the interference current I_N is conducted to the common ground point. This arrangement is suitable for low-signal frequencies.

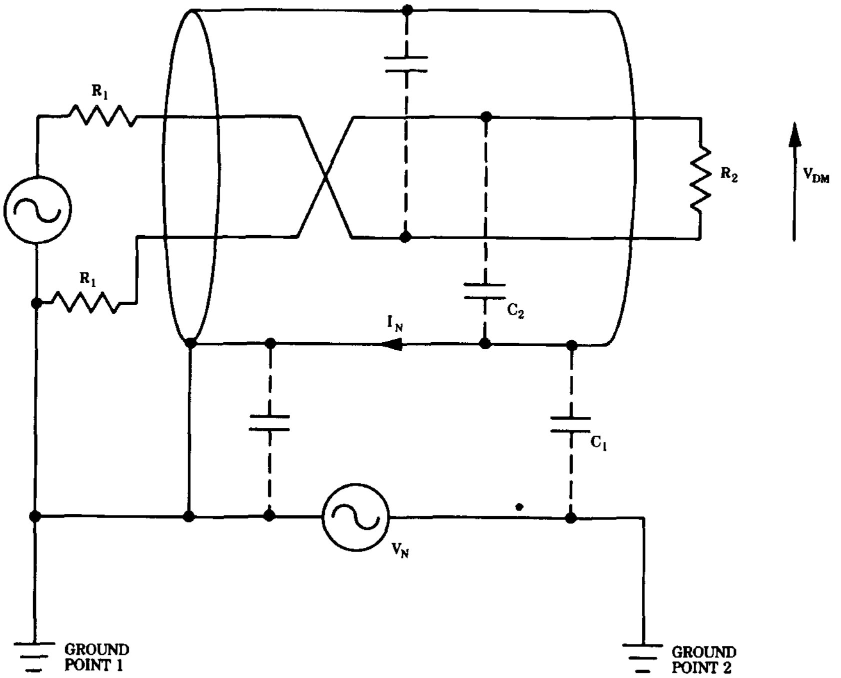


Figure 20—Shielded circuit grounded at one end

The common mode voltage, as before, is equal to the ground voltage V_N. However, with very high interference frequencies, the ground potentials become firmly coupled to the shield that in turn couples with the signal conductors through C_2.

Figure 21 shows shield grounding examples for both source and load. Note that 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. The shield should be grounded to be effective.

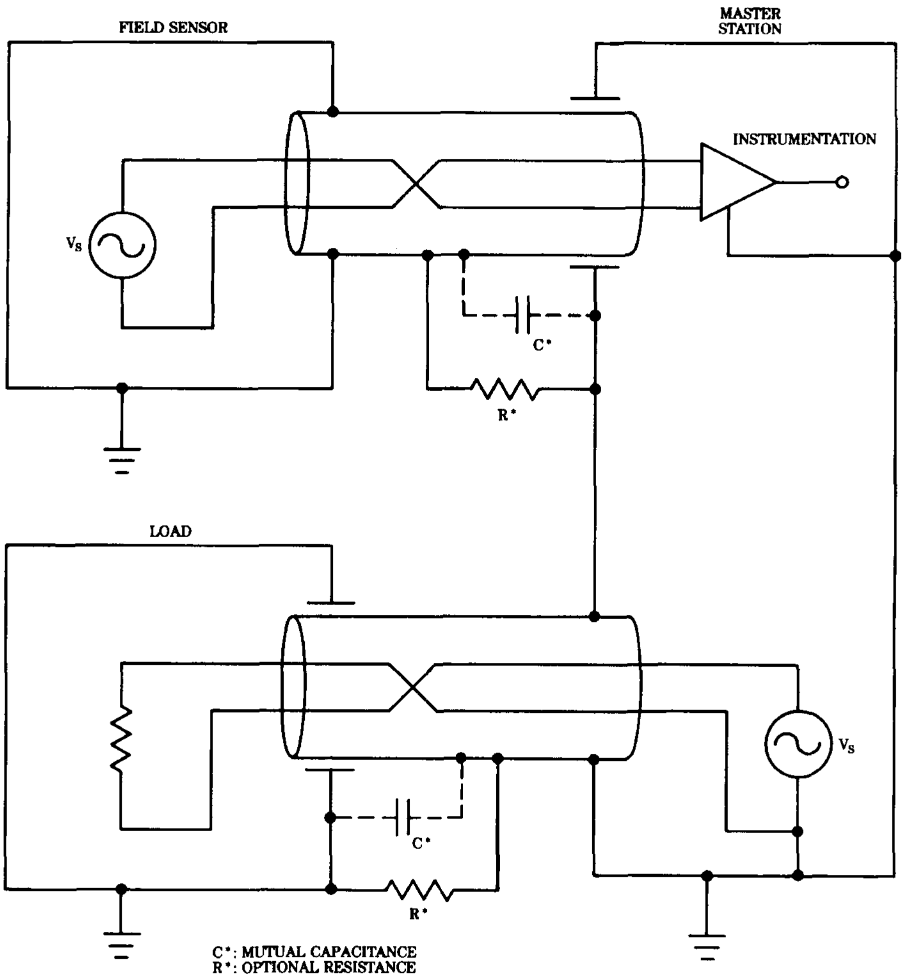


Figure 21—Shield grounded at signal source

6.2.3 Shielded circuit grounded at both ends

The ideal shield ground configuration is shown in figure 22. For no shield current to flow in this configuration, locations 1 and 2 have to be at the same voltage difference from ground.

The actual shield grounding configuration is shown in figure 23. In this configuration, the voltage difference between locations 1 and 2 is a common mode voltage (V_{CM}) that causes current to flow through the shield and the signal wires from capacitive coupling. Therefore, the input circuits have to process both the signal voltage and the common mode voltage (V_S and V_{CM}).

Another disadvantage of this method is that high-frequency ground potential differences produced by lightning or system faults will be coupled into the signal conductors.

The shield current can induce a differential mode noise voltage into the center conductor via magnetic coupling, unless the signal conductors are very carefully balanced. This is a particular problem for low-frequency signals and, for this reason, double-ended grounding should be used very cautiously.

Multiple-lead cable with individual wire shields 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 passes through a connector, a separate pin needs to be provided to carry the shield through. Double- or triple-shielded cable may be needed for high-input or high-output impedance circuits, especially in a high-electrostatic environment.

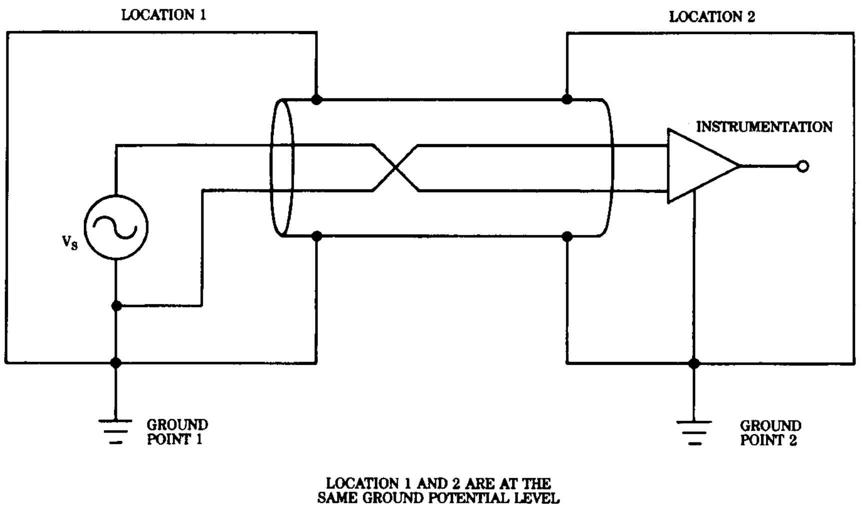


Figure 22—Shield grounded at both ends—ideal

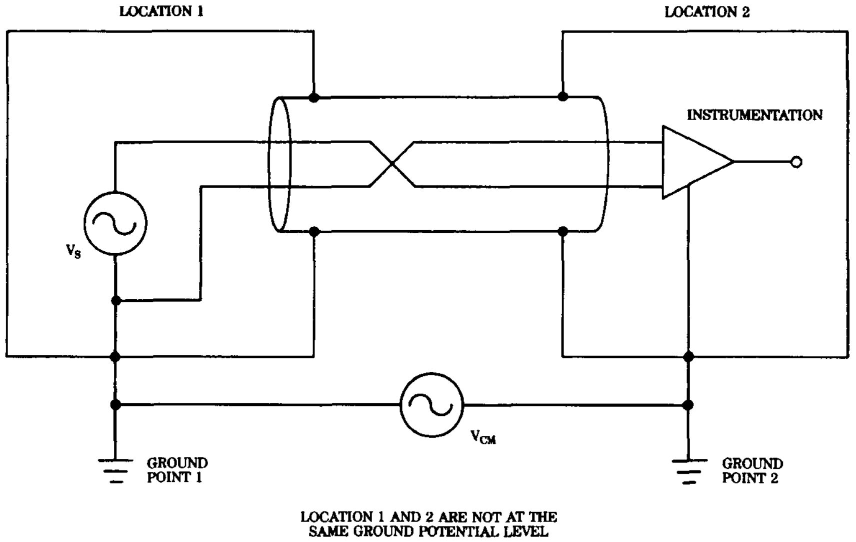


Figure 23—Shield grounded at both ends—actual

6.3 Central distribution frame (CDF) grounding practice

In order to minimize noise transfer to signal, the ideal grounding practice is to ground all cable shields only at the signal source. However, this would result in a widely distributed ground system throughout the station, with the following disadvantages:

a) An increased difficulty of controlling shield grounding practice through both design and construction phases with the probability of introducing multiple-ground loops
b) A substantial increase in commissioning time due to difficulty in tracking down ground loops
c) The difficulty and cost of providing a widely distributed insulated ground reference system

Some utilities have accepted a compromise approach of providing a central grounded reference at, or close to, the receiving end. Combined with other practices of minimizing noise generation in a generating station, this system has been proven to provide protection to minimize coupling to acceptable levels. More sensitive signal and processing systems can be treated separately with the shield grounded at the source end.

In addition to countering the above three disadvantages of conventional practice, the CDF provides an ideal system to permit trunk cabling systems. These may have substantial cost and schedule advantages.

6.3.1 Principles of CDF grounding

A single, insulated 4/0 ground is brought directly from the station ground mat (not from the building distributed ground system) to an insulated copper bus (typical cross section 25 mm x 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 system for all field signals not connected to the computer and to those sensitive signals not grounded at their source.

If there are a number of separate CDF ground buses, these should be connected radially (in a “tree” or “star” configuration) from the bus that has the station ground connection. Insulated 4/0 cables should be used.

6.3.2 Auxiliary computer CDF grounding

It may be expedient to provide a separate but similar ground bus at the computer for all field signals directly connected to the computer. This bus is connected radially by an insulated 4/0 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, using a minimum of No. 2 AWG insulated wire.

6.4 Coaxial cable

Signals at frequencies above 300 kHz are often transmitted by coaxial cable. In this type of cable, the outer conductor (shield) acts as a return path and also provides a bleed-off for stray voltages.

At lower frequencies, the return current travels primarily through the ground plane rather than through the shield. Therefore, at low frequencies, the shield offers practically no magnetic shielding.

The particular frequency below that a shield will offer practically no attenuation is termed the cutoff frequency, and is defined as

$$f_c = R_\mathrm{s} / (2\pi L_\mathrm{s})$$

where

R_s is the shield resistance
L_s is the self-inductance of the shield

Cutoff frequencies for standard coaxial cables range from 0.5–10 kHz. As the frequency increases above the cutoff frequency, the shield offers increasing attenuation. The improvement in shielding effectiveness is due to the reduction in loop area caused by current returning on the shield, rather than via the ground plane, and not by any magnetic shielding properties of the shield itself. At extremely high 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.

For coaxial shielding to be effective, the shield should be properly terminated. The practice of twisting the braid of a coaxial cable and point soldering it to the base of a connector may result in a 20 dB degradation in the effectiveness of the shield at high frequencies. The braid should be soldered so that it completely encloses the inner conductor at the connection junction.

The maximum possible bend radius should be used when routing coaxial cable. The bend radius should not be less than 10 times the nominal diameter of the cable. It should be noted that most braided coaxial shields provide only about 85% coverage of the center conductor.

6.5 Twisted-pair cable

At audio and power system frequencies where ground loops are a nuisance, common mode rejection ratios of up to 60 dB can be achieved by using twisted-pair cables feeding balanced loads. By twisting the wires, a series of adjacent loops is formed in the instrument circuit rather than one loop, which would be formed by using two parallel conductors. Any magnetic field that goes through both loops of the instrument cable will tend to be canceled, as the currents induced by the magnetic fields into adjacent loops in each wire are in opposite directions.

Twisted pair cable is also effective for capacitive coupling by ensuring that any coupled noise is balanced. Protection should still be provided for the common mode noise that results from the equal coupling.

6.6 Balanced circuits

For the common mode rejection to be effective, the terminal impedance and the pair should both be balanced. This implies that if the circuit is to be grounded, it should be center grounded (see figure 24).

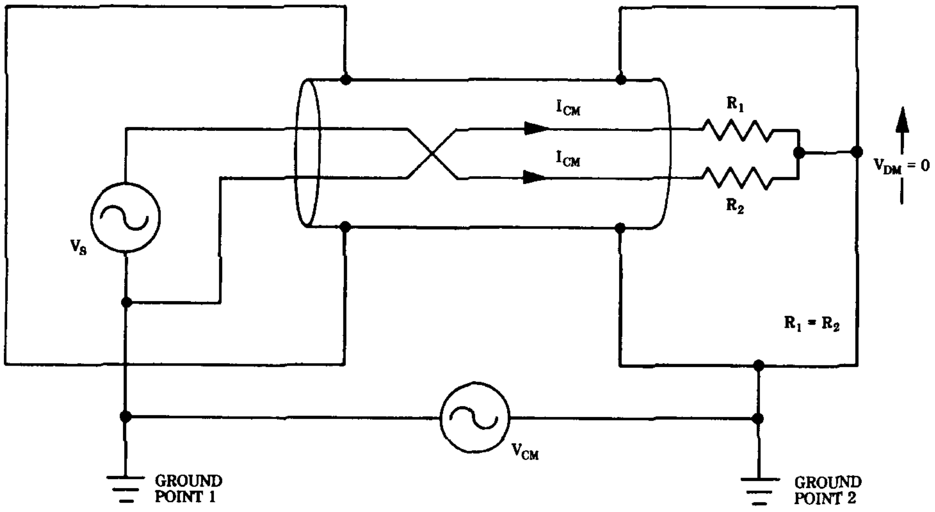


Figure 24—Common mode rejection with balanced circuits

If the circuit has been grounded on one end, however, half of the induced common mode current will flow through the load, thereby reducing the common mode rejection from about 60 dB to 6 dB (see figure 25). There is little benefit from using a twisted pair if the circuit is unbalanced by connecting one side to ground.

If balanced grounding is not a viable option, it may be better to float the receiver at its enclosure to lower the common mode current in the twisted pair.

The shorter the lay of the twisted pair, the greater the noise reduction. Since shorter loops are more costly to manufacture, 18 turns/m is often taken as optimum.

At high frequencies, imbalances in the stray capacitances and inductances make common mode rejection less effective. For this reason, shielded and twisted pairs should be utilized, since as the twisted pairs become less effective at higher frequencies, the shield effectiveness increases.

