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IEEE Guide for Instrumentation and Control Equipment Grounding in Generating Stations

IEEE Power Engineering Society

Sponsored by the
Energy Development and Power Generation Committee



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IEEE Guide for Instrumentation and Control Equipment Grounding in Generating Stations

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

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Abstract: Instrumentation and control (I&C) equipment grounding methods to achieve both a suitable level of protection for personnel and equipment, and suitable electric noise immunity for signal ground references in generating stations are identified.

Keywords: control, generating stations, grounding, I&C, instrumentation

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Introduction

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

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

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

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

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

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IEEE Guide for Instrumentation and Control Equipment Grounding in Generating Stations

1. Overview

1.1 Scope

This application guide was developed to identify instrumentation and control (I&C) equipment grounding methods to achieve both a suitable level of protection for personnel and equipment, and suitable electric noise immunity for signal ground references in generating stations. Both ideal theoretical methods and accepted practices in the electric utility industry are presented.

This guide is intended to give information on grounding methods for generating station instrumentation and control equipment. Grounding design is normally based on the concept of two separate grounding systems, the equipment ground and the signal reference ground. The concepts of equipment grounding are well covered in other IEEE standards. The concepts of grounding of instrument chassis, cable shields, signal pairs, and other related instrumentation and control items require special care in order to ensure that both personnel working on equipment are adequately protected from electrical shock and that interference signals are not inadvertently coupled into signal circuits. Although safety takes top priority, the I&C systems must be simultaneously safe and operationally reliable.

The basic theory and guidelines that should be understood before designing I&C grounding are presented in Clause 4. Clause 5 presents various approaches for the grounding of equipment associated with generating station I&C systems. Clause 6 presents accepted practices in grounding the shields of I&C cables, while Clause 7 covers the testing of I&C grounding systems.

1.2 Purpose

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

The generally low-level electrical signals transmitted from various I&C equipment in a generating station through often lengthy cables may undergo signal distortion as they travel to the receiving end. This distortion is typically caused by noise pickup either at the signal source or along the cable run. The level of noise on the received signal may cause operational errors and in extreme cases, damage to equipment which in turn may result in costly unit downtime. The use of proper grounding and shielding techniques can prevent a large percentage of noise problems. It should be recognized that there are numerous accepted grounding techniques and that the actual installation of a ground system should be made with reference to the recommendations of the I&C equipment manufacturers since the techniques used to solve one problem may result in the creation of a different problem.

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

2. Normative references

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

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

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

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

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

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

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

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

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

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

IEEE Std 525™-1992 (Reaff 1999), IEEE Guide for the Design and Installation of Cable Systems in Substations.

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

IEEE Std 1100™-1999, IEEE Recommended Practice for Grounding Electronic Equipment (IEEE Emerald Book).

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

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

3. Definitions and acronyms

3.1 Definitions

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

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

3.3 central distribution frame grounding: A type of grounding system where all signal grounds are referenced to a central point rather than at their respective signal sources. For certain systems this technique provides a good functional compromise between the ideal signal grounding methods and ease of installation and troubleshooting.

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

- a) Electrostatic induction (E-field capacitive coupling) via near field effects. With equal capacitance between the set of victim conductors and their immediate surroundings, the noise voltage and current developed will be the same on all victim wires in the same circuit.
- b) Magnetic induction (H-field transformer coupling) via near field effects. With the magnetic field linking the set of victim conductors equally, the noise voltage and current developed will be the same on all victim conductors in the same circuit.
- c) Electromagnetic wave coupling via far-field effects. Electric dipole (or monopole) antennas and/or magnetic loop antennas inadvertently formed in the victim conductor system can accept electromagnetic wave radiation and cause it to appear as common-mode noise and current on their path.
- d) A variation in potential between two or more ground references to which the victim circuit's conductors are connected. An example would be two separate buildings with a metallic signal or power cable routed between them along with a grounded circuit or signal conductor. When a lightning

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

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

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

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

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

3.7 cutoff frequency: a) (General) The frequency that is usually identified with the first -3 dB transition between a passband and an adjacent attenuation band of system or transducer. **b) (Of a waveguide)** For a given transmission mode in a nondissipative waveguide, the frequency at which the propagation constant is 0.

