PART I
EMC Theory

1 Electromagnetic Compatibility

1.1 INTRODUCTION

The widespread use of electronic circuits for communication, computation, automation, and other purposes makes it necessary for diverse circuits to operate in close proximity to each other. All too often, these circuits affect each other adversely. Electromagnetic interference (EMI) has become a major problem for circuit designers, and it is likely to become even more severe in the future. The large number of electronic devices in common use is partly responsible for this trend. In addition, the use of integrated circuits and large-scale integration has reduced the size of electronic equipment. As circuitry has become smaller and more sophisticated, more circuits are being crowded into less space, which increases the probability of interference. In addition, clock frequencies have increased dramatically over the years—in many cases to over a gigahertz. It is not uncommon today for personal computers used in the home to have clock speeds in excess of 1 GHz.

Today's equipment designers need to do more than just make their systems operate under ideal conditions in the laboratory. Besides that obvious task, products must be designed to work in the "real world," with other equipment nearby, and to comply with government electromagnetic compatibility (EMC) regulations. This means that the equipment should not be affected by external electromagnetic sources and should not itself be a source of electromagnetic noise that can pollute the environment. Electromagnetic compatibility should be a major design objective.

1.2 NOISE AND INTERFERENCE

Noise is any electrical signal present in a circuit other than the desired signal. This definition excludes the distortion products produced in a circuit due to nonlinearities. Although these distortion products may be undesirable, they are not considered noise unless they are coupled into another part of the circuit. It follows that a desired signal in one part of a circuit can be considered to be noise when coupled to some other part of the circuit.

Electromagnetic Compatibility Engineering, by Henry W. Ott

Noise sources can be grouped into the following three categories: (1) intrinsic noise sources that arise from random fluctuations within physical systems, such as thermal and shot noise; (2) man-made noise sources, such as motors, switches, computers, digital electronics, and radio transmitters; and (3) noise caused by natural disturbances, such as lightning and sunspots.

Interference is the undesirable effect of noise. If a noise voltage causes improper operation of a circuit, it is interference. Noise cannot be eliminated, but interference can. Noise can only be reduced in magnitude, until it no longer causes interference.

1.3 DESIGNING FOR ELECTROMAGNETIC COMPATIBILITY

Electromagnetic compatibility (EMC) is the ability of an electronic system to (1) function properly in its intended electromagnetic environment and (2) not be a source of pollution to that electromagnetic environment. The electromagnetic environment is composed of both radiated and conducted energy. EMC therefore has two aspects, emission and susceptibility.

Susceptibility is the capability of a device or circuit to respond to unwanted electromagnetic energy (i.e., noise). The opposite of susceptibility is *immunity*. The immunity level of a circuit or device is the electromagnetic environment in which the equipment can operate satisfactorily, without degradation, and with a defined margin of safety. One difficulty in determining immunity (or susceptibility) levels is defining what constitutes performance degradation.

Emission pertains to the interference-causing potential of a product. The purpose of controlling emissions is to limit the electromagnetic energy emitted and thereby to control the electromagnetic environment in which other products must operate. Controlling the emission from one product may eliminate an interference problem for many other products. Therefore, it is desirable to control emission in an attempt to produce an electromagnetically compatible environment.

To some extent, susceptibility is self-regulating. If a product is susceptible to the electromagnetic environment, the user will become aware of it and may not continue to purchase that product. Emission, however, tends not to be self-regulating. A product that is the source of emission may not itself be affected by that emission. To guarantee that EMC is a consideration in the design of all electronic products, various government agencies and regulatory bodies have imposed EMC regulations that a product must meet before it can be marketed. These regulations control allowable emissions and in some cases define the degree of immunity required.

EMC engineering can be approached in either of two ways: one is the *crisis approach*, and the other is the *systems approach*. In the crisis approach, the designer proceeds with a total disregard of EMC until the functional design is finished, and testing—or worse yet—field experience suggests that a problem

exists. Solutions implemented at this late stage are usually expensive and consist of undesirable "add ons." This is often referred to as the "Band Aid" approach.

As equipment development progresses from design to testing to production, the variety of noise mitigation techniques available to the designer decreases steadily. Concurrently, cost goes up. These trends are shown in Fig. 1-1. Early solutions to interference problems, therefore, are usually the best and least expensive.

The systems approach considers EMC throughout the design; the designer anticipates EMC problems at the beginning of the design process, finds the remaining problems in the breadboard and early prototype stages, and tests the final prototypes for EMC as thoroughly as possible. This way, EMC becomes an integral part of the electrical, mechanical, and in some cases, software/firmware design of the product. As a result, EMC is designed into—and not added onto—the product. This approach is the most desirable and cost effective.

If EMC and noise suppression are considered for one stage or subsystem at a time, when the equipment is initially being designed, the required mitigation techniques are usually simple and straightforward. Experience has shown that when EMC is handled this way, the designer should be able to produce equipment with 90% or more of the potential problems eliminated prior to initial testing.

A system designed with complete disregard for EMC will almost always have problems when testing begins. Analysis at that time, to find which of the many possible noise path combinations are contributing to the problem, may not be simple or obvious. Solutions at this late stage usually involve the addition of extra components that are not integral parts of the circuit. Penalties paid include the added engineering and testing costs, as well as the cost of the

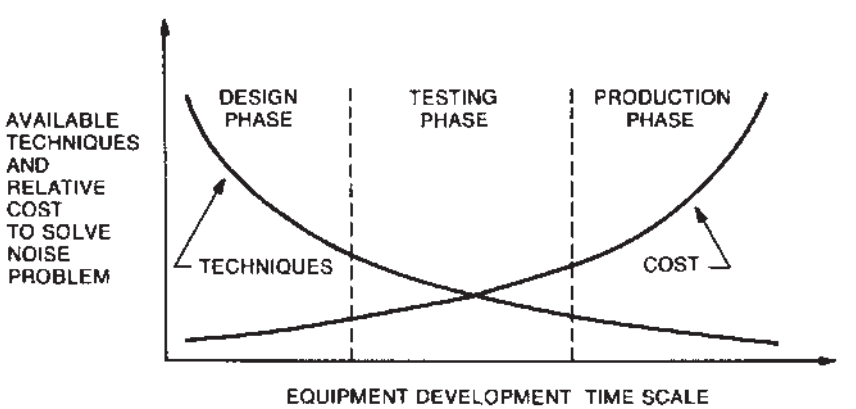

FIGURE 1-1. As equipment development proceeds, the number of available noise-reduction techniques goes down. At the same time, the cost of noise reduction goes up.

mitigation components and their installation. There also may be size, weight, and power dissipation penalties.

1.4 ENGINEERING DOCUMENTATION AND EMC

As the reader will discover, much of the information that is important for electromagnetic compatibility is not conveyed conveniently by the standard methods of engineering documentation, such as schematics, and so on. For example, a ground symbol on a schematic is far from adequate to describe where and how that point should be connected. Many EMC problems involve parasitics, which are not shown on our drawings. Also, the components shown on our engineering drawings have remarkably ideal characteristics.

The transmission of the standard engineering documentation alone is therefore insufficient. Good EMC design requires cooperation and discussion among the complete design team, the systems engineer, the electrical engineer, the mechanical engineer, the EMC engineer, the software/firmware designer, and the printed circuit board designer.

In addition, many computer-assisted design (CAD) tools do not include sufficient, if any, EMC considerations. EMC considerations therefore must often be applied manually by overriding the CAD system. Also, you and your printed circuit designer often have different objectives. Your objective is, or should be, to design a system that works properly and meets EMC requirements. Your printed circuit board (PCB) designer has the objective of doing what ever has to be done to fit all the components and traces on the board regardless of the EMC implications.

1.5 UNITED STATES' EMC REGULATIONS

Added insight into the problem of interference, as well as the obligations of equipment designers, manufacturers, and users of electronic products, can be gained from a review of some of the more important commercial and military EMC regulations and specifications.

The most important fact to remember about EMC regulations is that they are "living documents" and are constantly being changed. Therefore, a 1-year-old version of a standard or regulation may no longer be applicable. When working on a new design project, always be sure to have copies of the most recent versions of the applicable regulations. These standards may actually even change during the time it takes to design the product.