6.7 Other cable shielding considerations

Other cabling considerations that should be taken are as follows:

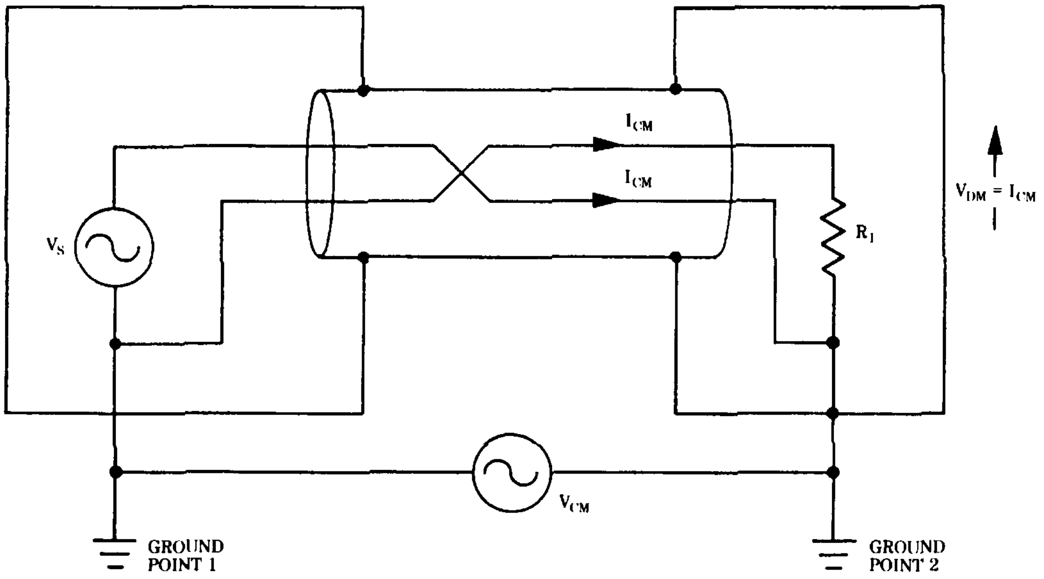


Figure 25—Common mode rejection nullified by ground

a) Connecting the spare conductors in a cable-to-ground at both ends has been found to reduce the amount of high-frequency coupling. In multiple-conductor control cables, however, such a procedure can also increase the level of 60 Hz interference from ground loops.

b) If the control cables are being laid in a cable trench, additional low-frequency shielding of the cables can be provided by running a 4/0 ground grid conductor either inside or on top of the trench.

c) In areas of extremely high voltage (345 kV and above), it has been found necessary to shield all power cables, such as yard lighting and station 120 V service, as a result of operating problems caused by high-frequency transients propagating along these cables.

6.8 Comparison of cable shielding effectiveness

Comparisons of the magnetic and electric shielding effectiveness of various cable systems can be found in IEEE Std 518-1982 and [B45].

6.9 Application of cable shield grounding methods

Grounding of computer and multiplexed I & C equipment is required for both safety and reliability. Although safety takes top priority, the computer and multiplexed system should be simultaneously safe and operationally reliable.

The three basic concepts of single-point, multiple-point, and floating ground systems were defined in 5.3. Each concept has its advantages and disadvantages, and a typical generating station signal ground system may use a combination of all three.

6.9.1 Single-point ground

This concept protects equipment from the relatively low-frequency noise in a generating station grounding system; but it is really only economical for situations where there is a high density of electronic equipment, such as in the control equipment rooms.

6.9.2 Multiple-point ground

This concept protects equipment from relatively high-frequency interference. This system is generally simpler to achieve than single-point grounding. It also simplifies some systems, such as where coaxial cable is used, since the outer conductor does not have to be floated relative to the equipment enclosure. This system will, however, permit the low-frequency noise within the station ground to enter the signal ground system. The use of multiple-point grounding with short conductors appears to be the most reliable and simple method for coping with signals over 300 kHz in frequency.

By using bypass capacitors instead of direct ground connections at one end of the shield, it is possible to make a cable shield appear to be grounded at high frequencies where the capacitors have a low impedance. At low frequencies, the capacitors carry negligible current, so the same system may have the characteristics of a single-point ground at low frequencies (refer to figure 22).

The multiple-point system should be used in systems where high-frequency interference is expected. The practical application is to use the equipment chassis as a signal reference. The chassis is then connected to the equipment case (and equipment ground) with a large number of connections (refer to figure 15).

6.9.3 Floating ground

A true floating ground system is difficult to achieve in practice and will commonly be found only in subsystems. Because floating subsystems represent a safety hazard, any that are provided with vendor supplied equipment should be contained within a grounded enclosure.

6.10 General requirements for control loop grounding

Control loops not associated with direct digital control or computer-based systems require effective ground connections for safety, noise minimization, and for the establishment of reference voltage. Control loop grounding can be categorized into two groups: local ground and floating ground. The cable shield should be grounded at the point of maximum capacitance between the shield and the circuit reference. This reduces the possibility of creating a ground loop through the capacitance while also minimizing charging current flow and the resultant common mode noise that can be produced.

6.10.1 Local ground

Instruments that have grounded connections should have their cable shields connected to ground as close to the instrument ground as possible, as in figure 26.

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 maximum capacitance, which is usually the signal source.

6.10.2 Floating ground

Signals that are ungrounded (i.e., floating) should have their cable shields connected to ground as close to the source as possible, as shown in figure 27. Transmitters, isolation amplifiers, and all ungrounded inputs should have their cable shields grounded in this manner (see 6.2.2).

6.11 Floating ground for digital communications in a distributed system

Differential amplifiers, drivers, and receivers are designed to operate with two grounding reference potentials. Figure 28 illustrates this concept.

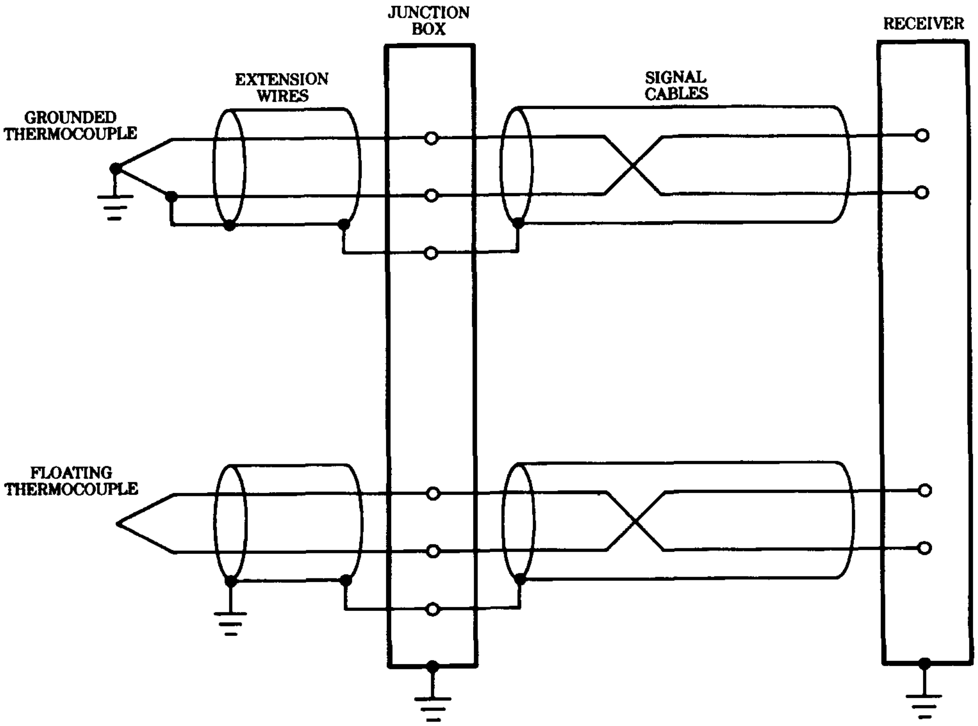


Figure 26—Examples of locally grounded instruments

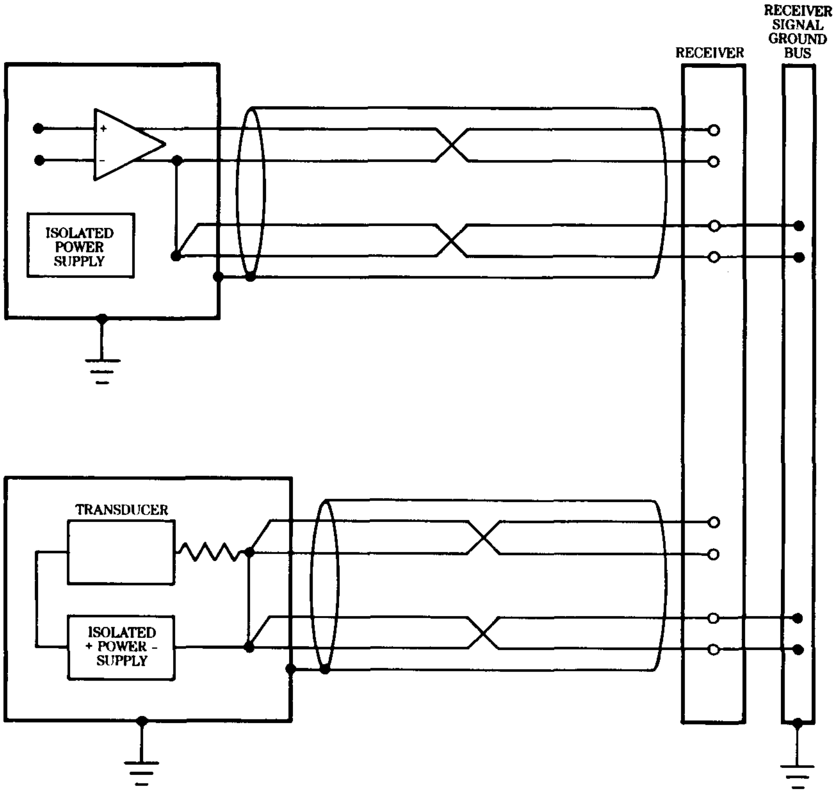
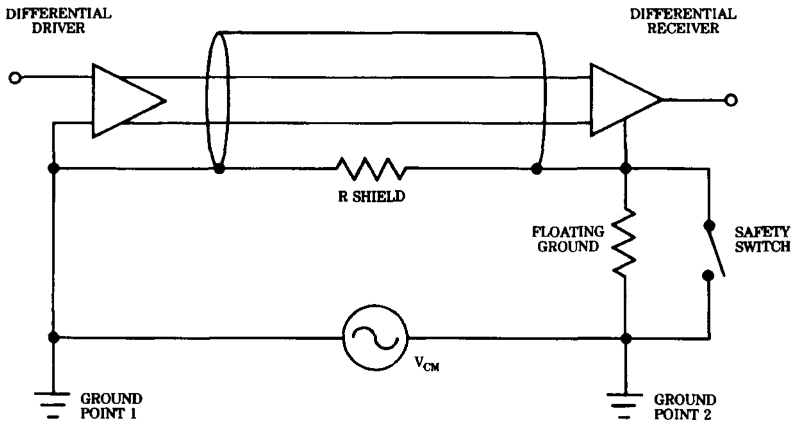


Figure 27—Examples of floating instrumentation loops



NOTE—A fraction of the full common mode voltage is applied on the differential receiver when the safety ground switch is used.

Figure 28—Grounding differential drivers and receivers

The following points should be considered:

a) The shield should be connected to ground at the point of maximum capacitance to prevent a ground loop from forming between the shield connection to ground and the stray capacitance. This point of maximum capacitance is often the signal source.

b) 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.

7. Testing

7.1 General

This clause addresses testing to detect ground loops on instrument ground systems that use the single-point grounding concept. This clause does not address testing on those high-frequency systems where multiple-point grounding may be used.

7.2 Sources of ground loops

The primary sources of ground loops are as follows:

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

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 due to moisture normally occur at circuit devices, terminal strips, or connectors.

7.3 Ground loop prevention and detection

Ground loops are formed whenever two or more connections are made to different locations on the station grounding from different points on a signal cable or cable shield. 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, ground loops would provide a path for current flow through the signal cable and/or shield via the multiple ground points. This current flow will create common mode noise on the signal circuit and may cause noise problems if the common mode noise is converted to normal mode noise by the circuits and terminations. The noise currents are most commonly 60 Hz or a harmonic of 60 Hz, with the third harmonic being typical.

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., check for isolation from ground using an ohmmeter or some other calibrated device capable of measuring insulation integrity. The resistance between the wire or shield and station ground should be greater than 1 MΩ..

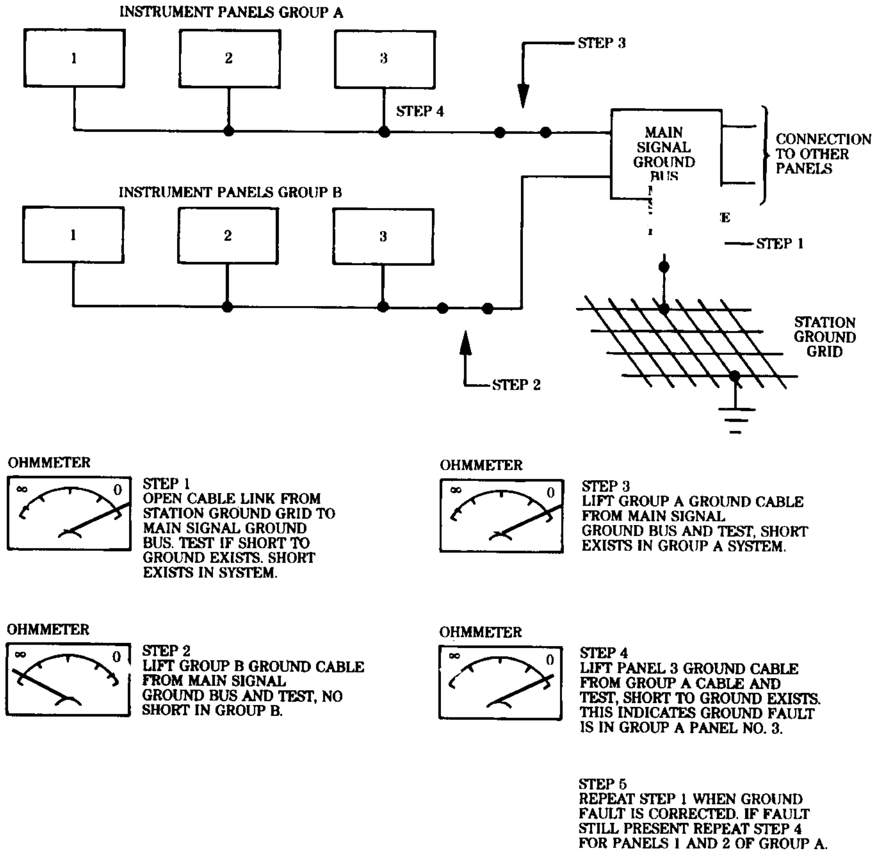
b) Where low resistance indicates an improper ground, defective cabling, moisture, etc., the deficiency should be corrected. Only after the deficiency is corrected should the circuit, shield, etc., be connected to ground.

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 ground loops, except for those ground loops formed when cable shields and the associated signal circuits are grounded at different locations. The capacitance between the shield and the signal wires will permit ground current to flow between the ground points through the capacitance. The best way to avoid loops formed in this manner is careful design, construction, and field verification of the installation.

7.4 Testing for ground loops

Ground loops formed by multiple direct or resistive ground connections to the station ground grid can be detected by the procedure described below and illustrated in figure 29. 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 29—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 50 V source and a milliammeter to detect high-resistance ground loops.

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 cause equipment grounded to the instrument ground system to operate incorrectly. Hence, the 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 include only 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 needs to be utilized. This could involve a procedure such as follows:

a) Measure noise current/voltage on instrument 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. Note that it is normal for some current to flow in a ground system due to capacitive coupling between energized circuit conductors and ground conductors (such as shields). The presence of voltage or current on an instrument ground cable does not necessarily mean a problem exists. Additionally, the absence of noise or of no incorrect operation of circuits does not indicate the absence of ground loops or potential problems. Problems caused by intermittent noise sources, such as transients and power system ground faults, would be virtually impossible to locate during testing since ground loops would only create a problem when a transient or power system ground fault occurred. Thus, noise measurement tests may not be effective in locating 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 would indicate the power ground system as the source; the presence of 120 Hz and 180 Hz would indicate a power supply as the source. Any high-frequency noise on a data system may be generated within the data system.

