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IEEE Guide on Shielding Practice for Low Voltage Cables

Sponsor

Insulated Conductors Committee
of the
IEEE Power Engineering Society

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Abstract: A concise overview of shielding options for various types of interference and recommendations on shielding practices, including suggestions on terminating and grounding methods, are provided.

Keywords: grounding methods, interference, low voltage cables, shielding practice, terminating methods

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Introduction

(This introduction is not a part of IEEE Std 1143-1994, IEEE Guide on Shielding Practice for Low Voltage Cables.)

A guide on the use of shielding on low voltage cables was proposed in Subcommittee No. 9 of the Insulated Conductors Committee due to the lack of a single source of information on this topic. For example, information on shielding of medium voltage and high voltage cables was available in several documents, but the same could not be said for low voltage cable. Subsequently, a task group was formed to develop the guide.

It quickly became evident to the task group that an extensive amount of information was available on the shielding of low voltage cable. The task group began its work by preparing a bibliography of the information by key topic. These topics eventually made their way into an outline of the guide. A first draft was prepared, and after review and comment, the draft was broken into two sections: Section I, covering shielding; and Section II, providing background information on the need for shielding. This approach was taken because an understanding of the need for shielding helps achieve the purpose of the guide—which is to provide the user with an understanding of cable shielding practices for low voltage cables.

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CLAUSE PAGE

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IEEE Guide on Shielding Practice for Low Voltage Cables

1. Overview

1.1 Scope

This function of this guide on shielding practice for low voltage cables is to inform and familiarize the reader with shielding practice. An overview of shielding practice, systems, and test methods is provided. These tests may not be standardized; however, they are included to inform the reader and provide an overview as to what has been done to characterize shielding.

This guide provides the following:

- An enumeration of sources of electrostatic and electromagnetic interference
- A review of shielding techniques to control electrostatic and electromagnetic interference for varying types of low voltage cable uses for power, control and instrumentation services, including signal and communications cable
- An overview of the functional characteristics of various types of shielding
- Criteria for defining the most favorable techniques to combat interference
- Suggested tests or techniques for measuring shielding effectiveness
- Recommendations on shielding practices, including suggestions on terminating and grounding methods

1.2 Purpose

The main purpose of this guide is to show how shielding can be used to minimize the effects of interference on low voltage cables. The secondary purpose is to familiarize the user with the topic of shielding and provide background information on the need for shielding. Alternate approaches will be given to achieve these purposes.

2. References

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

ANSI C63.4-1992, Methods of Measurement of Radio-Noise Emissions from Low-Voltage Electrical and Electronic Equipment in the Range of 9 kHz to 40 GHz.[1]

ANSI/NEMA WC55-1992/ICEA S-82-552, Instrument Cables and T. C. Wire.[2]

ANSI/NEMA WC57-1990/ICEA S-73-532, Standard for Control Cables.

ANSI/NFPA 70-1993, National Electrical Code (NEC).[3]

EIA/TIA 455-181 (Feb. 1993), FOTP-181, Lightning Damage Susceptibility Test for Fiber Optic Cables with Metallic Components.[4]

IEEE Std 422-1986 (W1994), IEEE Guide for the Design and Installation of Cable Systems in Power Generating Stations.[5]

IEEE Std 518-1982 (Reaff 1990), IEEE Guide for the Installation of Electrical Equipment to Minimize Electrical Noise Inputs to Controllers from External Sources (ANSI).[6]

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

IEEE Std 576-1989, IEEE Recommended Practice for Installation, Termination, and Testing of Insulated Power Cable as Used in the Petroleum and Chemical Industry (ANSI).

IEEE Std 690-1984 (W1994), IEEE Standard for the Design and Installation of Cable Systems for Class 1E Circuits in Nuclear Power Generating Stations.[7]

IEEE Std 789-1988 (Reaff 1994), IEEE Standard Performance Requirements for Communications and Control Cables for Application in High Voltage Environments (ANSI).

IEEE Std C62.41-1991, IEEE Recommended Practice for Surge Voltages in Low-Voltage AC Power Circuits (ANSI).

NEMA WC-61-1992, Transfer Impedance Testing (Modified MIL-C-85485 Test Method). [8]

3. Definitions

3.1 absorbing clamp: A portable testing device that is effective at detecting electromagnetic radiation. The absorbing clamp has a great capacity for electromagnetic compatibility cable measurements in the frequency range of 30–1000 MHZ, and is non-destructive to the specimen. The test fixture clamps over the sample cable and inductively detects signal leakage.

3.2 aeolian flexure: Flexure of cables caused by the wind.

3.3 bonded sheath: Cable shielding that is bonded to a plastic jacket by means of a plastic coating on the shielding.

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[1] ANSI publications are available from the Sales Department, American National Standards Institute, 11 West 42nd Street, 13th Floor, New York, NY 10036, USA.

[2] ANSI/NEMA publications are available from the National Electrical Manufacturers Association, 2101 L Street NW, Washington, DC 20037, USA.

[3] ANSI/NFPA publications are available from Publications Sales, National Fire Protection Association, 1 Batterymarch Park, P.O. Box 9101, Quincy, MA 02269-9101, USA.

[4] EIA/TIA publications are available from Global Engineering, 1990 M Street NW, Suite 400, Washington, DC, 20036, USA.

[5] IEEE Std 422-1986 has been withdrawn; however, copies can be obtained from the IEEE Standards Department, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, U SA.

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

[7] IEEE Std 690-1984 has been withdrawn; however, copies can be obtained from the IEEE Standards Department.

[8] NEMA publications are available from the National Electrical Manufacturers Association, 2101 L Street NW, Washington, DC 20037, USA.

3.4 braided shield: Cable shield that consists of groups of metallic strands, one set woven in a clockwise direction and interwoven with another set in a counter-clockwise direction. Braided shields provide superior structural integrity, while maintaining good flexibility and flex life.

3.5 broadband (electrical noise, interference): Electrical noise that contains energy covering a wide frequency range. *Contrast with:* **narrowband electrical noise**.

3.6 capacitance: The ratio of a conductor's electrostatic charge to the potential difference between conductors (required to maintain that charge).

3.7 capacitive coupling: *See:* **electrical coupling**.

3.8 chop: A sudden cessation of the flow of arc current during circuit interruption.

3.9 combination effect: An electric disturbance not caused by one of the following mechanisms, but to some extent by a combination of them: normal-mode noise (transverse or differential), common-mode noise (longitudinal), and common-mode to normal-mode conversions. *See also:* **common-mode noise (and longitudinal); normal-mode (transverse or differential)**.

3.10 common-modenoise (and longitudinal): The noise voltage that appears between each signal conductor to ground caused by electrostatic induction and/or electromagnetic induction.

3.11 continuous wave (CW): A sinusoidal wave that has reached a steady state value. Continuous wave noise would be noise at a single frequency (e.g., 60 Hz "hum").

3.12 corner frequency: The frequency at which the skin depth is equal to the thickness of the shield.

3.13 Crawford cell: *See:***transverse electromagnetic (TEM) cell**

3.14 crosstalk: An electromagnetic field in the space surrounding a cable circuit created by an electrical signal. This field induces currents and electromotive forces in other circuits located close enough to the disturbing cable circuit to be affected.

3.15 cutoff frequency: The frequency below which a waveguide fails to transmit a signal in the differential mode.

3.16 dropouts: A subset of gain hit, dropouts are a loss of data caused by a decrease in signal, usually greater than 12 dB and lasting longer than 4 ms. Dropouts interrupt the information flow between two modems. Furthermore, even when the signal returns, some modems will take additional time to recover. Experience suggests that dropouts occur less often than the other types of transients. However, each dropout causes modem errors. *See also:* **gain hit or change; phase hit or change**.

3.17 electrical coupling: Electrical charges in conductors of a disturbed circuit formed by electrical induction. Since the ratio of a conductor's electrostatic charge to the potential difference between conductors (required to maintain that charge) is the general definition of capacitance, electrical coupling is also called capacitive coupling. Its magnitude depends on the cable geometry and the cable insulation properties: dielectric constant and dissipative losses. Magnetic coupling introduces electromotive force in the disturbed circuit due to magnetic induction. This electromotive force opposes the change in the current that generated it. *Syn:* **capacitive coupling**.

3.18 electric field: The field surrounding a charged object. *See also:* **magnetic field**.

3.19 electrical noise: Unwanted voltage or current, or both, that appears in an electrical system. For given system characteristics, electrical noise may or may not impair proper functioning. The unwanted noise can have effects that range from totally undetectable to system malfunction or even damage or destruction.

3.20 electromagnetic compatibility (EMC) (of an electrical system): An electrical system's ability to perform its specified functions in the presence of electrical noise generated either internally or externally by other systems. The goal of EMC is to minimize the influence of electrical noise.

3.21 electromagnetic field: The energy field radiating from a source and containing both electric and magnetic field components. *See also:* **electric field; magnetic field**.

3.22 electromagnetic induction (EMI): *See:* **electromagnetic interference**.

3.23 electromagnetic interference (EMI): Electromagnetic energy from sources external or internal to electrical or electronic equipment that adversely affects equipment by creating undesirable responses (degraded performance or malfunctions). EMI can be divided into two classes: continuous wave (CW) and transient. *Syn:* **electromagnetic induction**. *See also:* **continuous wave (CW); electrical noise; transient electrical noise**.

3.24 electromagnetic pulse (EMP): A high-energy electromagnetic pulse initiated by a nuclear reaction (e.g., upper atmospheric detonation of a nuclear weapon).

3.25 electrostatic discharge (ESD): Electrical discharges of static electricity that build up on personnel or equipment, generated by interaction of dissimilar materials.

3.26 foil shield: A thin, self-supported, metallic tape wrapped longitudinally or spirally around the cable core, and intended to act as a shield against EMI.

3.27 gain hit or change: A sudden increase or decrease in amplitude, usually not exceeding 12 dB of the received signal. Gain hits last at least 4 ms but may continue for hours. (Example: Modems that use amplitude modulation carry the information by the level of the signal, and a gain hit may look like data to these modems.) *Contrast with:* **impulse noise**.

3.28 galvanic action: Noise currents due to the junction or thermal potentials resulting from a combination of different metals. This current can be a part of the disturbing current passing through the conductors or shield of the signal cable.

3.29 harmonic distortion: Nonlinear distortion that appears as harmonics of a single-frequency input.

3.30 hum test: Measures low-frequency shield effectiveness against electric field coupling (dc to 100 kHz).

3.31 impulse noise: A component of the received noise signal that is much greater in amplitude than the normal peaks of the message circuit noise, and that occurs as short-duration spikes or energy bursts.

3.32 induction zone (of EMI): The area where the distance to the source of electromagnetic interference is less than the wavelength of the interference. In the induction zone the circuit or system will be affected by transverse or longitudinal fields. *Contrast with:* **radiation zone (of EMI)**.

3.33 intermodulation distortion: Nonlinear distortion of multiple-frequency inputs that shows up as harmonics of the individual inputs plus the sum and difference products of the inputs and their harmonics.

3.34 magnetic coupling: *See:* **electrical coupling**.

3.35 magnetic field: The field surrounding any current-carrying conductor. *See also:* **electric field**.

3.36 narrowband electrical noise: A disturbance at a single frequency or in a narrowband of frequencies about a single frequency.

3.37 nonlinear: The amplitude of the output is not linearly proportional t the input. If a true sine wave were transmitted through a nonlinear device, its shape would b changed.

3.38 nonlinear distortion: The generation of new signal components not present in the original transmitted signal.

3.39 normal-mode (transverse or differential): The voltage that appears differentially between two signal wires and that acts on the circuit in the same manner as the desired signal.

3.40 phase hit or change: A sudden change in the received signal phase (or frequency) lasting longer than 4 ms. Since two common modulation techniques for high-speed data transmission are phase an frequency modulation, phase hits cause errors by looking like data. *See also:* **dropouts; gain hit or change**.

3.41 radiation zone (of EMI): The area where the distance to the source of electromagnetic interference is greater than the wavelength of the interference. In the radiation zone, the circuit or system will be affected by plane waves. *Contrast with:* **induction zone (of EMI)**.

3.42 surge impedance: The impedance of an electrical circuit under surge conditions (which ma differ significantly from the impedance of a circuit under steady state conditions).

3.43 transient electrical noise: An electrical disturbance that occurs in a time interval separated fro other interferences. Transient electrical noise may be superimposed on other transients or o continuous waves. Transient electrical noise may be of several types, such as pulse, step, o oscillatory. It may occur as a response to a network to one of these types. Sources of transient affecting low voltage circuits are impulse noise, power switching, or lightning.

3.44 transverse electromagnetic (TEM): A wave that propagates with the electric field and magnetic field vectors transverse (at right angles to) the direction of propagation. (At high frequencies waves may also propagate in transverse electric [TE] or transverse magnetic [TM] waves that bounce back and forth between guiding structures such as waveguides.)

3.45 transverse electromagnetic (TEM) cell: A rectangular transmission line segment that produces a transverse electromagnetic (TEM). Cables, cable/connector assemblies, and/or electronic devices are placed inside the cell. Alternatively, the cell can be used as a detector to measure radiation emitted by a cable or device inside the cell. *See also:* **absorbing clamp**. *Syn:* **Crawford cell**.

Section I: Shielding

4. Nature of interference

4.1 Definition of sources

For the purpose of this guide, electrical noise is defined as an unwanted electrical signal that produces undesirable effects in the circuits of the system in which it occurs. As such, it may cause malfunctioning of electrical equipment.

In its simplest terms, before an electrical noise problem can exist, three basic elements are required:

a) A source of noise
b) A circuit sensitive to the noise
c) A means of interaction between source and circuit

The solution to this three-element problem is obtained by controlling any one of the three elements. This means that if an installation is malfunctioning because of electrical noise, it can be made to work correctly by suppressing the noise at its source, eliminating the way the noise is getting into the system, or making the equipment insensitive to the noise. The possibility of eliminating the source or the sensitive circuit should also be considered.

4.2 Nature of interference

The source of interference may be anywhere; it may be produced within the system containing the sensitive circuit or outside of the system. It may be man-made or natural. The effect on the circuit is somewhat independent of the origin of the interference, but the protection techniques applied will depend on whether the designer controls the source or treats the source as a part of the operating environment of the circuit.

4.3 Source-circuit interaction

For a circuit to be affected by interference from a source, the electromagnetic waves produced by the source must interact with elements of the sensitive circuit. This interaction involves propagation of waves through free space or along guiding structures (such as wires, transmission lines, and cables) between the source and the system. Upon arriving at the system, coupling of the electromagnetic fields to elements of the system induces currents, voltages, and electromagnetic fields on the system. These currents, voltages, and fields must then penetrate the system to reach the internal sensitive circuit of concern.

These three aspects of interaction are particularly important to systems that have natural or deliberate shields. The shields can be used to separate the interaction problem into external and internal interaction. The propagation, coupling, and penetration apply to both the external interaction problem and to the internal interaction problem.

4.3.1 Propagation

Propagation of a space wave occurs if the source launches the wave into a medium, such as air or vacuum. Radio and radar transmissions, distant lightning, and other atmospheric noise are examples of space waves that may interfere with systems that do not wish to receive them. Guided waves propagate along conductors, such as power lines and interconnecting cables. Switching transients, 60 Hz “hum,” and lightning transients are examples of guided waves that propagate to the system along power and communication lines. (Guided waves have been called “conducted interference” and space waves have been called “radiated interference” in the literature.)

4.3.2 Coupling

Coupling is the interaction of electromagnetic fields with conductors to induce currents and voltages on the conductors. Magnetic fields parallel to a conducting surface induce a current density on the surface; electric fields perpendicular to a conducting surface induce a charge density on the surface. Time-varying electric fields induce current on the surface of a conductor or, if the electric field is produced by the voltage on another conductor, the conductors are said to be capacitively coupled. Time-varying magnetic fields induce voltages in loops. If the magnetic field is produced by the current in another conductor, the coupling is described as mutual inductance or inductive coupling. (The coupled currents and voltages have been improperly called “radiated interference” in the literature.)

4.3.3 Penetration

Penetration is the entry of the electromagnetic interference into the system of concern. It is presumed that this system is surrounded by some form of barrier or boundary that separates it from the outside. In protected systems, the barrier might be a metal case or housing with openings for air flow, light transmission, and wires for energy supply and data input and output. Interference penetration may occur on these wires from electromagnetic fields that enter through the openings and from fields that diffuse through the metal walls of the housing.

4.4 Types of interference

Interference may be characterized as transient, repetitive, or narrowband.

4.4.1 Transient interference

Transient interference is an individual electromagnetic event, such as a lightning flash, a switching transient, or an electrostatic discharge. A transient is completely characterized by its waveform (amplitude as a function of time). For many practical purposes, transients may be characterized by their peak amplitude, rate-of-rise, energy, charge transfer, or other property that affects the sensitive circuit. Transients tend to be a problem for broadband systems, such as digital electronic circuits and computer controlled systems.

4.4.2 Repetitive interference

Repetitive interference is an electromagnetic wave that is repeated periodically (or nearly periodically). Repetitive interference is characterized by its waveform. For many practical purposes, repetitive interference may be characterized by its peak amplitude, fundamental frequency, and harmonic or spectral content. Repetitive interference may degrade analog circuit performance by reducing the signal-to-noise ratio, particularly if the operating frequency coincides with a harmonic of the interference. It also degrades digital circuit performance if the amplitude is large or if the repetition frequency coincides with the digital circuit operating frequency.

4.4.3 Narrowband interference

Narrowband interference is a nearly sinusoidal wave or the sinusoidal equivalent of broadband noise in a narrow bandwidth. Narrowband interference is completely characterized by its amplitude, frequency, and bandwidth or by its power spectral density and frequency. Narrowband interference affects the signal-to-noise ratio of a radio receiver, and it may similarly affect analog circuits operating at low levels. If large enough, it may also interfere with digital circuit operation.

Broadband sources of interference, such as transients and repetitive sources, have often been characterized by their narrowband spectral density. This characterization is useful for specifying the interference environment for narrowband analog systems. For digital circuits and systems, the narrowband spectral density is less useful, because it does not define the properties of transients and repetitive interference that are most likely to affect digital circuits—namely peak value, energy or action, charge transfer, and rate-of-change.

Narrowband spectral density has also been used to characterize broadband noise produced by random processes such as thermal noise, shot noise, and atmospheric noise. These are rather weak sources that are of interest primarily to designers of sensitive communication equipment and high-gain amplifiers, for which the narrowband spectral density is appropriate.

4.5 Sources of electromagnetic interference (EMI)

When electromagnetic energy from sources external or internal to electrical or electronic equipment adversely affects that equipment by creating undesirable responses (degraded performance or malfunctions), the electromagnetic energy is defined as electromagnetic interference or induction (EMI), and the adversely affected equipment is said to be susceptible to EMI.

4.5.1 Natural sources of EMI

The natural sources of electromagnetic interference are the earth's magnetic field, discharges in the atmosphere, such as lightning, and radiation from outside the earth's atmosphere, such as solar flares.

4.5.2 Man-made sources of EMI

For the purpose of completeness, it should be noted that sometimes man-made sources can be broken into two categories defined by the distance to the source of interference.

- *Induction zone:* When the distance to the source is less than the wavelength of the interference. In the induction zone the circuit or system will be affected by transverse or longitudinal fields.
- *Radiation zone:* When the distance to the source is greater than the wavelength of the interference. In the radiation zone the circuit or system will be affected by plane waves.

4.5.2.1 Electrical equipment and wiring

a) *Rotating machinery:* The brush and commutator action of dc motors or generators and sliding contacts from slip rings in synchronous motors and generators produce repetitive interference.
b) *Transformers:* Corona or partial discharges (pd) can occur in the high voltage winding insulation bushings, and voltage tap terminals. The transformer's core and windings have an inherent electromagnetic field.
c) *Switching:* Sudden changes in circuit impedance due to switching cause current and voltage transient interference.
d) *Dimmers:*Dimmers usually produce high levels of repetitive interference. Silicon-controlled rectifiers produce an especially high level of interference.

4.5.2.2 Discharge-type lighting fixtures

Fluorescent lighting fixtures, especially the slim-line type, produce repetitive EMI. The arcing process taking place during the lamp operation produces an electromagnetic field around the lamp and in the surrounding environment. The lamp and ballast feed conducts interference back into the branch circuit and the wiring system supplying the power.

4.5.2.3 Other sources

Some electronic equipment, such as diathermy and microwave ovens, produce considerable narrowband interference. Other miscellaneous sources are ultrasonic devices, ignition systems, an broadcasting transmitters (these include radio, television and airport radar, and carrier frequency currents). Other sources are power and communication systems, industrial radios, and telephone dialing and electronic switching equipment.

4.6 Electrical noise produced by power processing and control

4.6.1 Arcs or sparks

Current chopping in electrical contacts causes discharges known as arcs or sparks. During circuit interruption, arc current will suddenly cease to flow. This step change in current is an electrical noise transient. Peak voltages of the arc are a function of the contact gap breakdown, which depends upon number and size of the contact gaps, contact material, and surrounding atmosphere. Sliding contacts in ac motors and dc motor commutators also create showering arcs and repetitive interference.

4.6.2 Solid-state switching devices

Power line voltage transients can be initiated by switching power loads. For example, closing a switch to a resistive load when the voltage is not zero allows the current to rise to the normal value as rapidly as the circuit constants will permit, thereby producing a voltage transient.

Solid-state switching devices switch faster than mechanical contacts. Because of their speed, a common use is to control power by repeated switching operations (every half-cycle is common). This results in repetitive electrical interference.

4.6.2.1 Resistive loads

Phase control for lamp dimmers or heater controls are solid-state switching devices and can be a source of electromagnetic noise.

4.6.2.2 Inductive loads

Silicone-controlled rectifier (SCR) drives are solid-state switching devices and can be a source of electromagnetic noise. The noise is produced when the current flowing in one line must suddenly stop and be established in another line.

4.6.2.3 Circuit switching

The switching on and off of multispeed motors, capacitor banks, transformers, distribution circuitry, and fluorescent lights can be sources for electromagnetic noise.

4.6.3 Faults

Faults interrupted by current limiting fuses, arcing, and restrikes on switching can create transients and electromagnetic noise.

4.6.4 Welding and power lines

Power-frequency electric and magnetic fields can result from resistance welding machines and power lines.

4.6.5 High voltage equipment

Corona or partial discharges occur when the electric field on the surface of an object, usually a conductor, exceeds the ionization potential of the surrounding dielectric medium (gas, liquid, solid, or combinations thereof). This causes the immediate surroundings to become ionized, producing interference. This generally occurs at cable splices, terminations, and gaps between live conductors.

5. Types of cable shielding

5.1 Introduction

Figure 1 shows the many types of shields used for cables. These differ in design and material composition and therefore have different shielding properties.

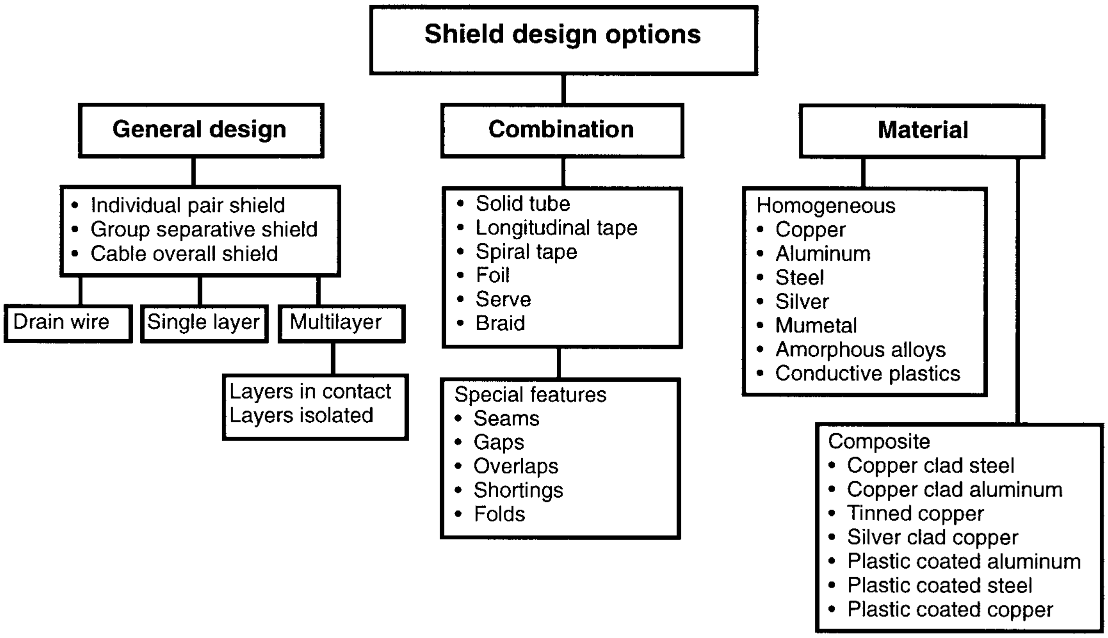

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Figure 1—Electrical cable shield design options

The cable shield is a part of an electromagnetic barrier that separates the shielded circuits from the external sources of EMI (or confines EMI effects to the shielded volume). An electromagnetic barrier is a closed surface made up of shields and other elements to exclude (or confine) electromagnetic waves propagating in space or guided along conductors. The barrier may be made up of metal or conductively coated equipment cases, interconnecting cable shields, filters or surge arresters on wires that penetrate the shield, and mesh or waveguides (below cutoff frequency) at ventilation openings. In a protected system, the barrier is everywhere sufficiently impervious to guided and space waves so that EMI sources outside the barrier do not degrade the performance of the protected system.