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

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

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

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

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

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

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

3.15 neutral:* The terminal of a single or polyphase electrical power source that carries only the unbalanced or triplen harmonic currents between the connected loads and the power source. On a two-wire, single-phase power source, the term "neutral" is also applied to the common terminal of the ac system. This term is also applied to the circuit conductor(s) that is connected to the power source's neutral terminal. The

neutral may be either solidly grounded, resistance grounded, impedance grounded, or ungrounded depending upon the design requirements for the ac system.

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

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

- a) Any of the previously described common-mode (CM) interference mechanisms that occur on victim signal paths where the induced CM voltage or current is not carried in equally on circuit conductors.
- b) Electrostatic fields linking unequally with the distributed capacitance of the victim signal wires.
- c) Magnetic induction linking magnetic fields unequally with the victim signal wires.
- d) Electromagnetic wave coupling. Electric dipole (or monopole) antennas and/or magnetic loop antennas inadvertently formed in the signal wiring or cabling can detect electromagnetic wave radiation and cause it to appear as normal mode noise on the circuit conductors.
- e) Junction or thermal potentials due to the use of dissimilar metals in the connection system.
- f) Common-mode to normal-mode noise conversion in the victim path, particularly via transformer coupling actions.

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

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

3.2 Acronyms

ac	alternating current
CCVT	coupling capacitor voltage transformer
CDF	central distribution frame
CM	common mode
CT	current transformer
dc	direct current
DM	differential mode
EG	equipment ground
EGC	equipment grounding conductor
EMC	electromagnetic compatibility
EMI	electromagnetic interference
ESD	electrostatic discharge
GIS	gas insulated switchgear
I&C	instrumentation and control
I_{cm}	common-mode current
I_N	noise current
LC	inductive/capacitive
LCR	inductive/capacitive/resistive
MOV	metal oxide varistor

Q	quality factor
RC	resistive/capacitive
R	radio frequency
RTD	resistance temperature detector
SCR	silicon controlled rectifier
SDS	separately derived ac system
SE	service entry
SE	shielding effectiveness
SEQ	service equipment
SF ₆	Sulfur Hexafluoride
SIS	solidly interconnected ac system
SRS	signal reference structure
TVSS	transient voltage surge suppression
V _S	signal voltage
V _{CM}	common-mode voltage
VDM	differential-mode voltage
VN	noise voltage
VT	voltage transformer
0V RTN	Zero Volt Return (Signal Ground Reference)

4. Design considerations for electrical noise minimization

4.1 Typical noise sources and their characteristics

Noise sources can be divided into several categories:

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

4.1.1 Natural sources

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

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

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

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

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

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

Analysis of the continuing current component of the lightning flash striking a power line indicates that it initially behaves as a traveling wave and subsequently as a dc source. In cases where the lightning stroke terminates on a tower or lightning terminal, it may be analyzed through circuit analysis.

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

4.1.2 Incidental sources

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

4.1.2.1 High-voltage switching

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

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

The above transients are also capable of being electrostatically (E-Field) or magnetically (H-Field) coupled by near-field action to nearby cables. In far-field fashion they are radiated as an electromagnetic (radio) wave to sensitive systems. Typical values are:

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

4.1.2.2 Capacitor bank switching

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

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

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

If other nearby capacitor banks are connected to the same line, they lower the impedance seen by the switched capacitor bank, thereby increasing the magnitude and initial frequency transition. They also decrease the oscillatory decay (ringing) frequency of the transients since more capacitance is added to the system by their presence. Energy stored in the nearby bank may further contribute to the severity of the transient if its polarity is such that it algebraically adds to that being introduced by the first set of capacitors to be switched.