7.5 Signal ground system integrity

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

a) Measure the resistance between the main signal ground bus and the station grounding system.
b) Measure the resistance between each cabinet signal ground point and the main instrument ground bus.
c) Compare the resistances to design 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)

Examples of I & C grounding methods

This clause contains examples of I & C grounding in generating stations. Beginning with figure A2, each example is illustrated twice, first as the ideal method recommended by theory, and second as the Central Distribution Frame (CDF) method, which trades off maximum shielding effect for other practical benefits (see 6.3).

NOTE—On many of the following figures such as figure A2, 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 other shield(s).

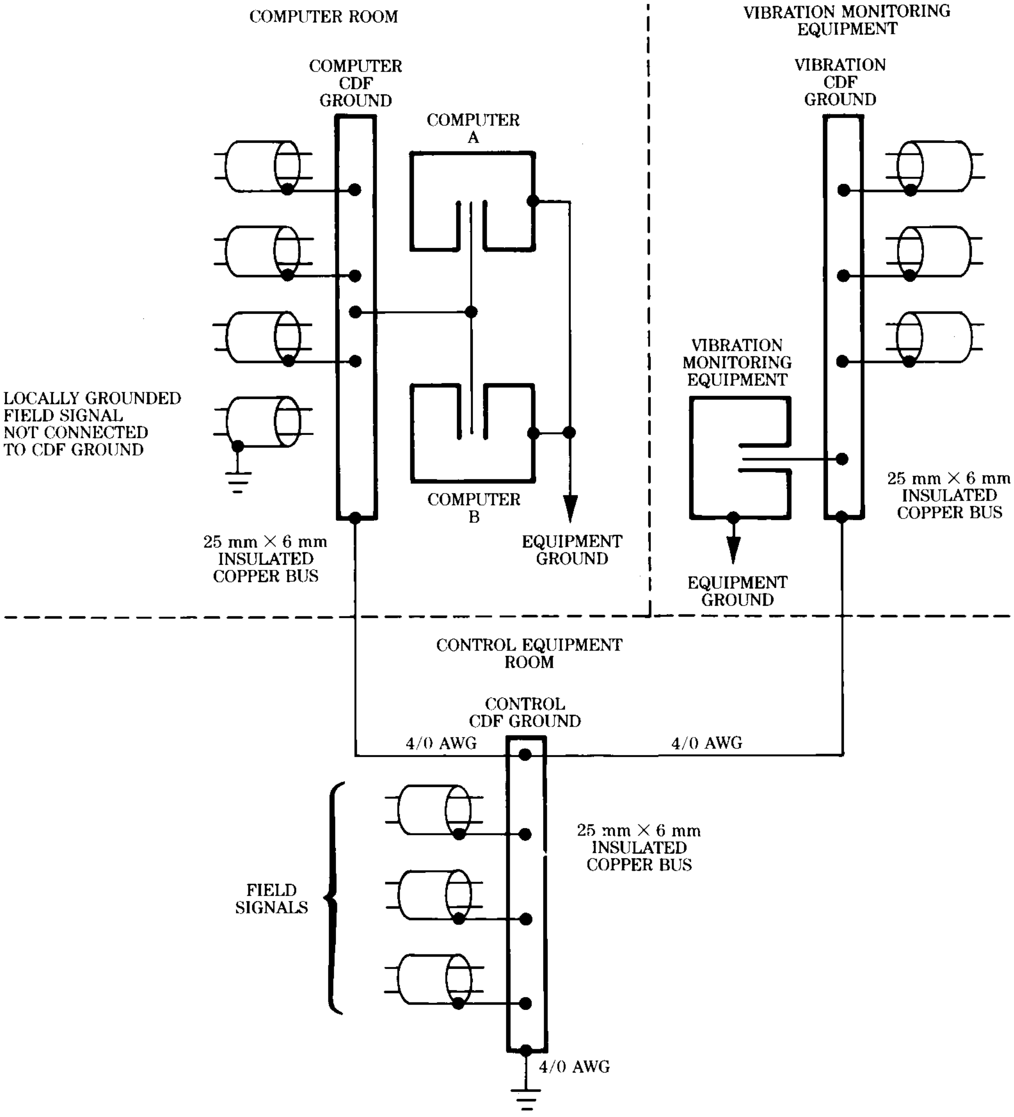


Figure A1—Example of CDF grounding arrangement

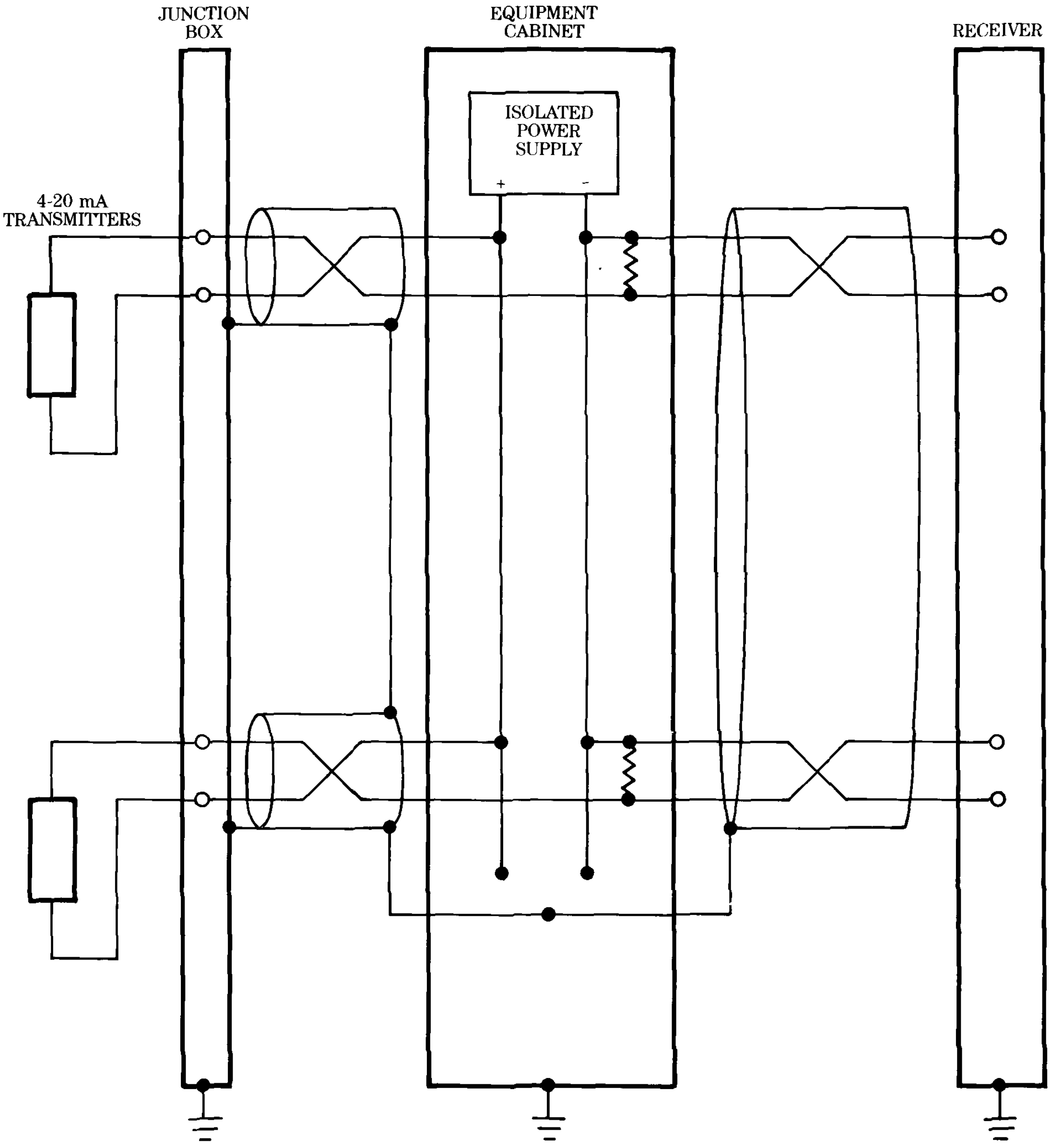


Figure A2–Analog control loops–ideal

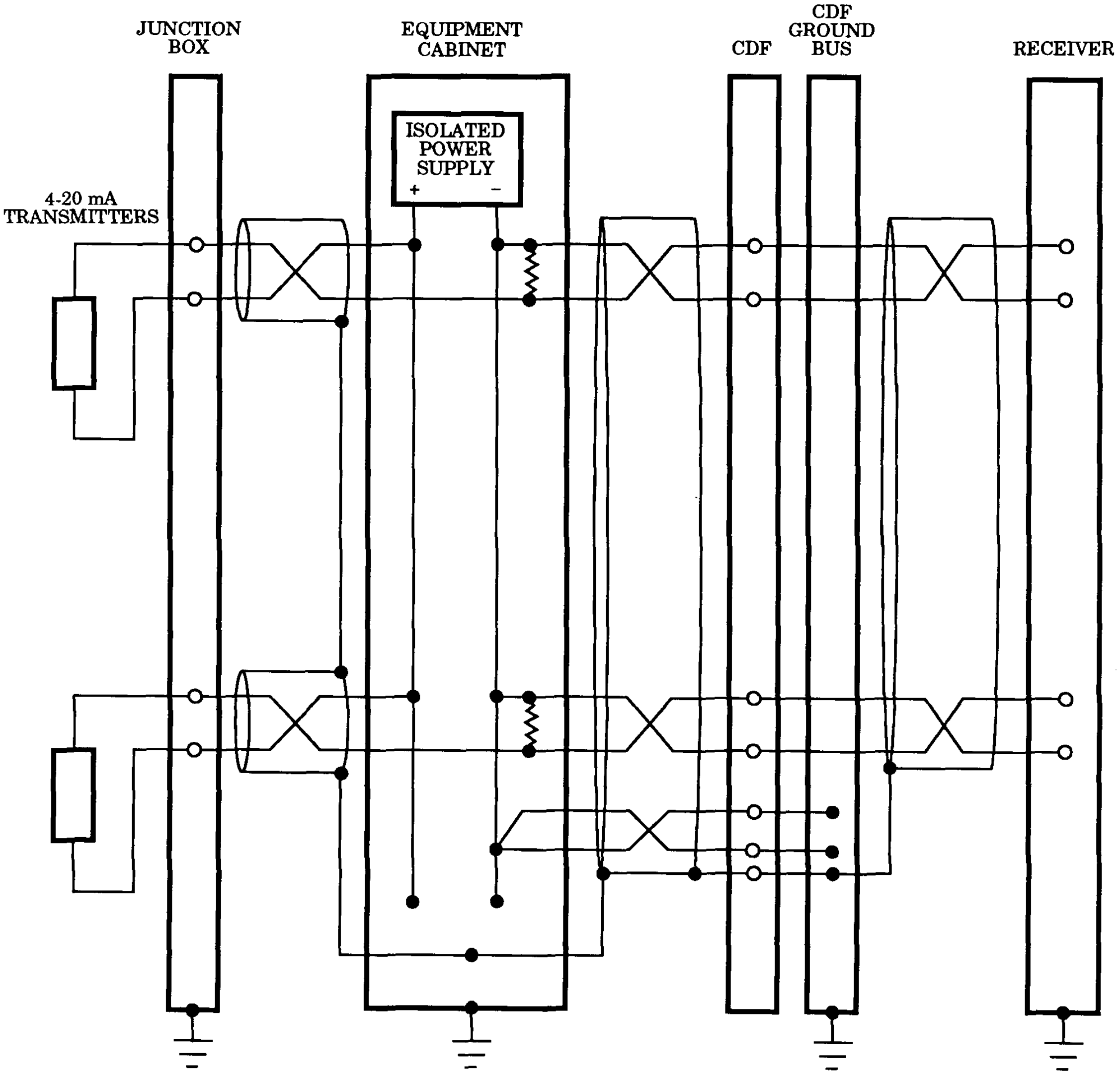


Figure A3—Analog control loops–CDF

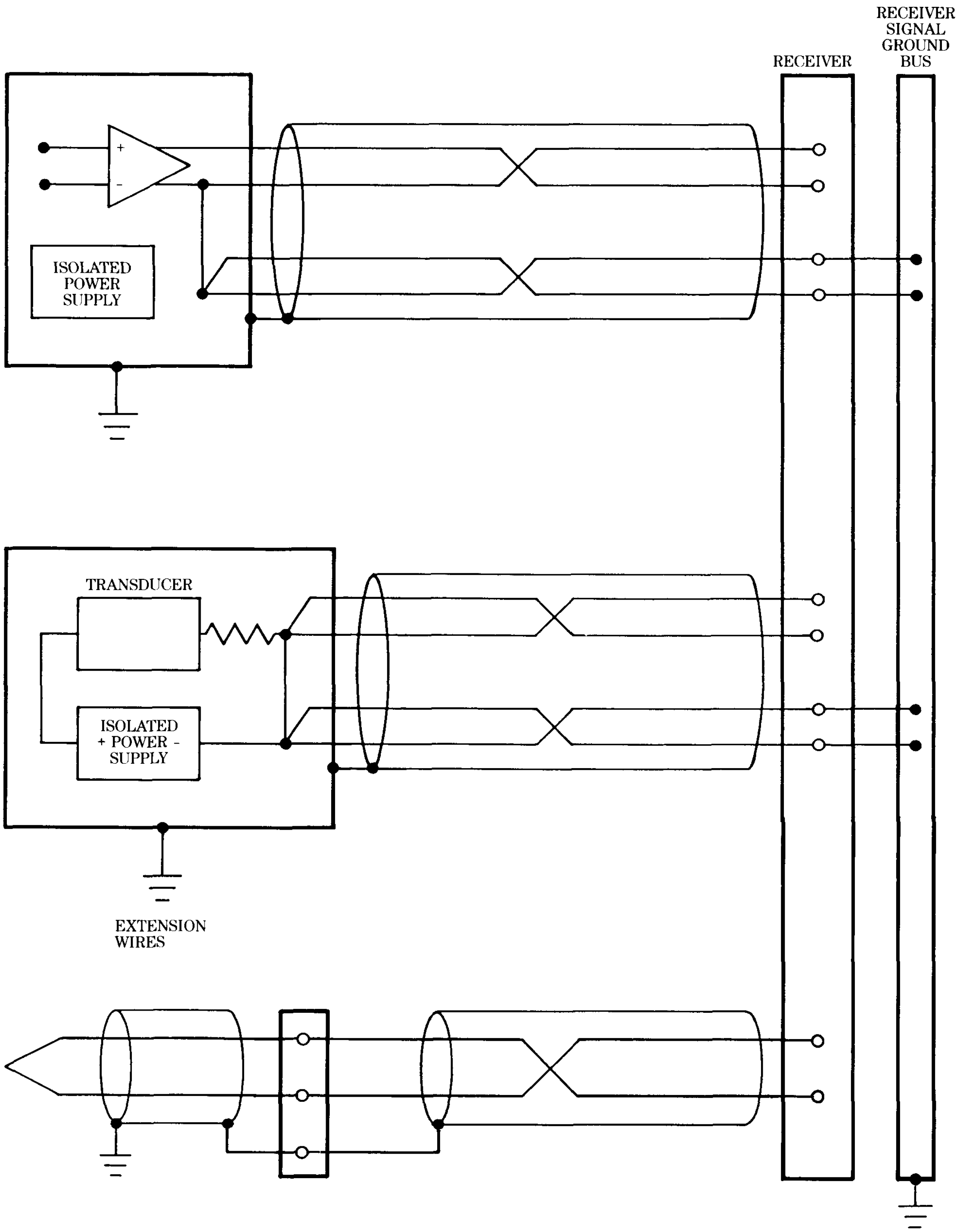


Figure A4—Floating signal loops–ideal

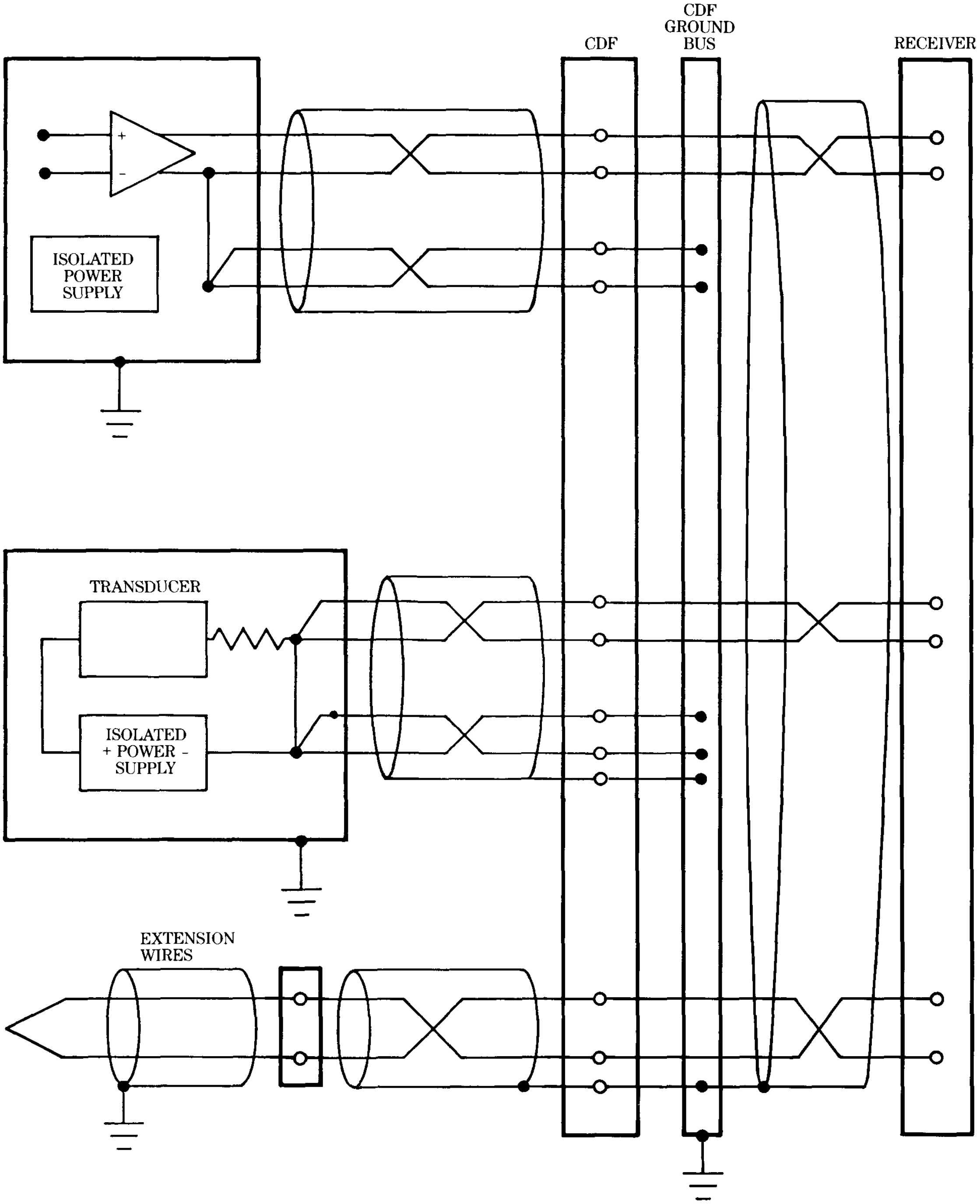


Figure A5—Floating signal loops–CDF

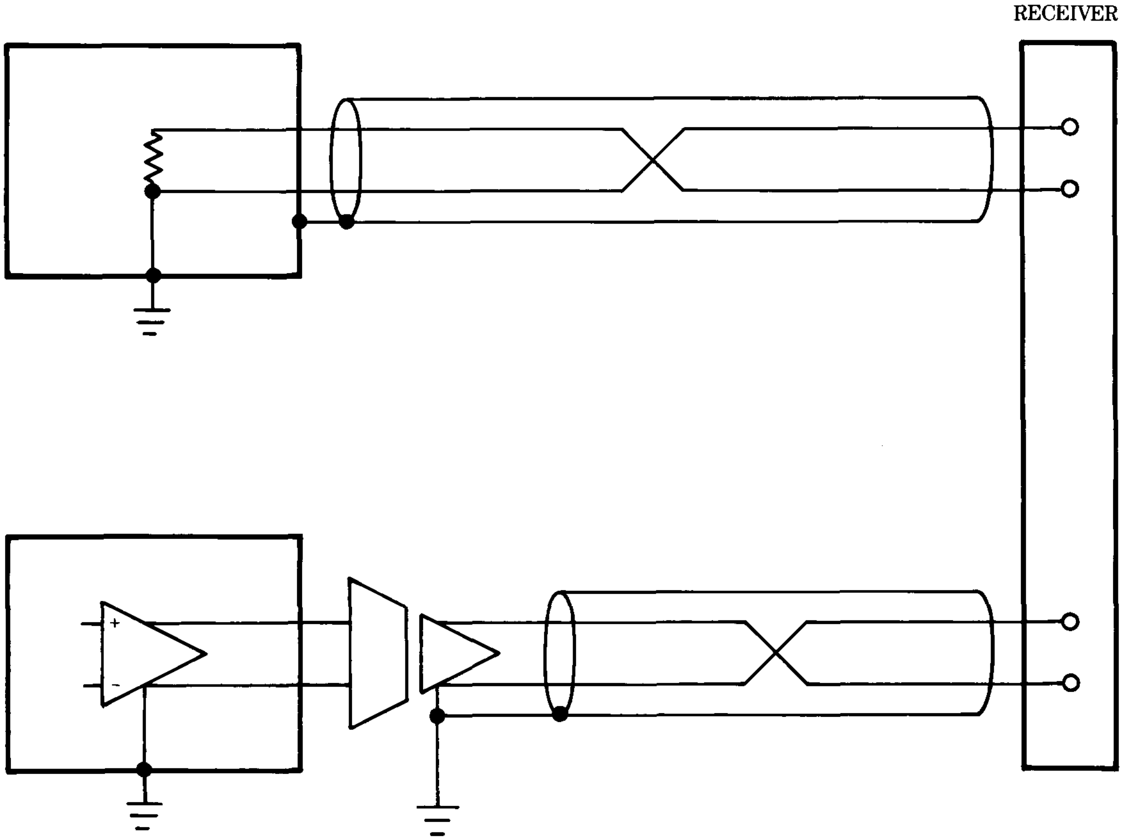


Figure A6—Grounded signal loops–ideal

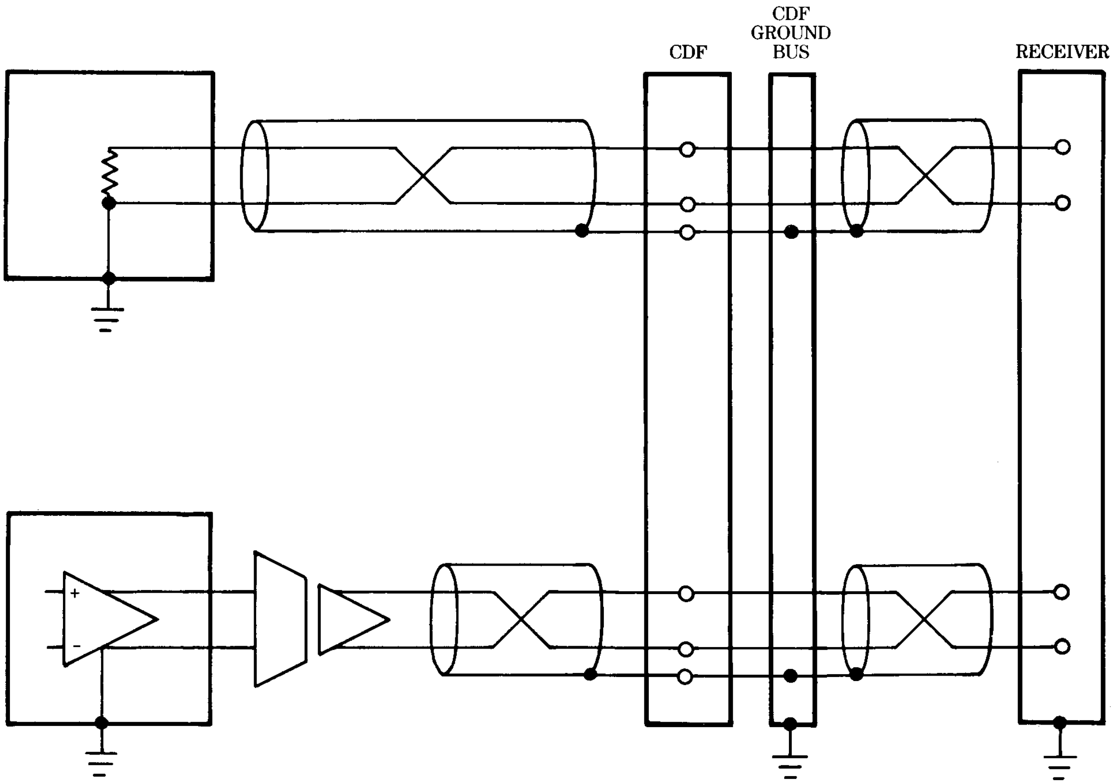


Figure A7—Grounded signal loops–CDF