A perfectly conducting cylindrical shell that is closed at both ends would allow no external electromagnetic effects to affect circuits inside the shell. Since it is a closed shell, there are no apertures or conductors through which electromagnetic fields can penetrate and interact with the internal conductors. Because the cylindrical shell is a perfect conductor, no fields diffuse through the shell.

Practical cable shields are made of braided wires and tapes that have apertures through which electromagnetic fields may penetrate. Carriers in braided wire shields shuttle between the outer surface and the inner surface in the woven braid; this allows current induced at the outer surface to be carried to the inside of the shield where it can interact with the internal circuits. Spiral-wound tape shields may behave as solenoids when the turn-to-turn contact is poor. Tape shields are wrapped with an overlap that may act as one aperture. Practical shields are made from finitely conducting materials that may allow some fields to diffuse through the shield material.

Cable material characteristics and cable construction techniques affect EMI shielding effectiveness and frequency dependence. For instance, with a braided shield, the braid weave angle and optical coverage affect the amount of leakage. Tape shields allow leakage at the tape overlaps. Foil shields with interlocking slots may also exhibit leakage at very high frequencies. Apertures are also a factor in shielding effectiveness.

The coupling into the interior of a coaxial cable through an isolated aperture in the shield is shown in figure 2. Both electric and magnetic fields can couple through the aperture; thus the presence of shield apertures leads to capacitive and inductive coupling between the exterior and the interior of the cable.

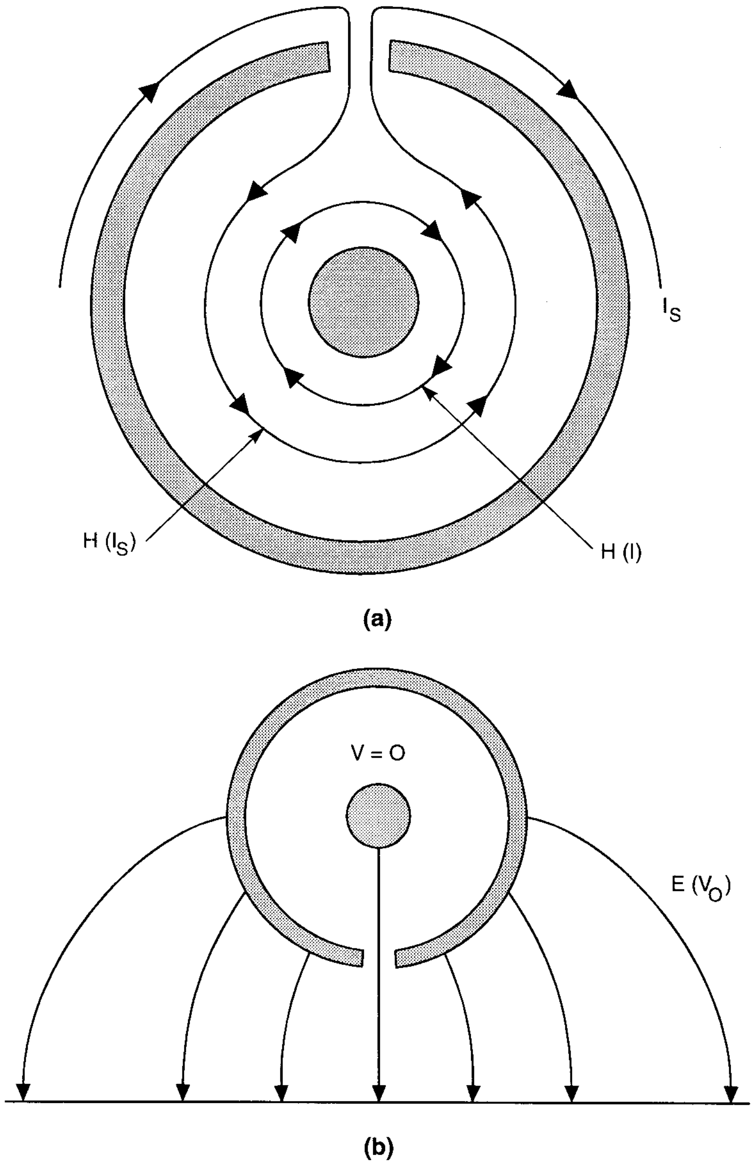

Figure 2—Electrical and magnetic field coupling through aperture in coaxial cable shield (a) Magnetic coupling, (b) Electrical coupling

5.2 Solid tube shield

A solid wall tube shield displays the most favorable high-frequency shielding properties. Its performance is a direct function of skin effect and the diffusion transfer processes. The greater the shield conductivity, magnetic permeability, and thickness, the better the shielding properties.

Despite their excellent shielding characteristics, tubular shields have limited use where flexibility is a requirement. They are normally used in permanent installations.

5.3 Single layer foil shield with drain wire

A foil shield is a thin, self-supported metallic tape, wrapped longitudinally (figure 3) or spirally (figure 4) around the cable core. Usually, aluminum foil is used, although some cables use copper, magnetic alloys, and conductive plastics. Occasionally, metallized film has been used.

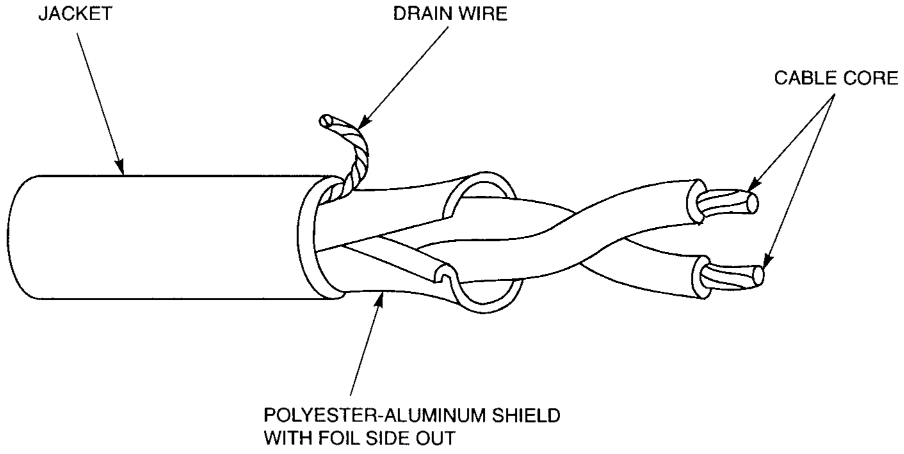

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Figure 3—Longitudinally applied foil shield

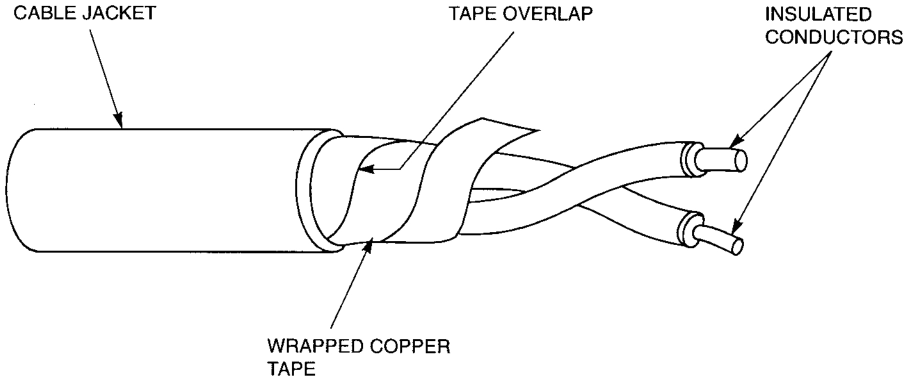

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Figure 4—Spirally applied foil shield

5.3.1 Aluminum-foil shield

To provide the necessary mechanical strength, the foil is usually bonded to the cable insulation or laminated to a polyester tape, or both. Figure 5 shows the use of a drain wire inside or outside the shield. Since the dc resistance of the foil is large, a drain wire is used to facilitate shield termination.

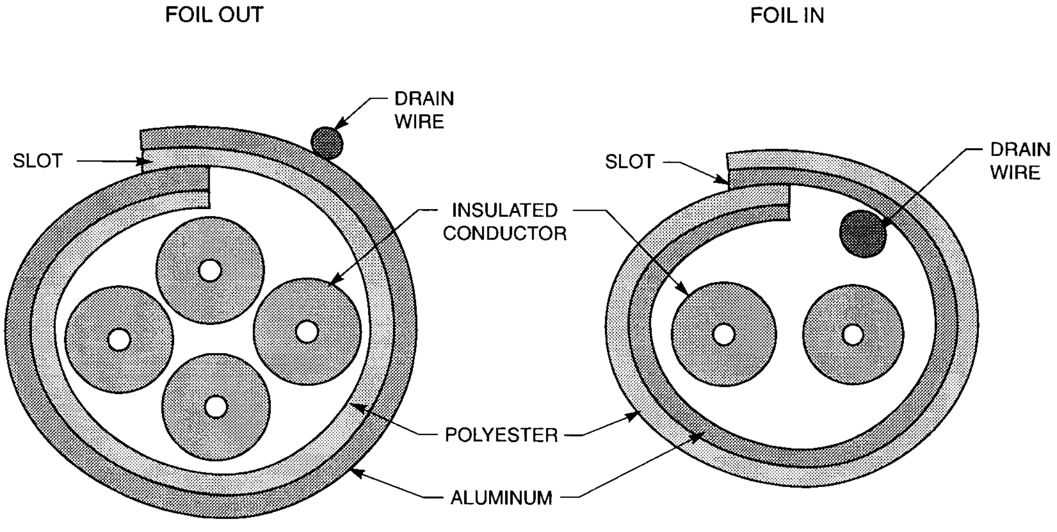

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Figure 5—Slot in film-foil shield with overlap

When the plastic layer on the foil shield prevents metal-to-metal contact at the overlap, it creates a slot that allows signal leakage to occur. This slot is shown in figure 5. A special shorting-fold technique reduces the signal leakage through the slot (figure 6) [B52]. A low wrap angle also improves foil-shield high-frequency performance.

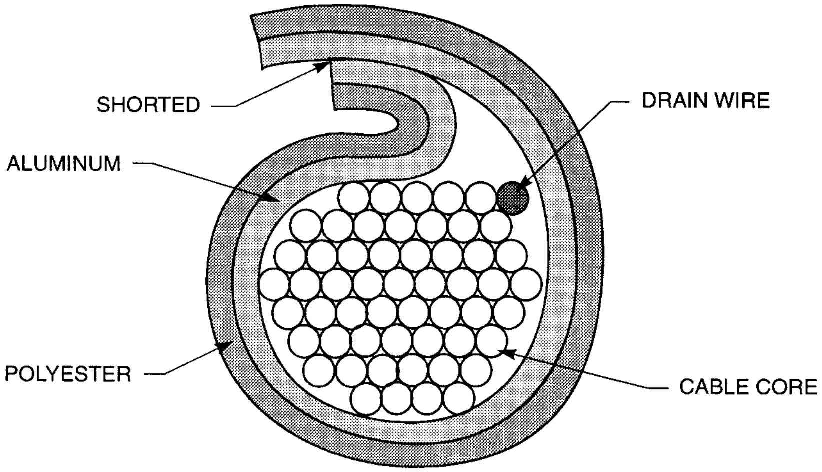

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Figure 6—Shorting-fold design for better high-frequency performance

5.3.2 Metallized plastic shields

A metallized plastic film, made by vacuum depositing 2–5 μm of metal on a plastic film, can be used as a shield. Such a shield is useful where only low-frequency electric field protection is needed, and where the cable is not subject to flexing or corrosive environments.

Such a thin metal coating cannot carry much current and does not provide much protection against induced longitudinal currents. The resistance of such shields is on the order of 0.1 Ω/m and its cutoff frequency is on the order of 300 MHz. Because the metal film is very thin, it has little mechanical strength, and it is easily cracked, scratched, or spalled by mechanical flexure. It is also easily damaged in a corrosive environment.

5.4 Multilayer shield with drain wire

A shorting-fold shield (figure 7) has reduced shielding at high frequencies because of contact resistance in the shorted fold, which acts as a slot at higher frequencies. Therefore, to achieve high shielding efficiency, multilayer shields are used. Very good shielding efficiency is achievable by combining, in a proper way, foil and braid layers.

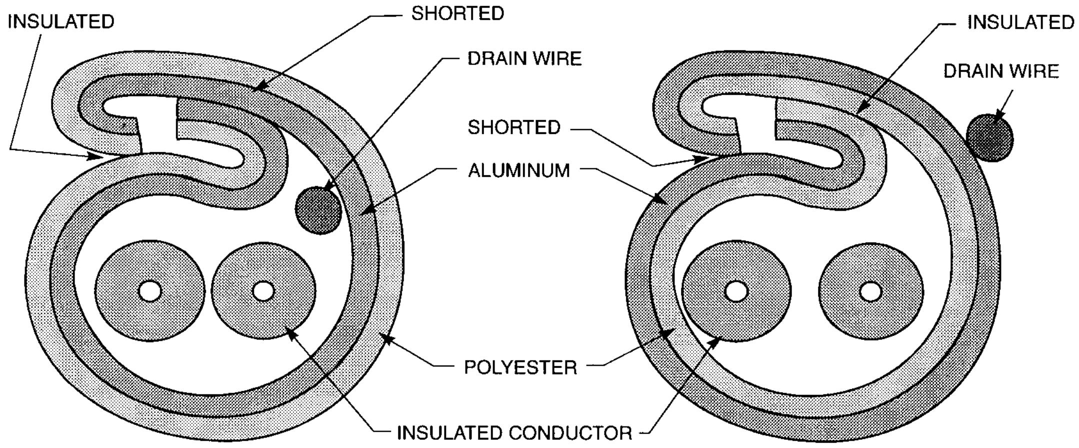

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Figure 7—Additional shorting-fold designs

5.5 Spiral shield

Spiral shields may be helically applied to tape or wire (see figure 8). These shields provide flexibility. The spiral shields, however, produce longitudinal, solenoidal magnetic fields inside the cable, similar to the field in inductance coils. These solenoidal fields result in poor shielding characteristics at high frequencies. Therefore spiral shields find use only in the low-frequency range (audio frequency electronic cables, microphone, musical, retractile cords).

5.6 Braided wire shield

A braided shield consists of groups of coated or uncoated metallic strands, one set woven in a clockwise direction and interwoven with another set in a counter-clockwise direction (figure 9).

Braided shields provide structural integrity, while maintaining good flexibility and flex life. These shields are most useful for minimizing low-frequency interference and have lower dc resistance than foil. Braided shields are effective at audio and RF ranges. Generally, the higher the braid coverage, the more effective the shield. Typical braid coverage is between 80% and 95%. Coverage of 100% is unattainable with a braid shield. Other features to consider when choosing a braid shield are the weave angle, strand diameter, number of carriers (strand groups), and number of ends (strands).

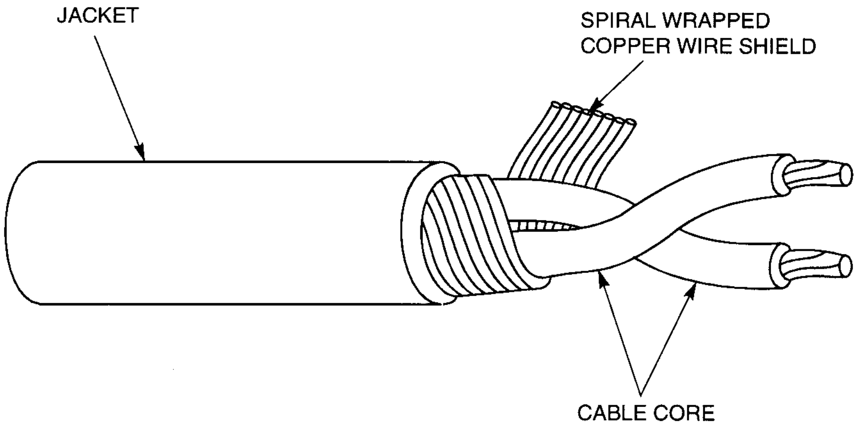

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Figure 8—Spiral shield of wire serve

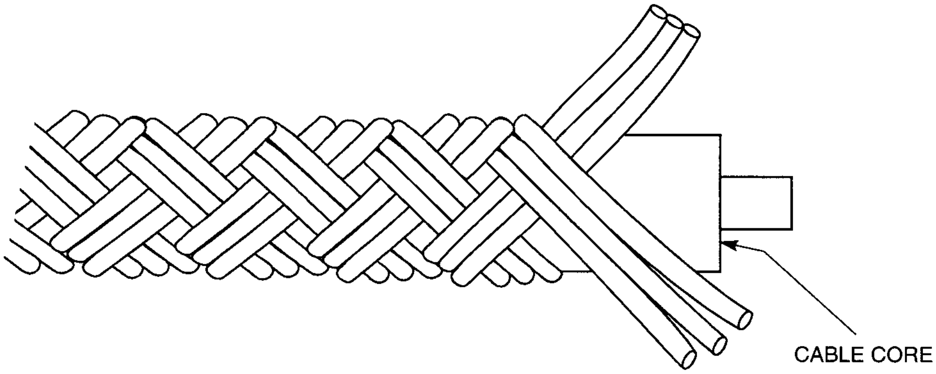

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Figure 9—Braid shield

Braided wire shields have apertures through which both electric and magnetic fields can pass. The weaving process creates small diamond-shaped apertures where the bands of shield wires cross. The developed surface of such a shield is shown in figure 10.

Braided shields are generally bulkier and heavier than other shields. Crimp or heat-shrinkable terminating devices are available for braid shields [B7].

5.7 Combination shields

Improved high-frequency performance can be achieved by combining foil and braided shields. Covering a two-layer foil shield with a braided shield can result in a shielding characteristic that begins to resemble that of the solid-wall copper tube. Since the foil provides 100% optical coverage, braid apertures may be increased. Therefore, braids with optical coverage in the 40–80% range are useful.

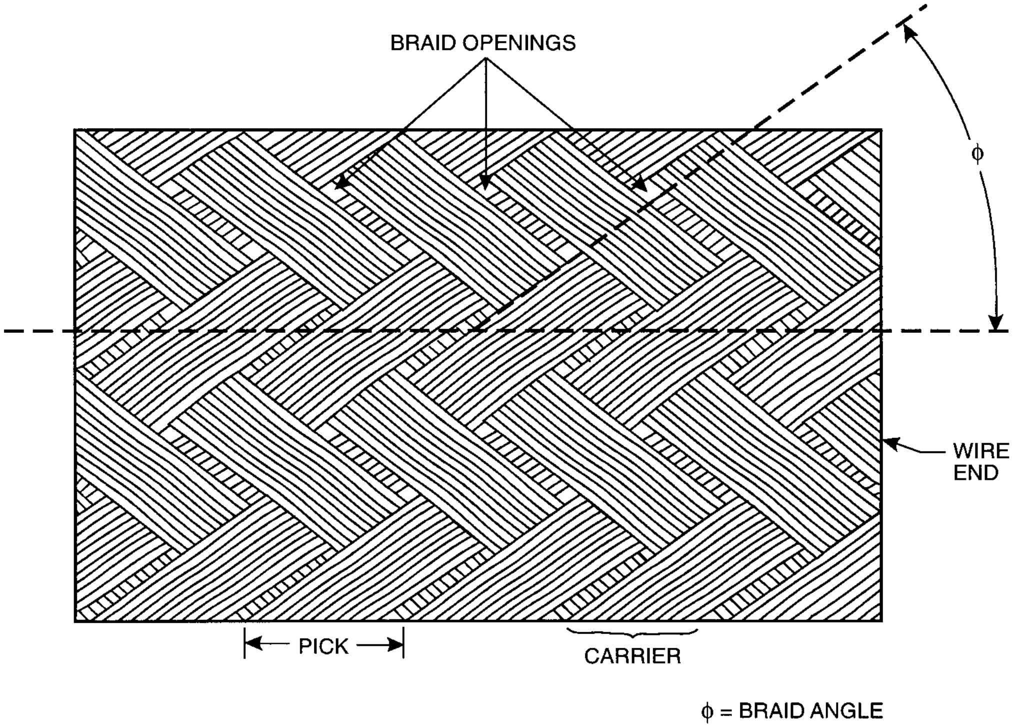

Figure 10—Developed surface of braid shield

Multiple layers of foil and braid can be used to get an even closer approximation of solid-wall copper tube characteristics. A good example of this type of approach is found in the cable used for the Ethernet local area network. Ethernet cable has a polyester-backed foil shield bonded to the inner-conductor insulation, covered by a two-foil shield sharing a common polyester backing, and a tinned-copper braided shield with 92% coverage. This shield configuration provides shielding up to 30 MHz. Three-layer shields developed for CATV coaxial cables use a bonded-foil/braid/foil-with-shorting-fold shielding format and exhibit good shielding up to 80–100 MHz [B34].

A spirally-wrapped plastic-foil tape is poor in shielding effectiveness, and effectiveness worsens with increasing frequency. This suggests poor turn-to-turn electrical contact. Longitudinally-wrapped tape is more effective. For example, a single overlapped longitudinal copper tape formed into a tube acts very much like a solid copper tube from a shielding point of view. The comer frequency at which the skin depth is equal to the thickness of the foil is about 1 MHz. A braided shield over this tape provides shielding that is more independent of frequency.

5.8 Overall shields

Overall shields are used primarily with multiconductor cable in the following types of applications:

- Telemetering
- Communications
- Instruments
- Supervisory
- Control
- Electronic

These shields may be of four types, as follows:

- Longitudinally-wrapped and corrugated
- Longitudinally-wrapped and smooth
- Continuously welded corrugated or smooth
- Seamless

Longitudinally-wrapped corrugated shields of plastic coated or bare aluminum, coated or bare copper, plastic coated or bare steel have been used extensively in exchange area telephone cables. In the cable manufacturing process, an in-line corrugator corrugates the tape; then the corrugated tape is formed around the cable core so that the edges overlap (see figure 11). Corrugating the tape increases the axial strength and flexibility of the cable. Such shields give 100% optical coverage. Overall shields are more effective as electrostatic shields (because of the greater shield mass) than aluminum foil-polyester laminate. Cables with longitudinally corrugated shields have greater current handling capability, but larger diameters and less flexibility than cables with only foil-polyester laminates.

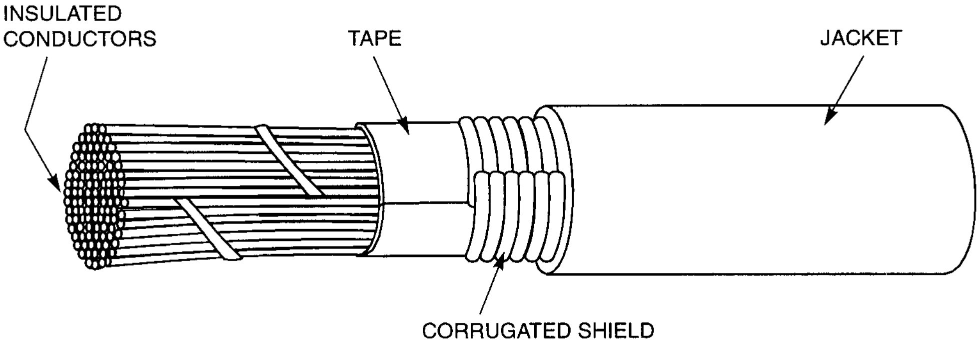

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Figure 11—Corrugated tape shield

Shields of coated aluminum or coated copper utilize a plastic coating to adhesively bond the shield to the cable jacket. When the shield is bonded the jacket, the cable is said to have a “bonded sheath.” Bonded sheath cables allow the shield to be wrapped in a smooth configuration, although corrugated plastic coated metallic tapes can be used as well. Figure 12 shows the use of a smooth tape. The bonded sheath provides the cable with improved mechanical properties by combining the flexibility of the plastic jacket with the strength of the metallic tape. The bond between the jacket and shield also forms a water block at this interface. The plastic coatings provide the shield with corrosion protection [B6].

Corrugated aluminum or smooth coated aluminum shields are lighter and easy to handle for aerial installations. Corrugated coated aluminum and copper shields are flexible and provide corrosion protection to the shield for duct and direct burial applications. Bimetallic shields use metallurgical bonding to combine two layers of copper with one layer of stainless steel or low carbon steel. Bimetallic shields and coated steel armor provide protection against damage by wildlife.

Longitudinally applied overall shields serve both electrical and mechanical functions. When grounded at both ends, these shields become an electromagnetic shield. As such, they provide protection against lightning surges and low-frequency induction. They provide lower resistance, and hence are better longitudinal conductors for fault currents than corresponding spiral shields of similar thicknesses or conductivity.