4.1.2.3 Transmission line switching

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

4.1.2.4 Coupling capacitor voltage transformer (CCVT)

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

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

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

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

4.1.2.5 Gas insulated switchgear (GIS)

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

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

Typical values for GIS measured at the bushing:

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

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

4.1.2.6 Vacuum insulated switchgear (VIS)

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

4.1.2.7 Earth ground voltage differences

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

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

4.1.2.8 Current transformers (CTs)

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

4.1.2.9 Electro-mechanical equipment

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

- a) Partial (corona) discharges within the stator winding insulation of motors. Note that this can also occur on dry-type transformers.
- b) Slot discharges between coil surfaces and the stator iron.
- c) Sparking from exciters with brushes.
- d) Arcing associated with conductor strands that have fractured from copper fatigue. This arcing is not continuous but is caused by a movement of conductor surfaces as a result of steady-state and transient magnetic forces.
- e) DC machine brushes.
- f) Centrifugal switch contact operation and arcing.
- g) Older types of non metal-enclosed or other inadequately shielded motor-controllers with arcing contacts. These may be of the manual or contactor type. Non-interlocked, manually operated reversing and motor “plugging” types of controls are potential problem sources since they may be operated while the motor is still spinning.
- h) Variable frequency or pulse inverter drives. These are also capable of producing both conductive and radiated EMI from the fast transition times associated with SCR, IGBT, or similar motor inverter-driver switching schemes. The largest number of conducted EMI problems involving this type of equipment occur in the range of the first 100 harmonics of the fundamental frequency of the driver circuit.

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

4.1.2.10 Silicon controlled rectifiers (SCRs)

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

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

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

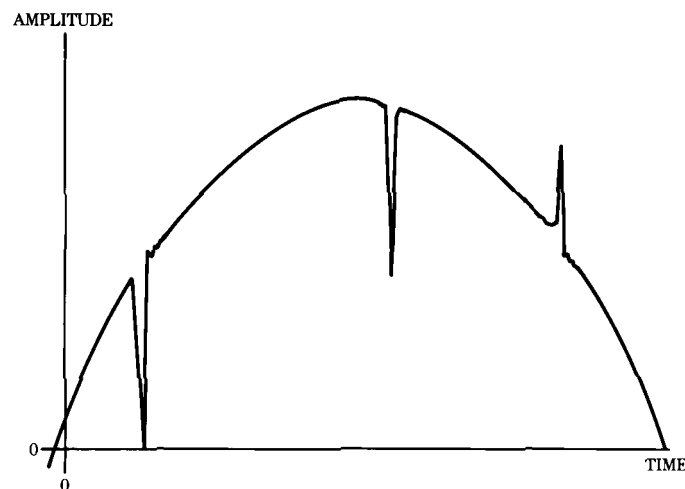


Figure 1—Line-notching waveshape

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

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

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

The major contributing devices to EMI have the following characteristics:

- a) *CRT display.* Noise sources within a CRT display are the video circuitry (typical 20–50 V swing at 10–20 MHz) and the horizontal yoke drive circuitry (typical 3 A peak-to-peak amplitude at 10–20 MHz). Near-field EMI in the form of very low-frequency H-fields up to several tens of kHz from the horizontal yoke itself, are also encountered. This latter condition is a common problem when two or more CRT displays are placed very close to one another and the mutual EMI coupled between them affects the stability of the raster and produces effects such as slowly wavy lines, swimming display, or horizontal bands rolling up or down.
- b) *Switching power supply.* The radiated noise generated by these devices is dependent upon the switching frequency (typical 10–100 kHz) and the switching amplitude. These devices also provide large amounts of EMI in the form of conducted harmonic current waveform distortion on the ac power supply wiring up to a few kHz. Most of this conducted EMI will involve odd-ordered harmonics from the ac system's fundamental.
- c) *Printers.* The major noise sources for these devices fall into two categories. For impact printers, the EMI is generated from the drivers and collapsing fields of printhead solenoids and the printhead or carriage positioning motors along with the associated internal wiring to and from them. For laser printers, the EMI is generated by the gated SCR or transistor switched power control circuits that are used to control the current for high-intensity drum erasure lamps and the heaters used with toner fuser rolls.
- d) *Cabling.* One of the most overlooked sources of radiated EMI noise in a computer system is the interconnect cabling. The noise generated is dependent upon the signal level, the number of conductors within each cable and their physical orientation (symmetry of twisting or lack thereof), and the type of shielding provided if any. The connectors used at the ends of these cables are also known to be a point of EMI emission if they are not properly shielded and grounded. Crosstalk between different circuits being carried in the same cable is also a common means of EMI propagation on these cables.