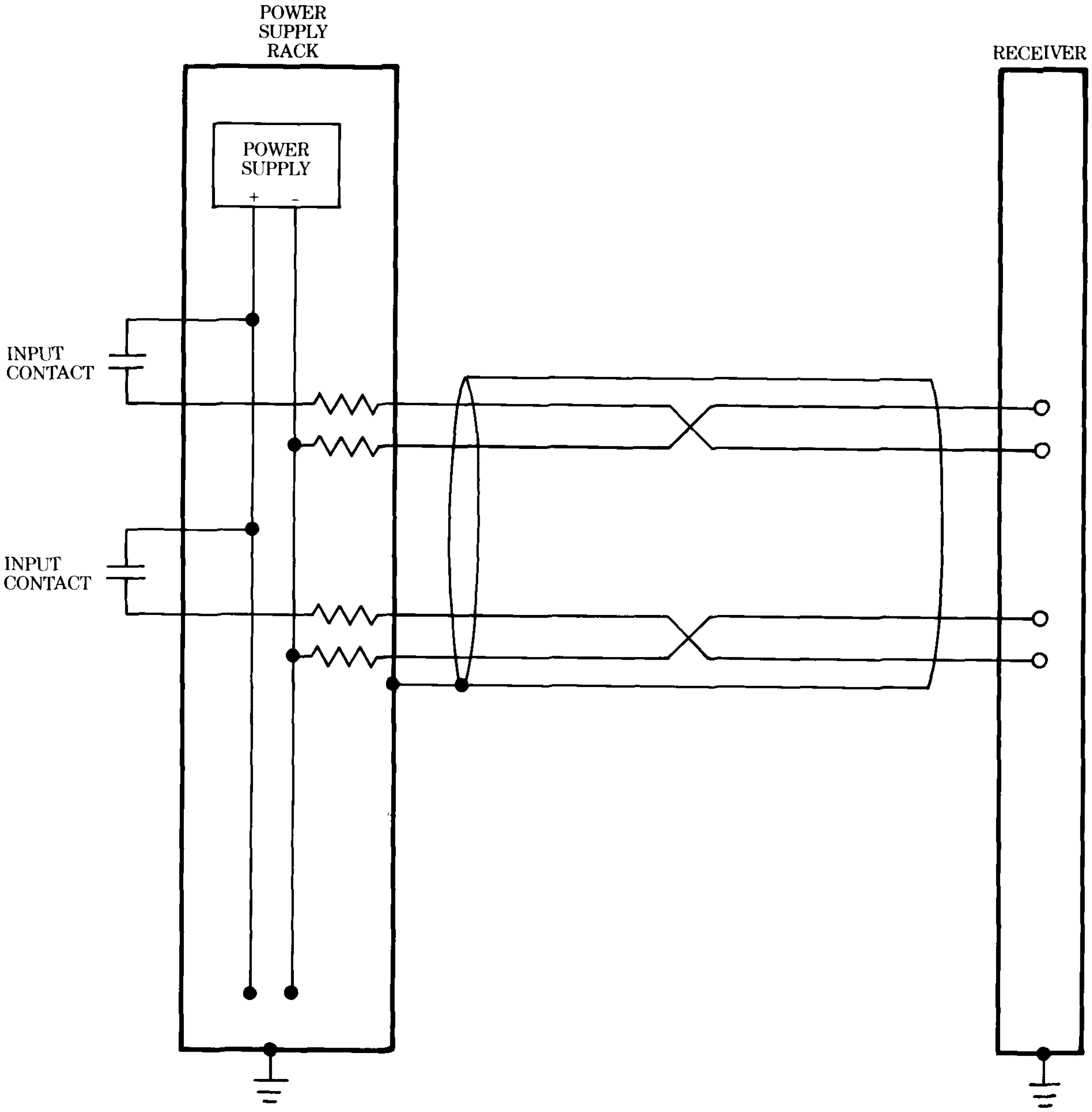


Figure A8—Digital (dry contact) input–ideal

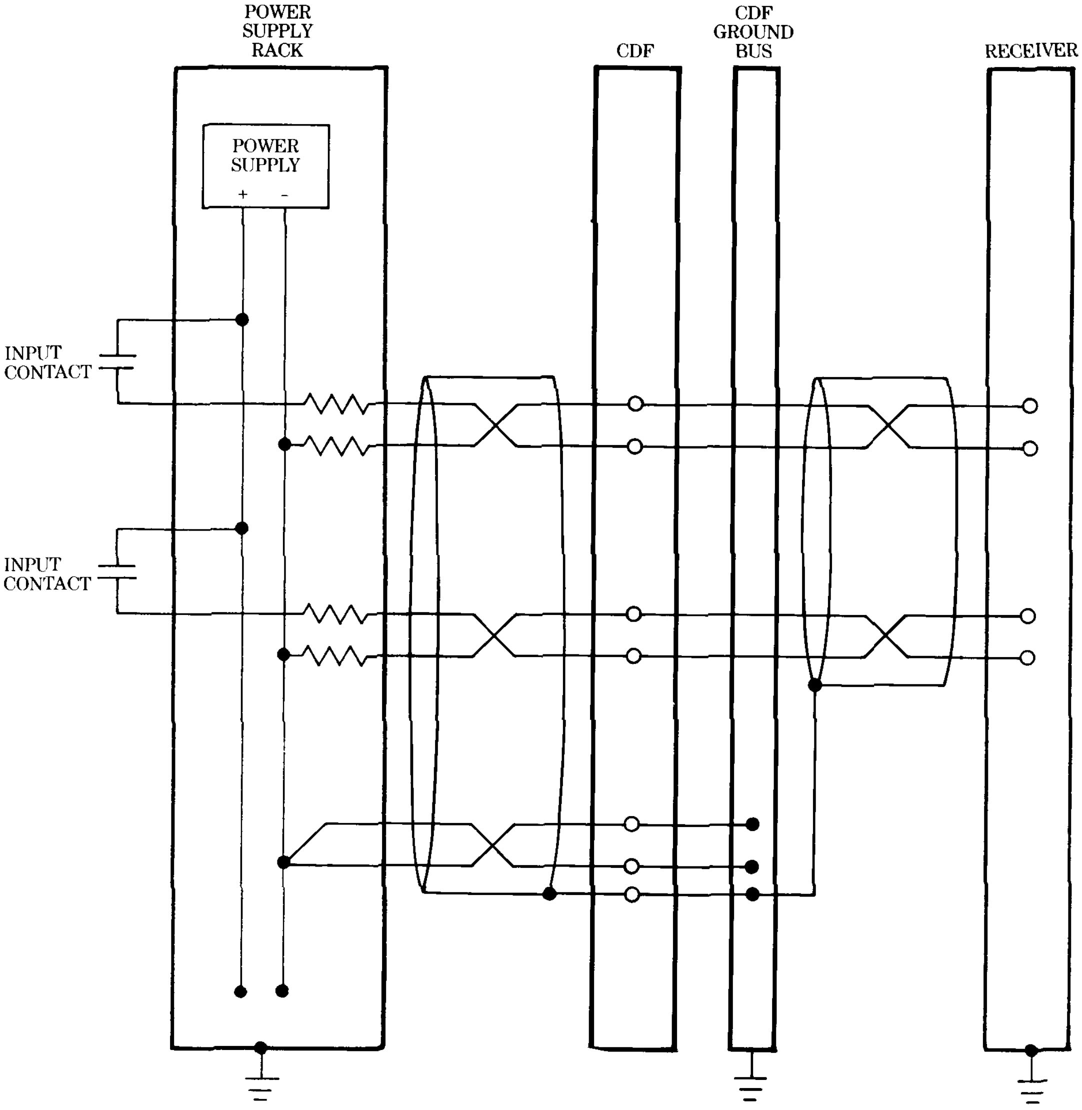


Figure A9—Digital (dry contact)–CDF

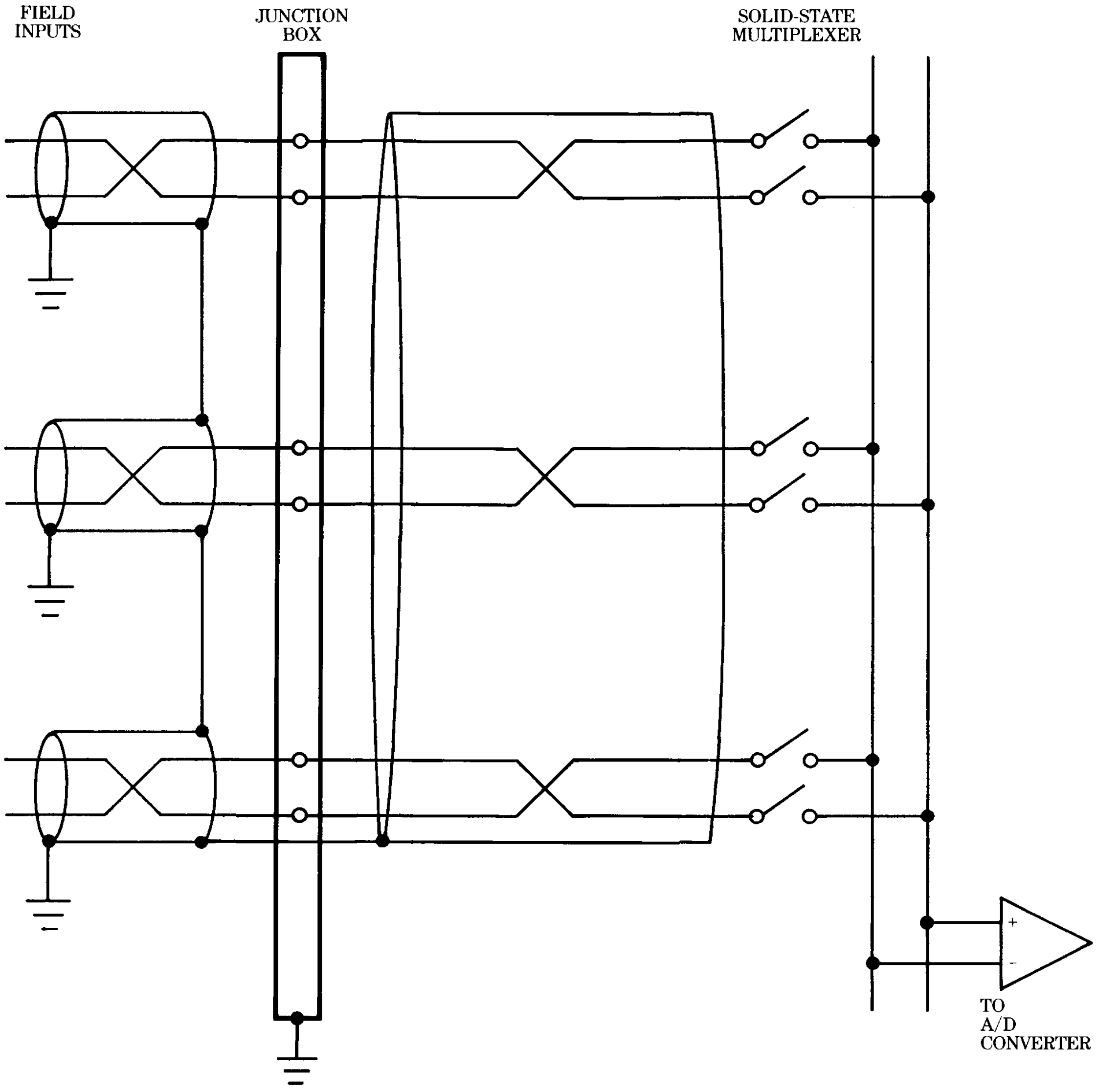


Figure A10—Computer analog input connections–ideal

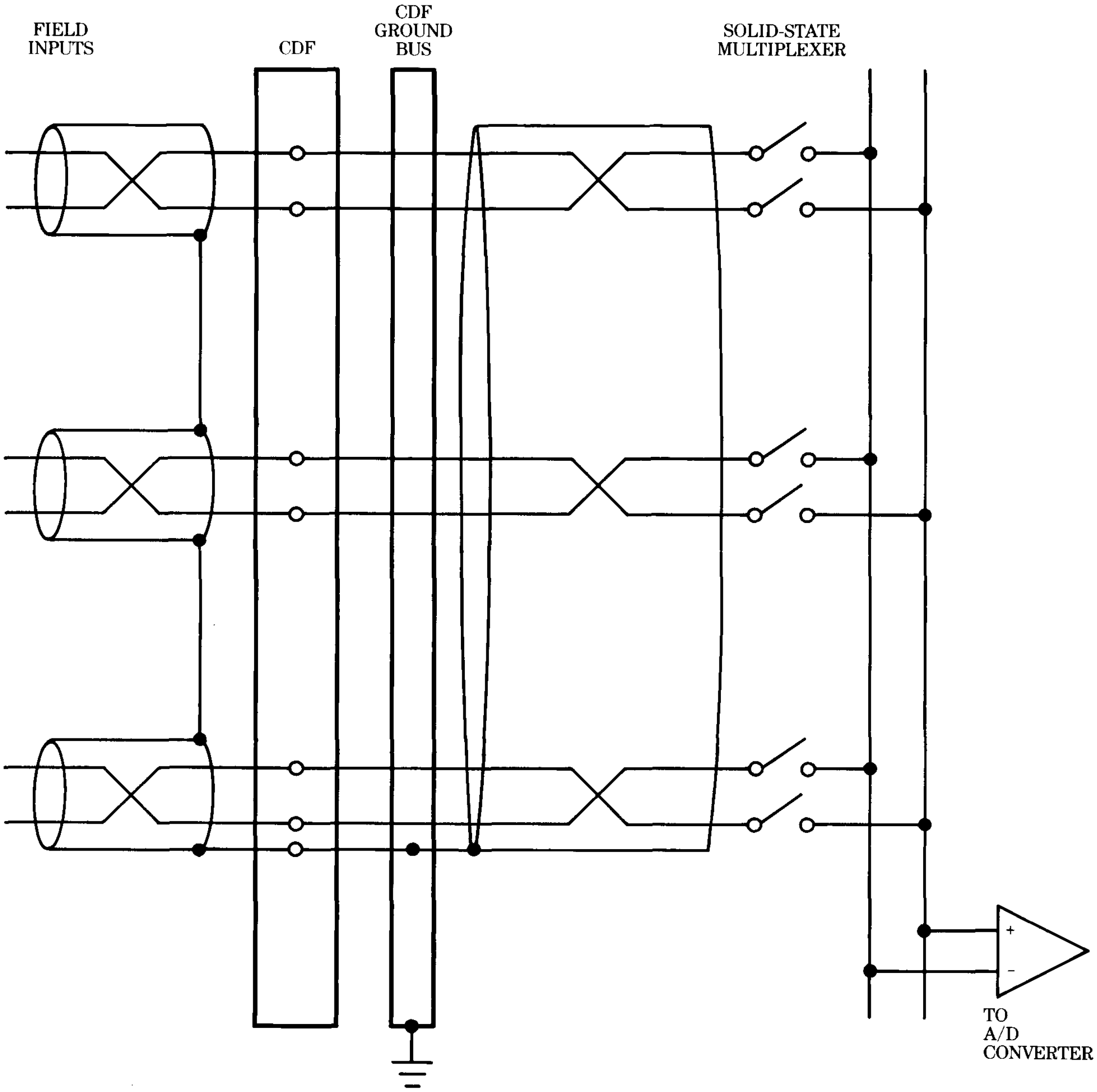


Figure A11—Computer analog input connections–ideal

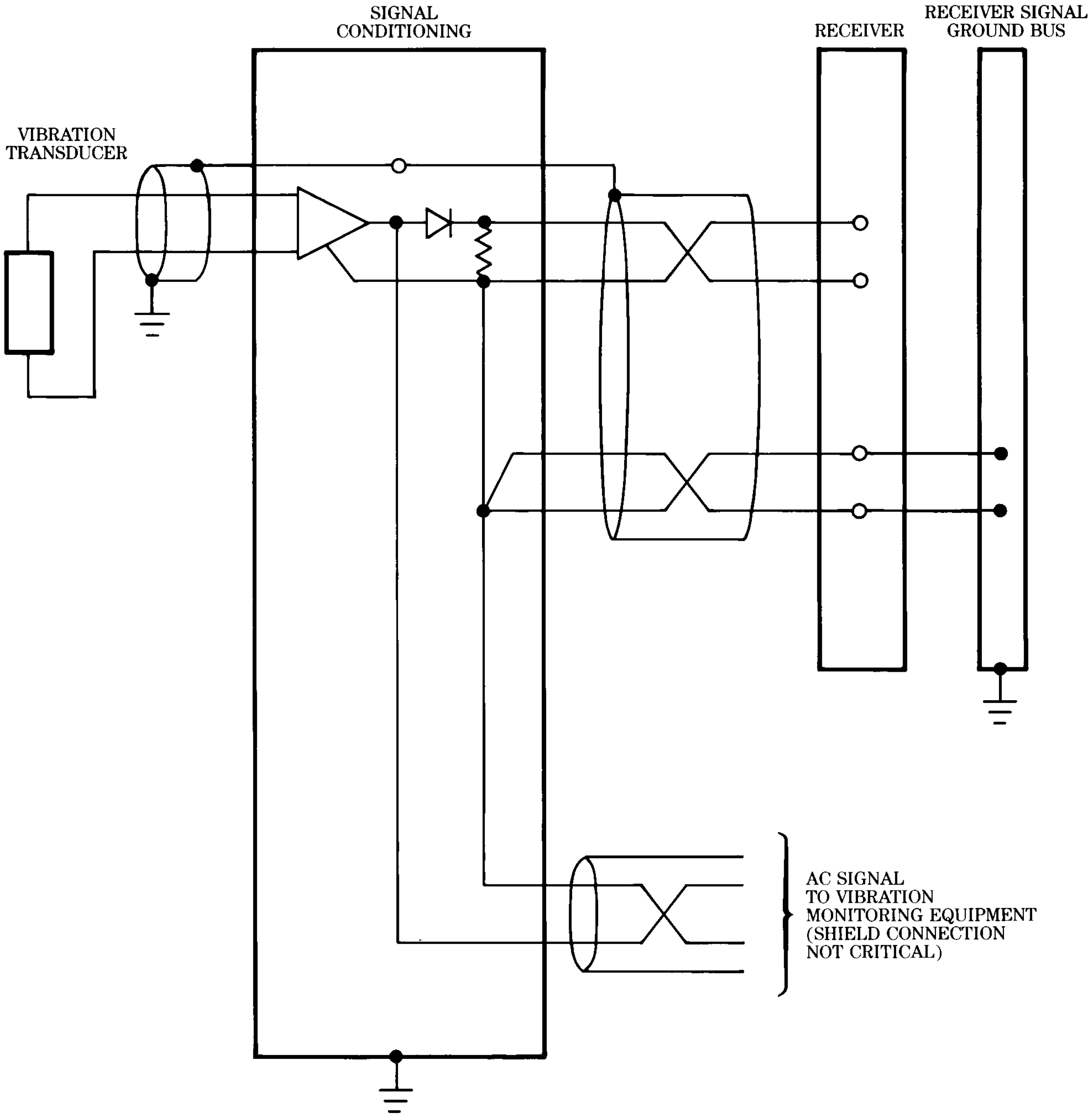


Figure A12—Vibration signals–ideal

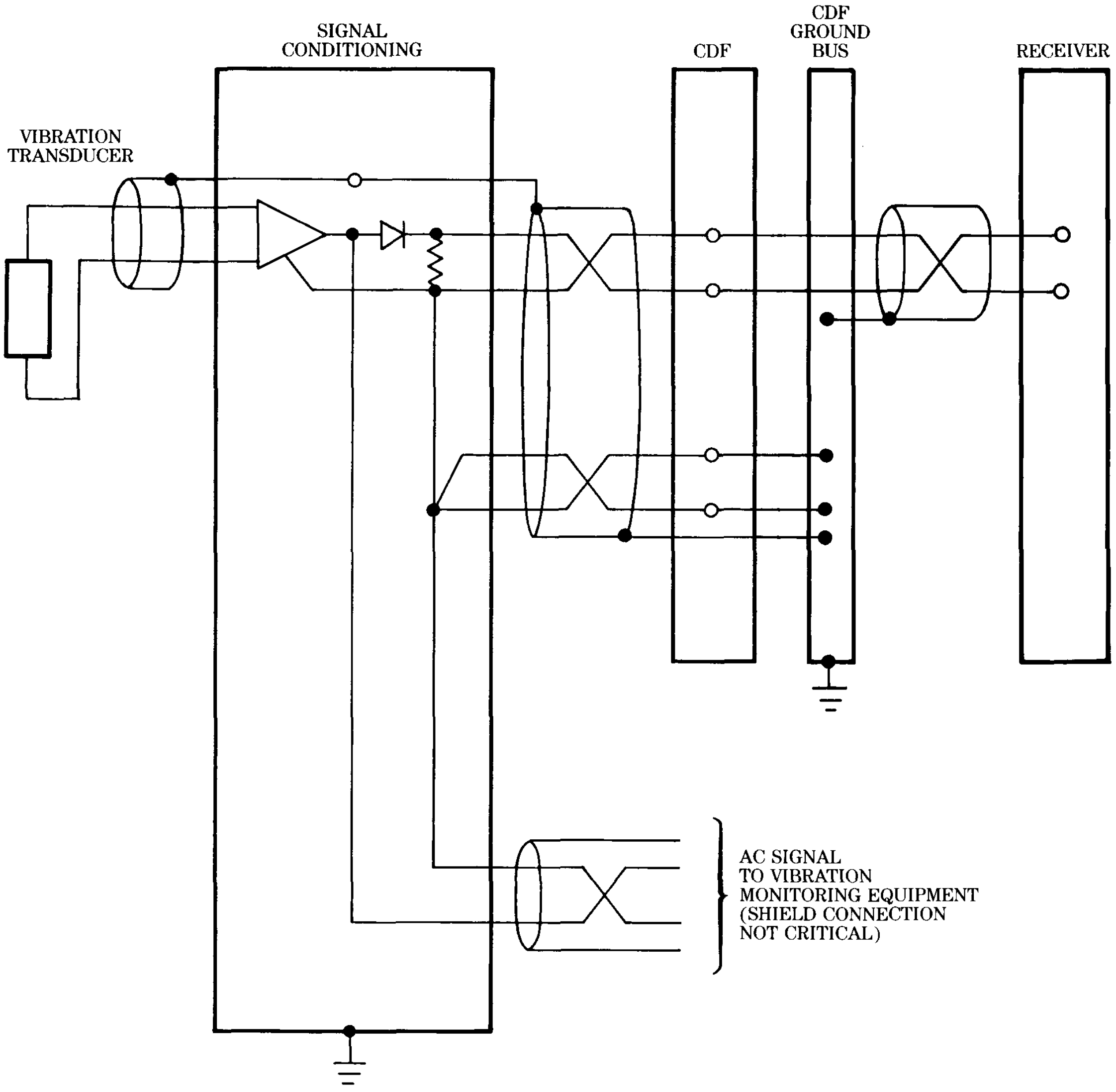
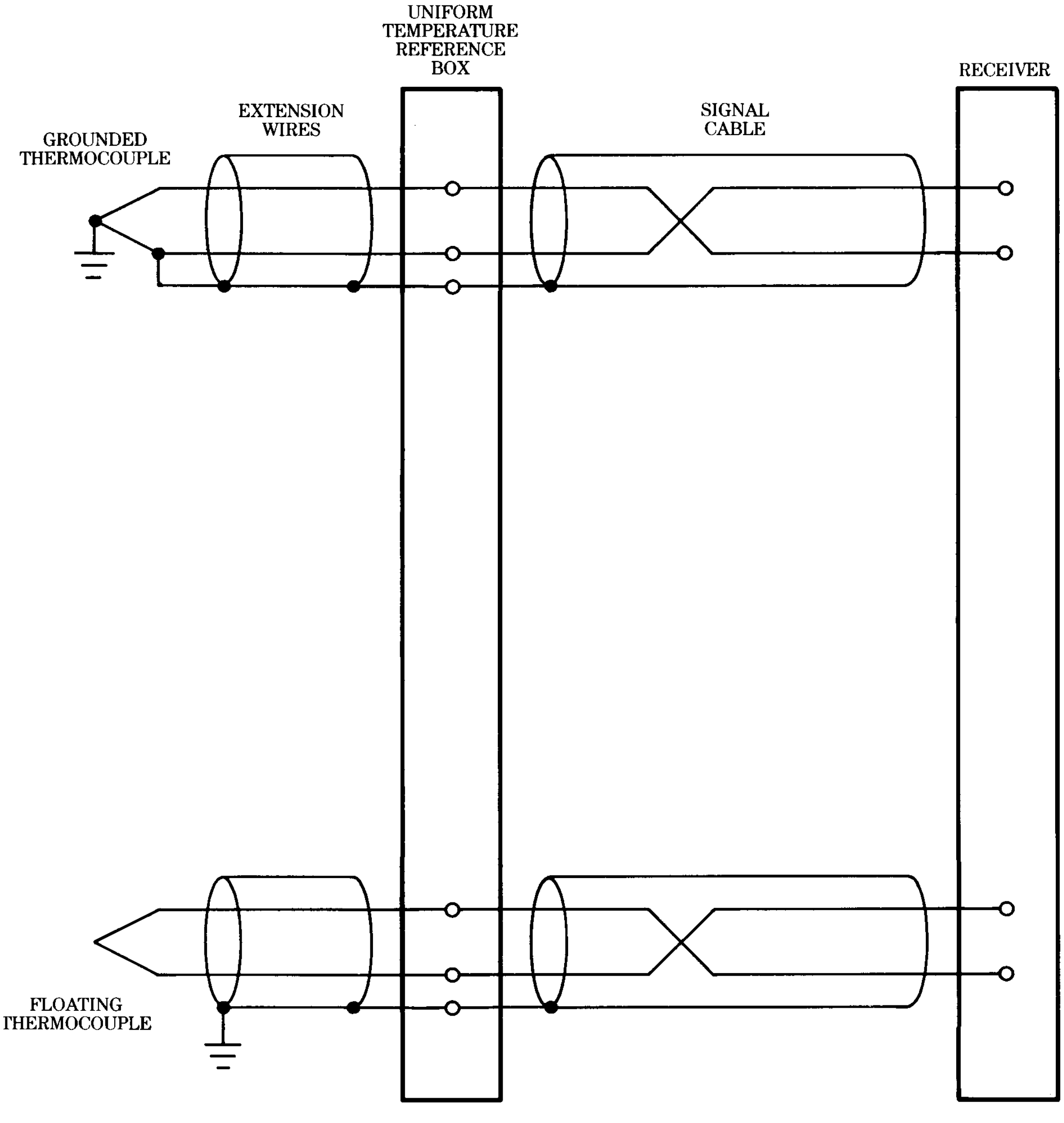


Figure A13—Vibration signals–CDF


UNIFORM
TEMPERATURE
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RECEIVER
EXTENSION
WIRES
SIGNAL
CABLE
GROUNDED
THERMOCOUPLE
FLOATING
THERMOCOUPLE