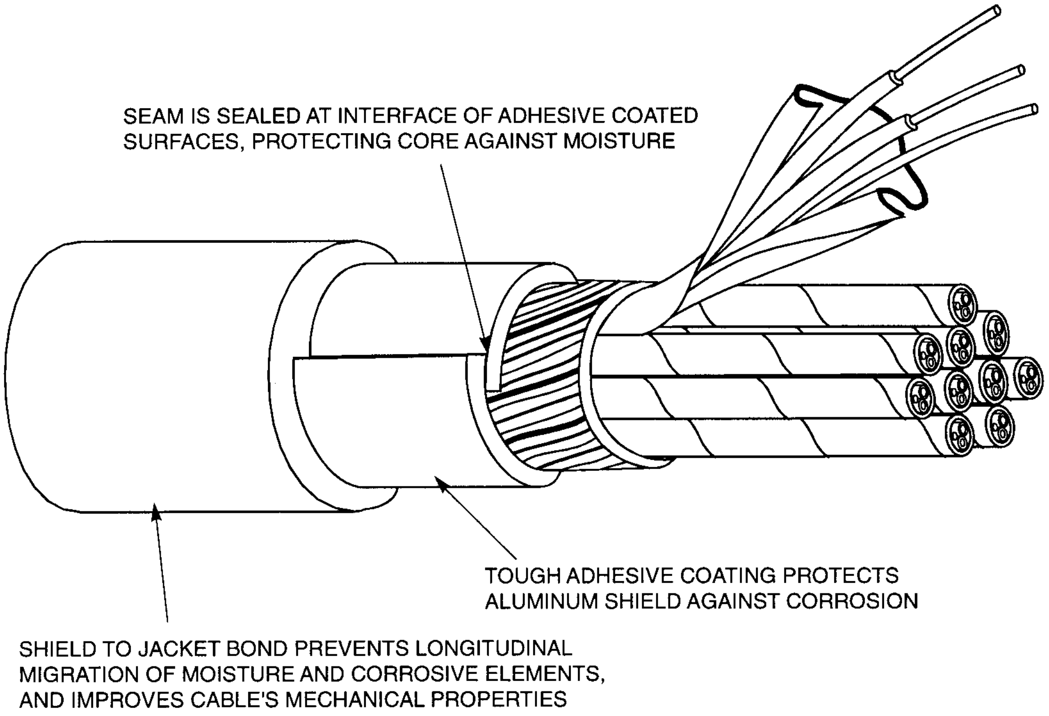

Figure 12—Bonded sheath cable

The desirability of hermetically sealed cables has grown. Considerable improvements in moisture and chemical resistance can be attributed to the use of the composite “bonded sheath,” comprised of coated 0.2 mm (8 mil) aluminum, coated 0.125 mm (5 mil) copper or 0.15 mm (6 mil) coated steel and a plastic jacket. A thin layer of a plastic coating adhering to one or both sides of a metallic strip provides the bonding. After this metallic strip is formed into a tube and overlapped, the extrusion of the final plastic jacket over the tube fuses the adjacent jacket and coating together. This provides a waterblock between the shield and jacket. The overlap is sealed with the plastic coatings and the heat of extrusion (sometimes a hot melt adhesive is inserted into the overlap to facilitate sealing). The result is a “sealed seam” or “sealed overlap.” The bond to the jacket and sealed seam provide the cable with a hermetically sealed metallic shield or armor. The cable is known as having a moisture barrier sheath. However, the seal at the overlap effectively puts an insulating layer between the surfaces of the overlap, which results in a slot. This slot can be a source of signal leakage, possibly limiting the use of the shield in cables operating at high frequencies. However, the main purpose of such shields is to provide protection against the effects of transients such as those originating in lightning or power system disruptions.

A databus cable makes excellent use of the composite shield concept and an overall bonded sheath [B6]. This design uses a 95% coverage braid of tinned copper as the electrical shield, a 70% coverage braid of tinned copper covered steel as a magnetic shield, and a coated 0.19 mm (8 mil) aluminum tape as a moisture barrier and overall shield. (The shielding performance of composite shields is discussed in 12.2.)

Corrugated welded smooth tubes, as well as seamless tubes, can provide a high degree of shielding effectiveness. In order to be fabricated, they must be considerably thicker than longitudinally folded shields. Typically they have a thickness of 0.38–1.27 mm (15–50 mils) vs. 0.19–0.20 mm (7–8 mils) for longitudinal shields.

5.9 Conductive plastics

A variety of plastics can be loaded with carbon or metallic powders. The degree of loading will influence the conductivity and many other properties of the material. Their conductivity, however, is significantly less than metals, making them generally unsuitable as electromagnetic shields. Inherently conductive polymers have made their appearance; however, their costs at this stage are very high, thus limiting commercial applications. Their conductivity and low current carrying capacity may limit their shielding effectiveness.

5.10 Shield and armor options

The shielding properties of shields and armors vary over a wide range. Spiral wound metal tapes provide very little electromagnetic shielding—they behave as solenoids—but they can provide low-frequency shielding against electric fields. Longitudinal tapes provide better electromagnetic shielding, but may be less flexible and have poor flexural durability unless a bonded structure is used. Braided wire shields provide good electromagnetic shielding and flexural durability. They are somewhat more expensive, and their shielding at high frequencies (above about 1 MHz) is poorer than that of tubular shields [although their shielding at low frequencies is better than that of tubular shields (and thin tapes)]. Table 1 summarizes some of the shield construction options.

Table 1—Shield options

Item	Class 2 (150 V) and Class 3 (300 V)
Over cable components such as twisted pairs and triples	A. Aluminum/polyester laminate tape wit copper drain wire; or B. Coated or uncoated metallic braid, and shield isolation by polyester tape or jacket.
Over cable core (overall shield)	A. Aluminum/polyester laminate tape with copper drain wire; or B. Braid with or without additional metallic coatings; or C. Aluminum/polyester laminate plus metallic braid combination; or D. Spiral tape: 0.075 mm (0.003 in), 0.125 mm (0.005 in) or 0.25 mm (0.010 in) copper, or 0.20 mm (0.008 in) aluminum; or E. Corrugated tape applied longitudinally, bare or plastic coated: 0.125 mm (0.005 in), 0.15 mm (0.006 in), or 0.25 mm (0.010 in) copper, or 0.20 mm (0.008 in) aluminum; or F. Smooth tape applied longitudinally: plastic coated 0.125 mm (0.005 in), 0.15 mm (0.006 in) or 0.25 mm (0.010 in) copper, plastic coated 0.20 mm (0.008 in) aluminum.

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Compound shields, such as spiral tapes and braided wire, provide some of the electromagnetic shielding advantages of both, and some of the mechanical disadvantages of both. The tape and braid shield has better high-frequency shielding but is stiffer and has poorer flexural durability than braid alone. Table 2 summarizes the important properties of the individual and compound shields.

Metal armor may also be applied to cables for mechanical protection. Exterior cables for power and telecommunications applications frequently use the shield and/or armor for an electrical role (power neutral or telephone cable shield) as well as mechanical protection. Interior cables that are exposed to contact or stress may also be armored for mechanical protection. Rigid or flexible conduit and braided steel wire or strip may be used as armor. The quality of the armor as an electromagnetic shield may vary from very poor to very good. The armor may be a very poor electromagnetic shield if it is an interlocked-spiral flexible conduit or served with a single layer of wire. It can be very good if it is a welded, corrugated armor/shield or a longitudinally folded tape. Table 3 provides some of the important properties of cable armors.

Table 2—Shield options

Option	Advantages	Disadvantages
Interior cable		
Longitudinally applied Aluminum/polyester tape plus drain wire	100% shield coverage Low cost Light weight Small diameter Easy to terminate P ractical pair shielding Provides low cost pair-to-pair shield isolation	Minimum physical protection Unsuitable for high voltage protection Low current capability
Braided copper	Flexibility Physical protection Modern current capability	Higher cost Less than 100% coverage Used as a conductor pair or overall shield—for individual pairs or triples, must be wrapped or jacketed to provide shield isolation
Aluminum/polyester tape plus braided shield	Tape increases shield coverage to 100% Tape applied over shield reduces jacket penetration into braid	Used as conductor, pair, or overall shield Less flexible
Spiral copper tape	100% coverage Optimum transient voltage protection Greater protection in high voltage areas Mechanical protection	Increased diameter Practical only as overall shield Poor high-frequency shielding
Spiral aluminum tape	Lighter than copper Lower cost vs. copper	Less effective than copper May corrode Practical only as overall shield Very poor high-frequency shielding
Outside cable		
Corrugated copper, aluminum, bimetallic or copper alloy tape, or smooth or corrugated coated copper, coated aluminum	Increased strength and flexibility Maximum shield conductivity May be bonded to jacket if coated Transient protection Magnetic protection Electrostatic protection	Practical only as overall shield Corrugations increase cable diameter
Corrugated coated steel	May be bonded to jacket Increased strength Improved mechanicals Transient protection Magnetic protection Electrostatic protection	Practical only as overall shield Corrugations increase cable diameter

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Table 3—Armor options (outside cable)

Option	Advantages	Disadvantages
Spiral (copper, steel)	Acts as shield or armor Frequently used for direct burial	Requires outer jacket Tape overlaps can buckle during bending Resistance can approach that of helix Very poor high-frequency shielding
Braid (aluminum, bronze, or galvanized steel)	Offers protection from sharp edges and abrasion Aids pulling tension Flexible Small increase in cable diameter	Higher cost
Spiral wire (wrap or serve) (galvanized steel)	Provides impact protection Aids pulling Vertical support strength	Requires outer jacket Extruded jacket (with rip cord) desirable under armor Very poor shielding
Interlocked (galvanized steel or aluminum)	Flexibility protection against impact	Limits bending radius Extruded jacket (with rip cord) desirable under armor Very poor shielding
Longitudinally folded smooth tape (plastic coated aluminum and plastic coated copper)	Acts as shield or armor Bond to jacket provides mechanical strength and moisture protection	Special terminations may be required
Longitudinally folded, corrugated tape (plastic coated or bare aluminum, steel, copper, bimetallic, copper alloys)	Rodent protection (steel, copper alloy, bimetallic) Bonding to jacket increases flexibility and mechanical strength moisture and chemical protection if coated	Increase in cable diameter over smooth tapes
Welded smooth or corrugated	Mechanical protection Moisture protection	Corrosion due to moisture penetration at armor-jacket interface Limited bend radius Flexibility

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5.11 Balanced mode transmission on twisted pairs

An important property of twisted pair is that the signal is transmitted in the wire-to-wire, or signal, mode while the interference is frequently induced in the common mode (i.e., equally in each wire). If the terminal equipment is balanced and responds only to the signal mode, the common-mode interference does not contaminate the signal. This is illustrated in figure 13. Note that if the circuit is unbalanced by grounding one wire of the pair, the common-mode interference is forced to flow through the terminations, where it contaminates the signal (see figure 14).

Both interference emission and susceptibility can be controlled by using balanced twisted pairs. Thus, 60 Hz interference produced by power leads can be reduced by using twisted pair for the power, and twisted pair reduces the signal-mode interference induced on signal and control leads. Because the reactance due to stray capacitance and inductance becomes significant at frequencies above approximately 1 MHz, it is difficult to maintain a balanced line or terminal impedance at high frequencies. Twisted pairs can be used for signal transmission well above 1 MHz. However, it may be difficult to maintain a balanced line or terminal impedance at high frequencies. Therefore, common-mode rejection is most effective below 1 MHz. Shielded twisted pairs may be appropriate for controlling interference and crosstalk at these higher frequencies.

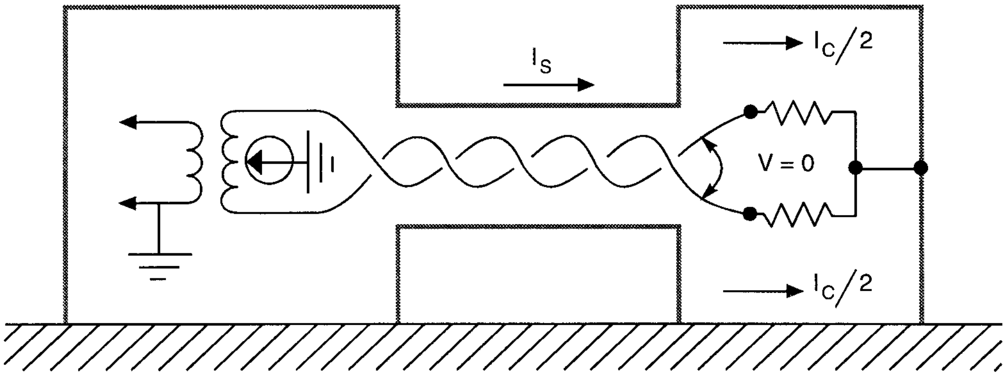

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Figure 13—Common-mode rejection with balanced circuits

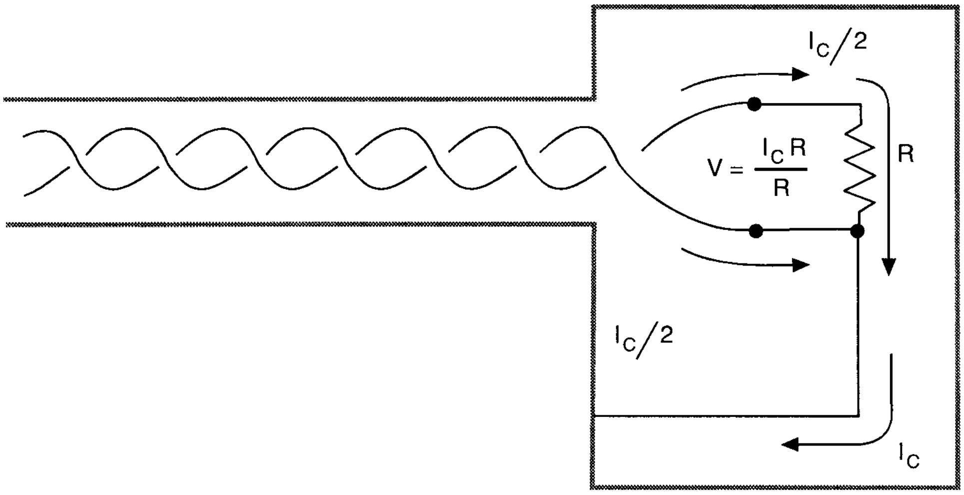

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Figure 14—Common-mode rejection nullified by ground

If the twisted pair is immersed in the quasistatic electric field of a neighboring conductor, a current $i = Cdv/dt$ is injected onto each wire of the twisted pair. Here C is capacitance between the neighboring conductor and either wire of the twisted pair, and v is the voltage between the neighbor and the pair. If the pair were not twisted, C could be different for each wire and the injected current would not be a pure common-mode current. If C is of the order of 10 pF/m, the injected common-mode current is < 1 µA/m at 10 kHz for each volt. The small current induced by this form of coupling is important (if the terminal circuits are unbalanced) for 1) high-impedance circuits, 2) very-small-signal circuits, and 3) crosstalk in long lines. Since C varies as the inverse of the logarithm of the separation between the pair and its neighbor, increasing the spacing helps, but the improvement that can be achieved by this tact is quite limited. Shielding is much more effective than separation.

If the twisted pair is immersed in the magnetic field of a neighboring conductor, a voltage $v = Mdi/dt$ will be induced in each wire of the pair. Here, i is the current in the neighboring wire and M is the mutual inductance between the neighbor and either wire of the pair. If the terminal equipment is balanced, it will not respond to this common-mode voltage. The voltage induced on each wire by a 1 A, 10 kHz current in the neighboring wire through a 1 µH/m mutual inductance is over 60 mV/m. If converted into a signal-mode voltage, this would be a significant interference level in many circuits. The mutual inductance *M* also depends on the logarithm of the separation between the pair and its neighbor. Increasing the separation reduces the coupling, but slowly. The coupling is also proportional to length. It is minimized if the twisted pair and the neighbor wire are orthogonal. When orthogonality cannot be assured, an electromagnetic shield may be necessary.

Generally, both electric and magnetic field coupling occur, and the coupling is distributed along the length of the line. The electric field (capacitive) coupling behaves as a distributed shunt current source, and the magnetic field (inductive) coupling behaves as a distributed series voltage source, both in the common mode. When both occur, the resultant currents or voltages will be different at the two ends of the pair. The shunt current source injects current that flows toward both ends of the line, while the series voltage source causes current to flow in only one direction. These currents combine constructively at one end and destructively at the other end. This characteristic is important when making shielding effectiveness measurements.

If the pair is not twisted, the magnetic field from a neighboring wire may induce a normal-mode voltage between the pair or wires. This occurs because the magnetic field links the area between the wires, or because the mutual inductances between the neighboring wire and the wires of the pair are different (because *D1* and *D2* are different), as illustrated in figure 15. The electric coupling may also induce a normal-mode current because the capacitances between the neighboring wire and the wires of the pair are different (also because *D1* and *D2* are different.) Twisting the pair tends to equalize both the mutual inductance (see figure 16) and the capacitance per unit length. A well-balanced twisted pair with balanced terminations can provide 60 db of common-mode rejection at low frequencies (< 30 kHz).

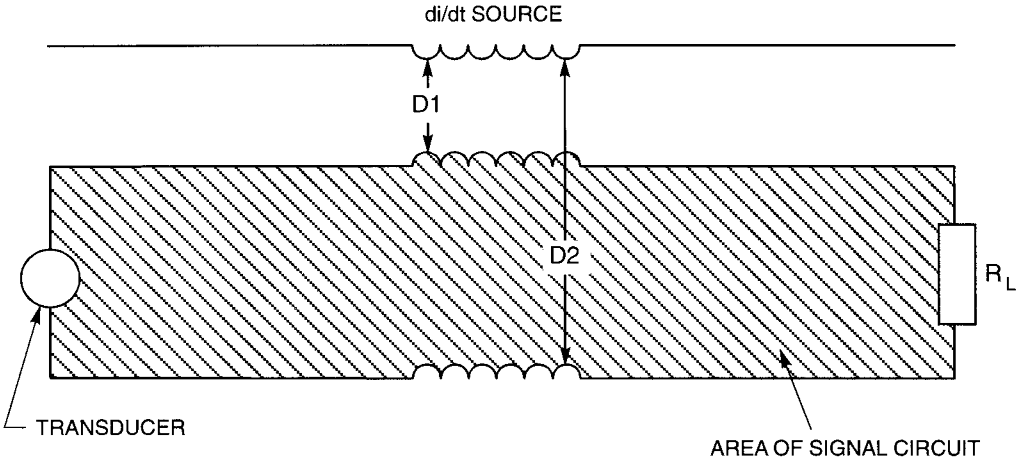

Figure 15—Magnetic noise coupling

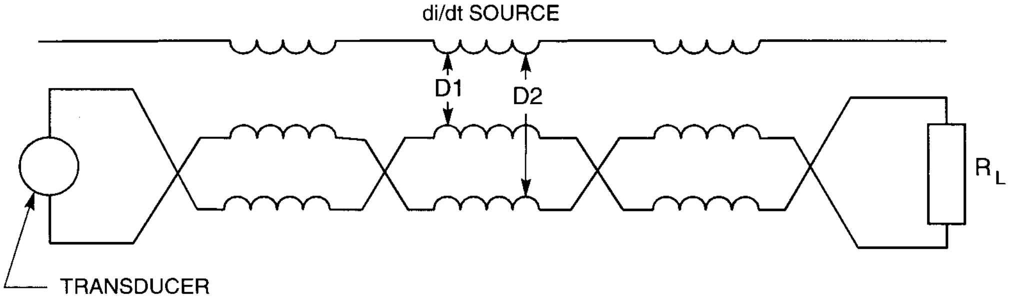

Figure 16—Reducing magnetic noise by twisting of wires

Table 4 illustrates the effectiveness of using twisted pair wires in reducing magnetic field noise in signal circuits. Good noise cancellation is provided by 1 inch (25 mm) lay or 12 twists/ft (39 twists/in). Theoretically, the use of twisted wires could nearly eliminate both electric field and magnetic field noises. Some manufacturers have gone to 0.5 in lay to obtain enough balance to avoid the use of shielded wire.

Table 4—Magnetic interference reduction

	Noise Reduction	
Type	**Ratio**	**dB**
Parallel wires	1:1	0
Parallel wires in 25 mm (1 inch) rigid steel conduit	22:1	27
Twisted wires		
101.6 mm (4 inch) lay	14:1	23
76.2 mm (3 inch) lay	71:1	37
50.8 mm (2 inch) lay	112:1	41
25.4 mm (1 inch) lay	141:1	43

NOTES:
1 — Frequency: 60 Hz
2 — Length: 1 m (3.28 ft)

5.12 Balanced mode transmission on shielded twisted pairs

The addition of a shield to the twisted pair may be necessary for several reasons, as follows:

- The terminal equipment may not be able to tolerate the common-mode voltages or currents.
- The common-mode rejection for high-frequency or transient interference is inadequate.
- The circuit is not balanced so that the common-mode interference is converted to normal-mode interference.

A shield, properly installed, reduces the common-mode interference induced on the signal pair. The interference is now induced on the shield.

A shield applied to twisted pair has two shielding effects. It (1) excludes external fields and (2) improves the balance of the pair (the latter by excluding the effects of external structure on one wire of the pair). Both effects improve the ability of the balanced circuit to operate in a high-frequency interference environment. An electromagnetic shield is most effective if it encloses the entire circuit. If possible, the cable shield should be circumferentially bonded to the terminal equipment housings to ground the shield.

Less shielding may be acceptable in special cases where it is known that the interference will be caused only by low-frequency electric field coupling. In this case, a very lightweight shield that is closed (or grounded) at one end may suffice, since the shield need only carry small low-frequency currents and intercept electric fields that would otherwise terminate on the pair wires.

If the pair is exposed only to low-frequency magnetic fields, such as those produced by an adjacent power conductor or those associated with ground-plane currents and gradients, the shield must be capable of carrying larger currents than the electrostatic shield. Thus, several mils or tenths of millimeters of metal foil or braided wire are required. For low frequencies, some inductance and a small aperture (i.e., a “pigtail”) are tolerable at the connection of the cable shield to the terminal equipment shield. It is not good practice in either the electric or magnetic shielding case to "ground" the shield to the ground of the protected circuit (as in figure 14), because this allows the interference current to enter the protected circuit and negate much of the benefit of the shield.

In general, it is not known if the interference will be entirely at low frequencies or coupled only by electric fields. Transients and other sources in the high-frequency spectrum are present in most industrial environments, and modem broadband digital electronic circuits are affected by such sources. Broadband techniques using closed electromagnetic shields are appropriate for these conditions.

If shielding is required because the circuit is unbalanced, it may be more prudent to balance the circuit than to add a shield. If the twisted pair has been deliberately unbalanced by grounding one side, as shown in figure 17, it may be possible to restore sufficient common-mode rejection by restoring the balanced configuration.

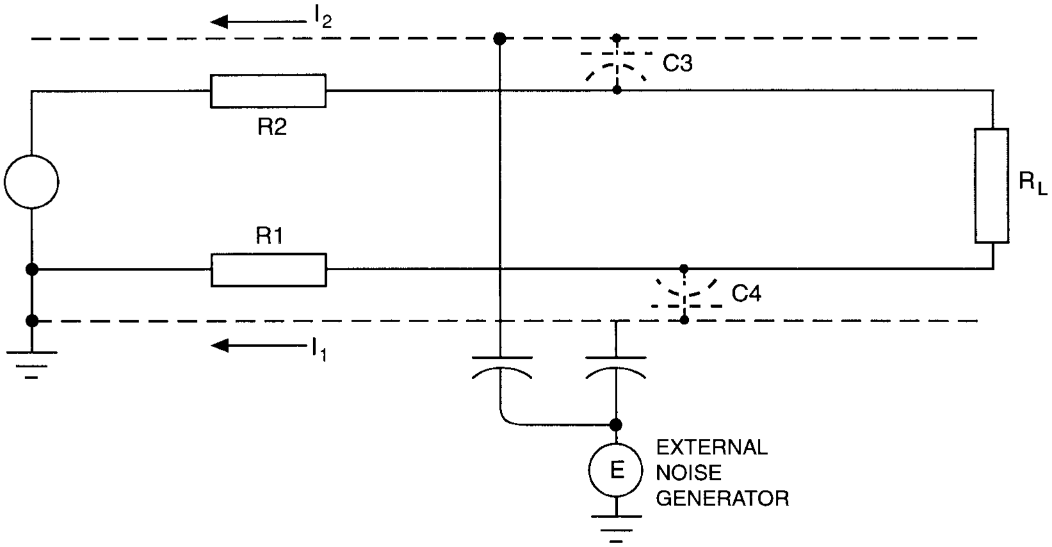

Figure 17—Interference in signal circuit due to unbalanced grounding

Table 5 shows the effectiveness of various types of wire shielding in reducing electrostatic field noise in signal circuits. As can be seen from the table, lapped or taped shields provide more shield coverage and are more effective. Because these shielded wires are relatively ineffective against magnetic field interference, twisted wire should be employed within the shield. Because of manufacturing expense, only 1.5 in and 2 in lay wires are commonly available within the shield. This combination has been found to be more than adequate for most applications. An insulated jacket should be placed over the shield. The shield should be grounded at one end only.