1.5.1 FCC Regulations

In the United States, the Federal Communications Commission (FCC) regulates the use of radio and wire communications. Part of its responsibility

concerns the control of interference. Three sections of the FCC Rules and Regulations* have requirements that are applicable to nonlicensed electronic equipment. These requirements are contained in Part 15 for radio frequency devices; Part 18 for industrial, scientific, and medical (ISM) equipment; and Part 68 for terminal equipment connected to the telephone network.

Part 15 of the FCC Rules and Regulations sets forth technical standards and operational requirements for radio frequency devices. *A radio-frequency device is any device that in its operation is capable of emitting radio-frequency energy by radiation, conduction, or other means (§ 2.801)*. The radio-frequency energy may be emitted intentionally or unintentionally. Radio-frequency (rf) energy is defined by the FCC as any electromagnetic energy in the frequency range of 9 kHz to 3000 GHz (§15.3(u)). The Part 15 regulations have a twofold purpose: (1) to provide for the operation of low-power transmitters without a radio station license and (2) to control interference to authorized radio communications services that may be caused by equipment that emits radio-frequency energy or noise as a by-product to its operation. Digital electronics fall into the latter category.

Part 15 is organized into six parts. Subpart A—General, Subpart B—Unintentional Radiators, Subpart C—Intentional Radiators, Subpart D—Unlicensed Personal Communications Devices, Subpart E—Unlicensed National Information Infrastructure Devices, and Subpart F—Ultra-Wideband Operation. Subpart B contains the EMC Regulations for electronic devices that are not intentional radiators.

Part 18 of the FCC Rules and Regulations sets forth technical standards and operational conditions for ISM equipment. ISM equipment is defined as any device that uses radio waves for industrial, scientific, medical, or other purposes (including the transfer of energy by radio) and that is neither used nor intended to be used for radio communications. Included are medical diathermy equipment, industrial heating equipment, rf welders, rf lighting devices, devices that use radio waves to produce physical changes in matter, and other similar noncommunications devices.

Part 68 of the FCC Rules and Regulations provides uniform standards for the protection of the telephone network from harm caused by connection of terminal equipment [including private branch exchange (PBX) systems] and its wiring, and for the compatibility of hearing aids and telephones to ensure that persons with hearing aids have reasonable access to the telephone network. Harm to the telephone network includes electrical hazards to telephone company workers, damage to telephone company equipment, malfunction of telephone company billing equipment, and degradation of service to persons other than the user of the terminal equipment, his calling or called party.

In December 2002, the FCC released a Report and Order (Docket 99-216) privatizing most of Part 68, with the exception of the requirements on hearing

* Code of Federal Regulations, Title 47, Telecommunications.

aid compatibility. Section 68.602 of the FCC rules authorized the Telecommunications Industry Association (TIA) to establish the Administrative Council for Terminal Attachments (ACTA) with the responsibility of defining and publishing technical criteria for terminal equipment connected to the U.S. public telephone network. These requirements are now defined in TIA-968. The legal requirement for all terminal equipment to comply with the technical standards, however, remains within Part 68 of the FCC rules. Part 68 requires that terminal equipment connected directly to the public switched telephone network meet both the criteria of Part 68 and the technical criteria published by ACTA.

Two approval processes are available to the manufacturer of telecommunications terminal equipment, as follows: (1) The manufacturer can provide a Declaration of Conformity (§68.320) and submit it to ACTA, or (2) the manufacturer can have the equipment certified by a Telecommunications Certifying Body (TCB) designated by the Commission (§68.160). The TCB must be accredited by the National Institute of Standards and Technology (NIST).

1.5.2 FCC Part 15, Subpart B

The FCC rule with the most general applicability is Part 15, Subpart B because it applies to virtually all digital electronics. In September 1979, the FCC adopted regulations to control the interference potential of digital electronics (at that time called "computing devices"). These regulations, "Technical Standards for Computing Equipment" (Docket 20780); amended Part 15 of the FCC rules relating to restricted radiation devices. The regulations are now contained in Part 15, Subpart B of Title 47 of the Code of Federal Regulations. Under these rules, limits were placed on the maximum allowable radiated emission and on the maximum allowable conducted emission on the alternating current (ac) power line. These regulations were the result of increasing complaints to the FCC about interference to radio and television reception where digital electronics were identified as the source of the interference. In this ruling the FCC stated the following:

> Computers have been reported to cause interference to almost all radio services, particularly those services below 200 MHz,* including police, aeronautical, and broadcast services. Several factors contributing to this include: (1) digital equipment has become more prolific throughout our society and are now being sold for use in the home; (2) technology has increased the speed of computers to the point where the computer designer is now working with radio frequency and electromagnetic interference (EMI) problems—something he didn't have to contend with 15 years ago; (3) modern production economics has replaced the steel cabinets which shield or reduce radiated emanations with plastic cabinets which provide little or no shielding.

* Remember this was 1979.

In the ruling, the FCC defined a digital device (previously called a computing device) as follows:

> An unintentional radiator (device or system) that generates and uses timing signals or pulses at a rate in excess of 9000 pulses (cycles) per second and uses digital techniques; inclusive of telephone equipment that uses digital techniques or any device or system that generates and uses radio frequency energy for the purpose of performing data processing functions, such as electronic computations, operations, transformations, recording, filing, sorting, storage, retrieval or transfer (§ 15.3(k)).

Computer terminals and peripherals, which are intended to be connected to a computer, are also considered to be digital devices.

This definition was intentionally broad to include as many products as possible. Thus, if a product uses digital circuitry and has a clock greater than 9 kHz, then it is a digital device under the FCC definition. This definition covers most digital electronics in existence today.

Digital devices covered by this definition are divided into the following two classes:

Class A: A digital device that is marketed for use in a commercial, industrial, or business environment (§ 15.3(h)).

Class B: A digital device that is marketed for use in a residential environment, notwithstanding use in commercial, business, and industrial environments (§ 15.3(i)).

Because Class B digital devices are more likely to be located in closer proximity to radio and television receivers, the emission limits for these devices are about 10 dB more restrictive than those for Class A devices.

Meeting the technical standards contained in the regulations is the obligation of the manufacturer or importer of a product. To guarantee compliance, the FCC requires the manufacturer to test the product for compliance before the product can be *marketed* in the United States. The FCC defines marketing as shipping, selling, leasing, offering for sale, importing, and so on (§ 15.803(a)). Until a product complies with the rules, it cannot legally be advertised or displayed at a trade show, because this would be considered an offer for sale. To advertise or display a product legally prior to compliance, the advertisement or display must contain a statement worded as follows:

> This device has not been authorized as required by the rules of the Federal Communications Commission. This device is not, and may not be, offered for sale or lease, or sold or leased, until authorization is obtained (§ 2.803(c)).

For personal computers and their peripherals (a subcategory of Class B), the manufacturer can demonstrate compliance with the rules by a Declaration of Conformity. A Declaration of Conformity is a procedure where the manufacturer makes measurements or takes other steps to ensure that the equipment

complies with the applicable technical standards (§ 2.1071 to 2.1077). Submission of a sample unit or representative test data to the FCC is not required unless specifically requested.

For all other products (Class A and Class B—other than personal computers and their peripherals), the manufacturer must verify compliance by testing the product before marketing. *Verification* is a self-certification procedure where nothing is submitted to the FCC unless specifically requested by the Commission, which is similar to a declaration of conformity (§ 2.951 to 2.956). Compliance is by random sampling of products by the FCC. The time required to do the compliance tests (and to fix the product, and redo the test if the product fails) should be scheduled into the product's development timetable. Precompliance EMC measurements (see Chapter 18) can help shorten this time considerably.

Testing must be performed on a sample that is representative of production units. This usually means an early production or preproduction model. Final compliance testing must therefore be one of the last items in the product development timetable. This is no time for unexpected surprises! If a product fails the compliance test, then changes at this point are difficult, time consuming, and expensive. Therefore, it is desirable to approach the final compliance test with a high degree of confidence that the product will pass. This can be done if (1) proper EMC design principles (as described in this book) have been used throughout the design and (2) preliminary pre-compliance EMC testing as described in Chapter 18 was performed on early models and subassemblies.