4.1.2.12 DC control circuits

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

$$V = I \frac{L}{C} \quad (1)$$

where

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

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

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

4.1.2.13 Mechanical vibration

Mechanical vibration and shock can produce arc discharge EMI whenever loose electrical connections are moved or electromechanical switch contacts bounce open or closed and produce an arc discharge. This is true even for low-voltage circuits, since voltages as low as 9 V across gold alloy contacts can produce an arc discharge. Also, many low-voltage circuits can involve the switching of very large amounts of available current. Power supply buses rated at ± 5 , ± 12 Vdc logic and 12, 24, or 48 Vdc control power are commonly rated for several tens of continuous amperes to more than a hundred amperes on larger items of equipment.

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

4.1.2.14 Chemical contamination

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

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

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

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

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

4.1.2.15 Human interaction via electrostatic discharge (ESD)

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

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

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

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

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

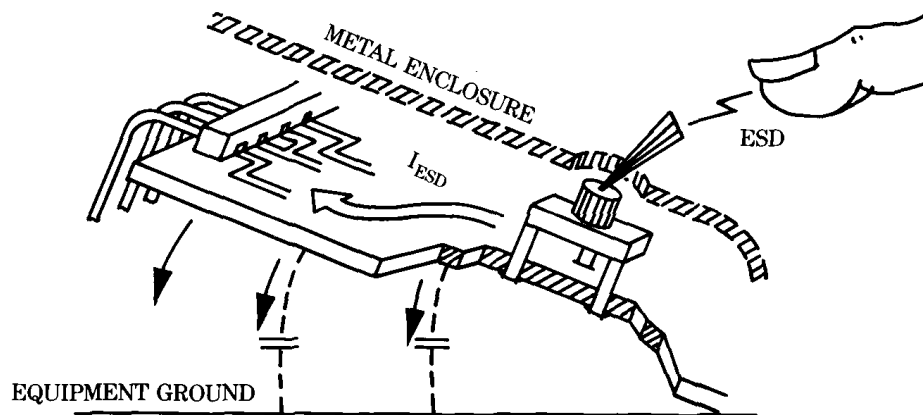


Figure 2—Electrostatic discharge noise generation

4.1.2.16 Cable resonance

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

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

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

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

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

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

$$f = c/l \quad (2)$$

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

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

4.1.2.17 Reflections and traveling waves

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

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

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

4.1.2.17.1 Velocity factor

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

For example, the leading edge (first transition) of a radiated wave will travel 30 m in free space during one cycle of a 10 MHz clock signal in a microprocessor. However, within an insulated conductor in a cable, it

may travel only 21 m due to a reduced velocity factor, which, in this case, would be $0.7 \times (21\text{m}/30\text{m} = 0.7)$. If the voltage wave reflects from the cable termination where the cable has been terminated “open” or at least in a very high impedance in comparison to the signal cable’s characteristic impedance, and is in phase with a new wave, resonance will occur and line oscillations will be greatly magnified. Also, if one end of the circuit is grounded, the first resonance at 10 MHz occurs when the conductor is only 5.25 m or $1/4$ wavelength long.