Table 5—Electrostatic interference reduction

Shield	Noise reduction	
	Ratio	dB
Copper braid (85% coverage)	103:1	40.3
Spiral wrapped copper tape	376:1	51.5
Aluminum—polyester tape with drain wire (total coverage)	6610:1	76.4
No shield	1:1	0

NOTES:
1 — Frequency: 1000 Hz
2 — Cable length: 15.2 m (50 ft)

5.13 Twisted pairs for transmission of high-speed data

Shielding is added to twisted pairs to confine the electric and magnetic fields. In this way any susceptibility to EMI is further reduced. However, there is an important side effect on the pair's loss of signal per unit length (attenuation). For high-speed digital signals (half a megabit per second or more) the attenuation, α, of the shielded pair is well approximated by:

$$\alpha = 14 \cdot 24R\sqrt{\frac{C}{L}}\frac{db}{km}$$

where

R is the high-frequency (skin effect) resistance of the pair, Ω/km
C is mutual capacitance, F/km
L is inductance, H/km

Adding a shield to a twisted pair confines the electric and magnetic fields associated with the signal voltage and current to a smaller volume, thereby increasing the capacitance *C* and reducing the inductance *L*. The magnetic field of the signal current also induces eddy currents in the shield. Electric fields in the shielded pair also increase the dielectric losses. The eddy currents in braided wire shields are smaller than in continuous tubular or foil shields because the strands break up the eddy current paths.

Nevertheless, adding the shield increases the signal attenuation of the pair, as well as decreases the induced interference. Because of this and the greater cost of shielded pair, the use of shielded pair for long, high-speed data lines should be evaluated carefully.

Where interference control beyond that provided by a balanced twisted pair is required, a shielded pair may be necessary. For example, if induced common-mode interference can be carried outside equipment on the pair, it may contaminate other equipment or violate emission requirements. Shielded pair can be used to confine the common-mode interference so that it does not contaminate the environment (provided the pair shield and equipment housing form a closed shield.) If the interference reduction needed is small, common-mode chokes on unshielded pair may suffice.

6. Shielding application principles

6.1 Functions

Modern process control systems perform a variety of functions, as follows:

a) Measure—Liquid, vapor, and gas flow; liquid level; temperature; pressure; density; etc.
b) Transmit—From sensor to controller or computer
c) Indicate, display, or record—Using lights, meters, instrument panels, strip or circular recording charts, etc.
d) Control—Regulate motor speed and direction; set and maintain temperature, pressure, exposure or reaction time, and other control functions within precise limit points by activating relays, switches, valves, and motor controls

These functions result directly from data acquisition and signal transmission between remote sensors, controllers and computers, and process devices. Cables to carry data and signals are available in several “standard” configurations. The selection of any particular one depends on the volume and type of data transmitted, the operational environment, and the required degree of reliability.

6.2 Single or multiconductor

In a typical system, thousands of signal wires bring status information to, or transmit control commands from, a central control/computer location. There are two fundamentally different wiring practices presently in use. In one, individual cables connect field devices directly to the control board or logic cabinet in the control area. In the other, large multiconductor trunk cables transmit signals from a central distribution area to different zones in the plant or control room. Multiconductor cable offers savings in material and installation costs through use of a 25 or 50 pair trunk cable instead of many smaller cables having the same total conductor count. Potential disadvantages are higher labor costs for splicing and decreased reliability associated with additional terminations.

6.3 Dedicated or multiplexed

Some plants transmit each signal from sensor to computer or computer to actuator over their own dedicated wires. Multiplexing is an alternative method of signal transmission that allows the carrying of many signals on a single wire pair, coaxial, or fiber optical cable. A single pair, coaxial, or fiber optical cable can serve many circuits because the signals are transmitted sequentially (time division multiplexing) or modulated onto carrier frequencies (frequency division multiplexing). Multiplexing reduce the amount of wiring but requires more sophisticated electronics and greater bandwidths. In the modern continuous process industrial plant and in its specialized utility counterpart, the generating station, basic process area are usually regulated by a system of electrical control circuits. Integrating these areas into a process control program is generally accomplished with an overlay of electronic circuits, through which computer control is applied to the whole operation. The wires and cables making up the electronic control circuits are instrumentation cable; those associated with electrical control circuits are control cable.

6.4 Cable construction types

Virtually all industrial instrument cable requirements are satisfied by one or more of the following configurations:

a) Single, pair, or triple—unshielded, overall jacket
b) Single, pair, or triple—shielded, overall jacket
c) Multiple singles, pairs, or triples—unshielded individual components, overall shield and jacket
d) Multiple singles, pairs, or triples—shielded individual components, overall shield and jacket

6.5 Cable selection

The proper application of instrumentation cables depends on accurate evaluation of the following circuit considerations:

a) Signal type(s) transmitted; voltage: ac, dc, or pulsed; voltage level; current magnitude
b) Sensor type(s) used
c) Receiving element type(s)
d) Type of noise exposure for the sensors and receivers
e) Noise level to be tolerated or emitted

Table 6 lists recommended cable constructions for many combinations of the above variables [B39].

Table 6—Instrumentation cable application guide

Circuit conditions			**Noise conditions**		**Recommended constructions**	
Signal level	**Signal origins**	**Receiving devices**	**Type**	**Level**	**Single pairs**	**Cables pairs each pair**
DC voltages						
< 100 mV	Thermocouples	Potentiometers	Static Magnetic Common mode	Low	Unshielded	Unshielded
				Medium	Unshielded	Unshielded
				High	Unshielded	Unshielded
		Potentiometers and Bridge instruments Amplifiers, A to D converters, Computers		Low	Shielded	Unshielded
				Medium	Shielded	Shielded
				High	Shielded	Shielded
				Low	Shielded	Shielded
				Medium	Shielded	Shielded
				High	Shielded	Shielded
	Bridge circuits, Thermistors, RTD's Chromatographic pH, Magnetic flow meters	Potentiometer and Bridge instruments Amplifiers, A to D converters, Computers	Static Magnetic Common mode	Low	Shielded	Unshielded
				Medium	Shielded	Shielded
				High	Shielded	Shielded
				Low	Shielded	Shielded
				Medium	Shielded	Shielded
				High	Shielded	Shielded
100 mV-10 V	Analog computer outputs	Potentiometer and Bridge instruments Amplifiers, A to D converters, Computers	Static Magnetic	Low	Shielded	Unshielded
				Medium	Shielded	Unshielded
				High	Shielded	Unshielded
				Low	Shielded	Unshielded
				Medium	Shielded	Shielded
				High	Shielded	Shielded
10 V–125 V	Annunciators, Alarms, Retransmission potentiometers	Potentiometer and Bridge instruments Amplifiers, A to D converters, Computers	Static Magnetic	Low	Unshielded	Unshielded
				Medium	Unshielded	Unshielded
				High	Shielded	Unshielded
				Low	Shielded	Unshielded
				Medium	Shielded	Unshielded
				High	Shielded	Unshielded

Circuit conditions			Noise conditions		Recommended constructions	
Signal level	**Signal origins**	**Receiving devices**	**Type**	**Level**	**Single pairs**	**Cables pairs each pair**
AC voltages						
< 100 mV	Bridge circuits, Carrier” transducers	Potentiometers and Bridge instruments Amplifiers, A to D converters, Computers	Static Magnetic Common mode Crosstalk	Low Medium High	Shielded Shielded Shielded	Shielded Shielded Shielded
				Low Medium High	Shielded Shielded Shielded	Shielded Shielded Shielded
10 mV-10 V	Turbine flow meters, Tachometers	Potentiometers and Bridge instruments Amplifiers, A to D converters, Computers	Static Magnetic Crosstalk	Low Medium High	Shielded Shielded Shielded	Shielded Shielded Shielded
				Low Medium High	Shielded Shielded Shielded	Shielded Shielded Shielded
10 V-125 V	Annunciator pickup circuits	Potentiometers and Bridge instruments Amplifiers, A to D converters, Computers	Static Magnetic Crosstalk	Low Medium High	Shielded Shielded Shielded	Shielded Shielded Shielded
				Low Medium High	Shielded Shielded Shielded	Shielded Shielded Shielded
Current systems						
1–5 mA 4–20 mA 10–50 mA	Force balance, P/I transducers, P flow meters	Torque motors	Magnetic	Low Medium High	Unshielded Unshielded Unshielded	Unshielded Unshielded Unshielded
		Potentiometers and Bridge instruments Amplifiers, A to D converters, Computers		Low Medium High	Unshielded Unshielded Shielded	Unshielded Unshielded Unshielded
				Low Medium High	Unshielded Unshielded Shielded	Unshielded Unshielded Shielded

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6.6 Shield types—application guide

6.6.1 Foil shield

A foil shield should be chosen for protection against capacitive (electric field) coupling where shield coverage is more important than low dc resistance. A foil shield should be considered when possible sources of interference include TV signals, crosstalk from other circuits, radio transmitters, fluorescent lights, or computing equipment. Also, a foil shield should be considered for metropolitan area television (MATV), community antenna television (CATV), video, local area networks (LANs), computer cables in office industrial or commercial environments where ambient EMI levels are low or where FCC requirements need to be met [B7].

6.6.2 Braid shield

A braid shield should be chosen for superior resistance to diffusion coupling at low frequencies where low dc resistance is important, and to a lesser extent, capacitive and inductive coupling. A braid shield is effective in the following circumstances:

a) When possible sources of interference exhibit low impedance characteristics, such as motor control circuits and switches that operate inductive loads
b) For computer to terminal interconnects for process, instrumentation, or control applications

6.6.3 Spiral shield

A spiral shield should be chosen for functional shielding against diffusion coupling at low frequencies and capacitive coupling at audio frequencies only, under the following circumstances:

a) When possible sources of interference are power lines and fluorescent lights
b) For applications when flexibility and flex life are major concerns, such as microphone and audio cables and retractile cords

6.6.4 Combination shield

A combination shield should be chosen for shielding against high-frequency radiated emissions, coupling, and electrostatic discharge (ESD). This type combines the low resistance of braid and 100% coverage of foil shields. The combination shield is effective for the following:

a) When possible sources of interference include radio transmitters, TV stations, motor control circuits, and computing equipment
b) For video, CATV, MATV, FCC, LANs, computer cables, and computer-aided manufacturing applications

6.6.5 Overall shield

An overall shield should be chosen for power surges, or other transients and for protection against magnetic field (inductive) coupling [B8].

7. Grounding and installation

7.1 Introduction

Power grounding is for the purposes of electrical safety and to enhance the reliability and operation of electrically operated or supplied equipment within a facility. Signal grounding, on the other hand, is to assure “noise free” operation and reliability of the electronics system. Of greater importance, however, is the harmonizing of the safety and high-frequency grounding techniques so that electrical safety is not sacrificed in order to obtain satisfactory operation of the electronic system. The National Electrical Code (NEC) (ANSI/NFPA 70-1993) should be satisfied first; then, the signal grounding should be satisfied in a compatible way that does not undo the safety aspects of the installation. It is recommended that the system safety requirements be fully understood by all concerned with the design, and then the electronic requirements be overlaid onto the electrical safety basics, in such a way as to not diminish safety [B30].

7.2 Shield grounded at one end

This is a technique to handle low-frequency noise and may not be appropriate for high-frequency noise or noise due to transients. The shielding may be grounded at either the sending end or the receiving end. The advantages and disadvantages of each are described in 10.3.2 and 10.3.3.

7.2.1 Shield grounded at sending end

Grounding the overall shield of a cable or a shielded pair at the sending end eliminates the transient voltage on the cable due to the electric field. However, a different condition prevails for the magnetically induced potential. Grounding the shield at the sending end has no effect on the magnetically induced component.

7.2.2 Shield grounded at receiving end

Grounding the overall shield or a shielded pair at the receiving end again prevents the electric field from reaching the cable, eliminating the electric field component. For the magnetically induced component, the input capacitance is now the only circuit element between the voltage source and the cable. The capacitance between the cable and ground and the input capacitance forms a voltage divider. This arrangement reduces the surge voltage on the cable. The amount of reduction increases with cable length [B27].

7.3 Shield grounded at both ends

Here, for electric-field-induction, the displacement currents to the cable through capacitive coupling to the interference source are diverted to ground at each end and no transient voltage appears on the cable.

Grounding the shield at both ends completes a closed loop through the cable and ground mat system if the equipment or electronics at each grounded end are independently grounded. The magnetic field linking this loop induces a potential which in turn causes a secondary current to flow in the loop. The magnetic field due to this induced current opposes the primary field so that the net field in the loop is just sufficient to induce a potential drop related to the total resistive and reactive impedance around the current loop. This current flows axially along the shield of the cable. Therefore, there is only a small magnetically induced voltage between the cable and the shield at the receiving end.

With the shield grounded at two relatively greater in separation points, there is a risk that potential gradients in the ground mat system during faults may cause relatively larger shield currents to flow. Damage to the shielded cable may result if the shield is not a robust conductor. Therefore a heavier (thicker) shield (rather than a foil shield) is required. Use of an overall shield of corrugated 0.125 mm (0.005 in) copper or 0.2 mm (0.008 in) aluminum is usually sufficient to handle these surge currents [B4].

7.4 Transient protection with overall shields

When two electrical or electronic units are interconnected by a cable with the shield grounded at only one end, the load and source have an impedance to the common reference (usually ground). This establishes a “ground loop” between source and load, via the conductors, and the common “ground” reference. The common reference could be earth, and the example might represent wiring between two buildings. If a transient such as lightning causes fast changing electromagnetic lines of force to intercept the cable, then a current will be induced or coupled into all metallic portions of the cable except those open (ungrounded) at both ends, including the conductors and the shield(s).

The current induced into the inner conductors of the cable will be proportional to the loop impedance of each conductor, and it will be in the common-mode. This makes it difficult, for example, to detect and measure small differential currents with instrumentation connected line-to-line. In practice, the induced currents may be identical if they are common mode and very close in magnitude to one another because of similarities in loop impedances. The induced current is now capable of driving large surge currents into the source or load with the potential for destroying electronics connected to ends of the conductors.

A cable having an overall shield of sufficient thickness can be used to compensate for the induced currents in the conductors. For a cable with a shield that is effectively grounded at both ends, there is protection from the electromagnetic influence. (NOTE—Sometimes "bonded" is used to describe the grounding of the shield. Usually, the shield represents a lower total impedance throughout its length, and its impedance to the common grounding medium at either end is lower than that of the inner conductors. The shield must be grounded continuously over its length and at both ends so that there are no random paths established through the electronic components. With a lower loop impedance, the shield can develop a greater induced "noise" or surge current than the inner conductors. This condition is an advantage because as the shield carries more current, it also becomes another electromagnetic influence affecting the inner conductors. The result is a second induced current in the conductors from the current flow on shield. However, the induced current from the shield is opposite in phase to that induced by the original transient influence. Under these conditions, the inner conductors are confronted with two induced currents, but of opposite polarity. The result is a current in the conductor which is 180° out of phase with the noise current. As a result, the induced current from the shield cancels ("bucks out") the original surge ("noise") current in the conductors [B5].

The function of an overall shield is illustrated in figure 18. The transient magnetic fields from the interference current (I_m) induce a potential which causes transient current to flow in the shield (I_s) and conductors (I_c). Since the source of the shield current (I_s) and conductor current (I_c) was the same (i.e., the interference current), these currents are in phase. The shield and conductors are tightly coupled to each other in a parallel path over the entire length of cable. Therefore, the current flowing in the overall shield induces a second current (I_{sc}) into the conductors. I_{sc} is 180° out of phase with the shield current (I_s). As a consequence, this counter current nearly cancels out the interference current in the conductors. In order to handle the magnitude of current required to effectively cancel out the interference current, the cable needs an overall shield of 0.19 mm (7.5 mil) aluminum, 0.125 mm (5 mil) copper, or other overall shield or armor material as described in tables 1 and 2. The canceling or bucking action of the counter current is never exact but does result in a definite and significant reduction in net induced current. This discussion has assumed that the voltage reference of the control circuit is an external ground. If the control circuit instrument is referenced to the shield, grounding the shield at both ends can increase the interference current in the conductors.

Grounding techniques for overall shields and foil shields are discussed in more detail in 10.4.2.

The effect of an overall shield consisting of longitudinally formed plastic coated 0.19 mm (7.5 mil) aluminum on reducing the effect of transients was verified experimentally [B5]. A test circuit of instrument cable with two pairs of twisted conductors was pulsed with a 62.5 kHz, 50 kV, 8730 A oscillatory surge. The voltages measured to ground of the overall shield and the conductors for an open or grounded shield are listed in table 7. This data shows that grounding the shield at both ends substantially reduces the induced voltage on the conductors. If the overall shield is left floating, or grounded only at one end, it will not be a complete circuit like the conductors. Therefore, counter current to cancel the interference current in the conductors cannot flow. As a result, the control circuit is not protected from the transient. The data also indicate that the use of a twisted pair, or foil shield, is not sufficient to shield signal conductors from electrical transient.

To maximize the flow of this counter current, everything that affects current flow should receive close attention. In particular, electrical continuity of the shield, electrically stable connections of low resistance, and grounds with low resistance are necessary. For two separated areas sharing a common grounding path, it is possible to drive a current directly through this ground path. Under this condition, the shield is still lower in impedance and forms a path in parallel with the signal conductors that usually have a higher impedance. Therefore, most of the noise current flows in the shield circuit rather than in the signal conductor.

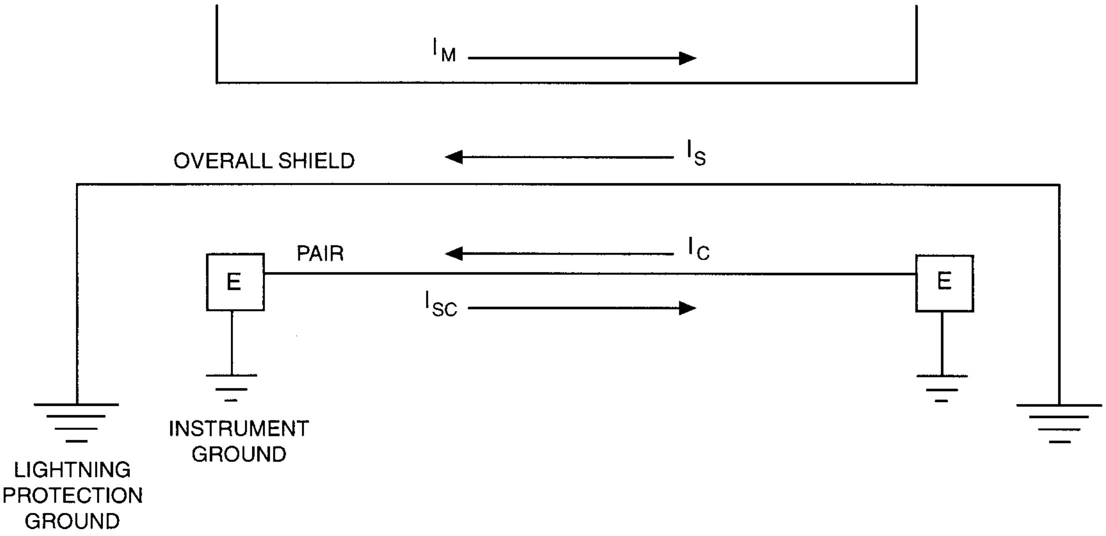

Figure 18—Performance of an overall shield during an electrical transient

Table 7—Effect of an oscillatory surge on bonded sheath cable with overall shield

Counter current (Amp)	Overall shield		Conductors*
	“A” end	“B” end	Induced voltage
0	Grounded	Open	2000
1400	Grounded	Grounded	50

*Twisted pair

Leaving the shield ungrounded (“floating the shield”) will negate the ability of the shielding system to cancel electromagnetically induced currents. Overall shields grounded/bonded at both ends still retain their electrostatic shielding ability as well as provide electromagnetic shielding [B30].

In the quasistatic model above, the shield is merely a low-impedance conductor that acts as a shorted turn to nullify the inducing magnetic field. In the electrodynamic model, the shield is a conducting surface that encloses the cable conductors. The shield excludes external electromagnetic fields and confines internal electromagnetic fields. (A perfectly conducting shield does this perfectly; no external fields penetrate to the internal wires, and no internal fields can be detected outside the shield.) Practical shields made of finitely conducting metals, perhaps with apertures, allow some fields to penetrate the apertures and diffuse through the metal. These fields can induce voltages and currents in the internal conductors. The external fields that drive the shield are the surface magnetic field associated with the shield current and the surface electric field associated with the shield voltage. These operate through the shield transfer impedance and the transfer admittance to induce the internal longitudinal (series) voltages and shunt currents, respectively. Good shielding is associated with small transfer impedance and admittance.

7.5 Grounding of cable with foil shields and overall shields

7.5.1 Grounding system

Grounding is applied first and foremost as a personnel safety protection device; second, as a means of limiting damage to equipment and cables; and third, for selective electrical system coordination (protection). The proper practice for modern plants is to provide single point grounding [B5]. A list of separate systems that may need to be connected to this ground is as follows:

a) Power system ground (system ground)
b) Instrument signal ground system
c) Computer signal ground system
d) Lightning protection ground system

Anywhere from one to four separate ground systems may be specified or designed. These systems use conductors to connect to each other and are grounded at one point to form a single point ground system.

The purpose of earth grounding is protection from lightning and transmission line ground faults, utilizing the earth as part of the return path for these currents. The grounding principle applicable for utilization voltages of < 600 V is not to use the “earth” as the current return path, but rather to use a system of interconnected conductors to equalize the voltage differences. This system can more effectively limit voltage differences than multiple ground connections.

For the transient and high-frequency interference control, the grounding system must be viewed as a possible interference distribution system. Transients injected onto the grounding system by power switching or other sources can propagate to all parts of the grounding conductors, including small-signal electronic circuits, that share the common grounding system. This can happen because the ground electrode has a surge impedance much greater than zero and the grounding conductors connected to it have surge impedances much less than infinity.

To prevent the grounding system from becoming an interference distribution system, the grounding must be coordinated with the shielding. That is, the local shield (equipment case, rack, shield room, or building) should serve as the grounding point for all circuits inside the shield, and grounding conductors should not penetrate any shield. This shielding and grounding topology is illustrated in figure 19, where the shield surfaces are shown as dashed lines and the grounding conductors are shown as solid lines. The shields are closed surfaces, and the grounding conductors are not allowed to penetrate the shield surfaces. The external ground is connected to the outside surface and the internal ground is connected to the inside surface. Thus, no transient or broadband interference waves are allowed to enter the protected space on the grounding conductor.

In particular, large transients generated outside the building (such as power switching transients or lightning) can be almost totally excluded from the sensitive integrated circuits inside the equipment case, since these waves are interrupted by several layers of shielding. Yet the safety requirements are satisfied, since within any shielded volume, all cases, racks, and equipment are grounded to the local shield structure. In addition, dc and 60 Hz fault currents can flow to actuate fuses and circuit breakers, since the shields are transparent to power frequencies.

The cable shield is a part of the shield system in figure 19—it is not a grounding conductor. For a subsystem, the shield may consist of two equipment cases interconnected by a shielded cable. The complete shield (the two equipment shields and the cable shield) should be closed by connecting the cable shield to the equipment cases at each end—preferably with a circumferential bond between the cable shield and the equipment shield. The pigtail connection is adequate only for audio frequencies; at higher frequencies its inductive reactance is sufficient to produce a significant discontinuity between the shielded parts. The electrostatic shield is also a special case that cannot be applied to transient and broadband shielding.

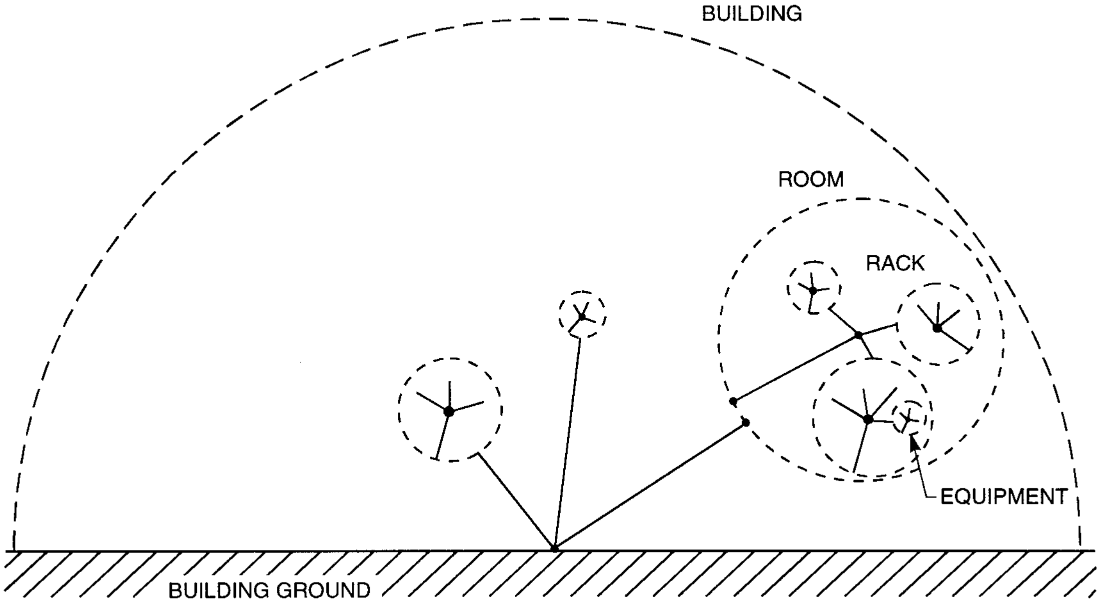

Figure 19—Zoned application of the single-point grounding method

7.5.2 Grounding cable with overall shield and foil shields

Figure 20 shows how an instrument cabling system may be grounds. Each pair of this cable has an individual shield of polyester/aluminum foil. A second foil shield of polyester/aluminum can be applied over the core. Typical foil thickness is .02 mm (.0085 in). An overall outer shield of .19 mm (.0075 in) aluminum, plastic coated with .05 mm (.002 in) of copolymer, is then applied over the entire construction. The foil shields are grounded at one end while the overall outer shield is grounded at both ends.