It should be noted that the limits and the measurement procedures are interrelated. The derived limits were based on specified test procedures. Therefore, compliance measurements must be made following the procedure outlined by the regulations (§ 15.31). The FCC specifies that for digital devices, measurements to show compliance with Part 15, must be performed following the procedures described in measurement standard ANSI C63.4–1992 titled "Methods of Measurement of Radio-Noise Emissions from Low-Voltage Electrical and Electronic Equipment in the Range of 9 kHz to 40 GHz," excluding Section 5.7, Section 9, and Section 14 (§ 15.31(a)(6)).*

The test must be made on a complete system, with all cables connected and configured in a reasonable way that tends to maximize the emission (§ 15.31(i)). Special authorization procedures are provided in the case of central processor unit (CPU) boards and power supplies that are used in personal computers and sold separately (§ 15.32).

* Section 5.7 pertains to the use of an artificial hand to support handheld devices during testing. Section 9 pertains to measuring radio-noise power using an absorbing clamp in lieu of radiated emission measurements for certain restricted frequency ranges and certain types of equipment. Section 14 pertains to relaxing the radiated and/or conducted emission limits for short duration ($\leq$200 ms) transients.

1.5.3 Emissions

The FCC Part 15 EMC Regulations limit the maximum allowable conducted emission, on the ac power line in the range of 0.150 to 30 MHz, and the maximum radiated emission in the frequency range of 30 MHz to 40 GHz.

1.5.3.1 Radiated Emissions. For radiated emissions, the measurement procedure specifies an open area test site (OATS) or equivalent measurement made over a ground plane with a tuned dipole or other correlatable, linearly polarized antenna. This setup is shown in Fig. 1-2. ANSI C63.4 allows for the use of an alternative test site, such as an absorber-lined room, provided it meets specified site attenuation requirements. However, a shielded enclosure without absorber lining may not be used for radiated emission measurements.

The specified receive antenna in the 30- to- 1000-MHz range is a tuned dipole, although other linearly polarized broadband antennas may also be used. However, in case of a dispute, data taken with the tuned dipole will take precedence. Above 1000 MHz, a linearly polarized horn antenna shall be used.

Table 1-1 lists the FCC radiated emission limits (§ 15.109) for a Class A product when measured at a distance of 10 m. Table 1-2 lists the limits for a Class B product when measured at a distance of 3 m.

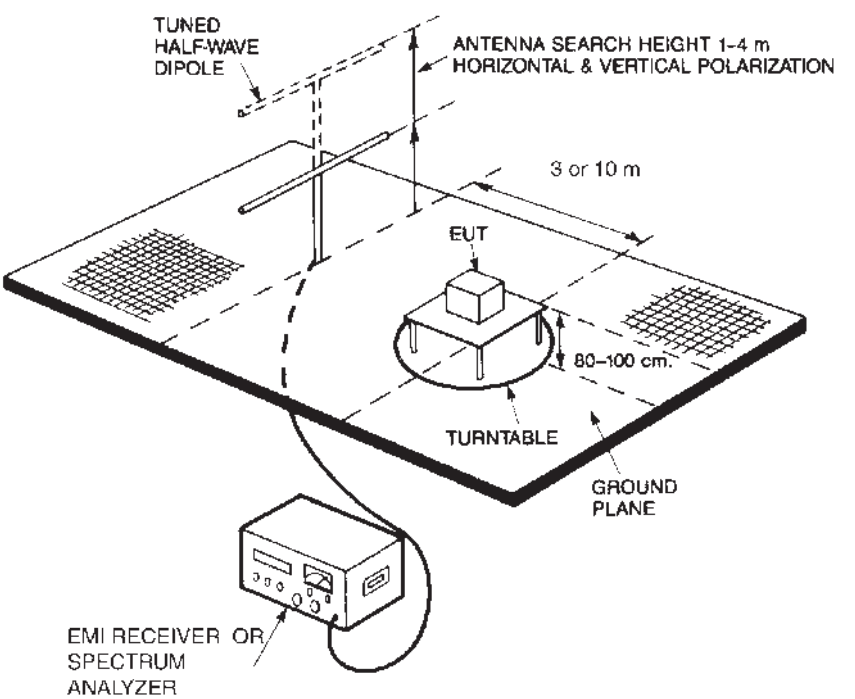

FIGURE 1-2. Open area test site (OATS) for FCC radiated emission test. The equipment under test (EUT) is on the turntable.

TABLE 1-1. FCC Class A Radiated Emission Limits Measured at 10 m.

Frequency (MHz)	Field Strength (μV/m)	Field Strength (dB μV/m)
30–88	90	39.0
88–216	150	43.5
216–960	210	46.5
>960	300	49.5

TABLE 1-2. FCC Class B Radiated Emission Limits Measured at 3 m.

Frequency (MHz)	Field Strength (μV/m)	Field Strength (dB μV/m)
30–88	100	40.0
88–216	150	43.5
216–960	200	46.0
>960	500	54.0

TABLE 1-3. FCC Class A and Class B Radiated Emission Limits Measured at 10 m.

Frequency (MHz)	Class A Limit (μV/m)	Class B Limit (dB μV/m)
30–88	39.0	29.5
88–216	43.5	33.0
216–960	46.5	35.5
>960	49.5	43.5

A comparison between the Class A and Class B limits must be done at the same measuring distance. Therefore, if the Class B limits are extrapolated to a 10-m measuring distance (using a 1/d extrapolation), the two sets of limits can be compared as shown in Table 1-3. As can be observed, the Class B limits are more restrictive by about 10 dB below 960 MHz and 5 dB above 960 MHz. A plot of both FCC Class A and Class B radiated emission limits over the frequency range of 30 MHz to 1000 MHz (at a measuring distance of 10 m) is shown in Fig. 1-5.

The frequency range over which radiated emission tests must be performed is from 30 MHz up to the frequency listed in Table 1-4, which is based on the highest frequency that the equipment under test (EUT) generates or uses.

1.5.3.2 Conducted Emissions. Conducted emission regulations limit the voltage that is conducted back onto the ac power line in the frequency range of 150 kHz to 30 MHz. Conducted emission limits exist because regulators believes

TABLE 1-4. Upper Frequency Limit for Radiated Emission Testing.

Maximum Frequency Generated or Used in the EUT (MHz)	Maximum Measurement Frequency (GHz)
<108	1
108–500	2
500–1000	5
>1000	5^{th} Harmonic or 40 GHz, whichever is less

TABLE 1-5. FCC/CISPR Class A Conducted Emission Limits.

Frequency (MHz)	Quasi-peak (dB μV)	Average (dB μV)
0.15–0.5	79	66
0.5–30	73	60

TABLE 1-6. FCC/CISPR Class B Conducted Emission Limits.

Frequency (MHz)	Quasi-peak (dB μV)	Average (dB μV)
0.15–0.5	66–56[a]	56–46[a]
0.5–5	56	46
5–30	60	50

[a]Limit decreases linearly with log of frequency.

that at frequencies below 30 MHz, the primary cause of interference with radio communications occurs by conducting radio-frequency energy onto the ac power line and subsequently radiating it from the power line. Therefore, conducted emission limits are really radiated emission limits in disguise.

The FCC conducted emission limits (§ 15.107) are now the same as the International Special Committee on Radio Interference (CISPR, from its title in French) limits, used by the European Union. This is the result of the Commission amending its conducted emission rules in July 2002 to make them consistent with the international CISPR requirements.

Tables 1-5 and 1-6 show the Class A and Class B conducted emission limits, respectively. These voltages are measured common-mode (hot to ground and neutral to ground) on the ac power line using a 50-Ω/50-μH line impedance stabilization network (LISN) as specified in the measurement procedures.* Figure 1-3 shows a typical FCC conducted emission test setup.

* The circuit of an LISN is shown in Fig. 13-2.