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

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

4.1.2.18 Power circuit inrush current

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

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

4.1.2.19 Other incidental sources

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

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

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

4.1.3 Intentional sources

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

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

4.2 Noise-coupling methods

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

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

Both capacitive and inductive coupling refer primarily to near-field coupling. This is also often referred to as the reactive field where the energy is stored or as stray (parasitic) reactive coupling. A control circuit or cable is considered to be in the near field of an electromagnetic source when the source to circuit distance is less than $1/6 \lambda$ of the highest source frequency. Radiation coupling refers to circuits located in the far field of a source where the source's emissions are seen as a true traveling electromagnetic wave. This latter situation involves radio wave transmissions and antennae effects.

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

4.2.1 Characteristics of electromagnetic fields

Electromagnetic waves consist of two oscillating fields at right angles to one another: the electric field (E-field) and the magnetic field (H-field). The electromagnetic wave impedance (Z_w) in ohms is defined as the ratio of the E-field intensity expressed in V/m to the H-field intensity expressed in A/m. In the reactive or near field, where the energy is stored, the E-field and H-field can be considered independently where the wave impedance does not apply.

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

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

4.2.2 Common impedance coupling

Conductive coupling is also known as common impedance coupling, and can be created by galvanic action or an arc. As shown in Figure 3, when two or more circuits share a wire or conductor as a common section of

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

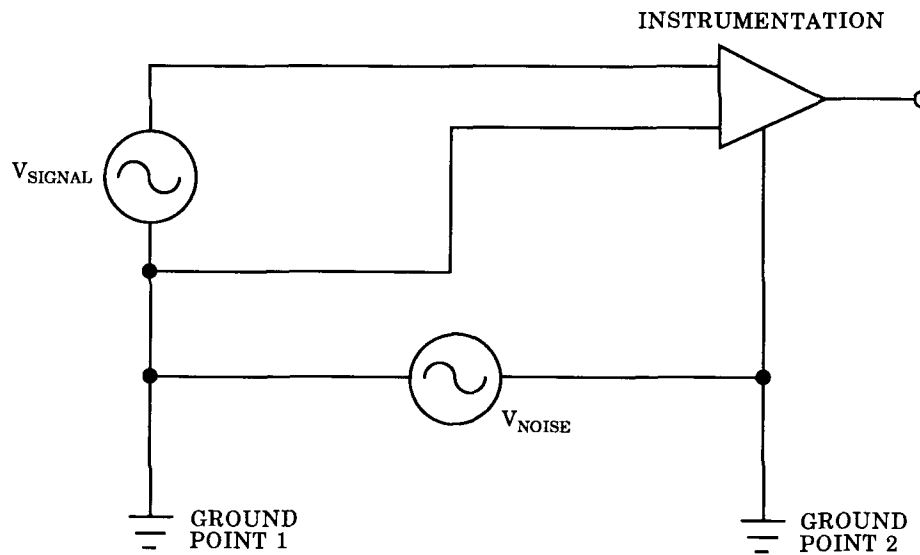


Figure 3—Example of common impedance coupling (ground loop)

4.2.3 Capacitive coupling (electric)

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

$$I = C \, de/dt \quad (3)$$

where:

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

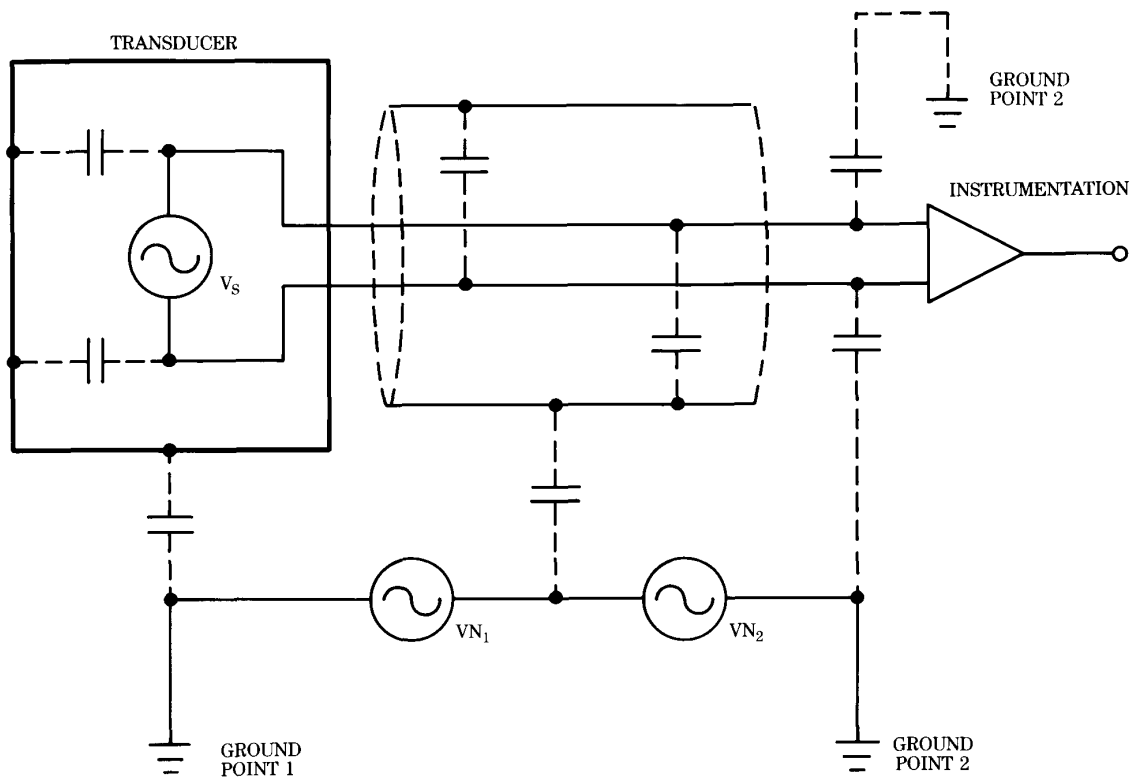


Figure 4—Example of capacitive coupling

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

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

4.2.4 Inductive coupling

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

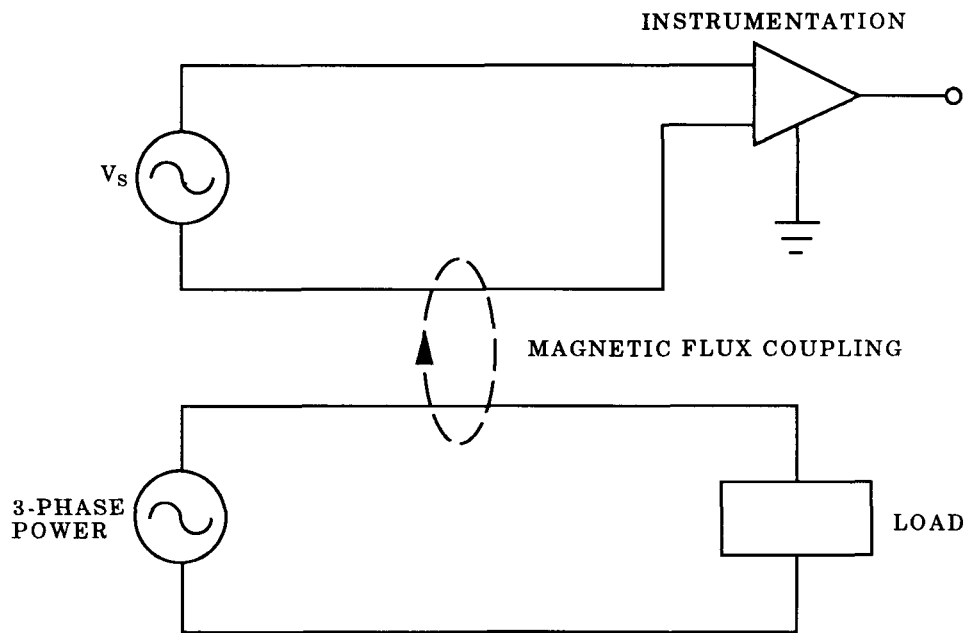


Figure 5—Example of inductive coupling

When a current change occurs in one of these circuits, a changing electromagnetic field through the area of its loop is produced. A voltage will be induced when some of this magnetic flux passes through a second circuit. The amplitude of the induced voltage is directly proportional to the area of the second circuit which encloses the flux from the disturbing circuit. The induced voltage is determined from Equation (4):

$$E = M \, di/dt \quad (4)$$

where:

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

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

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

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

4.2.5 Radiation coupling

This type of coupling is also known as electromagnetic or radio wave coupling. High-frequency signals produced by an external source may transfer a significant amount of energy to the control circuit by radiation of an electromagnetic wave and coupling through unintentional antennas. Even though the interference fre-