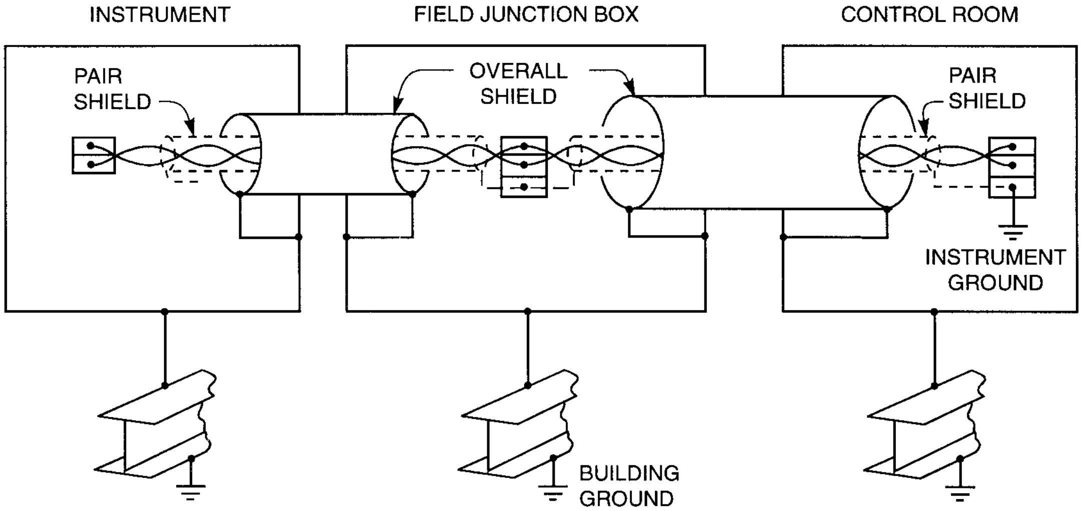

Figure 20—Grounding of an instrument cable system with twisted shielded pairs and overall shield

Polyester/aluminum foil shields over the cable pairs provide electrostatic (electric field) shielding to the cable. These shields should be grounded at only one end. The use of twisted pairs can provide a high level of protection against magnetic fields. The use of a relatively thick (0.20 mm aluminum or 0.125 mm copper) overall metallic shield grounded at both ends also provides both electrostatic protection and electromagnetic shielding to the cable conductors. The overall shield should be grounded at both ends to provide this electromagnetic shielding. The combination of shields properly grounded are the foundation for minimizing noise and voltage surges in instrumentation and control systems.

7.5.3 Termination practice for overall shield

Shield bonding connectors are electrical shield terminating devices that serve a very important function in the protection of instrument and control systems from electromagnetic interference. The primary function of the connectors is to pass shield currents associated with electrical interference from the cable shield to the equipment shield without allowing the electrical interference to enter the equipment. Therefore, electrical stability of the connectors is essential.

An evolution in the design of connectors has resulted in connectors suitable for cable with plastic coated or bare overall shields. These connectors do not require the jacket to be stripped when the jacket is bonded adhesively to the overall shield. The connectors are slipped, over both the jacket and overall shield, using small tangs to lock into the jacket and to penetrate the plastic coatings on the inner side of the shield. Sophisticated test requirements have been developed by the telecommunications industry to assure reliable performance of the connectors. Generally, the following types of tests should be passed successfully for acceptance:

a) Connector resistance
b) Environmental requirements—vibration, temperature cycling, hydrogen sulfide exposure, and salt fog exposure
c) Endurance tests—fault current and current surge

A common treatment of a shield at a connector is to insulate the shield with tape and connect it to the back shell of the equipment housing or case through a pigtail. The tail can introduce into the circuit an inductance of about 1000 nH/m, an inductance much higher than the transfer inductance produced by an equal length of overall shield. The shield current flowing through the inductance of the pigtail creates an interference voltage between the cable shield and the equipment case. It is important to keep grounding connections to the shield as short as possible.

For certain cables it may be possible to terminate the overall shield concentrically on the connector shell with no gaps in the circumference. When this procedure is followed, there is much less voltage introduced into the conductors for the following reasons [B22]:

a) Length of the path through which the shield current must flow is shorter
b) Field intensity inside the shield is nearly zero because the magnetic field is entirely external to the region occupied by the signal conductors (major factor)
c) Field intensity external to the shield is reduced by virtue of the inherently larger diameter of the path upon which the current flows (minor factor)

8. Shield testing methods

8.1 General

There are a variety of test methods for measuring the effectiveness of shielding. These methods may be broken down into those evaluating continuous wave egress and ingress and those evaluating cables with shields over twisted pairs. The former methods are well developed due to military and FCC requirements; the latter are not. These latter methods generally have been developed to show relative differences. They have been included in this guide to instruct the user and provide familiarity with what has been done. Both steady-state and transient test methods are reviewed.

8.2 Continuous wave test methods

8.2.1 Transfer impedance

The transfer impedance test is the most widely accepted, absolute measure of the performance of a shield. It evaluates cable shield performance in the frequency range of dc to 1000 MHz. This method is recommended by the military and the International Electrotechnical Commission (IEC). The formula for transfer impedance is:

$$Z_t = \frac{1}{I_o} \cdot \frac{dV}{dz}$$

where

I_o	is a longitudinal disturbing or interfering current introduced by a signal generator onto one surface (inner or outer) of the shield
$\frac{dV}{dz}$	is the longitudinal voltage per unit length generated by I_0 appearing on the opposite surface of the shield

This value of transfer impedance depends solely on the shield construction. Transfer impedance is measured in mΩ/m. The lower the value of transfer impedance, the more effective the shielding.

Each of the shield properties imparts a frequency-dependent characteristic to the shield transfer impedance. The transfer impedance relates open circuit voltage v induced (per unit length z) on an internal conductor to the total current I on the shield.

Solenoidal tapes produce transfer impedances of the form $jw\ L$ (where $w = 2\pi f$), with L an inductance that is much larger for solenoidal tapes than for braid wires. Apertures in braided wire and longitudinal tapes produce transfer impedances of the opposite sign: $-jw\ M$ where M is a mutual inductance. Diffusion through the shield produces a transfer impedance that approaches the dc resistance per unit length when the skin depth is much greater than the shield thickness, and decreases exponentially with the square root of the frequency when the skin depth is much smaller than the shield thickness.

8.2.2 Transfer admittance

The transfer admittance test should be used to measure capacitive coupling or electric field coupling in the high-frequency range (30–1000 MHz). The coupling data is extracted from measurements taken with the transfer impedance fixture.

8.2.3 Absorbing clamp

The absorbing clamp is an accurate, portable testing device that measures cable current. It can measure current in the frequency range of 30–1000 MHz. It is also nondestructive to the specimen.

The test fixture clamps over the sample cable and inductively detects leakage. By slowly moving it along the length of the sample, the detection device registers maximum values of current at the test frequencies in the desired range. These current values are then compared to the current of an unshielded sample of the same length as the cable under test. Shielding effectiveness is the difference between the two values in decibels, where the larger the value, the better the shield performance.

8.2.4 Transverse electromagnetic (TEM) cell

The TEM cell, also known as the Crawford cell, is a rectangular transmission line segment that operates in the TEM mode. Cables, cable/connector assemblies, and/or electronic devices are placed inside the cell. The item under test is subjected to a known field intensity provided by powering the cell. Alternatively, the cell can be used as a detector to measure radiation emitted by the cable or device inside the cell. The test is used mainly for devices or equipment.

Testing is done in a manner similar to the absorbing clamp technique, where the radiation from a shielded cable (or detection of powered cell field) is compared to that of an unshielded, similarly-constructed cable. The frequency range covered by this method is dc to 800 MHz. Shielding effectiveness is measured in decibels where higher readings represent greater effectiveness.

8.2.5 Antenna site

The FCC recommends the open field antenna site test method to determine compliance with FCC Docket 20780 [B18]. Recommended guidelines for testing are given in Docket 80–284 [B19].

The open field test site consists of a fiat concrete slab covered by a heavy wire screen to create a ground plane. A sample of cable is mounted on nonmetallic support poles and a movable antenna is used to detect radiated emissions from the cable.

Open field site measurements are conducted with a spectrum analyzer, tracking generator, and broadband or tuned antennas. To measure radiated emissions (egress), the antennas are used according to FCC guidelines. As with the Crawford cell, the test is used mainly for devices or equipment. Although not required by the FCC, the antennas may also be used to irradiate sample shield to measure ingress and thereby measure the susceptibility of the cable to radiated emission. The frequency range covered by this method is 30–1000 MHz. The antenna test measures electric field strength in µV/m vs. frequency. Lower readings are better.

8.2.6 Hum test

The hum test measures low-frequency shield effectiveness against electric field coupling (dc to 100 kHz).

A sample cable is inserted into a brass tube. Eight hundred volts are applied to the brass tube and the induced voltage, between the shielded conductor and ground, is measured in millivolts (mV). The voltage induced shows the shield effectiveness at the applied frequency. The smaller the induced voltage, the more effective the shield. Noise pickup is measured in millivolts.

8.2.7 Electrostatic discharge (ESD) test

This standard test procedure consists of a fixed sample cable length and a high voltage discharge source. The static discharge is applied to an ungrounded shielded termination, resulting in a surge current produced along the length of the sample. A specially designed fixture creates an air discharge in a one-shot fashion to develop the needed discharge waveform. The discharge characteristics are the same as those exhibited by the IEC human body model.[9]

---

[9] International Electrotechnical Commission, Working Group 4 of IEC Technical Committee 65.

The components of the ESD event contain high-frequency energy requiring a very broadband oscilloscope to observe the voltage induced across the shield to the center conductor circuit of the sample under test. The smaller the induced voltage measured the more effective the shield.

8.2.8 SEED

Developed and patented by Belden Wire and Cable Co., Patent No. US3839672, The Shield Effectiveness Evaluation Device (SEED) [B38], allows highly repeatable, comparative testing of shield performance. Both coaxial and multiconductor shielded cables can be evaluated [B7].

The SEED test device is a coaxial fixture, 5 ft in length, consisting of two concentric copper tubes forming a 50 Ω characteristic impedance.

A sample cable is terminated in its characteristics impedance and inserted inside the inner tube (conductor) of the fixture. Powered by a known signal level, the sample leaks a signal. The inner conductor of the fixture picks up this signal. The difference between the incident signal and that leaked by the sample is the resultant shielding effectiveness of the cable sample.

The military uses SEED. NEMA WC-61-1992 uses SEED for evaluating shield effectiveness.

8.2.9 Comparison chart

Figure 21 provides a test method comparison chart for the previous test methods [B7].

8.3 Testing of overall shield for single or multiconductor cable

There have been numerous attempts to study the shielding effectiveness of overall shields on low voltage cable. This clause describes various tests reported in the literature. In most cases, these tests are not standardized test methods. However, they do provide data that characterizes the effects of different materials in the shield, and different shield thicknesses. This data is included in the guide because it is the best available, and also to provide the user with familiarity on what has been done to characterize the shielding effectiveness of overall shields.

8.3.1 Gooding and Slade method

The Gooding and Slade method for measuring the effectiveness of overall shields in multiconductor (twisted pair) cable is shown in figure 22 [B23]. This method uses a flat rectangular loop of No. 19 AWG copper wire, 2.5 cm on centers, mounted coplanar with a 1 m long length of 300 Ω TV lead standard copper conductors spaced 6.75 mm (0.266 in) apart [B40]. The separation between the nearest wires of the two loops is 2.5 cm. The slots in the plate were such that the cylindrical shield under test will slip over the TV lead. This test measures the shield under the conditions of electromagnetic interference. The voltage induced in the TV lead is a differential mode voltage. The disturbing loop connects to a source of variable frequency power and the TV lead connects to a tuned voltmeter (see figure 23). The current in the disturbing loop is constant at 1.5 A from 60–150 kHz. The maximum current available at 150 kHz from the power source establishes the current value. The current waveform, monitored by an oscilloscope, is sinusoidal.

The ratio of the voltage (V_2) induced in the twin lead with a shield to that of the voltage induced without a shield (V_1) measures the shield effectiveness (V_2/V_1).

NOTE — Shield effectiveness by this method may be different from shield effectiveness defined by other methods.

For the Gooding and Slade method the terms of shielding effectiveness (SE) in dB where SE is given by:

$$SE = 20\log\frac{V_2}{V_1}$$

where

V_2 is voltage with shield present
V_1 is voltage without shield

Problems Anticipated	Transfer Impedance	Absorbing Clamp	TEM Cell	Antenna Site	Hum Test	ESD Test
EMI Types						
ESD	■					■
Electric Field Coupling			■		■	
Radiated Emissions Coupling	■	■	■	■		
Frequency Range						
dc–100 kHz	■		■		■	■
15 kHz–30 MHz	■		■			■
30 MHz–120 MHz	■	■	■	■		■
120 MHz–800 MHz	■	■	■	■		
800 MHz–1000 MHz	■	■		■		
Cable Performance Against						
Egress	■	■	■	■		
Ingress	■	■	■	■	■	■

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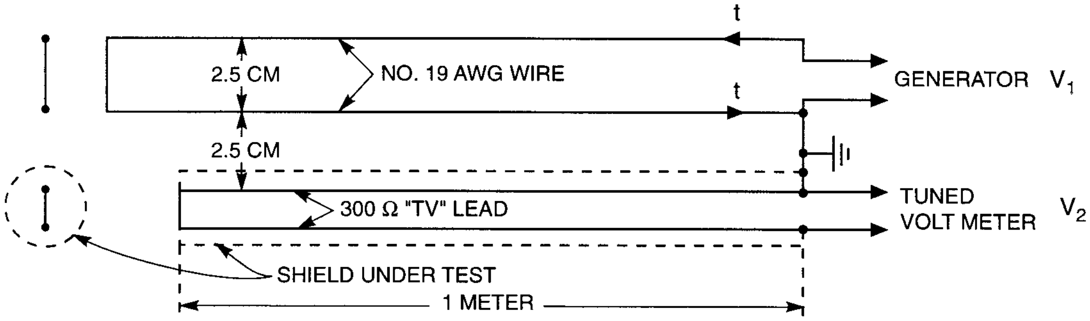
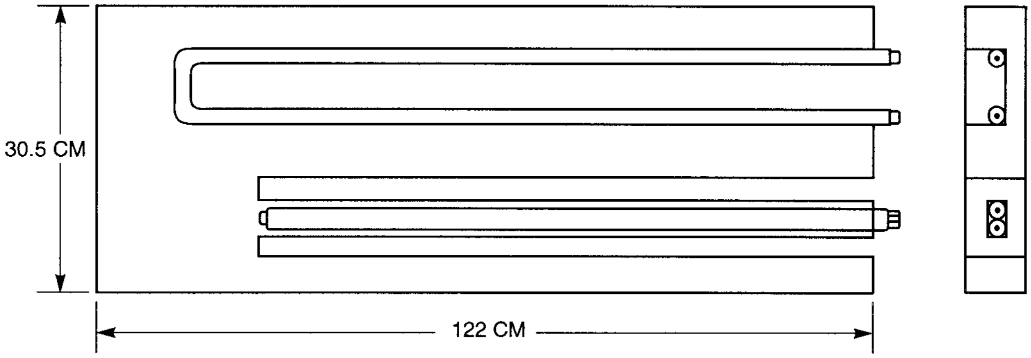
Figure 21—Test method comparison chart



1 A SCHEMATIC



1 B JIG

Figure 22—Circuit and jig, Gooding and Slade method

8.3.2 Reduction factor method

The reduction factor method, in its recommended configuration, is shown in figure 24. This test method is based on German Standard VDE 0472/3.69 [B11]. The intention of this system is for use with short duration excitation currents as high as 1000 A to simulate fault conditions. This requires a 1/0 AWG conductor. The loop is 19 AWG wire and a current level of 1 A is maintained.

The connection of the earth return circuit to the cable shield and its armor must be made very carefully. It is important to uniformly solder the connections around the circumference of the shields. This is not easily achieved with complete cable samples since damage is possible. Because this method is sensitive to the method of connection, the measurement is unfortunately not a measure of the shield alone. It is also very important that the physical layout of the system remain constant during the tests.

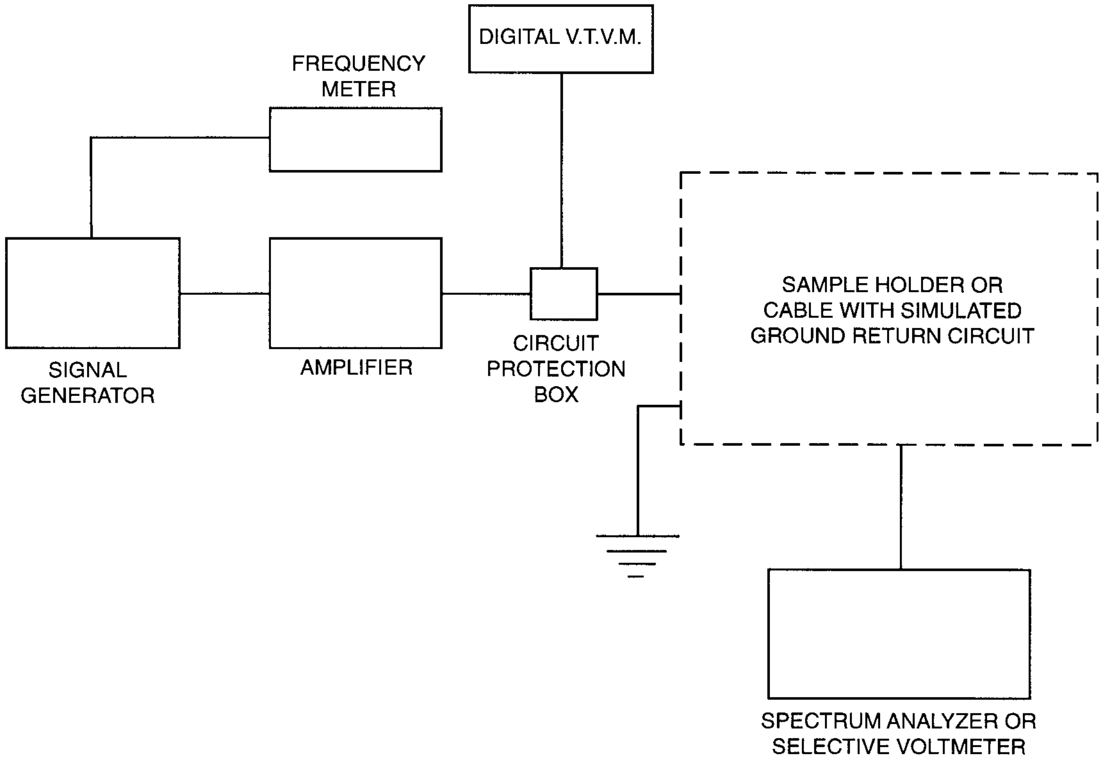


Figure 23—Apparatus connection scheme for measurement of shielding effectiveness

The reduction factor is a measure of V_2/V_1, where V_2 is the voltage between one of the core conductors and the shield, and V_1 is a measure of the excitation. Thus, this factor is a common-mode measurement only. This test could, of course, be modified to use a single, standard conductor instead of one of the cable conductors.

The reduction factor *rk* is determined by:

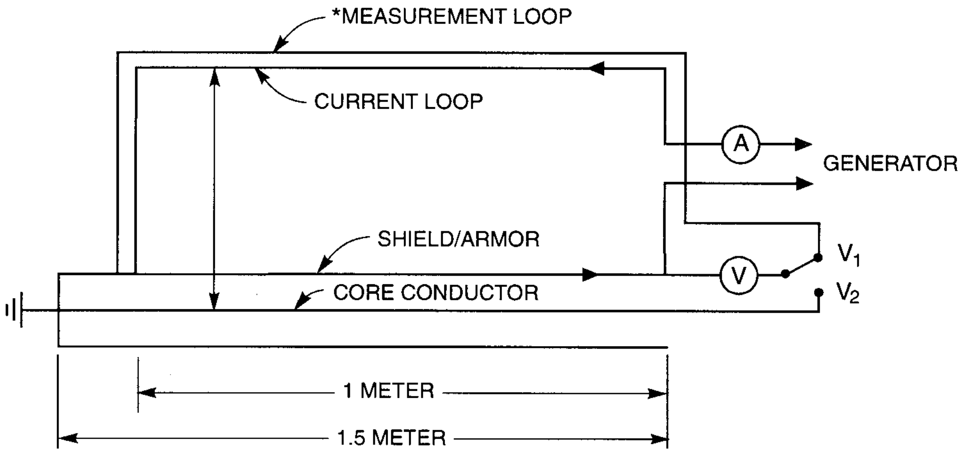
$$rk = \frac{V_2}{V_1}$$

where

V_2 is voltage between cable sheath and the measuring loop wire
V_1 is voltage between the core conductor and cable sheath

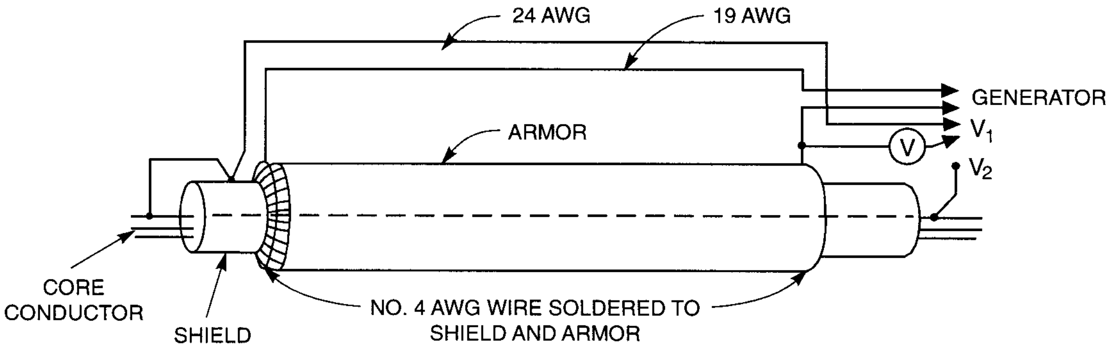
Values of the reduction factor will range from zero for a very good shield to almost unity for a very poor shield. Unity indicates that the excitation voltage is equal to the induced voltage on the signal-carrying conductors.

The reduction factor for a non-ferromagnetic shield is practically independent of the primary field strength. In contrast, with magnetic materials, the reduction factor decreases with increasing field, reaches a minimum, and then increases as the shield becomes magnetically saturated. This condition applies only for fault currents.



* THE CURRENT AND MEASUREMENT LOOP ARE MADE OF
NO. 1/0 AWG STRANDED WIRE (19 STRANDS).
1 STRAND OF WIRE IS REMOVED AND REPLACED WITH AN
INSULATED CONDUCTOR TO FORM THE MEASUREMENT LOOP.
LOOP HAS AN INDUCTANCE OF ≈ Z mH/km AT 60 Hz.

SCHEMATIC



CABLE PREPARATION

Figure 24—Reduction factor method

8.3.3 Lightning susceptibility of buried cable

This is a test of the ability of a cable to withstand large injected currents, such as a direct lightning stroke might produce. The test method has been standardized by the Electronics Industries Association/Telecommunications Industries Association (EIA/TIA) as EIA/TIA 455-181 (FOTP-181). This test method is targeted towards fiber optical cable, but has been used for cables with metallic conductors. The lightning susceptibility test uses a wooden box having internal dimensions of 0.75 m × 0.75 m × 1.2 m (30 in × 30 in × 30 in). The test medium is saturated and drained 20–40 mesh sand (specific gravity when dry approximately 1.70).

The cable specimens are approximately 1 m in length with all metallic members (such as core conductors and shields or armor) electrically shorted together at each end. A specimen is horizontal in the test box and the sand medium firmly tamped around it. The ends of the specimen extend outside the box. The sand medium is in a saturated and drained condition, especially in the region between the electrode and the specimen. The discharge electrode is near the center of the test box and is 25 – 0+2 mm (1 in) from the cable specimen. One terminal of the pulse generator connects to the electrode; the other terminal connects to the metallic members at both ends of the specimen. The specimen is appropriately treated to ensure that the discharge to the metallic members occurs at a point directly facing the electrode. For example, if the cable has a metallic shield covered by a plastic jacket, a slit or hole is made in the jacket facing the electrode. The slit or hole is as small as possible with a minimum removal of jacket material.

The test current is a damped oscillatory waveform with a time-to-peak value of 15 µs or less and a frequency no greater than 30 kHz. The time-to-half value of its envelope is from 40–70 µs. These values apply to the waveforms measured with a test specimen in place. The test method evaluates cable performance at three levels of current: 55 000 A, 85 000 A, and 110 000 A. The voltage level is generally determined by the equipment used and can be in the range of 10 000–50 000 V. After removal of the sample from the test box, the continuity of the shield and conductors is checked.