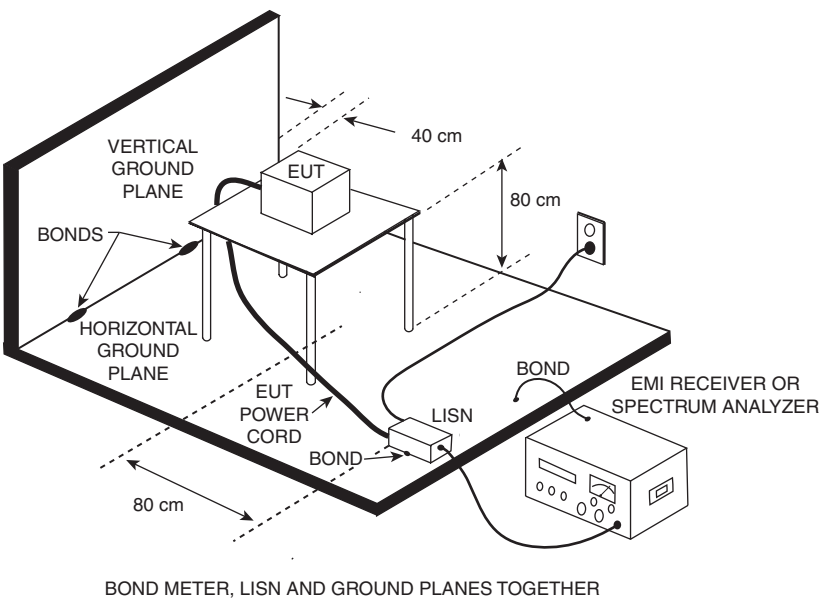

FIGURE 1-3. Test setup for FCC conducted emission measurements.

A comparison between Tables 1-5 and 1-6 shows that the Class B quasi-peak conducted emission limits are from 13 dB to 23 dB more stringent than the Class A limits. Note also that both peak and average measurements are required. The peak measurements are representative of noise from narrowband sources such as clocks, whereas the average measurements are representative of broadband noise sources. The Class B average conducted emission limits are from 10 to 20 dB more restrictive than the Class A average limits.

Figure 1-4 shows a plot of both the average and the quasi-peak FCC/CISPR conducted emission limits.

1.5.4 Administrative Procedures

The FCC rules not only specify the technical standards (limits) that a product must satisfy but also the administrative procedures that must be followed and the measuring methods that must be used to determine compliance. Most administrative procedures are contained in Part 2, Subpart I (Marketing of Radio Frequency Devices), Subpart J (Equipment Authorization Procedures), and Subpart K (Importation of Devices Capable of Causing Harmful Interference) of the FCC Rules and Regulations.

Not only must a product be tested for compliance with the technical standards contained in the regulations, but also it must be labeled as compliant (§ 15.19), and information must be provided to the user (§ 15.105) on its interference potential.

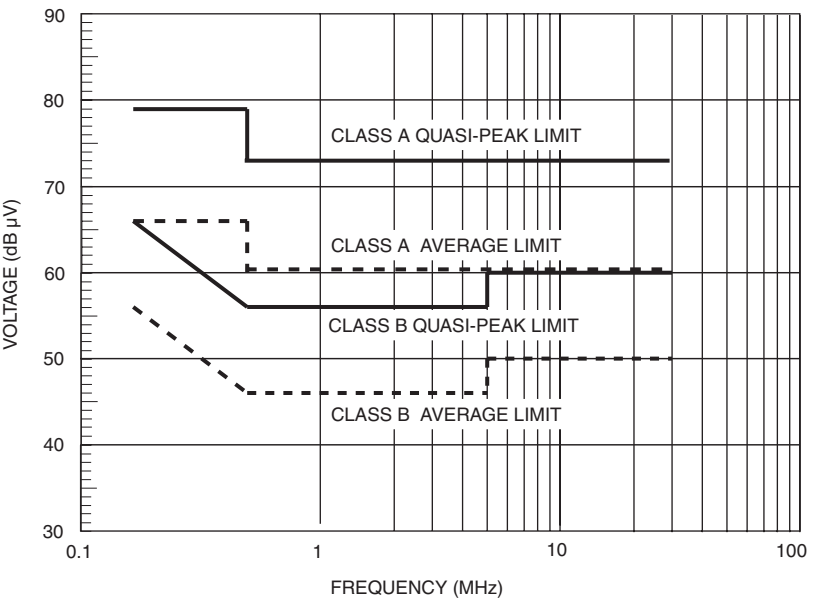

FIGURE 1-4. FCC/CISPR conducted emission limits.

In addition to the technical standards mentioned above, the rules also contain a noninterference requirement, which states that if use of the product causes harmful interference, the *user* may be required to cease operation of the device (§ 15.5). Note the difference in responsibility between the technical standards and the noninterference requirement. Although meeting the technical standards (limits) is the responsibility of the manufacturer or importer of the product, satisfying the noninterference requirement is the responsibility of the user of the product.

In addition to the initial testing to determine compliance of a product, the rules also specify that the manufacturer or importer is responsible for the continued, or ongoing, compliance of subsequently manufactured units (§ 2.953, 2.955, 2.1073, 2.1075).

If a change is made to a compliant product, the manufacturer has the responsibility to determine whether that change has an effect on the compliance of the product. The FCC has cautioned manufacturers (Public Notice 3281, April 7, 1982) to note that:

> Many changes, which on their face seem insignificant, are in fact very significant. Thus a change in the layout of a circuit board, or the addition or removal or even rerouting of a wire, or even a change in the logic will almost surely change the emission characteristics of the device. Whether this change in characteristics is enough to throw the product out of compliance can best be determined by retesting.

As of this writing (September 2008), the FCC has exempted eight subclasses of digital devices (§ 15.103) from meeting the technical standards of the rules. These are as follows:

1. Digital devices used exclusively in a transportation vehicle such as a car, plane, or boat.
2. Industrial control systems used in an industrial plant, factory, or public utility.
3. Industrial, commercial, or medical test equipment.
4. Digital devices exclusively used in an appliance such as a microwave oven, dishwasher, clothes dryer, air conditioner, and so on.
5. Specialized medical devices generally used at the direction or under the supervision of a licensed health care practitioner, whether used in a patient's home or a health care facility. Note, medical devices marketed through retail channels for use by the general public, are not exempted.
6. Devices with power consumption not exceeding 6 nW, for example, a digital watch.
7. Joystick controllers or similar devices (such as a mouse) that contain no digital circuitry. Note, a simple analog to digital converter integrated circuit (IC) is allowed in the device.
8. Devices in which the highest frequency is below 1.705 MHz and that does not operate from the ac power line, or contain provisions for operation while connected to the ac power line.

Each of the above exempted devices is, however, still subject to the noninterference requirement of the rules. If any of these devices actually cause harmful interference in use, the user must stop operating the device or in some way remedy the interference problem. The FCC also states, although not mandatory, it is strongly recommended that the manufacturer of an exempted device endeavor to have that device meet the applicable technical standards of Part 15 of the rules.

Because the FCC has purview over many types of electronic products, including digital electronics, design and development organizations should have a complete and current set of the FCC rules applicable to the types of products they produce. These rules should be referenced during the design to avoid subsequent embarrassment when compliance demonstration is required.

The complete set of the FCC rules is contained in the Code of Federal Regulations, Title 47 (Telecommunications)—Parts 0 to 300. They consist of five volumes and are available from the Superintendent of Documents, U.S. Government Printing Office. The FCC rules are in the first volume that contains Parts 0 to 19 of the Code of Federal Regulations. A new edition is published in the spring of each year and contains all current regulations codified as of October 1 of the previous year. The Regulations are also available online at the FCC's website, www.fcc.gov.

When changes are made to the FCC regulations, there is a transition period before they become official. This transition period is usually stated as x-number of days after the regulation is published in the Federal Register.

1.5.5 Susceptibility

In August 1982, the U.S. Congress amended the Communications Act of 1934 (House Bill #3239) to give the FCC authority to regulate the susceptibility of home electronics equipment and systems. Examples of home electronics equipment are radio and television sets, home burglar alarm and security systems, automatic garage door openers, electronic organs, and stereo/high-fidelity systems. Although this legislation is aimed primarily at home entertainment equipment and systems, it is not intended to prevent the FCC from adopting susceptibility standards for devices that are also used outside the home. To date, however, the FCC has not acted on this authority. Although it published an inquiry into the problem of Radio Frequency Interference to Electronic Equipment in 1978 (General Docket No. 78-369), the FCC relies on self-regulation by industry. Should industry become lax in this respect, the FCC may move to exercise its jurisdiction.