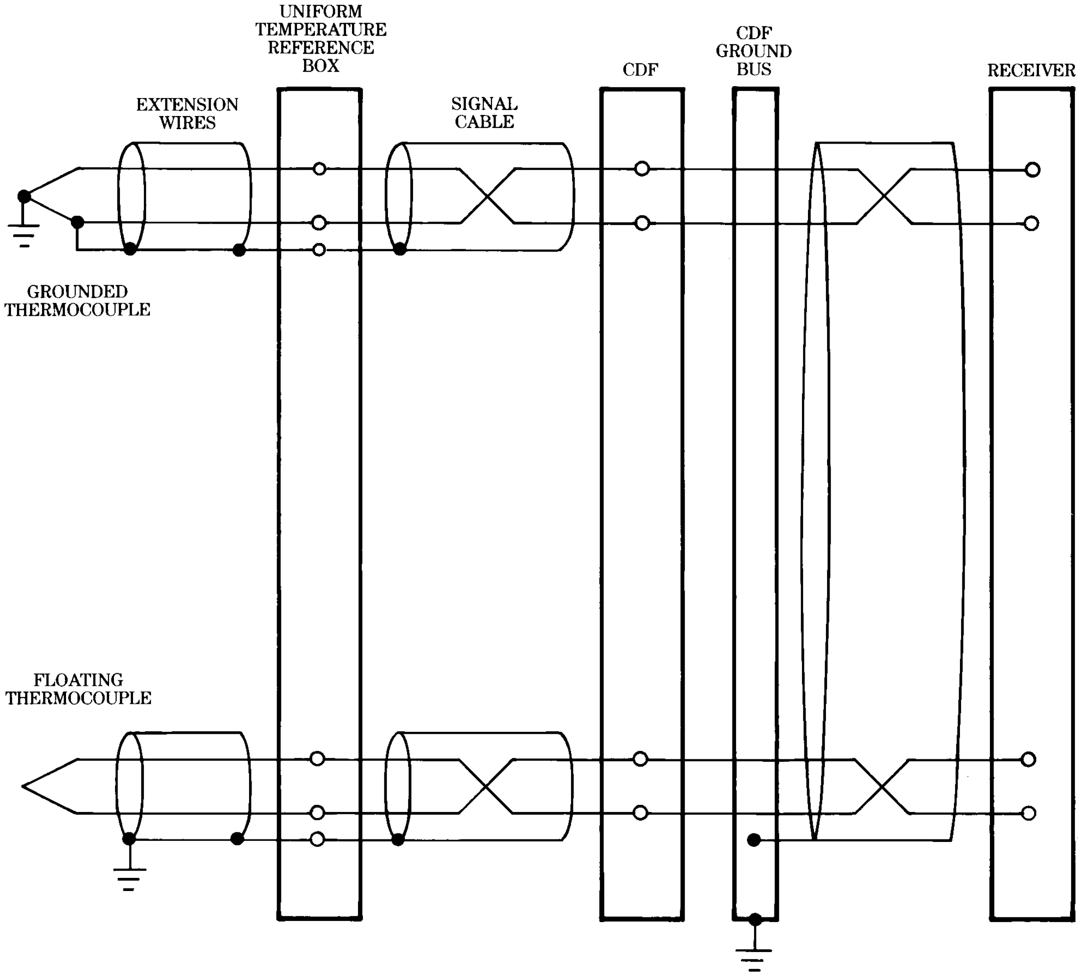

Figure A14—Thermocouples–ideal

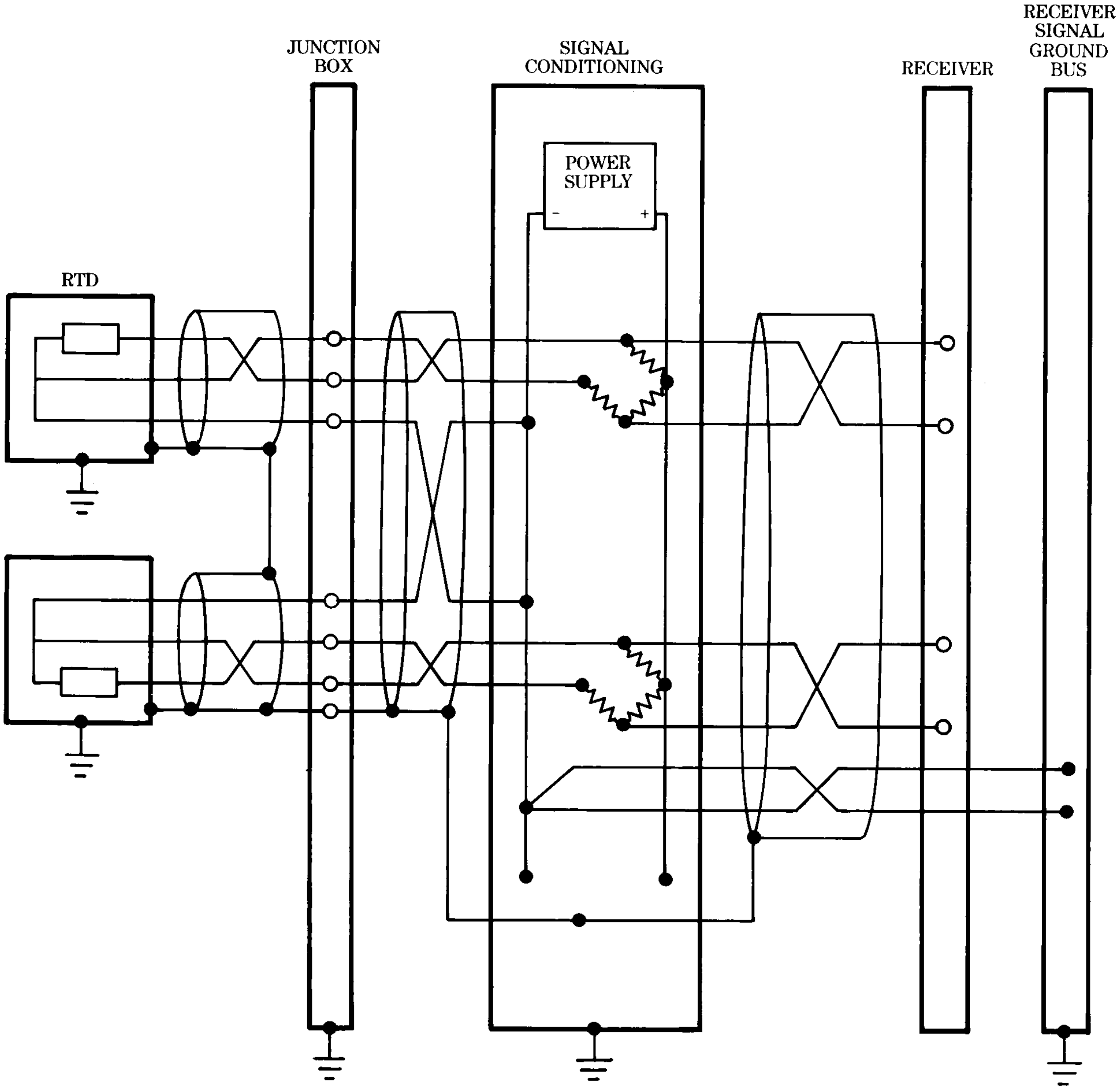

Figure A16—Grounded RTDs–ideal

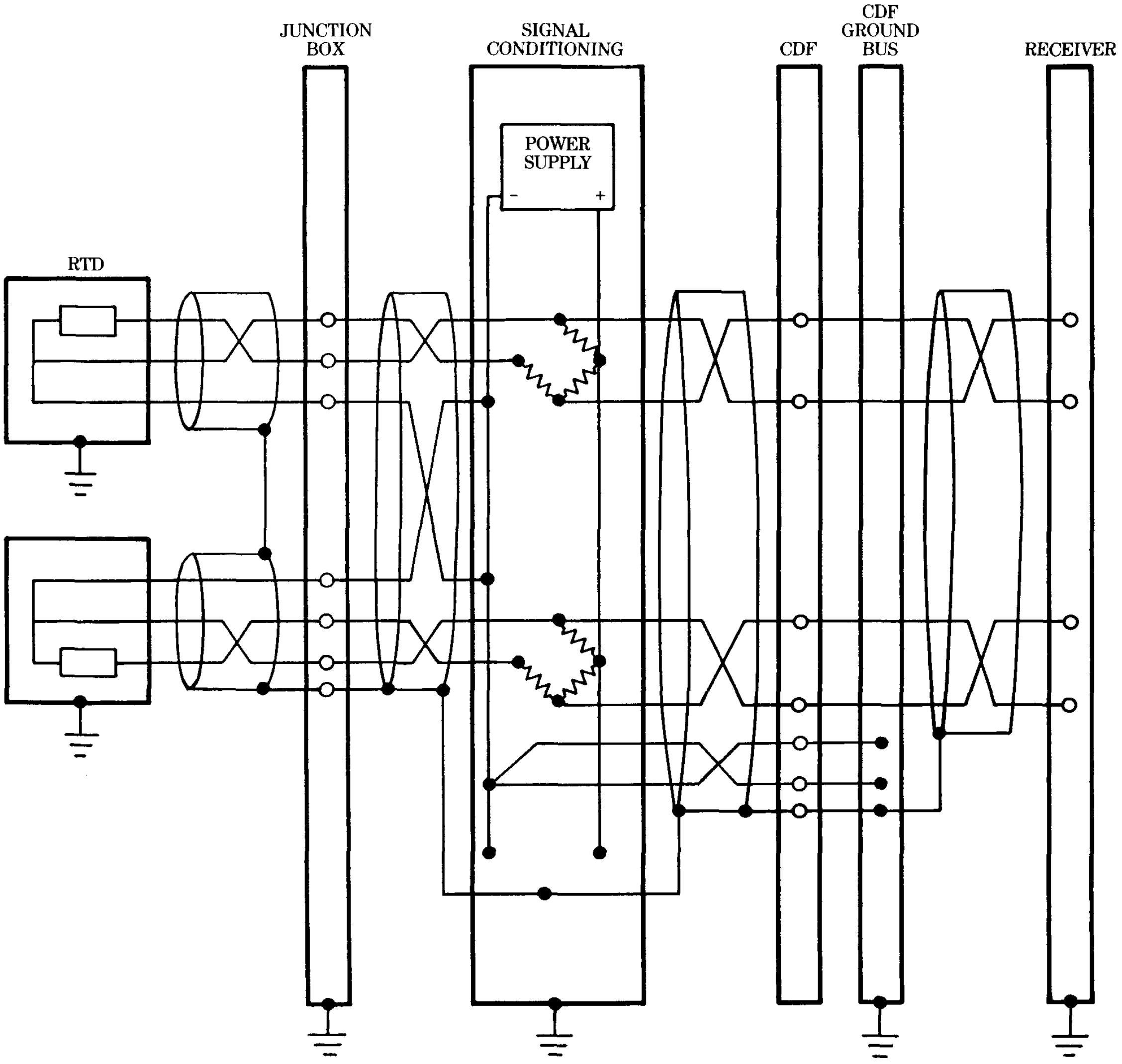

Figure A17—Grounded RTDs–CDF

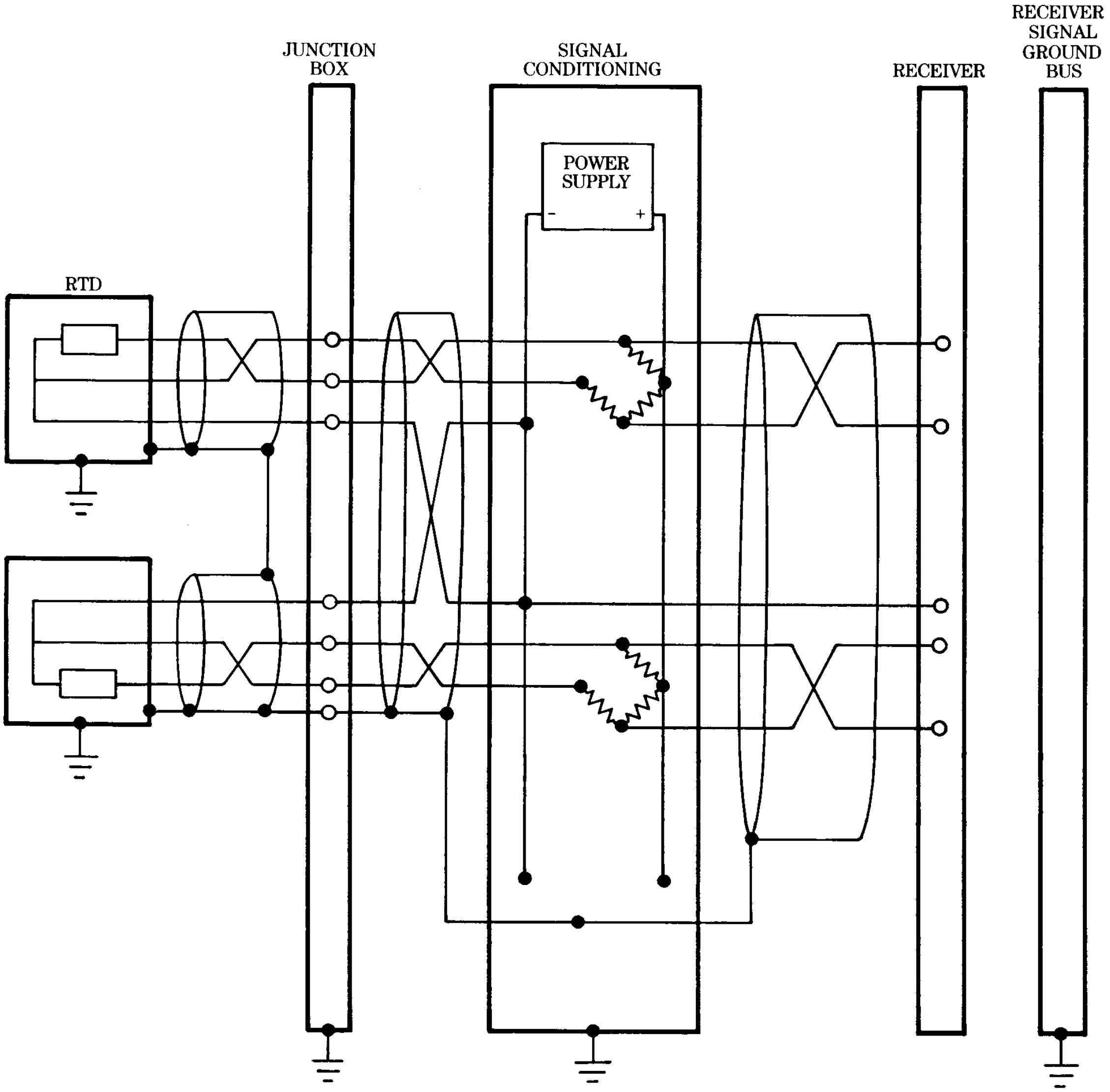

Figure A18—Ungrounded RTDs–ideal