9. Characterization of shielding

9.1 General

A shield is used on a cable to contain any unwanted radiation or to keep out unwanted interference. Shielding performance can be characterized by the various test methods described in clause 10.4.6. Shielding effectiveness measurements should be made under controlled temperatures, and over the range of expected cable operation [B42].

9.2 Shielding properties

The purpose of a shield is to exclude electromagnetic fields from a volume or confine them to a volume. The cable shield excludes the fields from the signal conductors or keeps the fields produced by the signal conductors from contaminating the region outside the shield. (Hereafter, only the excluding function will be discussed.) The external electromagnetic fields of importance in the cable shield case are the magnetic field encircling the cable (related to the shield current) and the electric field perpendicular to the shield surface (related to the shield voltage or charge density).

The properties of the cable shield that affect its ability to exclude electromagnetic fields and their associated currents and voltages depend on the shield material and construction. These properties are as follows:

- Conductivity and permeability of the shield material
- Thickness and diameter of the shield
- Size and density of the apertures in the shield
- Off-axis current direction imparted to the shield current by the construction (such as braid stranding or tape windings) of the shield

The inherent properties of the shield are defined by the transfer impedance and the charge transfer frequency. (The charge transfer frequency is related to the transfer admittance.)

The performance of a shielded cable in a system will depend on many other factors: its length, terminal impedance of signal conductors, shield terminations, as well as the inherent properties of the shield. Shielding effectiveness may be used to measure this performance. Shielding effectiveness is the ratio, expressed in decibels, of the current at some point on a core conductor (say at one end) with the shield removed to the current at the same point with the shield installed. Both currents are induced by the same CW source outside the shield. Shielding effectiveness depends on the terminating impedances of the core conductors, the location at which the current is measured, and many other factors in addition to the properties of the shield.

9.3 Architectural shielding effectiveness

Architectural shielding effectiveness can be a measure of the ability of a material by itself to prevent propagation of electromagnetic energy [B44]. Architectural shielding involves surrounding an area with a continuous, electrically conductive enclosure. This information is provided for background. It should be noted that the analysis applies to materials as an infinite plane and not as a closed three-dimensional shield. From a material point of view the analysis provides insight into the shielding performance of aluminum, copper, and steel.

This type of analysis usually is applied to electromagnetic shielding of buildings, facilities, and equipment. It relies on material properties to provide the shielding. Since discussions of this type of shielding are so prevalent in the general literature, this clause is included to provide some understanding of basic shielding terminology and methodology of shielding calculations for enclosures.

The factors contributing to shielding effectiveness of a material are illustrated in figure 25 and the following formula:

$$SE = R + A + B$$

where

SE	is shielding effectiveness, dB
R	is $R_1 + R_2$ = reflected power, dB, at the first and second boundaries
A	is absorbed power loss, dB, through the material
B	is degradation factor, dB, caused by multiple reflections in the material

The B term may be either plus or minus but may be neglected if $A > 10$ dB. Where $A < 10$ dB, the shield is considered electrically thin and either a different or a thicker material should be considered. R may also be positive or negative, but is always positive above 1 kHz.

Since reflection losses for magnetic fields are small for most materials, magnetic shielding depends on absorption losses or the formation of a counter current to “buck” the current included by the magnetic field (see 10.4.1). Electric fields, however, are easily reflected by metal shields, and reflected losses dominate. Since openings in the shield decrease shielding effectiveness, great care should be taken in designing enclosures where high-frequency radiation is present. Table 8 shows the change in absorption loss from 60 Hz to 10 GHz for copper, aluminum, and iron.

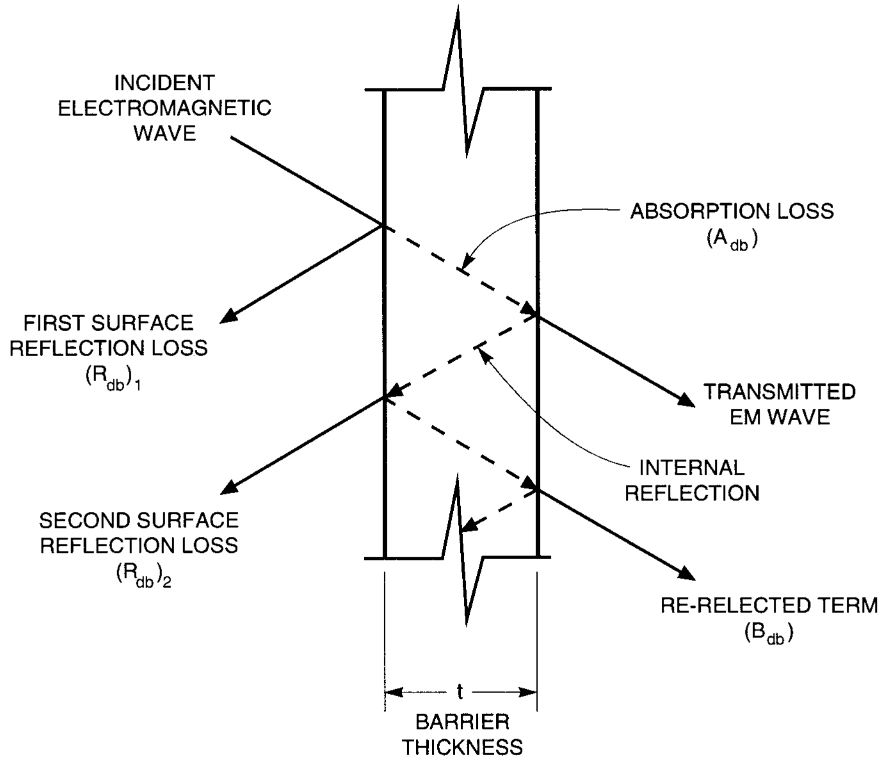


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Figure 25—Factors contributing to total shielding effectiveness

Table 8—Absorption loss of solid copper, aluminum, and iron materials at 60 Hz to 10 000 MHz

	Copper		Aluminum		Iron		Absorption loss, db/mil		
Frequency	**G**	**H**	**G**	**H**	**G**	**H**	**Copper**	**Aluminum**	**Iron**
60 Hz	1	1	0.61	1	0.17	1000	0.03	0.02	0.33
1000 Hz	1	1	0.61	1	0.17	1000	0.11	0.08	1.37
10 kHz	1	1	0.61	1	0.17	1000	0.33	0.26	4.35
150 kHz	1	1	0.61	1	0.17	1000	1.29	1.0	16.9
1 MHz	1	1	0.61	1	0.17	700	3.34	2.6	36.3
15 MHz	1	1	0.61	1	0.17	400	12.9	10.0	106.0
100 MHz	1	1	0.61	1	0.17	100	33.4	26.0	137.0
1500 MHz	1	1	0.61	1	0.17	10	129.0	100.0	168.0
10 000 MHz	1	1	0.61	1	0.17	1	334.0	260.0	137.0

9.4 Transfer impedance

Figure 26 presents the transfer impedance frequency characteristics of typical shields used in electronic cables. The characteristics of stainless steel and copper solid wall tubing “ideal” shields are included for comparison purposes [B52].

Note that the copper solid wall tube has a significantly lower transfer impedance than the same thickness stainless steel tube. In the low-frequency range, no skin effect takes place so the shield transfer impedance does not change with frequency. However, the attenuation of the shield to EMI increases with frequency as the skin depth increases, and the rapid decrease of the transfer impedance of the shield reflects this. This is not true for braided, spiral, or foil shields. In regard to figure 26, it should be noted that at some frequency transfer impedance increases rapidly.

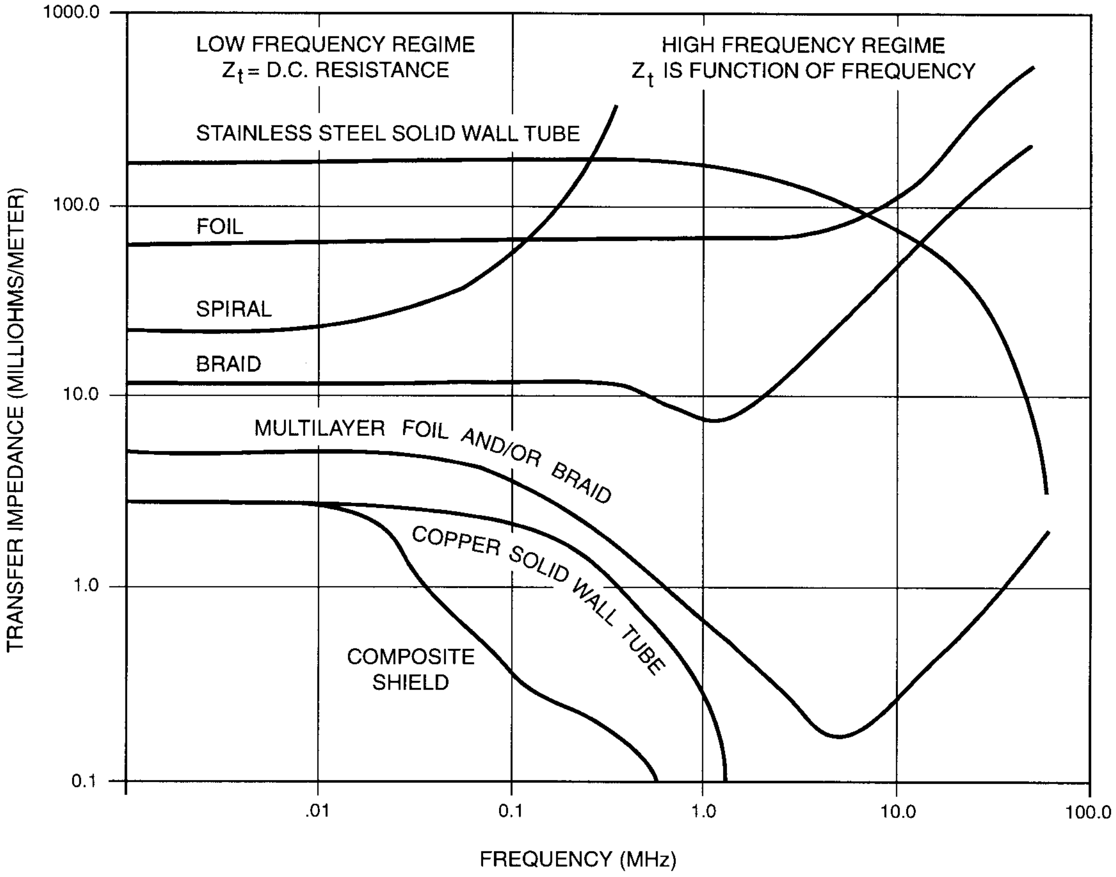

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Figure 26—Transfer impedance

When evaluating the shielding efficiency of these shields, four parameters have to be taken into account: thickness, conductivity, application method (such as winding angle), and coverage. Since the foil shields are thin (for instance, the typical thickness of the aluminum layers is 0.35 mil) their dc resistance is high. Thus, the skin effect is not noticeable until higher frequencies (5–10 MHz) are encountered. Since foil shields are usually wrapped longitudinally about the signal conductors, they provide 100% coverage. It might be expected that the shielding effectiveness of the foil shield would be equal to the dc resistance up to 5–10 MHz and then decrease like a solid wall tube ideal shield. Experience shows that at higher frequencies the foil shield becomes less effective. The cause of this shield effectiveness degradation is the overlap or slot of the foil shield. (Of course, gaps in the shield are to be avoided in order to obtain 100% coverage.)

It should be noted that in figure 26 the shielding effectiveness of a composite shield consisting of an electric (33 AWG, 95% braid, tinned copper), magnetic (33 AWG, 90% braid, tinned copper covered steel), and overall shield (0.19 mm [0.0075 in], copolymer coated aluminum tape, longitudinally folded) exceeds that of the copper tube (IEEE Std 789-1988). Although all three shields have slots or gaps, the combination is more effective than a solid tube.

9.5 Shielding effectiveness of overall shield

Figure 27 was developed using the Gooding and Slade method and provides information on performance of an overall shield in screening out magnetic fields on a twisted pair [B23]. The amount of voltage induced on the pair of signal conductors as a function of the current in the disturbance is used to measure the efficiency of the overall shielding system. First, it can be seen in figure 27 that 0.125 mm (0.005 in) copper longitudinally folded nearly matches the performance of a lead sheath. Second, only the steel braid (or steel tape) is effective below 20 kHz. The 0.125 mm (0.005 in) copper, which is electrically equivalent to 0.20 mm (0.008 in) aluminum, is much more efficient than the 0.10 mm (0.004 in) aluminum tape. The combination of copper tape (or braid) and steel braid (or tape) is the most effective shield, even at audio frequencies.

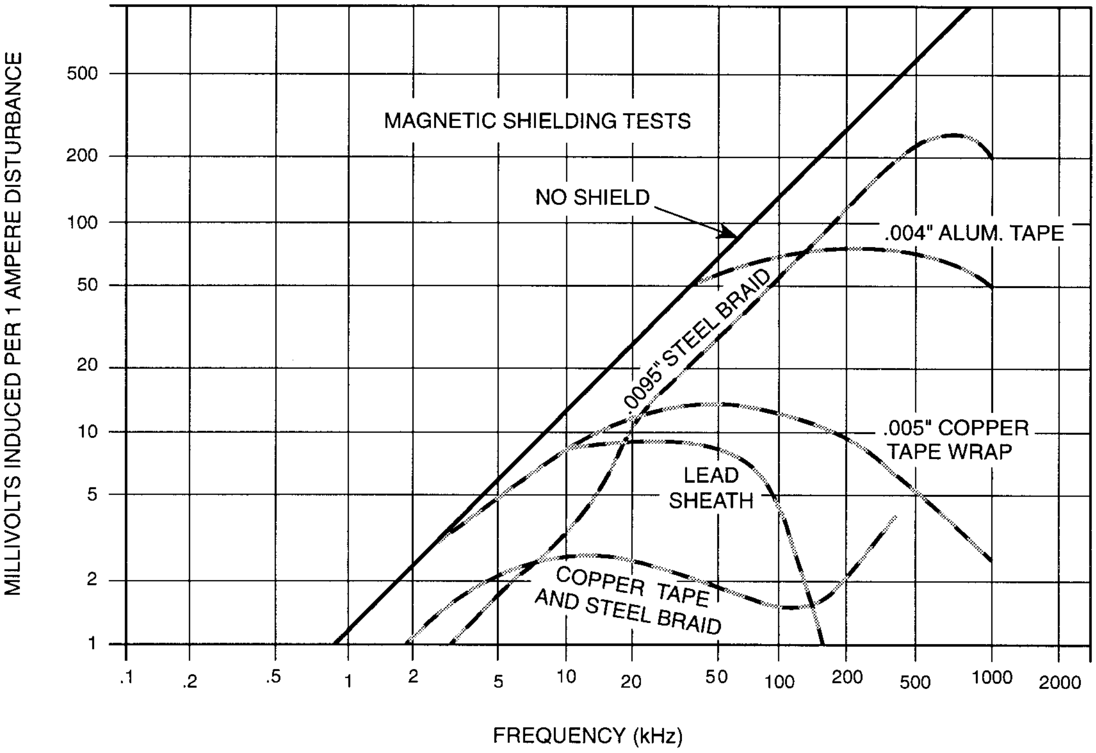

Figure 27—Efficiency of various types of overall shield in screening out magnetic fields on insulated conductors

Figure 28 was developed using the Gooding and Slade method (see 11.8) to compare the shielding performance of a dual shielding consisting of a shied/armor of 0.155 mm (0.006 in) steel and 0.20 mm (0.008 in) aluminum vs. a single 0.20 mm (0.008 in) aluminum shield [B17]. Combining aluminum and steel into a dual shielding system provides significantly better shielding at lower frequencies than the single shield. This is due to the ferromagnetic nature of the steel as well as the added conductivity of the steel. The shield factor for the non-ferromagnetic aluminum shield is practically independent of primary field strength. In contrast, with the magnetic steel, the shield factor decreases with increasing field strength.

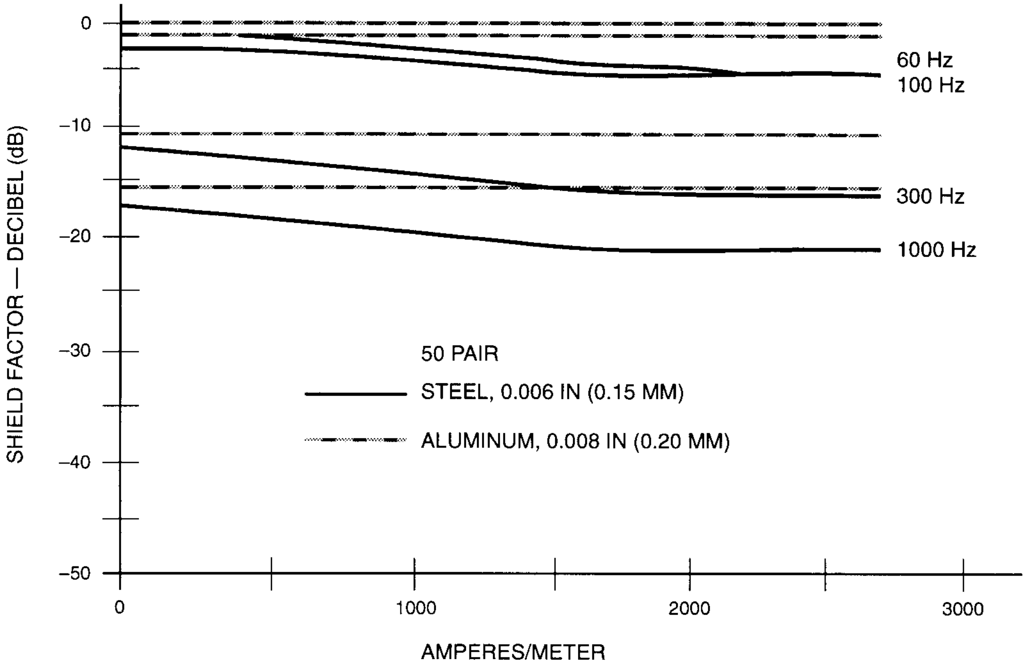

Figure 28—Shield factor of overall shield of aluminum or composite overall shield of aluminum and steel for protection of insulated conductors

9.6 Reduction factor with overall shields

The reduction factor method was used to examine the effectiveness of various shields/materials to protect an insulated conductor. Figure 29 shows the performance of 0.150 mm (0.006 in) copper alloy 194, 0.19 mm (0.0075 inch) coated aluminum and 0.150 mm (0.006 inch) a bimetallic of copper and stainless steel (0.002 inch copper/0.002 inch 430 stainless steel/0.002 inch copper). The performance of these three shielding materials is essentially the same [B40].

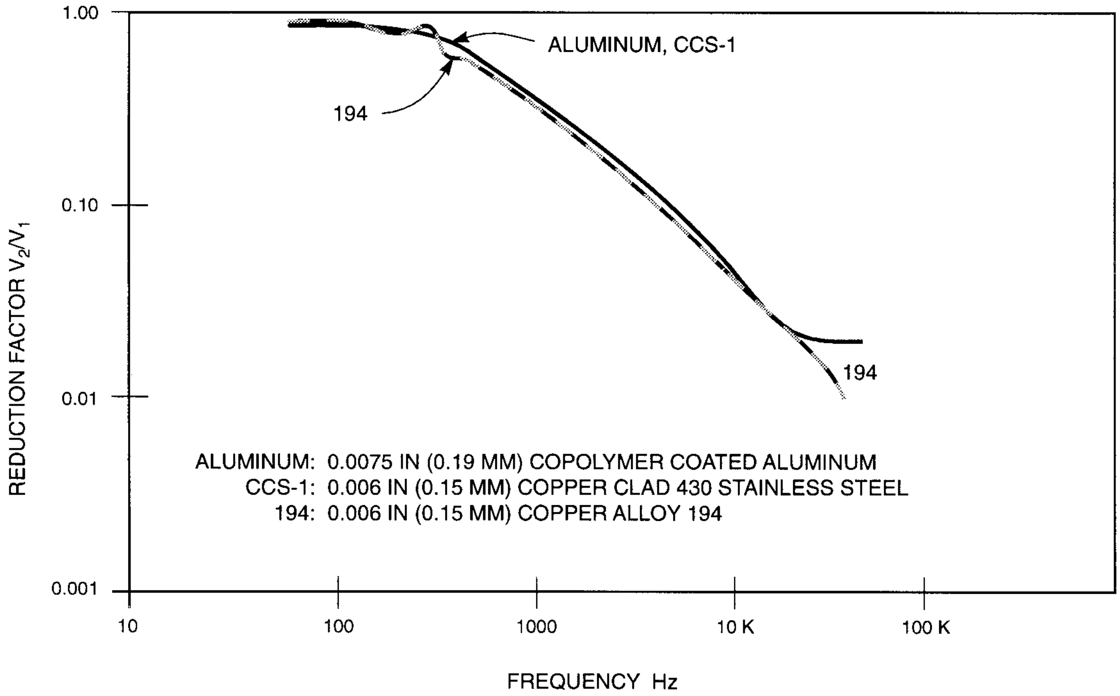

Figure 29—Reduction factor on insulated conductors for cables with overall shield

9.7 Transient (lightning) protection by overall shields

The lightning simulation test (see 11.8.2) can be used to gather information on the response of overall shields in protecting the core of a cable with twisted pair conductors [B21]. Figure 30 shows the potential difference in kV per kA as a function of cable length. A higher voltage per kiloampere was developed for non-magnetic materials such as aluminum, copper, or stainless steel lower voltages for the same levels of current for composite shields containing aluminum or copper and low carbon steel.

Overall shields of 0.125 mm (0.005 in) bare and coated copper, 0.19 mm (0.0075 in) bare and coated aluminum, and 0.155 mm (0.006 in) steel have been shown to be capable of handling longitudinally applied currents from a simulated lightning stroke up to 100 000 A [B4].

The heat and shock wave associated with discharge of a simulated lightning stroke to a cable in soil are important considerations in designing shield mechanical properties—just as electrical properties enter into the requirements for performance in a lightning or transient environment [B20]. In addition, the core construction is also an important element of cable design with respect to lightning resistance of a complete cable.

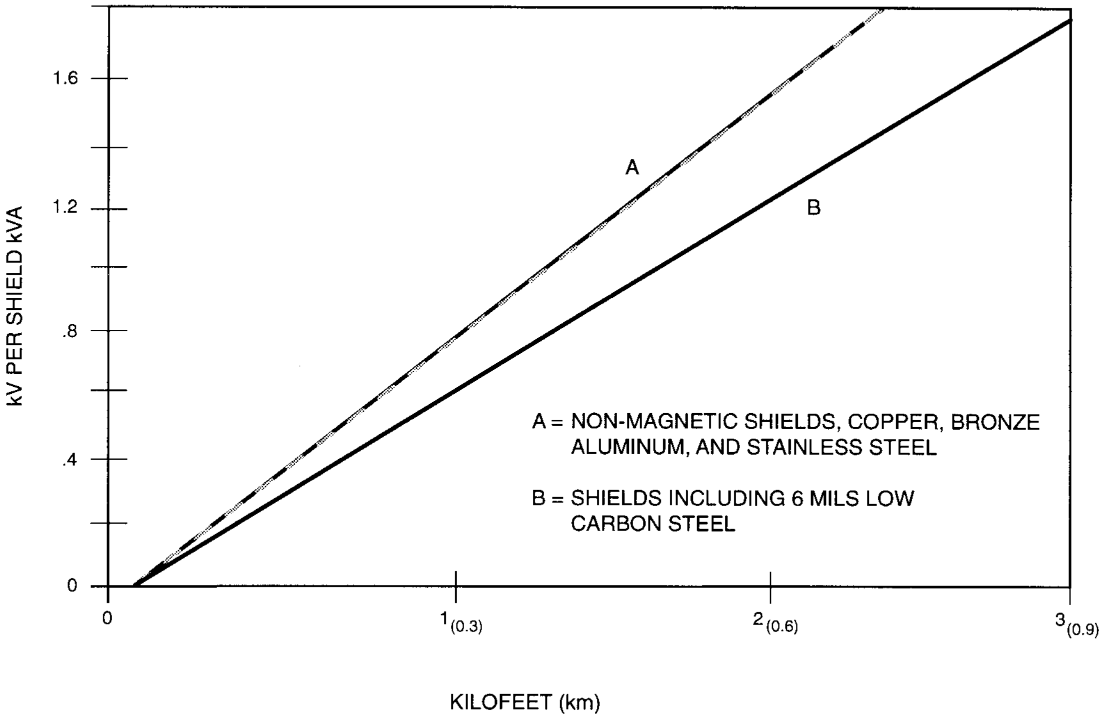

Figure 30—Conductor to shield potential for cables having shield resistance of 1Ω per kilofoot (0.3 km)

9.8 Aging effect on shielding

This aspect of shielding has not received extensive study. The two major factors affecting the characteristics of shields are oxidation and moisture.

9.8.1 Oxidation of shields

In figure 31, the effect of oxidation of the shield, after aging of the cable occurs, is shown by curves for a coaxial television drop wire with a longitudinally-folded, overlapped copper tape as outer conductor and covered with a copper braid [B35]. The curves shown were measured on the same sample: One as a new product, the other after a few days in a hot moist air oven. The layer of oxide that formed between the faces of the overlap was sufficient to change the shielding characteristics from the desirable curve (dropping with frequency) to the undesirable one (rising with frequency), representing an incomplete shield. This effect was previously noted in the field. A marked rise in radiation level was found near a length of cable with a damaged outer protective jacket. Exposure to the atmosphere allowed oxidation of a short length of shield.