Surveys of the electromagnetic environment (Heirman 1976, Janes 1977) have shown that a field strength greater than 2 V/m occurs about 1% of the time. Because no legal susceptibility requirements exist for commercial equipment in the United States, a reasonable minimum immunity level objective might be 2 to 3 V/m. Clearly products with susceptibility levels of less than 1 V/m are not well designed and are very likely to experience interference from rf fields during their life span.

In 1982, the government of Canada released an Electromagnetic Compatibility Advisory Bulletin (EMCAB-1) that defined three levels, or grades, of immunity for electronic equipment, and stated the following:

1. Products that meet GRADE 1 (1 V/m) are likely to experience performance degradation.
2. Products that meet GRADE 2 (3 V/m) are unlikely to experience degradation.
3. Products that meet GRADE 3 (10 V/m) should experience performance degradation only under very arduous circumstances.

In June 1990, an updated version of EMCAB-1 was issued by Industry Canada. This updated version concludes that products located in populated areas can be exposed to field strengths that range from 1 V/m to 20 V/m over most of the frequency band.

1.5.6 Medical Equipment

Most medical equipment (other than what comes under the Part 18 Rules) is exempt from the FCC Rules. The Food and Drug Administration (FDA), not

the FCC, regulates medical equipment. Although the FDA developed EMC standards, as early as 1979 (MDS-201-0004, 1979), they have never officially adopted them as mandatory. Rather, they depend on their inspectors' guideline document to assure that medical devices are properly designed to be immune to electromagnetic interference (EMI). This document, *Guide to Inspections of Electromagnetic Compatibility Aspects of Medical Devices Quality Systems*, states the following:

> At this time the FDA does not require conformance to any EMC standards. However, EMC should be addressed during the design of new devices, or redesign of existing devices.

However, the FDA is becoming increasingly concerned about the EMC aspects of medical devices. Inspectors are now requiring assurance from manufacturers that they have addressed EMC concerns during the design process, and that the device will operate properly in its intended electromagnetic environment. The above-mentioned Guide encourages manufacturers to use IEC 60601-1-2 Medical Equipment, Electromagnetic Compatibility Requirements and Tests as their EMC standard. IEC 60601-1-2 provides limits for both emission and immunity, including transient immunity such as electrostatic discharge (ESD).

As a result, in most cases, IEC 60601-1-2 has effectively become the unofficial, de facto, EMC standard that has to be met for medical equipment in the United States.

1.5.7 Telecom

In the United States, telecommunications central office (network) equipment is exempt from the FCC Part 15 Rules and Regulations as long as it is installed in a dedicated building or large room owned or leased by the telephone company. If it is installed in a subscriber's facility, such as an office or commercial building, the exemption does not apply and the FCC Part 15 Rules are applicable.

Telecordia's (previously Bellcore's) GR-1089 is the standard that usually applies to telecommunications network equipment in the United States. GR-1089 covers both emission and susceptibility, and it is somewhat similar to the European Union's EMC requirements. The standard is often referred to as the NEBS requirements. NEBS stands for New Equipment Building Standard. The standard is derived from the original AT&T Bell System internal NEBS standard.

These standards are not mandatory legal requirements but are contractual between the buyer and the seller. As such, the requirements can be waived or not applied in some cases.

1.5.8 Automotive

As stated, much (although not all) of the electronics built into transportation vehicles are exempt from EMC regulation, such as the FCC Part 15 Rules, in the United States (§ 15.103). This does not mean that vehicle systems do not have legal EMC requirements. In many regions of the world, there are legislated requirements for vehicle electromagnetic emissions and immunity. The legislated requirements are typically based on many internationally recognized standards, including CISPR, International Organization for Standardization (ISO), and the Society of Automotive Engineers (SAE). Each of these organizations has published several EMC standards applicable to the automotive industry. Although these standards are voluntary, the automotive manufacturers either rigorously apply them or use these standards as a reference in the development of their own corporate requirements. These developed corporate requirements may include both component and vehicle level items and are often based upon the customer satisfaction goals of the manufacturer—therefore, they almost have the effect of mandatory standards.

For example, SAE J551 is a vehicle-level EMC standard, and SAE J1113 is a component-level EMC standard applicable to individual electronic modules. Both standards cover emissions and immunity and are somewhat similar to the military EMC standards.

The resulting vehicle EMC standards cover both emissions and immunity and are some of the toughest EMC standards in the world, partly because of the combination of types of systems on vehicles and their proximity to each other. These systems include high-voltage discharges (such as spark ignition systems) located near sensitive entertainment radio receiver systems, wiring for inductive devices such as motors and solenoids in the same wiring harness as data communication lines, and with the newer "hybrid vehicles" high-current motor drive systems that operate at fast switching speeds. The radiated emission standards are typically 40 dB more stringent than the FCC Class B limits. Radiated immunity tests are specified up to an electric field strength of 200 V/m (or in some cases higher) as compared with 3 or 10 V/m for most non-automotive commercial immunity standards.

In the European Union, vehicles and electronic equipment intended for use in these vehicles are exempt from the EMC Directive (204/108/EC), but they do fall within the scope of the automotive directive (95/54/EC) that contains EMC requirements.

1.6 CANADIAN EMC REQUIREMENTS

The Canadian EMC regulations are similar to those of the United States. The Canadian regulations are controlled by Industry Canada. Table 1-7 lists the Canadian EMC standards applicable to various types of products. These standards can be accessed from the Industry Canada web page (www.ic.gc.ca).

TABLE 1-7. Canadian EMC Test Standards.

Equipment Type	Standard
Information technology equipment (ITE)[a]	ICES–003
Industrial, Scientific & Medical Equipment (ISM)	ICES–001
Terminal Equipment Connected to the Telephone Network	CS–03

[a]Digital Equipment.

The ITE and ISM standards can be accessed from the Industry Canada home page by following the following links: A-Z Index/Spectrum Management and Telecommunications/Official Publications/Standards/Interference-Causing Equipment Standards (ICES). The telecom standard can be accessed from the Industry Canada home page by following the following links: A-Z Index/Spectrum Management and Telecommunications/Official Publications/Standards/Terminal Equipment-Technical Specifications List.

The methods of measurement and actual limits for ITE are contained in CAN/CSA-CEI/IEC CISPR 22:02, Limits and Methods of Measurement of Radio Disturbance Characteristics of Information Technology Equipment.

To reduce the burden on U.S. and Canadian manufacturers, the United States and Canada have a mutual recognition agreement whereby each country agrees to accept test reports from the other country for equipment authorization purposes (FCC Public Notice 54795, July 12, 1995).

1.7 EUROPEAN UNION'S EMC REQUIREMENTS

In May 1989, the European Union (EU) published a directive (89/336/EEC) relating to electromagnetic compatibility, which was to be effective January 1, 1992. However, the European Commission underestimated the task of implementing the directive. As a result, the European Commission amended the directive in 1992 allowing for a 4-year transition period and requiring full implementation of the EMC directive by January 1, 1996.

The European EMC directive differs from the FCC regulations by including immunity requirements in addition to emission requirements. Another difference is that the directive, without exception, covers all electrical/electronic equipment. There are no exemptions—the EMC directive even covers a light bulb. The directive does, however, exclude equipment that is covered by another directive with EMC provisions, such as the automotive directive. Another example would be medical equipment, which comes under the medical directive (93/42/EEC) not the EMC directive.

1.7.1 Emission Requirements

As stated, the EU's conducted emission requirements are now the same as the FCC's (see Tables 1-5 and 1-6 as well as Fig. 1-4). The radiated emission

TABLE 1-8. CISPR Radiated Emission Limits at 10 m.