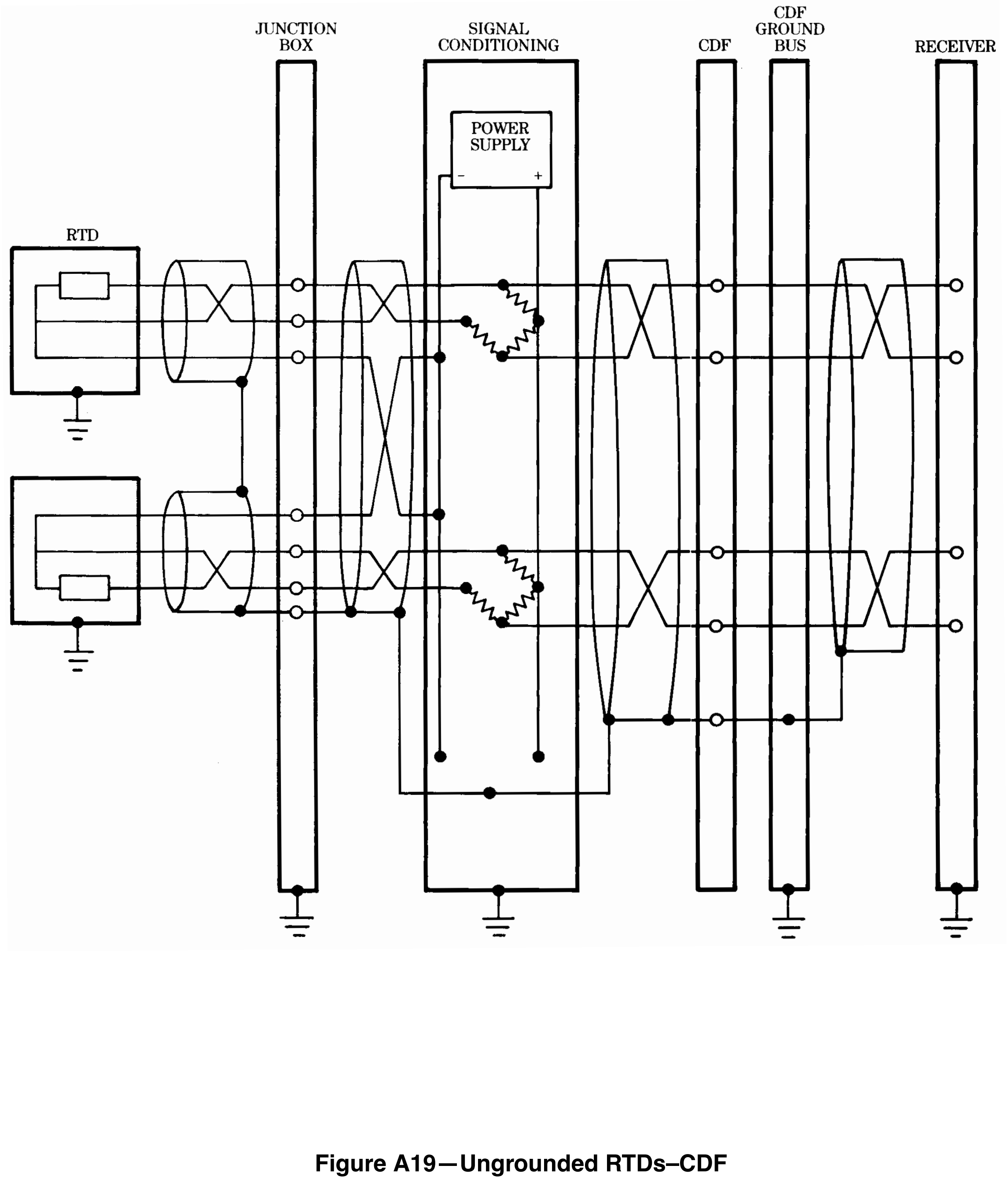

Figure A19—Ungrounded RTDs–CDF

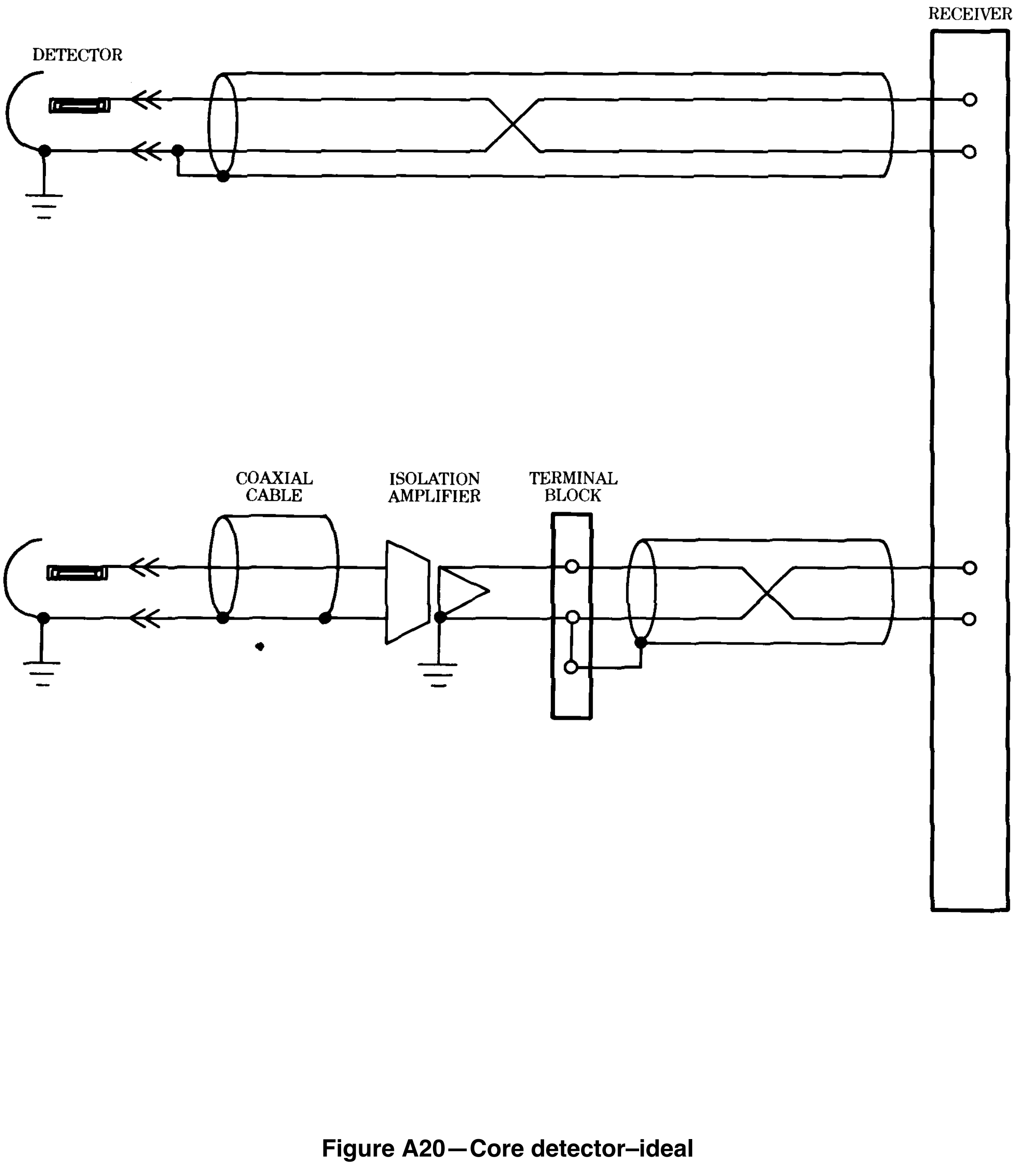

Figure A20—Core detector–ideal

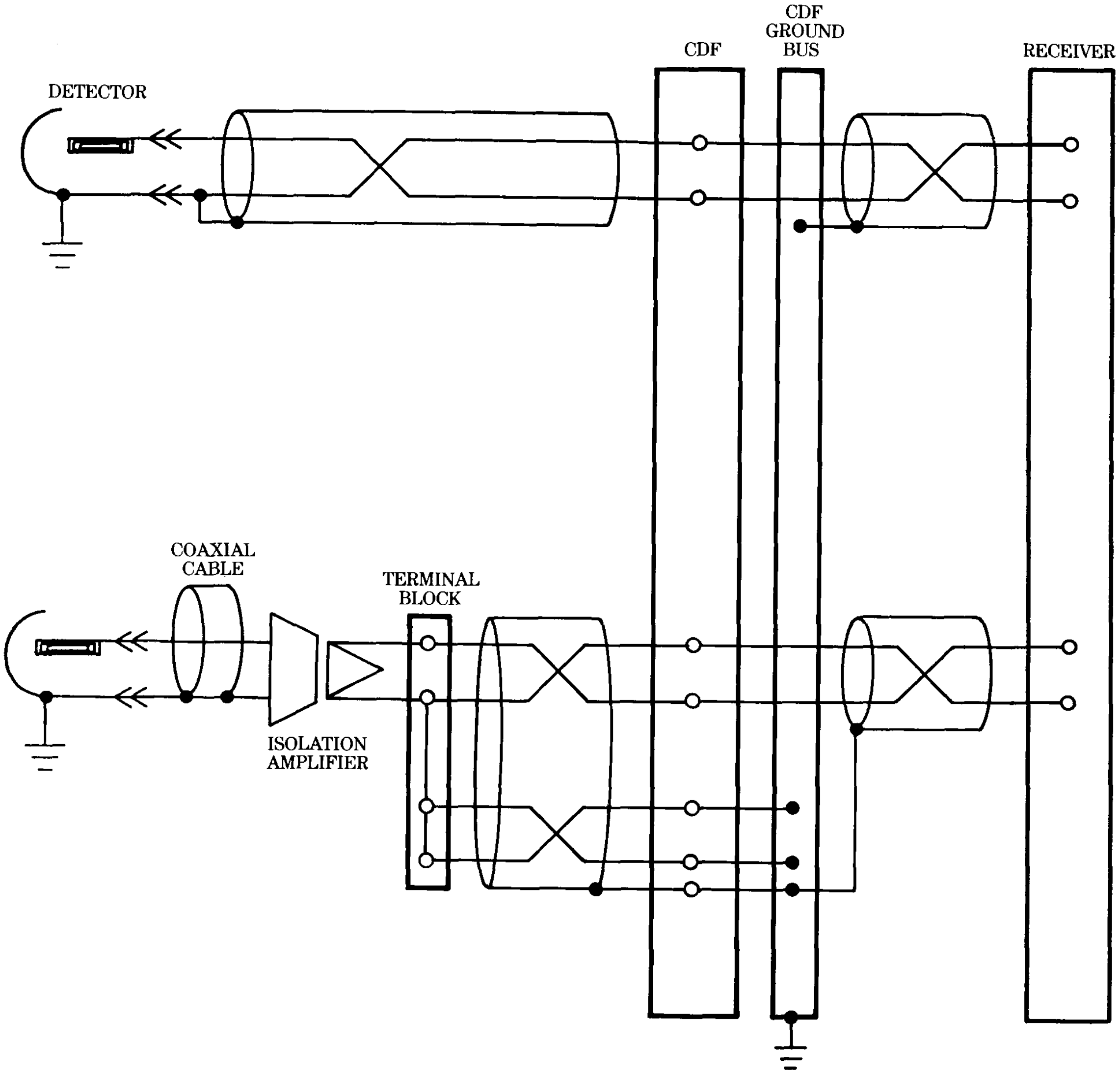

Figure A21—Core detector–CDF

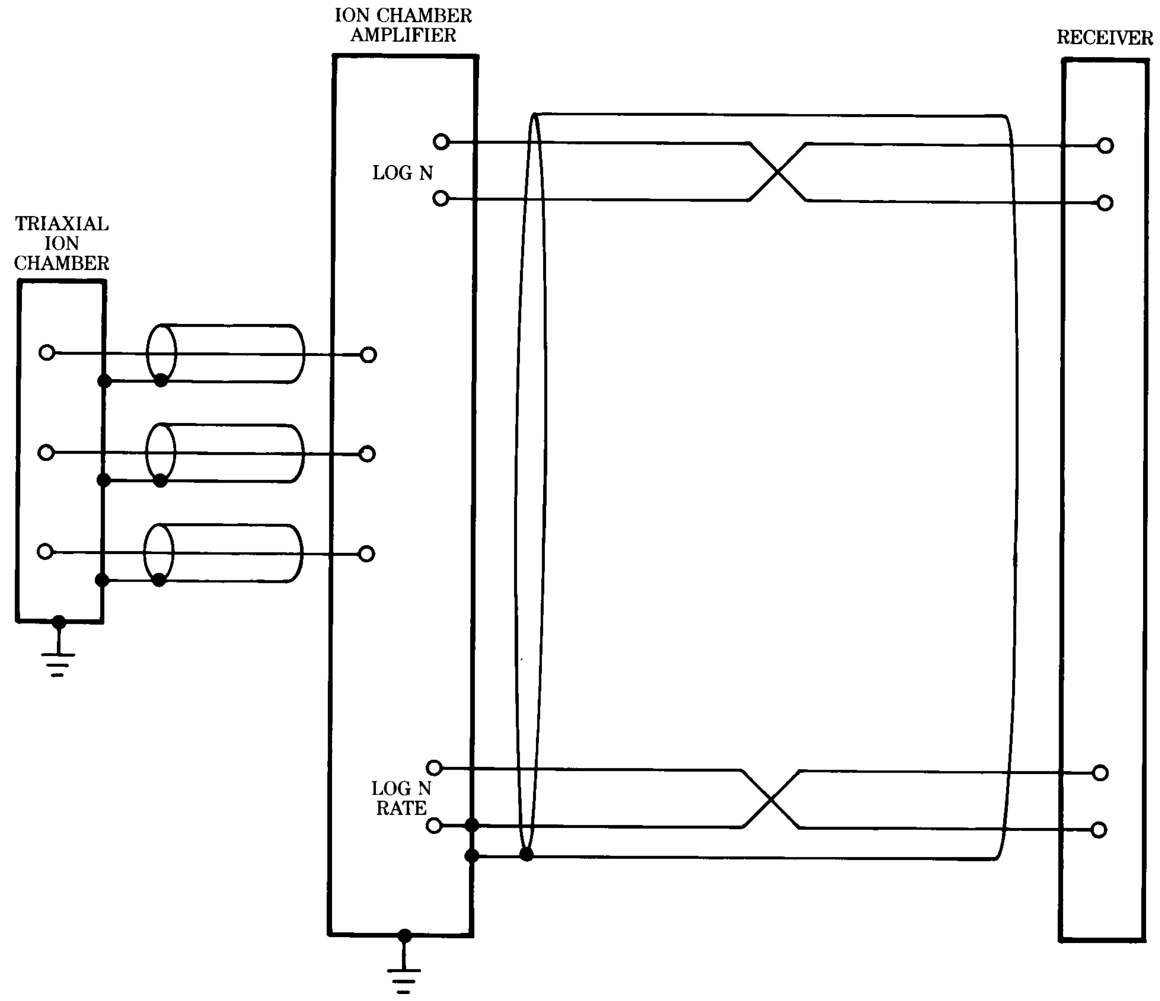

Figure A22—Ion chamber–ideal

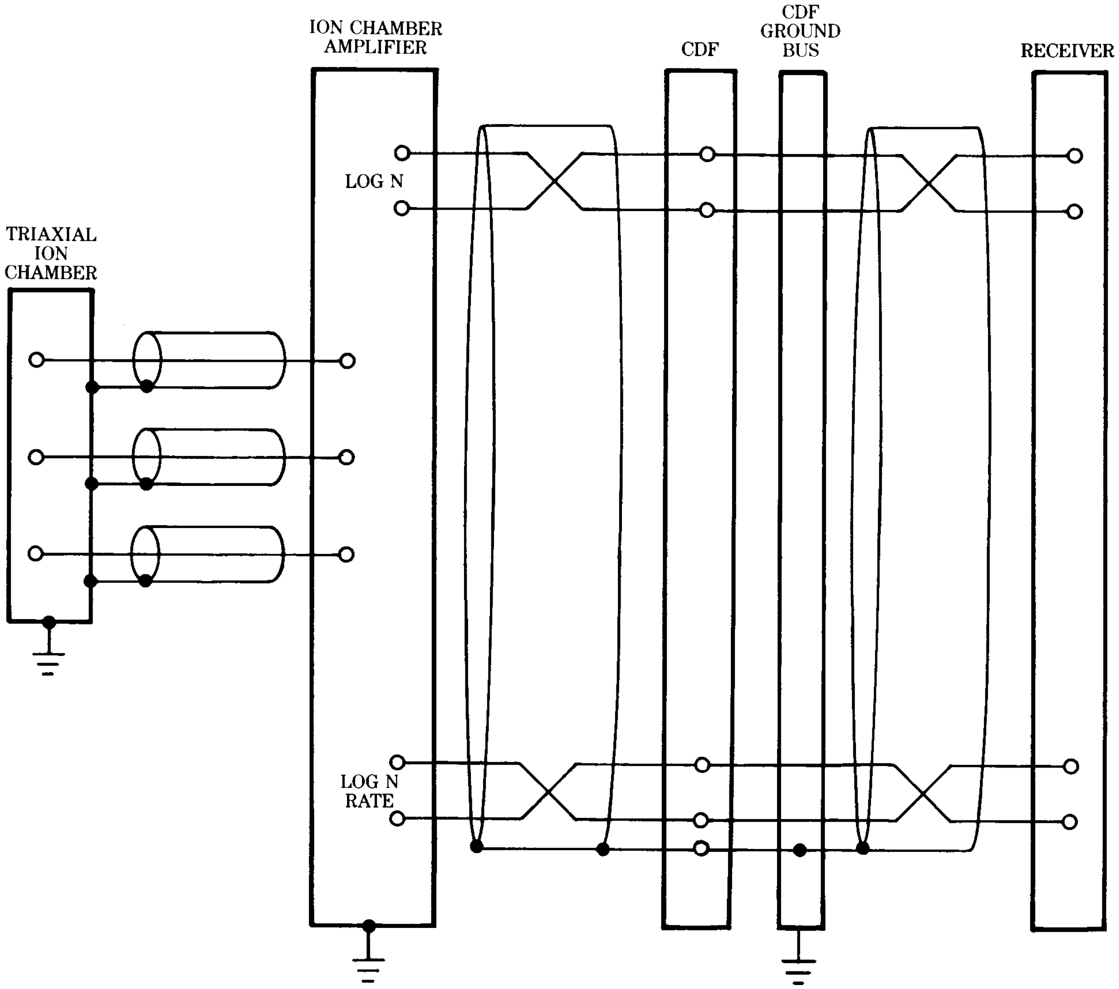