9.8.2 Moisture penetration into cable core

In this test, samples of standard coaxial cable with a jacket and the same type of cable with a coated 8 mil aluminum moisture barrier were energized at 600 Vac 1000 Hz and continuously immersed in 75 °C water for several months [B6]. The insulation resistance was periodically determined. Insulation resistance (*IR*) is calculated by measuring the leakage current through the insulation from the conductor to the water at ground potential. Since the applied voltage is known, the insulation resistance may be determined from Ohm's law.

Table 9 shows that the jacketed cable developed a sudden decrease and fluctuation in insulation resistance after five weeks, suggesting dielectric deterioration. The moisture barrier cable had no change in insulation resistance through the duration of the test. The moisture barrier layer effectively blocked the penetration of moisture vapor into the dielectric system.

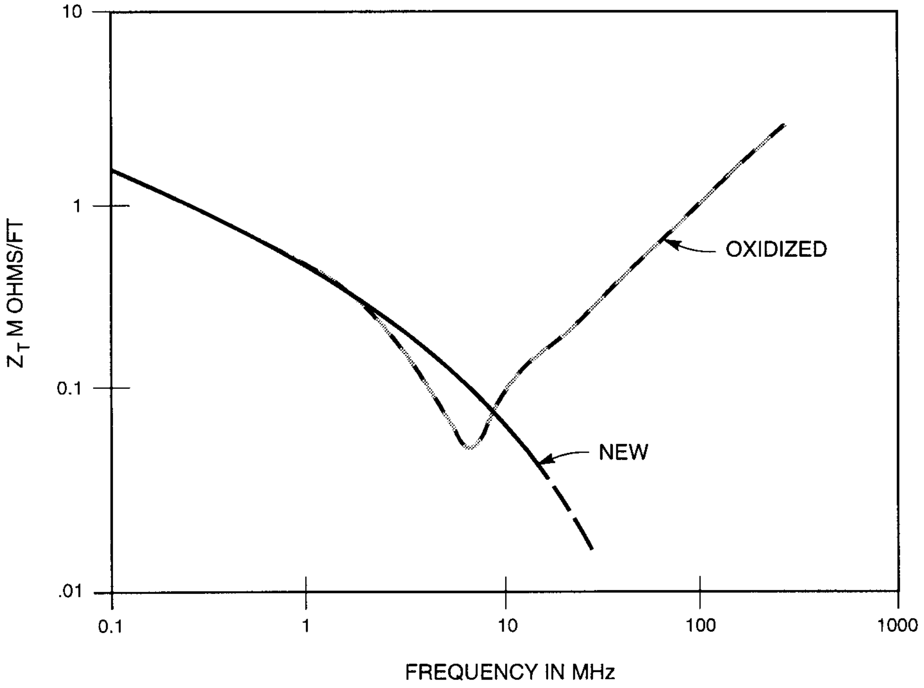

Figure 31—Transfer impedance of 59 type cable (shield = overlapped copper tape and copper braid)

Data source: Filtron/RFI Corporation, *EMI Engineering Guide* [B16]. Reprinted with permission.

Table 9—Long-term moisture resistance

Time	Insulation resistance (MΩ—1000 ft)	
	Jacketed	Moisture barrier
Initial	80 000	80 000
3 weeks	80 000	80 000
5 weeks	5700	80 000

9.8.3 Degradation of drop cable in service

Aging is also thought to be a result of aeolian (wind) flexure (this deduction is based on a visual observation of cable). "Galloping" is commonly observed if the wind is preceded by wet snow buildup on the cable. Accordingly, laboratory flexure tests simulating the aeolian flexure are used to age a cable, allowing prediction of performance for varying years of service. Field data have been correlated with laboratory flexure test results, showing that the laboratory evaluation of drop cable allows prediction of performance at any point in time after installation [B46].

Fifty drop cables were removed from cable systems and approximately 230 tests were performed on the samples. Cables were selected to confirm that the cable performance reported was typical for the same type manufactured in general by industry and to obtain performance for varying years in service. The shielding was evaluated using transfer impedance of the coaxial shield, The typical transfer impedance of drop cable with an aluminum foil and braided shield is shown in figure 32. Two curves are presented: Before installation in a system, and after 10 years in service. The maximum transfer impedance and maximum degradation occurs at the highest frequency. The degradation of the cable can be shown by plotting the 300 MHz transfer impedance vs. years in service.

The degradation of drops, whose shields are aluminum-plastic-aluminum laminate foil tapes without an adhesive and an aluminum braid, is shown in figure 33. The points plotted are actual measured performance. The solid curve, which is a reasonable average of these data points, is the average performance obtained from laboratory flexure (aging) tests using a correlation of 15 000 flexure cycles/year-in-service. This correlation is used for all aging tests. The cables are flexed at a rate of 40 cycles/min. One flexure cycle is ±8° of travel. This test simulates flexing caused by the wind. The severity of degradation could change with temperature. Therefore, the degradation vs. time could vary in geographical areas where the prevailing wind and/or temperature is substantially different from the areas evaluated.

The typical 300 MHz performance of the different types of drop cable is shown in figure 34. The curves are based on the flexure test using the average of cable from a number of cable manufacturers. There are essentially three types of drop cable shields in use.

1) Braids
2) Laminate foil tapes with a braid adjacent to one side of the tape and in metallic contact
3) Laminate foil tape with a metallic sheath adjacent to both sides of the tape and in metallic contact

The effect of flexing in the wind is simulated vs. the effect of aging. Adding aging effects may provide additional degradation.

Two 80% optical coverage braids are inferior to all constructions in transfer impedance and therefore shielding effectiveness. Two 96% copper braids significantly improve shielding. These braided shields have less degradation with flexing than the constructions using foil-braid shields. The extra cost of two 96% copper braids resulted in the advent of laminate foil tape-braid shields. The constructions with one foil and one braid have significantly lower or similar initial transfer impedance to two 96% copper braids, but they have higher degradation in service resulting in poorer shielding. The use of an adhesive foil decreases the degradation. The foil is adhesively bonded to the dielectric in the core. Single foil constructions using up to 95% braid coverages can be used, but the slight improvement in performance does not warrant the increased cost. Adding a second laminate foil tape over the braid significantly improves the initial performance (before installation in a system); however, this cable has very high degradation in service. Therefore, the net result is small improvement. Use of dual foil-braid construction initially results in lower shielding, but degradation in service is less. Adhesive foil-braid and foil-braid have the best overall performance, but more costly shield constructions may result.

A third drop cable type was introduced to significantly improve the shielding without a substantial increase in cost. The concept employed to improve the shielding and minimize the degradation in service was trapping a laminate foil tape between two braids. The two round wire braids electrically short circuit any openings in the tape, thereby eliminating or minimizing the electromagnetic coupling through the opening. This significantly decreases the transfer impedance, improving the shielding (a significant decrease in RF leakage). The drop cable that has two laminate foil tapes under a braid falls into this category (i.e., trapping a tape between two metallic sheaths). However, the metallic tape does not short circuit the openings as well as the round wire braid. This cable was considered the second best drop evaluated.

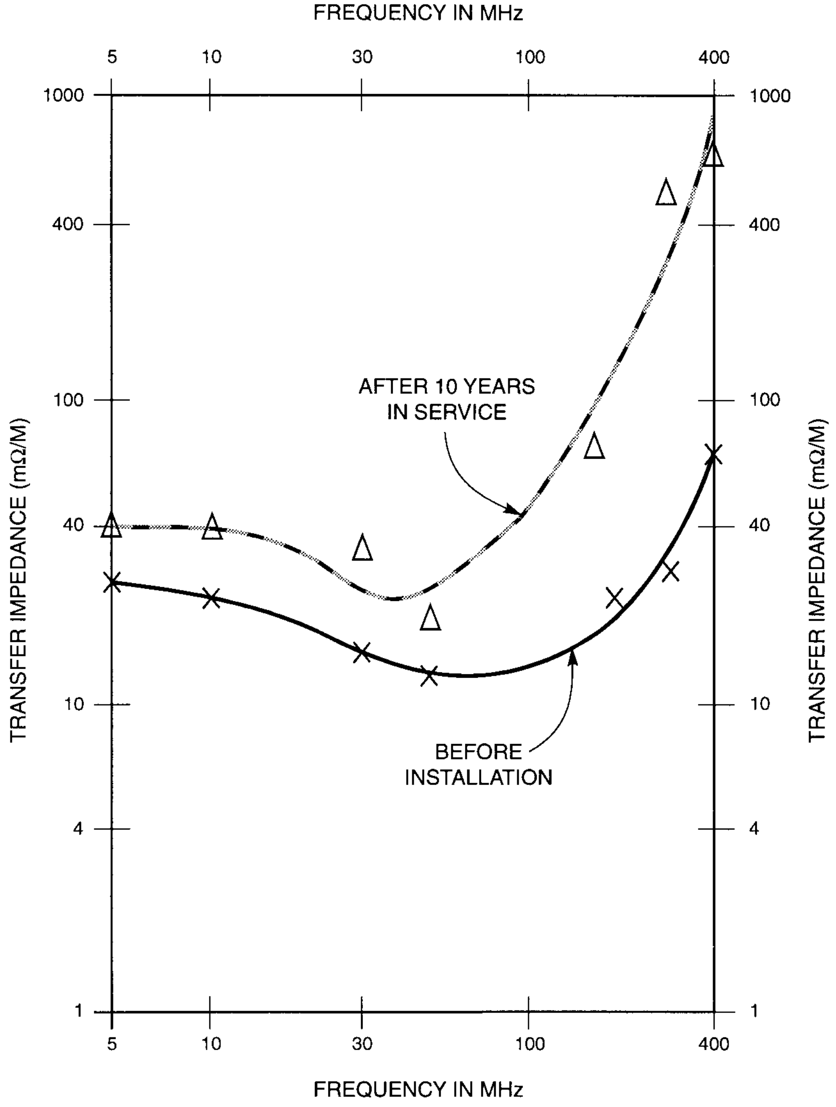

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Figure 32—Aluminum foil-braid transfer impedance vs. frequency

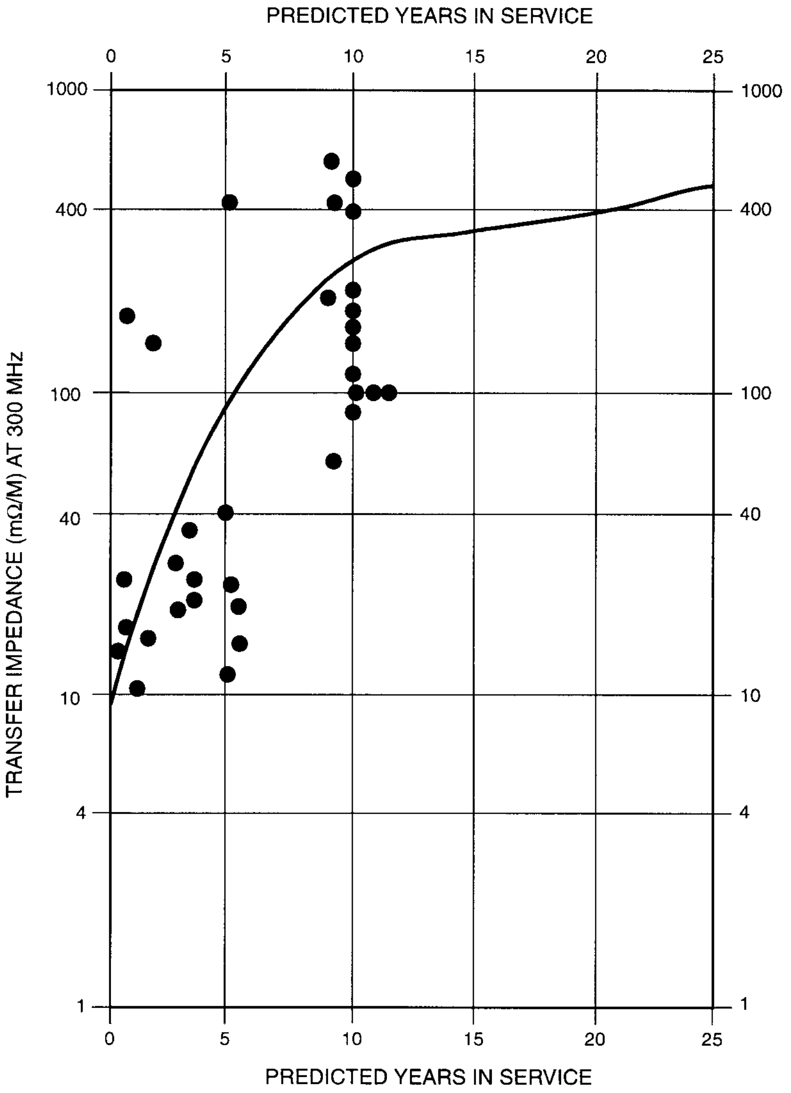

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Figure 33—Predicted aluminum foil-braid transfer impedance vs. years in service

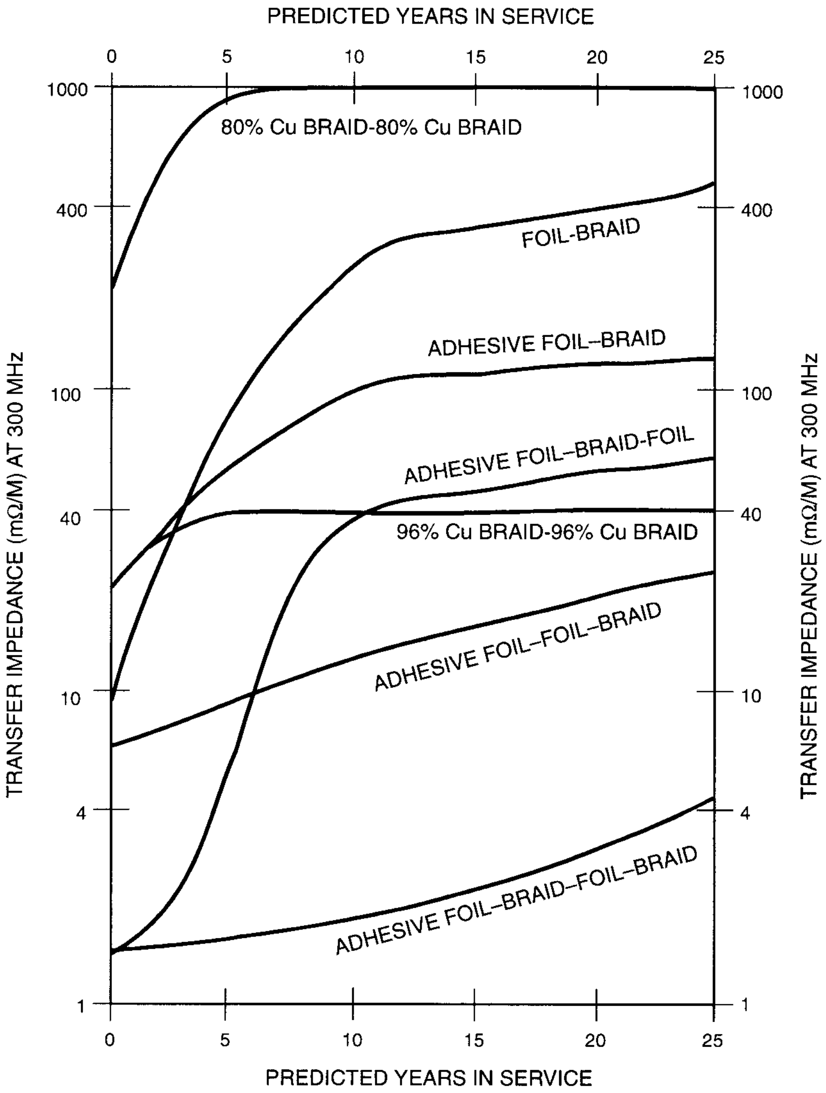

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Figure 34—Predicted transfer impedance for drop cable vs. years in service

Section II: Background and theory on need for shielding

10. Electrical noise susceptibility

10.1 Introduction

There are several basic mechanisms of coupling undesired signal noise or interference into cables. These mechanisms are described below.

10.1.1 Quasistatic electric induction

Low-frequency, or quasistatic, electric fields induce (or displace) charge on conductors exposed to the fields. Because the fields are time-varying, the induced charge is time-varying, and current must flow to accommodate the time-varying charge. Quasistatic fields may exist in the vicinity of high-voltage lines, vehicle ignition wires, and electrostatic discharges. Quasistatic coupling is also responsible for the transfer-admittance part of the coupling through apertures in cable shields, and capacitive coupling between conductors [B42].

10.1.2 Magnetic field induction

A time-varying magnetic field induces a voltage in any circuit it links. This voltage is induced in the circuit whether the circuit is open or closed. If the circuit is open, the voltage appears between the open terminals; if it is closed, the induced voltage drives a current through the circuit. The amount of current that flows depends on the impedance of the circuit. If the circuit contains no resistance or capacitance, the amount of current will be just sufficient to nullify the field linking the circuit.

The magnetic field induction of currents in shielded cables is a two-stage process. The magnetic field induces a voltage that drives a current through the cable shield, and the current in the shield induces a voltage on the wires inside the shield (i.e., the shielded conductors). The cable shield current induces a longitudinal or series voltage in the core conductors through the transfer impedance of the shield. This voltage is induced regardless of how the current in the shield is produced (i.e., by quasistatic magnetic fields or by incident waves). If the shield circuit is electrically large (dimensions equal to or greater than a wavelength) the incremental induced voltages must be integrated along the length of the cable with proper account for phase.

Shielding against low-frequency currents in the shield is difficult because massive amounts of metal are required to reduce the transfer impedance when the skin depth in the shield is large. Alternatively, relatively thinner shields of ferromagnetic material, grounded at both ends, have been used to reduce the effects of low-frequency induction [B17].

10.1.3 Electromagnetic interaction

Electromagnetic interaction is the general phenomenon, of which quasistatic electric and magnetic induction are subsets. Electromagnetic waves induce charge densities and current densities on all conductors in the field. The object of shielding is to allow these charges and currents to be induced on the shield and external structures rather than on the protected circuits inside the shield.

Electromagnetic interference is, in general, interference that may occur in any part of the electromagnetic spectrum. Modern broadband digital electronic circuits with a high density of integration and low operating levels are susceptible to repetitive and transient interference, which are broadband sources.

EMI energy entering interconnecting cables and power cables is carried from place to place in the cabling system. Its seriousness is found when erroneous data are introduced into data systems or data are lost. Reception of audio and video information can be affected.

Radiated EMI is emitted from a cable. A radiated field of EMI comprises both an electrical field and a magnetic field [B 1]. From the EMI standpoint, an electronic cable acts as “a means for radiating or receiving radio waves”—that is, as an antenna. Therefore, an “antenna” approach to cable electromagnetic compatibility (EMC) appears quite natural. Such an approach also uses a well-developed antenna theory and specific test methods. Depending on actual physical arrangements, the cable can be represented by an equivalent resonant or wave antenna of linear or loop shape, with directional patterns determined by the cable constants and system features. These directional patterns and antenna effective lengths are the same for both radiation and receiving regimes [B51].

In March 1980 the FCC adopted new regulations (FCC Docket No. 20780, Regulations Governing RFI/EMI Radiation [B 18]) regarding the allowable maximum radiation that could be emitted from computing devices. The FCC's definition of a computing device is intentionally broad to cover any system that uses digital techniques that generate RF frequencies over 10 KHz. Further, the FCC divided computing devices into two broad classes.

- *Class A devices*: Used in a commercial, industrial, or business environment
- *Class B devices*: Used in a residential environment

Class A equipment does not require certification by the FCC, but it should have a prominent label that states whether it conforms with the FCC limits. FCC limits are listed in table 10. When a Class A device causes interference in equipment outside its location, then it is the responsibility of the user to correct the problem.

Table 10—FCC limits

Limits on radiated emission			**Limits on conducted emission**		
Frequency (MHz)	**Class A (μV/m @ 30 m)**	**Class B (μV/m @ 3 m)**	**Frequency (MHz)**	**Class A (μV)**	**Class B (μV)**
30–88	39.1	40.0	0.45–1.705	60.0	48
88–216	43.5	43.5	1.705–30	69.5	—
216–960	49.5	54.0	—	—	—

Class A: Requires that tests be successfully performed on a facility that meets ANSI C63.4-1992.
Class B: Requires data submission and (usually) a test sample.

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Both Class A and Class B devices should be considered as a system. Only Class B devices will be certified by the FCC. Control consoles, computing devices, peripherals, and all interconnecting wire or cables should be included. These regulations have had a great effect on wire and cable design requirements. Since many systems use various hookup wires, interconnect cables, and databuses, shielding effectiveness is very important. Since each electronic device has its own design and operates at various frequencies, it is possible for a certain cable to comply with the regulations on one system but not comply when used in another system. Thus, the FCC cannot approve a cable alone as being in compliance. Electronic systems should be tested and certified [B42].

10.2 Galvanic action

Galvanic action is noise currents due to the junction or thermal potentials resulting from a combination of different metals. This current can be a part of the disturbing current passing through the conductors or shield of the signal cable.

10.3 Combination effect

A combination effect is an electric disturbance not caused by one of the following mechanisms (described in 13. through 13.1), but to some extent by a combination of them [B26].

10.3.1 Normal-modenoise (transverse or differential)

Normal-mode noise is the noise voltage that appears between two signal wires and acts on the 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
e) Unbalance or deliberate loading of the circuit

10.3.2 Common-mode noise (longitudinal)

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

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) *Magnetic induction*. With the magnetic field linking the signal wires equally, the noise voltage developed will be the same on both signal wires.
c) *Electromagnetic interaction*. Currents induced by electromagnetic waves impinging on the cable are in the common-mode.

Common-mode noise is also produced because different points throughout a cable system are at different ground potentials. Because of the resistances between various ground points in the system, there are voltage drops in the grounds and, hence, different ground potentials throughout the system. Typical ground potential differences in a cable system in a process plant, for example, may run anywhere from 1–10 V.

Common-mode noise is particularly troublesome with thermocouple circuits because they operate at low voltages [B26].

10.3.3 Common-mode to normal-mode conversion

Besides the common-mode voltages developed in the signal conductors by the general environmental sources of electromagnetic fields, differences in voltage exist between different ground points in a facility due to the flow of ground currents. These voltage differences are common-mode when connection is made to them either intentionally or accidentally, and the currents then produced are common-mode. These common-mode currents can develop normal-mode noise voltage across circuit impedances only if the circuit is unbalanced.

10.4 Transients or repetitive noise

There are some impairments that last only a few microseconds, but they can still cause data transmission problems. Most transients do not cause problems for voice communication but can disturb digital circuits. The transients are produced by sudden impulses, gain changes, phase changes, switching on or off, lightning, power system switching and operations or electromagnetic pulse. Much of what is described here has been accumulated from experience with analog signal or telecommunication circuits. However, with the increase in digital circuits for process and control circuitry, information is included on the types of interference that might be expected with digital circuits.

10.4.1 Impulse noise

Impulse noise is a component of the received noise signal that is much greater in amplitude than the normal peaks of the message circuit noise, and occurs as short duration spikes or energy bursts. Impulse noise spikes have a duration of < 1 ms, and all significant effects of the noise spike disappear within 4 ms.

Impulse noise affects data transmission by causing the loss of the information signal resulting in errors. In slow data rate systems, few errors occur because of impulse noise. It is easy for the receiving device to distinguish a data pulse from an impulse noise pulse. As the data rate increases, it becomes increasingly difficult for the receiving device to distinguish the data pulse from the noise pulse, resulting in errors. Impulse noise is most troublesome on data circuits rather than on signal circuits. Dialing pulses, contact noise, and keying devices are typical sources of impulse noise.

High-frequency, impulse-type noise on power distribution systems is of concern because of its generally adverse effect on the operation of data transmission systems, particularly those types proposed for power line communication systems that operate from about 5–200 kHz.

Significant levels of impulse noise can be attributed to synchronous switching devices using thyristor, diode rectifiers or inverters for motor-speed controls, and various types of industrial process controls [B31]. Thyristor and diode-type switching devices generate impulse noise because of the commutation process required to switch the flow of current from one conducting semiconductor to another. In a line-commutated converter, for example, during commutation, a temporary short circuit through two conducting thyristors occurs on the line-to-line supply voltage. This results in periodic notches on the voltage wave tens to hundreds of microseconds wide. These notches are rich in high-frequency spectral components. In an impulse-commutated converter, current to turn off a conducting thyristors comes from an auxiliary inductive-capacitive circuit. The capacitor is discharged rapidly compared to the supply frequency to produce a current in opposition to the supply-frequency current. Following the pass through zero current in the semiconductor, the commutating event completes by reversing the bias on the thyristor.

10.4.2 Gain changes hits

Gain changes are sudden increases or decreases in amplitude, usually not exceeding 12 dB of the received signal. Gain changes last at least 4 ms but may continue for hours. Modems that use amplitude modulation carry the information by the level of the signal. A gain change will look like data to these modems and will have the same sources as impulse noise.