Frequency (MHz)	Class A Limit (dB μV/m)	Class B Limit (dB μV/m)
30–230	40	30
230–1000	47	37

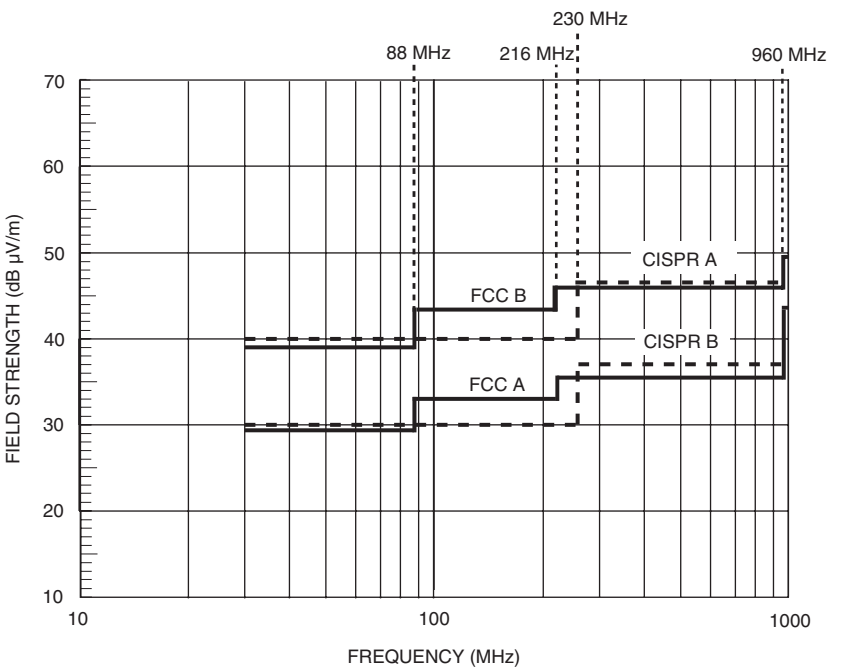

FIGURE 1-5. Comparison of FCC and CISPR radiated emission limits, measured at a distance of 10 m.

standards are similar but not exactly the same. Table 1-8 shows the European Union's Class A and Class B radiated emission limits when measured at 10 m.

Figure 1-5 compares the EU's radiated emission standard with the current FCC standard over the frequency range of 30 MHz to 1000 MHz. The FCC Class B limits have been extrapolated to a 10-m measuring distance for this comparison. As can be observed the European (CISPR) limits are more restrictive in the frequency range from 88 to 230 MHz. Below 88 MHz and above 230 MHz the CISPR and FCC limits are virtually the same (within 0.5 dB of each other). However, the EU has no radiated emission limit above 1 GHz, whereas the FCC limits, under some circumstances (see Table 1-4), go up to 40 GHz.

Table 1-9 is a composite worst-case combination of the FCC and CISPR radiated emission limits when measured at 10 m.

TABLE 1-9. Composite Worst-Case Radiated Emission Limits for Commercial Products, Measured at a Distance of 10 m.

Frequency (MHz)	Class A Limit (dB μV/m)	Class B Limit (dB μV/m)
30–230	39	29.5
230–1000	46.5	35.5
>1000	49.5	43.5

1.7.2 Harmonics and Flicker

The EU has two additional emission requirements that relate to power quality issues—harmonics and flicker. These regulations apply to products that draw an input current of 16 A per phase or less and are intended to be connected to the public ac power distribution system. The FCC has no similar requirement.

The harmonic requirement (EN 61000-3-2) limits the harmonic content of the current drawn by the product from the ac power line, (see Table 18-3). The generation of harmonics is the result of the nonlinear behavior of the loads connected to the ac power line. Common nonlinear loads include switched-mode power supplies, variable-speed motor drives, and electronic ballasts for fluorescent lamps.

A major source of harmonics is a full-wave rectifier connected directly to the ac power line and followed by a large-value capacitor input filter. Under these circumstances, current is only drawn from the power line when the input voltage exceeds that on the filter capacitor. As a result, current is drawn from the power line only on the peaks of the ac voltage waveform (see Fig. 13-4). The resultant current waveshape is rich in odd harmonics (third, fifth, seventh, etc.). Total harmonic distortion (THD) values of 70% to 150% are not uncommon under these circumstances.

The number of harmonics present is determined by the rise and fall time of the current pulse, and their magnitude by the current wave shape. Most switching power supplies (the exception is very low-power supplies) and variable-speed motor drives cannot meet this requirement without some kind of passive or active power factor correction circuitry.

To alleviate this problem, the ac input current pulse must be spread out over a larger portion of a cycle to reduce the harmonic content. Normally the THD of the current pulse must be reduced to 25% or less to be compliant with the EU regulations.

The flicker requirements (EN 61000-3-3) limit the transient ac power line current drawn by the product; see Table 18-4. The purpose of this requirement is to prevent lights from flickering, because it is perceived as being disturbing to people. The regulations are based on not providing a noticeable change in the illumination of a 60-W incandescent lamp powered off the same ac power supply as the equipment under test.

Because of the finite source impedance of the power line, the changing current requirements of equipment connected to the line produces corresponding voltage fluctuations on the ac power line. If the voltage variation is large enough, it will produce a perceptible change in lighting illumination. If the load changes are of sufficient magnitude and repetition rate, the resulting flickering of lights can be irritating and disturbing.

To determine an applicable limit, many people were subjected to light flicker to determine the irritability threshold. When the flicker rate is low (<1 per minute), the threshold of irritability is when the ac line voltage changes by 3%. People are most sensitive to light flicker when the rate is around 1000 times per minute. At a rate of 1000 times per minute, a 0.3% voltage change is just as irritating as a 3% change at less than one change per minute. Above about 1800 changes per minute, light flicker is no longer perceived.

Most EMC emission requirements are based on the magnitude of a measured parameter not exceeding a specified amount (the limit). However, flicker tests are different in that they require many measurements to be made and then a statistical analysis to be performed on the measured data to determine whether the limit is exceeded.

For most equipment, this requirement is not a problem because they naturally do not draw large transient currents off the ac power line. However, the requirement can be a problem for products that suddenly switch on heaters that draw large currents, or motors under a heavy load. An example would be when an air conditioner compressor or a large heater in a copy machine is suddenly switched on.

1.7.3 Immunity Requirements

The EU's immunity requirements cover radiated and conducted immunity, as well as transient immunity that include ESD, electrical fast transient (EFT), and surge.

The EFT requirement simulates noise generated by inductively switched loads on the ac power line. As a contactor is opened to an inductive load, an arc is formed that extinguishes and restarts many times. The surge requirement is intended to simulate the effect of a nearby lightning pulse.

In addition, the EU has susceptibility requirements that cover ac voltage dips, sags, and interruptions.

For additional information on these transient immunity and power line disturbance requirements, see Sections 14.3 and 14.4.

1.7.4 Directives and Standards

The European regulations consist of directives and standards. The directives are very general and are the legal requirements. The standards provide one way, but not the only way, to comply with the directive.

The EMC Directive 2004/108/EC (which superceded the original EMC Directive 89/336/EEC) defines the *essential requirements* for a product to be marketed in the EU. They are as follows:

1. The equipment must be constructed to ensure that any electromagnetic disturbance it generates allows radio and telecommunication equipment and other apparatus to function as intended.
2. The equipment must be constructed with an inherent level of immunity to externally generated electromagnetic disturbances.

These are the *only legal requirements* with respect to EMC and the requirements are vague. The directive provides for two methods of demonstrating compliance with its requirements. The most commonly used is by a declaration of conformity; the other option is the use of a technical construction file.

If a product is tested to and complies with the applicable EMC standards it is presumed to meet the requirements of the directive, and the manufacturer can produce a declaration of conformity attesting to that fact.