Figure A23—Ion chamber–CDF

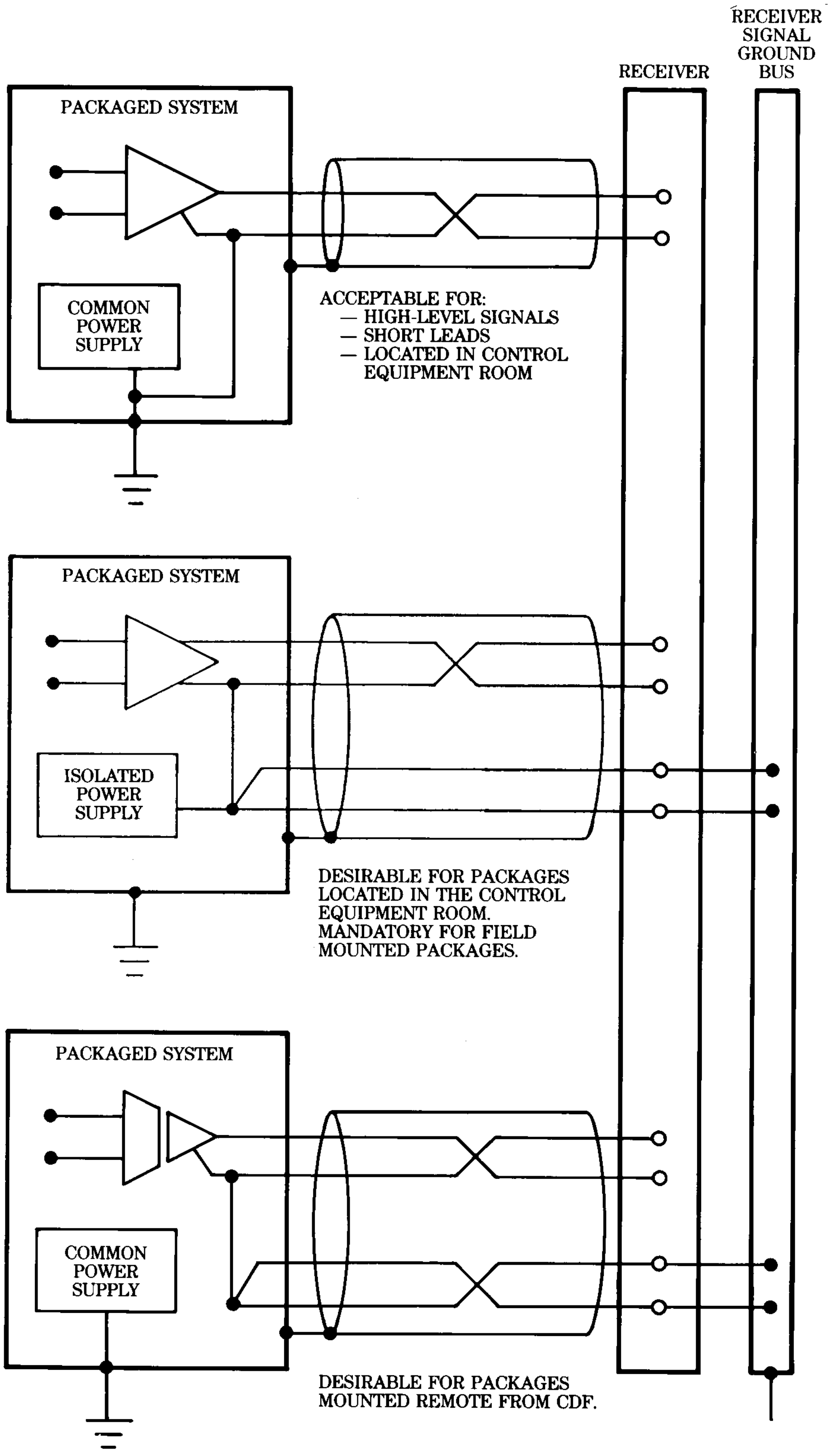

Figure A24—Installation methods for packaged systems–ideal

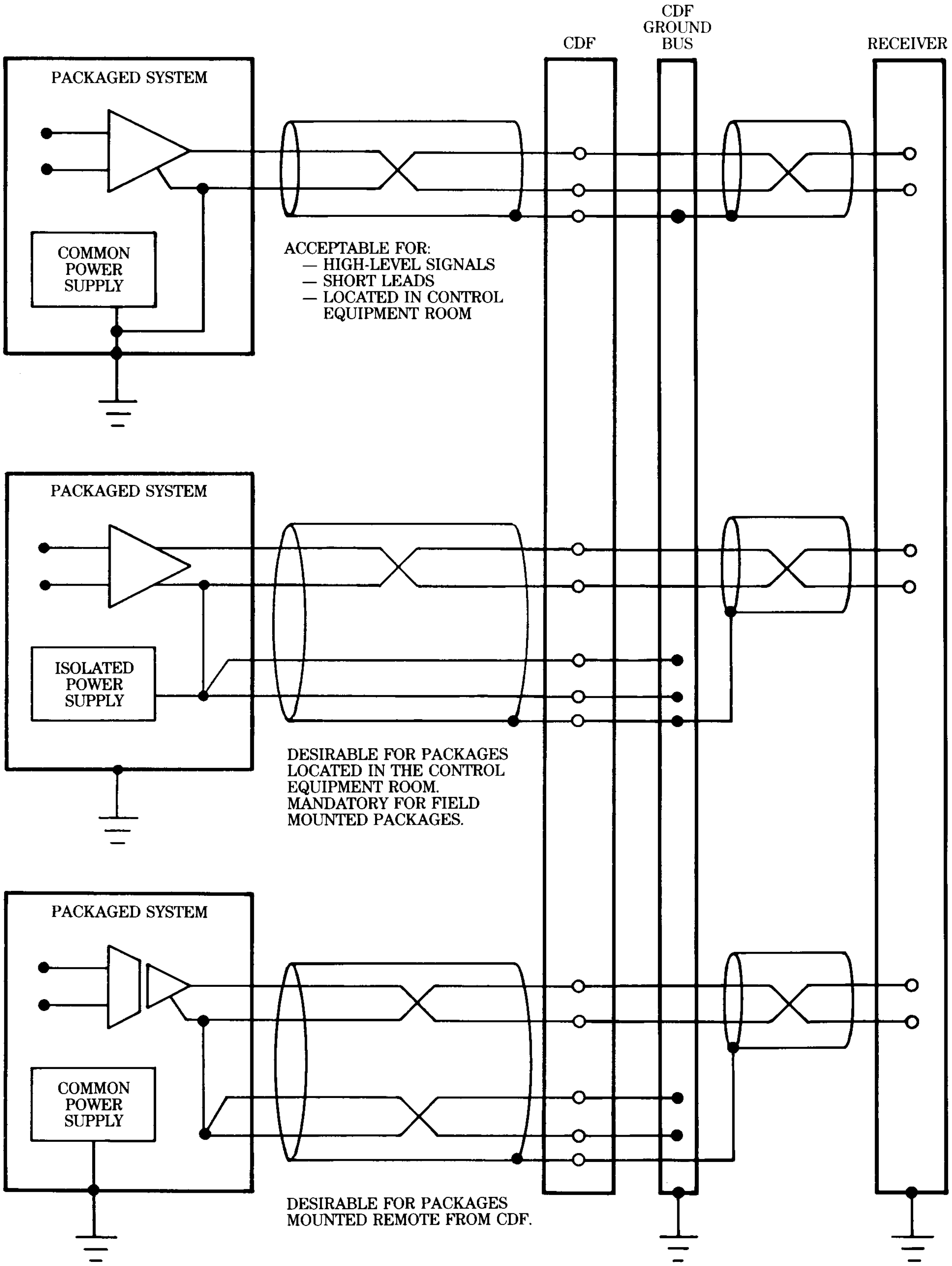

Figure A25—Installation methods for packaged systems–CDF

Annex B

(informative)

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