quencies may be much higher than those to which the control circuit will normally respond, they can become troublesome if they are modulated at the source by switching or by the ac power frequency or its harmonics and then picked up and non-linearly demodulated or rectified by the control circuit. This process of pickup and demodulation can produce additional harmonically related spurious signals in the victim instrument or control circuit. This circuit may then become a local re-radiation source of the EMI at the fundamental or harmonically-related frequency from antenna effects of the victim circuit's wiring.

4.2.6 Interference modes

4.2.6.1 Common-mode interference

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

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

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

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

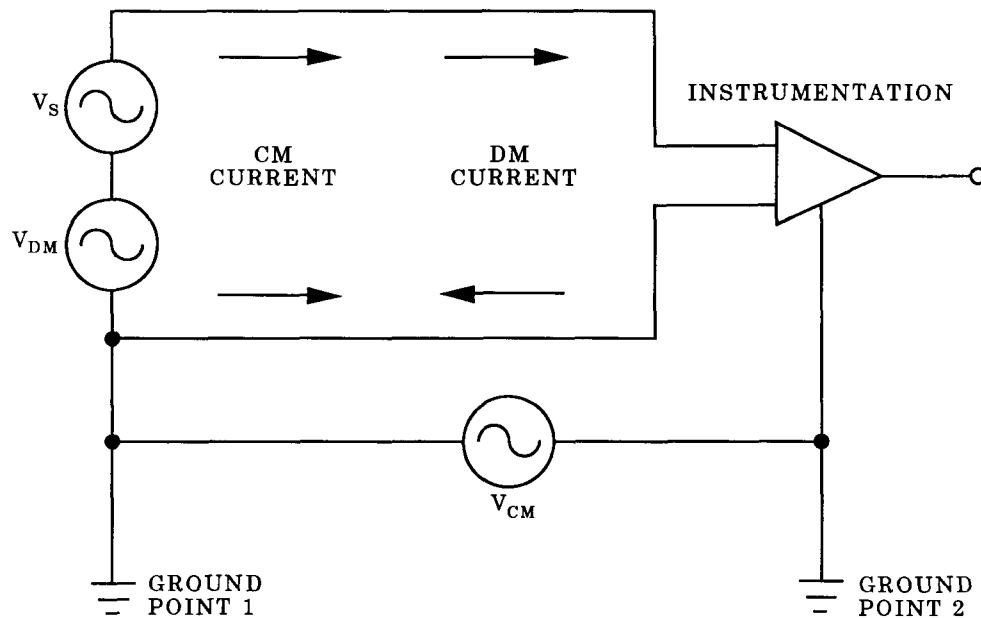


Figure 6—Example of common and differential-mode interference

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

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

4.2.6.2 Differential-mode (DM) interference

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

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

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