A declaration of conformity is a self-certification process in which the responsible party, manufacturer or importer, must first determine the applicable standards for the product, test the product to the standards, and issue a declaration declaring compliance with those standards and the EMC directive. The declaration of conformity can be a single-page document but must contain the following:

- Application of which council directives (all applicable directives)
- Standards used (including date of standard) to determine conformity
- Product name and model number, also serial numbers if applicable
- Manufacturer's name and address
- A dated declaration that the product conforms to the directives
- A signature by a person empowered to legally bind the manufacturer

The technical construction file approach to demonstrating conformity is unique to the European Union. The technical construction file is often used where no harmonized standards exist for the product and the manufacturer does not think that the generic standards are appropriate. In this case, the manufacturer produces a technical file to describe the procedures and tests used to ensure compliance with the EMC directive. The manufacturer can develop its own EMC specifications and test procedures. The manufacturer can decide how, where, when, or if, the product is tested for EMC. An independent *competent body*, however, must approve the technical construction file. The competent bodies are appointed by the individual states of the European Union, and the European Commission publishes a list of them in the Official Journal of the European Union. The competent body must agree that, using the manufacturer's procedures and tests, the product satisfies the essential

requirements of the EMC directive. This approach is acceptable, because in the European Union, the EMC directive is the legal document that must be satisfied, not the standards. In most other jurisdictions, the standards are the legal documents that must be complied with.

Products whose compliance with the EMC directive has been demonstrated by one of the above procedures shall be labeled with the *CE mark*. The CE mark consists of the lower case letters "ce" in a specified, distinctive font. Affixing the CE mark to a product indicates conformity to *all* applicable directives, not just the EMC directive. Other applicable directives might be, the safety directive, the toy directive, the machinery directive, and so on.

Two types of standards exist in the European Union: product specific and generic.* Product-specific standards always take precedence over generic standards. However, if no applicable product-specific standard exists for a product, the generic standards are then applicable. Emission and immunity requirements for a product are usually covered by different standards. Currently, over 50 different standards are associated with the EMC directive. Table 1-10 lists some of the more commonly applicable product-specific standards, as well as the four generic EMC standards. If a product-specific standard does not exist in a category, then the requirement defaults to the appropriate generic standard.

The EU's standards writing organization CENELEC (the European Committee for Electro-Technical Standardization) has been given the task of drawing up the corresponding technical specifications meeting the essential requirements of the EMC directive, compliance with which will provide a presumption of conformity with the essential requirements of the EMC

TABLE 1-10. European Union's EMC Test Standards.

Equipment Type	Emission	Immunity
Product Specific Standards		
Information Technology Equipment (ITE)	EN 55022	EN 55024
Industrial, Scientific & Medical Equipment (ISM)	EN 55011	–
Radio & Television Receivers	EN 55013	EN 55020
Household Appliances/Electric Tools	EN 55014-1	EN 55014-2
Lamps & Luminaries	EN 55015	EN 61547
Adjustable Speed Motor Drives	EN 61800-3	EN 61800-3
Medical Equipment[a]	EN 60601-1-2	EN 60601-1-2
Generic Standards		
Residential, Commercial, Light Industrial Environment	EN 61000-6-3	EN 61000-6-1
Heavy Industrial Environment	EN 61000-6-4	EN 61000-6-2

[a]Covered by the Medical Directive (93/42/EEC), not the EMC Directive

* A third type of standard also exists, which is a basic standard. Basic standards are usually test or measurement procedures and are referenced by the product-specific or generic standards.

directive. Such specifications are referred to as harmonized standards. Most CENELEC standards are derived from International Electro-Technical Committee (ITC) or CISPR standards—ITC for immunity standards and CISPR for emission standards. The CENELEC standards, or European Norms (EN), are not official until a reference to them is published in the "Official Journal of the European Union."

As new standards come into existence and existing standards are modified, as regularly happens, a transition period, usually of 2 years is specified in the standard. During the transition period, either the old standard or the new standard can be used to demonstrate compliance with the EMC directive.

The latest information on the EMC Directive 2004/108/EC and the harmonized standards can be obtained on the following website: http://europa.eu.int/comm/enterprise/newapproach/standardization/harmstds/reflist/emc.html.

In light of the large breadth and scope of the EMC Directive and the variety of products covered, the European Commission in 1997 felt it necessary to publish a 124-page guideline to the interpretation of the EMC directive to be used by manufacturers, test laboratories, and other parties affected by the directive (European Commission, 1997). This guideline was intended to clarify matters and procedures relating to the interpretation of the EMC Directive. It also clarified the application of the Directive to components, subassemblies, apparatus, systems, and installations, as well as the application of the Directive to spare parts, used, and repaired apparatus.

1.8 INTERNATIONAL HARMONIZATION

It would be desirable to have one international EMC standard for allowable emission and immunity of electronic products, instead of many different national standards. This would allow a manufacturer to design and test a product to one standard that would be acceptable worldwide. Figure 1-6 depicts a typical commercial product and shows the different types of EMC requirements, both emission and immunity, that it might have to meet in a harmonized world market.

Even more important than a single uniform EMC standard is a single uniform EMC test procedure. If the test procedure is the same, then an EMC test could be performed once and the results compared against many different standards (limits) to determine compliance with each regulation. When the test procedures are different, however, the product must be retested for each standard, which is a costly and time-consuming task.

The most likely vehicle for accomplishing harmonization is the European Union's EMC standards, which are based on the CISPR standards. CISPR was formed in 1934 to determine measurement methods and limits for radio-frequency interference to facilitate international trade. CISPR has no regulatory authority, but its standards, when adopted by governments, become

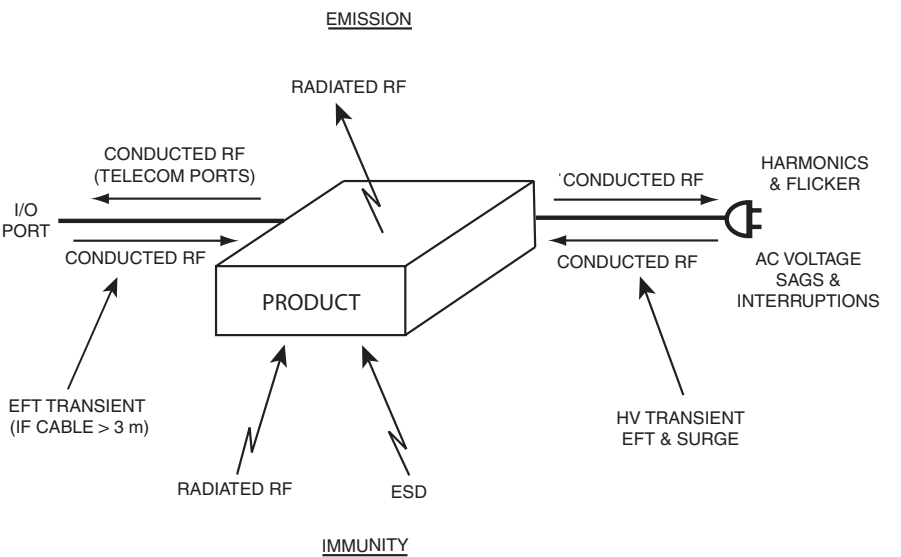

FIGURE 1-6. Typical composite worldwide commercial EMC requirements.

national standards. In 1985 CISPR adopted a new set of emission standards (Publication 22) for Information Technology Equipment (computer and digital electronics). The European Union has adopted the CISPR standard as the basis for their emission requirements. As a voting member of CISPR, the United States voted in favor of the new standard. This action puts considerable pressure on the FCC to adopt the same standards.

In 1996, the FCC modified its Part 15 Rules to allow manufacturers to use a Declaration of Conformity as a compliance procedure for personal computers and their peripherals, which is similar to that used by the EU's EMC regulations. As stated, the FCC also has adopted the CISPR limits for conducted emission.

1.9 MILITARY STANDARDS

Another important group of EMC standards are those issued by the U.S. Department of Defense and are applicable to military and aerospace equipment. In 1968, the Department of Defense consolidated the multitude of different EMC standards from the various branches of the service into two universally applicable standards. MIL-STD-461 specified the limits that had to be met, and MIL-STD-462 specified the test methods and procedures for making the tests contained in MIL-STD-461. These standards are more

stringent than the FCC regulations, and they cover immunity as well as emissions in the frequency range of 30 Hz to 40 GHz.