10.4.3 Dropouts

Dropouts are a subset of gain changes. They are signal decreases, usually > 12 dB and lasting longer than 4 ms. Dropouts interrupt the information flow between two modems. Furthermore, even when the signal returns, some modems will take additional time to recover. Experience suggests that dropouts occur less often than the other types of transients. However, each dropout causes more modem errors. Dropouts are a loss of data and will have the same sources as impulse noise.

10.4.4 Phase change or hit

A phase change or hit is a sudden change in the received signal phase (or frequency) lasting longer than 4 ms. Since two common modulation techniques for high-speed data transmission are phase and frequency modulation, phase hits cause errors by looking like data. They are a form of impulse noise and have the same sources as impulse noise.

10.4.5 Lightning

Extensive measurements of the shape and amplitude of lightning-induced longitudinal voltage surges on telecommunication facilities have been made on a worldwide basis [B47]. The measurements show that the longitudinal voltages generally are of the impulse form of the stroke current. The key waveform characteristics are crest amplitude, rise time-to-crest, decay time-to-half crest, and the voltage rate-of-rise. The statistical distributions for these waveform parameters vary with the type of cable facility, cable makeup, soil resistivity, and terminal effects. It is sufficient to state here that the distributions covering all the key waveform parameters are approximately log-normal.

The lightning discharge can cause transient voltages to appear in wiring systems. There are several mechanisms of energy transfer from the discharge into wiring. Examples are as follows:

a) Capacitive coupling from the electrical field
b) Inductive coupling from the magnetic field
c) Changes in potential of the ground plane

Transients of low magnitude (< 50 V peak) generally go unnoticed in analog circuits as analog signal loops will not respond to such fleeting events. Transients of greater magnitude do occur and they are capable of damaging semiconductor devices.

The need for protection should be considered early in a project to minimize the effect on equipment costs, and arrangement and design costs [B9]. Aspects needing consideration are as follows:

a) The frequency and severity of lightning storms
b) Vulnerability of the proposed instrumentation, particularly digital equipment
c) Exposure of the system wiring to involvement with a lightning discharge
d) Effect on the process as a result of instrumentation failure, including the nature of the process itself

10.4.6 Power systems

Surges in switching station control circuits are caused by two general sources: switching phenomena on the high voltage system and switching on any of the low voltage systems in the station, including the control system itself [B27]. Cable shielding is usually there to protect the control circuit conductors from surges outside the control circuit, the most severe being those originating on the high voltage system.

The nature of surges originating on the high voltage system is important. They usually have a high-frequency oscillatory property, are lightly damped, and occur during operation of switching devices. Frequencies from a few hundred kHz to several MHz are common. They originate in a sudden redistribution of trapped charges on lumped and distributed capacitances in high voltage equipment during switch restrike and clearing. The self inductances of bus sections, vertical connections to equipment, and portions of the station ground system become involved in determining the surge characteristics. They, to a large degree, establish the location and severity of the surge coupled into the control circuit.

The high voltage system in a station, the various capacitive paths through the equipment to the ground mat, and the mat itself form a three-dimensional matrix. During a surge, large transient oscillatory currents and voltages exist in this structure. These are accompanied by very strong, rapidly changing electric and magnetic fields.

As with lightning, transients from power systems can be transferred to the control circuits by direct, inductive, or common (ground) impedance coupling. The interference of concern usually is from abnormal power system conditions. Examples of such conditions are

a) Power line phase-to-ground faults
b) Crosses (contacts) with open wire
c) Voltages or currents from unbalanced power circuits

Power system interference is difficult to characterize, and as a result meager statistical data exists on frequency of occurrence or waveform characteristics. Nevertheless, power system interference poses a significant threat to signal transmission in control circuits. Since abnormal situations involving high voltages and currents do occur, a long duration fault permits the transfer of high energy to connected equipment.

10.4.7 Equipment power service

Power companies strive to maintain their line waveforms within certain standards. However, these waveforms are subject to the effects of lightning, random customer loading, and other considerations that result in high voltage surges. These surges can attain magnitudes that can either destroy or disrupt the operation of unprotected equipment. Typical surge characteristics as well as representative test waveforms are presented in IEEE Std C62.41-1991. The data base shows that the expectation of a 3 kV transient occurrence on a 120 V circuit ranges from 0.01–10 per year a given location. The practical limit on peak amplitudes is considered to be 6 kV. This limit is set by rare but possible occurrences and the sparkover characteristic of typical systems.

10.4.8 Central office switching transients

The collocation of a digital switch with existing step-by-step, crossbar, or electromechanical switching equipment can expose a signal system to high voltage and current transients. The transients associated with the making/breaking of relay or wiper switch contacts in these types of equipment can couple into the digital equipment via the cable racks or frame superstructure of the power service (ac and dc). The frequency and level of these transients are a function of the traffic load in the electro-mechanical equipment. Though statistics are meager, limited observations show that transient surges on low impedance circuits can reach several tens of amperes during heavy switching times [B47].

10.4.9 Electromagnetic pulse (EMP)

When a nuclear weapon is detonated at high altitude ($\geq$ 100 km), it produces an EMP that covers a very large area under the burst point [B42]. Downward directed gamma rays produced by the bomb interact with air molecules in the 20–40 km altitude range to produce Compton recoil electrons whose trajectories are bent into spirals by the earth's magnetic field. These accelerated Compton recoil electrons are responsible for generating the electromagnetic wave that propagates toward the earth's surface.

The electromagnetic pulse arriving at the earth's surface covers the entire area subtended by a cone with its apex at the burst point and its rays tangent to the earth. The entire U.S. could be covered by the EMP of a single weapon. Other forms of EMP are produced by high-altitude bursts on satellite systems and by surface bursts, but these effects are quite localized and are primarily of interest for military systems.

Although the high altitude EMP amplitude and pulse shape vary over the exposed surface, the incident field strength can be 50 kV/m with a rise time of less than 10 ns and a duration of about 100 ns. An EMP could induce short-circuit currents up to 10 kA in power lines, 1 kA in underground communication cables, and several kA in antennas (depending on the size of the antenna). Such currents may damage or upset circuits served by these elements.

10.5 Nonlinear distortion

Nonlinear distortion is the generation of new signal components not present in the original transmitted signal [B13]. The main cause is nonlinear electronic components such as amplifiers, modulators, and demodulators. Nonlinear means that the amplitude of the output is not linearly proportional to the input. If a true sine wave were transmitted through a nonlinear device, its shape would be changed. The effect is equivalent to adding lower amplitude signals whose frequencies are integer multiples of the original frequency (harmonics).

If a single frequency is transmitted, the nonlinear distortion will appear as harmonics of this input frequency (harmonic distortion). A single frequency input is not a very close approximation to datacomm signals. With multiple frequency inputs the nonlinear distortion shows up as harmonics of the individual inputs plus the sum and difference products of the inputs and their harmonics (intermodulation products).

11. Interaction (coupling)

11.1 Introduction

To minimize noise or unwanted electrical signals, lowering the coupling a practical technique. If some type of electrical interaction exists between the source of the noise and elements of the control circuit, a voltage will appear in the control circuit. The four possible types of interaction are discussed in this clause.

11.2 Impedance coupling or common impedance coupling

Impedance coupling exists when two or more circuits share a common impedance such as the ground return path or power supply. A current in one of the circuits will result in a signal voltage in the others.

Some of the common impedance situations are

a) Common power supply
b) Inductance of capacitors at high frequency
c) Inductance of lead wires
d) Stray capacitance from enclosure to ground
e) Resistance of the earth or ground

11.3 Magnetic coupling

Magnetic coupling exists between two or more conductors when a current change in one results in an induced voltage in another conductor.

An alternating magnetic flux from a disturbing wire induces a voltage in the receiving circuit. This voltage is proportional to the frequency of the disturbing current, the magnitude of the disturbing current, and the area enclosed by the receiving circuit. The conditions needed to introduce an interference voltage are a rate of change of current and a receiving circuit linked by the magnetic flux.

Magnetic coupling depends upon the rate of change of interference current. This type of coupling does not depend upon any conductive path between the noise source and control circuit.

11.4 Quasistatic electric coupling

Quasistatic electric coupling results from a time-varying electric field inducing a time-varying charge, or current, on a conductor. When the electric field is produced by an adjacent conductor, the two conductors are capacitively coupled. The short-circuit current induced in the cable experiencing interference is proportional to the voltage on the cable generating the interference and the rate of change (or frequency) of the voltage. The coupling capacitance between two parallel wires is proportional to the logarithm of their separation. Therefore, increasing the separation decreases the coupling rather slowly.

11.5 Coupling by electromagnetic radiation

The voltages induced by magnetic or electrostatic induction are near-field effects because this type of interference occurs close to interference sources. Farther from .the source, fields are propagating radio waves or radiation fields. Typically, radio waves occur at distances greater than 1/6 wavelength from the source of interference. Table 11 shows the relationship between frequency and 1/6 wavelength.

Table 11—Frequency wavelength relationship

Frequency	1/6 Wavelength
1 MHz	5000 cm (1970 in)
10 MHz	500 cm (197 in)
100 MHz	50 cm (19.7)
1 GHz	5 cm (1.97 in)

11.6 Crosstalk

When transmitting either pulsating dc signals or ac signals on one pair of multipair cable, there is a tendency for the signal to be superimposed on signals being carried in adjacent pairs. This effect is crosstalk [B26].

An electrical signal on a cable circuit creates an electromagnetic field in the surrounding space. This field induces currents and electromotive forces in other circuits located close to the disturbing cable circuit. This phenomenon is known as crosstalk. Crosstalk displays itself as interference in communications lines and computer connections. It deteriorates transmission quality and, in the most serious cases can lead to communications disruption and equipment malfunction.

Crosstalk is a result of excessive coupling between circuits sometimes caused by imperfections in the cable construction. Crosstalk should be treated as a general EMC operational problem when two circuits run close in the same, or different cables, for a distance from fractions of millimeters up to many miles [B51].

Crosstalk is affected by several factors including cable type and design, frequency range, transmission line length, and the relative location of transmitters and receivers at the ends of disturbing and disturbed circuits. The interacting circuits can be in the same cable or in different cables, near each other or separated by the shield or other pairs, or used in the frequency or time-domain mode. Much affects the character and magnitude of crosstalk, and the methods of reducing crosstalk.

11.7 Crosstalk between coaxial cables

Crosstalk between coaxial cables occurs when part of the signal leaks out of one cable and into an adjacent cable. This problem arises with braided wire outer conductors that exhibit high-frequency leakage because of apertures, and with tapes having longitudinal seams. For crosstalk between coaxial cables to occur, the interfering signal must penetrate two shields; it must escape the shield carrying it, and it must couple to and penetrate the shield of the cable experiencing interference. Crosstalk between coaxial cables is a problem primarily for high frequencies, for long runs of cable, when one cable carries a very large signal, or when one cable carries a very small signal.

11.8 Electromagnetic crosstalk

Crosstalk is electromagnetic coupling between disturbing and disturbed circuits.

There are several coupling mechanisms that can act simultaneously in cables. Interaction of a disturbing circuit with another disturbed circuit creates “direct crosstalk.” Indirect crosstalk results from the action of other conductors in the cable (including shields and ground wires), circuit impedance inconsistencies, and load mismatch. The crosstalk magnitude measured in cables is the result of direct and indirect interaction.

11.8.1 Direct crosstalk coupling

Transverse electromagnetic fields located perpendicular to the cable axis plane are the main cause of coupling in balanced cables.

11.8.2 Reflection

Reflection takes place when the signal traveling wave or pulse in the disturbing circuit encounters characteristic impedance mismatch in the line or at its ends. The signal or a portion of the signal is reflected back to the source producing interference.

11.8.3 Crosstalk summation

Electromagnetic coupling models describe crosstalk processes in very short cable lengths, where the signal attenuation and phase shift imposed by the cable can be neglected. When it comes to actual cable lines, the crosstalk from all such short lengths has to be summed. To obtain the total near- and far-end crosstalk in the disturbed circuit, all the coupling mechanisms should be considered along the whole cable length, including the ends of the disturbed circuit.

To understand the effect of frequency, the induced signal amplitude needs to be studied at separate frequencies. The crosstalk from different elements of the circuit should be determined for each frequency within the requirements of the desired spectrum. This obtains the near- and far-end crosstalk characteristics of the circuit. Another mechanism to be studied is the crosstalk related to time-domain effects.

Now, the shape of the induced pulse and its magnitude are affected. The near-end crosstalk processes begin simultaneously with the driving pulse, thus originating crosstalk in the disturbed circuit. The driving pulse moves toward the far end of the disturbing circuit and induces crosstalk voltages on each cable element. These voltages travel back to the near end of the disturbed circuit. The last crosstalk voltage portion to arrive at the disturbed circuit near end is the voltage induced at the far end of the line. Therefore, the duration of the total pulse induced at the near end of the disturbed circuit is equal to the sum of propagation time down the length of disturbing circuit and back on the disturbed circuit. If both circuits have identical propagation characteristics, the pulse induced at the near end of the disturbed circuit will have twice the propagation time as stated before. It is clear that at the far end of the disturbed circuit all the induced currents arrive at the same time (if the propagation times of both circuits are identical). Therefore, far-end crosstalk will affect the shape of the pulse (if no reflections are involved).

11.8.4 Electromagnetic coupling and crosstalk evaluation in cable lines

In the “audio” frequency range, capacitive coupling may dominate. However, at frequencies above this range, all the described coupling mechanisms cause crosstalk, and the resulting coupling is very complicated [B9].

12. Electrical noise susceptibility

12.1 Introduction

The level of susceptibility of a circuit or system is the interference level below which the circuit or system is assumed to function properly. The susceptibility of a given control circuit is a function of the design of the circuit and can vary widely even within a given class of devices. Usually, high power systems such as relay control systems have a low susceptibility while low power systems such as those using integrated circuits have a high susceptibility.

The EMC of an electrical system is its ability to do its specified functions in the presence of an expected level of electrical noise generated either internally or externally other systems and to perform its functions without contaminating the external environment with EMI.

Every electrical device or system has some inherent characteristic immunity to electrical noise, although it may not be specified or controlled. If the strength of the oncoming electrical noise is sufficiently below the threshold level of the receiver, be it a device or a system, there are no special precautions. However, if the strength of the electrical noise is above threshold level, it may degrade system performance and noise suppression measures may be needed.

12.2 System boundaries

Electrical noise can reach the system through many paths, including the following:

a) Power feed lines
b) Grounding conductors
c) Input signal lines
d) Output signal lines
e) External fields
f) Antennas
g) Piping
h) Structural metal

The susceptibility levels of the system will vary according to the paths of entry of the electrical noise. Furthermore, even for the same path of entry, the susceptibility will depend upon the type of electrical noise and the state of operation of the system.

A single circuit is sensitive to a potential difference applied between two input terminals, whether that potential be a noise voltage or a useful signal. Any voltage appearing between these input terminals is a normal-mode voltage. Any voltage difference appearing between both terminals and some common point is a common-mode voltage. Susceptibility is different for common-mode noise vs. normal-mode. For radiated noise, the susceptibility may depend upon the type of wave: electric, magnetic, or electromagnetic. It should be noted that multiple circuits will have multiple levels of susceptibility. This treatment of a single circuit is basically for illustration of the concept of susceptibility. Figure 35 shows the susceptibility to electrical noise control.

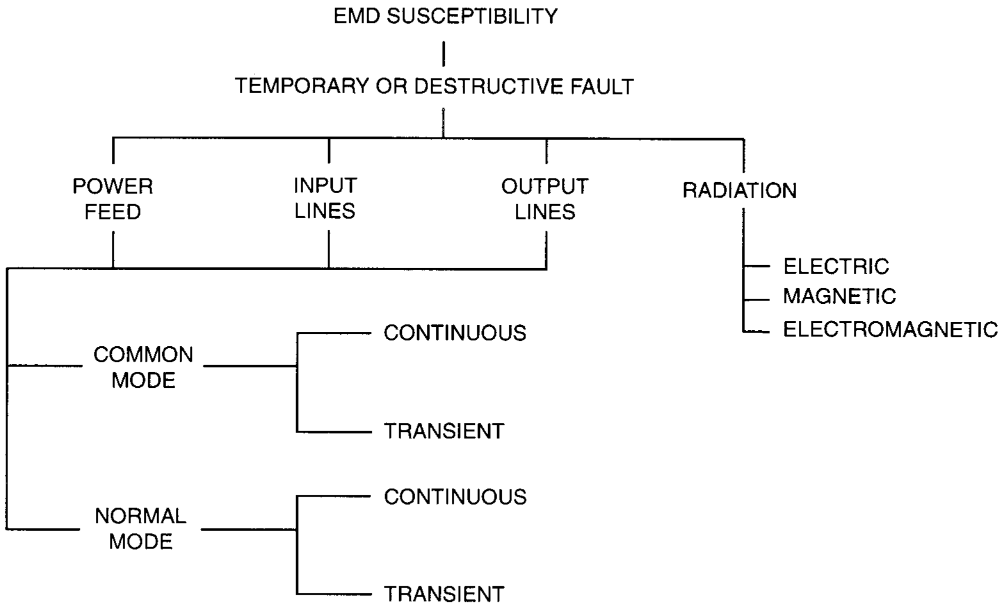

Figure 35—Classification of susceptibility to electrical noise

Most of the electrical noise problems in control systems arise from the conducted type of electrical noise while transient voltages cause almost all faults.

12.3 Sensitivity to noise

The characteristics of passive electrical circuits are frequency dependent. The susceptibility of an analog control circuit is a function of the specified accuracy of the circuit, that is, of the deviation or output tolerance of the circuit without any external electrical noise present. As long as the control circuit output stays within this normal tolerance in the presence of electrical noise, the circuit is not susceptible to that type and level of electrical noise. However, since most electrical systems contain both passive resistance-inductance-capacitance (RIC) elements and active devices, they have a very complex susceptibility to electrical noise.

12.4 General susceptibility

The susceptibility of a system is different for the various means of entry of the same type of electrical noise. This is not only because of the characteristics of the active devices, but also because the incoming electrical noise encounters different impedance networks.

12.5 Susceptibility to transient electrical noise

The susceptibility to transient electrical noise may be specified by the following:

a) Peak of transient voltage
b) Rate of rise
c) Waveshape of voltage (front time and duration)
d) Impulse or charge transfer
e) Energy

Transients in electrical systems occur at random. Two transients are seldom alike either in waveshape or in amplitude. However, industry standard waveshapes are in existence to test the susceptibility of equipment to transient electrical noise. The waveshape of the transient electrical noise is significant because the operation of many of the modern semiconductor devices utilizes the rate of rise of the voltage and current of the input signal. Transient voltages may last for microseconds or milliseconds.

13. Noise induced from power systems

13.1 Introduction

There are three basic parts that combine to produce power induced noise on control circuits in the outside plant. All three parts must be present to have noise on a circuit. The absence of any one part eliminates the possibility of noise.

a) Power influence. Refers to the interfering signals that are induced in the signal carrying system from the power system. This includes 60 Hz and the harmonics of 60 Hz. This is controlled by the power system.
b) The mutual coupling between the power line and the signal circuit is determined by the length of exposure between the signal and power lines and the separation between the two lines. This is a function of either or both systems.
c) The susceptibility of a signal circuit involves the balance of all elements comprising the circuit. This is controlled by the signal carrying system.

13.2 Interaction model

The general interaction model (figure 36) shows the three sources of interference [B37].

a) The contribution of the power system.
b) Coupling to the signal system. Owners of both systems have some control over coupling. Coupling is controlled by the geometry of the power and the signal lines, the spacing between the power and signal lines, the distance through which the lines are parallel, and the crossing angle, if the lines are not parallel. The earth resistivity and its lack of homogeneity, the frequency of the interfering earth currents, and the continuity and grounding of shield conductors all influence coupling.
c) Susceptibility of the signal circuit. Susceptibility is the responsibility of the owner of the signal circuit. Factors that influence susceptibility include the effects from the following:
    1) Unbalanced feeders—causing 60 Hz induction into parallel signal lines
    2) Overexcited transformers—causing high harmonic content in the exciting current, and causing high noise in parallel signal lines
    3) Multigrounded neutral wye (MGN) operation—causing ground-return currents to flow, and causing, in turn, much more induction into parallel signal lines than currents that flow strictly in metallic paths
    4) Solid-state loads without adequate filtering—causing high harmonic currents in the power system conductors, and causing, in turn, high noise in parallel signal lines
    5) Grounded power factor correction capacitors—providing a path to ground for harmonic currents, or even enhancing the flow of such currents, because of resonance with the system inductance, causing, in turn, high noise in parallel signal lines
    6) Ground-return currents. If power current did not return through the earth—if restricted to completely metallic paths, close to the phase conductors—there would seldom be an interference problem

Good load balance on a three-phase power cable can help minimize steady-state 60 Hz induction, but even a well-balanced feeder is subject to the flow of multiples of triple-odd harmonics, or triplins. These harmonics (such as 180 Hz, 540 Hz, or 900 Hz) can be thought of as “wiggling in phase” down the three-phase conductors, and returning in the neutral. If in the earth, they spread throughout a very large volume of the earth. Single-phase taps convert all harmonics to ground return, so all the triplins and all other odd harmonics of 60 Hz can flow deep in the earth.

High earth resistivity makes the problem worse by forcing the earth-return components to occupy an even larger volume of earth as the current filaments spread out. The earth-return alternating current tends to follow the route of the power line because of the self-inductance of the circuit; whereas direct current spreads out approximately radially from an earth electrode.

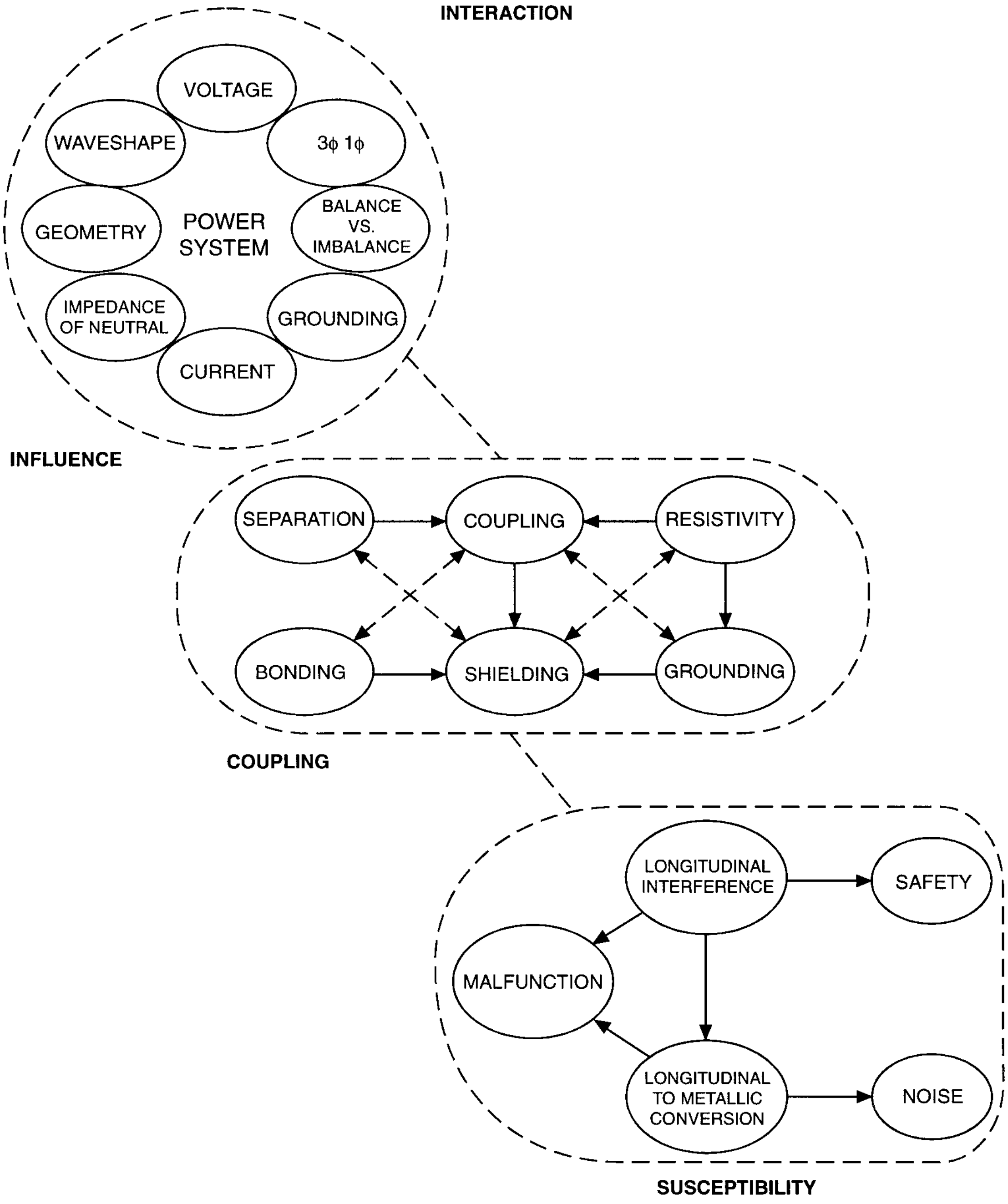

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Figure 36—General interaction model indicating three sources of interference: Power influence, mutual coupling, and susceptibility

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