Over the years, these standards have gone through revisions that ranged from MIL-STD-461A in 1968 to MIL-STD-461E in 1999. In 1999, MIL-STD-461D (Limits) and MIL-STD-462D (Test Procedures) were merged into one standard MIL-STD-461E that covered both limits and test procedures.*

Unlike commercial standards, MIL-STDs are not legal requirements; rather, they are contractual requirements. As such, test limits can be negotiated and waivers are possible. Earlier versions are still applicable to current products because the requirements are contractual, not legal. Normally whatever version the original procurement contract specified is still applicable.†

The test procedures specified in the military standards are often different than those specified by commercial EMC standards, which makes a direct comparison of the limits difficult. For radiated emissions the military standard specifies enclosed chamber (shielded room) testing, whereas the FCC and the EU rules require open-area testing. For conducted emission testing, the military standards originally measured current, whereas the commercial standards measure voltage.

As more was learned about EMC testing and its accuracy, the military has come under some criticism for some of its test procedures. As a result, the military has adopted some of the commercial test procedures. For example, MIL-STD-461E specifies the use of a LISN and the measurement of voltage rather than current for conducted emission testing. Also MIL-STD-461E requires that some absorber material must be used on the walls of chambers used for emission and immunity testing to make the chamber at least partially anechoic.

Table 1-11 is a list of the emission and immunity requirements established by MIL-STD-461E. Tests are required for both radiated and conducted emissions as well as for radiated, conducted, and high-voltage transient susceptibility.

The military standards are application specific, often with different limits for different environments (such as Army, Navy, aerospace, etc.). Some requirements listed in Table 1-11 are applicable to only certain environments and not to others. Table 1-12 lists the applicability of the requirements to the various environments.

1.10 AVIONICS

The commercial avionics industry has its own set of EMC standards, which are similar to those of the military. These standards apply to the entire spectrum of commercial aircraft, which includes light general aviation aircraft, helicopters,

* On December 10, 2007, MIL-STD 461F was released.

† By contrast, when a commercial standard is revised or modified, all newly manufactured products must comply with the new limits by the end of the specified transition period.

TABLE 1-11. Emission and Susceptibility Requirements of MIL-STD-461E.

Requirement	Description
CE101	Conducted Emissions, Power Leads, 30 Hz to 10 kHz
CE102	Conducted Emissions, Power Leads, 10 kHz to 10 MHz
CE106	Conducted Emissions, Antenna Terminals, 10 kHz to 40 GHz
CS101	Conducted Susceptibility, Power Leads, 30 Hz to 50 kHz
CS103	Conducted Susceptibility, Antenna Port, Inter–modulation, 15 kHz to 10 GHz
CS104	Conducted Susceptibility, Antenna Port, Rejection of Undesired Signals, 30 Hz to 20 GHz
CS105	Conducted Susceptibility, Antenna Port, Cross-modulation, 30 Hz to 20 GHz
CS109	Conducted Susceptibility, Structure Current, 60 Hz to 100 kHz
CS114	Conducted Susceptibility, Bulk Current Injection, 10 kHz to 40 MHz
CS115	Conducted Susceptibility, Bulk Current Injection, Impulse Excitation
CS116	Conducted Susceptibility, Damped Sinusoidal Transients, Cables and Power Leads, 10 kHz to 100 MHz
RE101	Radiated Emission, Magnetic Field, 30 Hz to 100 kHz
RE102	Radiated Emission, Electric Field, 10 kHz to 18 GHz
RE103	Radiated Emission, Antenna Spurious and Harmonic Outputs, 10 kHz to 40 GHz
RS101	Radiated Susceptibility, Magnetic Field, 30 Hz to 100 kHz
RS103	Radiated Susceptibility, Electric Field, 10 kHz to 40 GHz
RS105	Radiated Susceptibility, Transient Electromagnetic Field

TABLE 1-12. Requirement Applicability Matrix, MIL-STD-461E.

Equipment Installed In, On, or Launched From the Following Platforms or Installations	CE101	CE102	CE106	CS101	CS103	CS104	CS105	CS109	CS114	CS115	CS116	RE101	RE102	RE103	RS101	RS103	RS105
Surface Ships	N	A	L	A	S	S	S	N	A	L	A	A	A	L	A	A	L
Submarines	A	A	L	A	S	S	S	L	A	L	A	A	A	L	A	A	L
Aircraft, Army, & Flight Line	A	A	L	A	S	S	S	N	A	A	A	A	A	L	A	A	L
Aircraft, Navy	L	A	L	A	S	S	S	N	A	A	A	L	A	L	L	A	L
Aircraft, Air Force	N	A	L	A	S	S	S	N	A	A	A	N	A	L	N	A	N
Space Systems & Launch Eq.	N	A	L	A	S	S	S	N	A	A	A	N	A	L	N	A	N
Ground, Army	N	A	L	A	S	S	S	N	A	A	A	N	A	L	L	A	N
Ground, Navy	N	A	L	A	S	S	S	N	A	A	A	N	A	L	A	A	L
Ground, Air Force	N	A	L	A	S	S	S	N	A	A	A	N	A	L	N	A	N

A = applicable, L = limited applicability as specified in the standard, S = applicable only if specified in procurement document, N = not applicable.

and jumbo jets. The Radio Technical Commission for Aeronautics (RTCA) produces these standards for the avionics industry. The current version is RTCA/DO-160E *Environmental Conditions and Test Procedures For Airborne Equipment* and was issued in December 2004. Sections 15 through 23 and Section 25 cover EMC issues.

Like the military standard, DO-160E is a contractual, not legal, requirement, so its terms may be negotiable.

1.11 THE REGULATORY PROCESS

We are all probably familiar with the phrase *ignorance of the law is no defense*. How then do governments make their commercial EMC regulations public, so that we all presumably know of their existence? In most countries, regulations are made public by publication, or being referenced, in the "Official Journal" of that country. In the United States, the official journal is the *Federal Register*; in Canada, it is the *Canada Gazette*; and in the European Union, it is the *Official Journal of the European Union*.

Once a regulation is published, or referenced, in the official journal, *its official*, and everyone is presumed to know of its existence.

1.12 TYPICAL NOISE PATH

A block diagram of a typical noise path is shown in Fig. 1-7. As shown, three elements are necessary to produce an interference problem. First, there must be a *noise source*. Second, there must be a *receptor* circuit that is susceptible to the noise. Third, there must be a *coupling channel* to transmit the noise from the source to the receptor. In addition, the characteristics of the noise must be such that it is emitted at a *frequency* that the receptor is susceptible, an *amplitude* sufficient to affect the receptor, and a *time* the receptor is susceptible to the noise. A good way to remember the important noise characteristics is with the acronym FAT.

The first step in analyzing a noise problem is to define the problem. This is done by determining what is the noise source, what is the receptor, what is the coupling channel, and what are the FAT characteristics of the noise. It follows that there are three ways to break the noise path: (1) the characteristics of the noise can be changed at the source, (2) the receptor can be made insensitive to the noise, or (3) the transmission through the coupling channel

FIGURE 1-7. Before noise can be a problem, there must be a noise source, a receptor, and a coupling channel.

can be eliminated or minimized. In some cases, the noise suppression techniques must be applied to two or to all three parts of the noise path.

In the case of an emission problem, we are most likely to attack the source of the emissions by changing its characteristics—its frequency, amplitude, or time. For a susceptibility problem, we are most likely to direct our attention to modifying the receptor to increase its immunity to the noise. In many cases, modifying the source or receptor is not practical, which then leaves us with only the option of controlling the coupling channel.

As an example, consider the circuit shown in Fig. 1-8. It shows a shielded direct current (dc) motor connected to its motor-drive circuit. Motor noise is interfering with a low-level circuit in the same equipment. Commutator noise from the motor is conducted out of the shield on the leads going to the drive circuit. From the leads, noise is radiated to the low-level circuitry.

In this example, the noise source consists of the arcs between the brushes and the commutator. The coupling channel has two parts: conduction on the motor leads and radiation from the leads. The receptor is the low-level circuit. In this case, not much can be done about the source or the receptor. Therefore, the interference must be eliminated by breaking the coupling channel. Noise conduction out of the shield or radiation from the leads must be stopped, or both steps may be necessary. This example is discussed more fully in Section 5.7.

1.13 METHODS OF NOISE COUPLING

1.13.1 Conductively Coupled Noise

One of the most obvious, but often overlooked, ways to couple noise into a circuit is on a conductor. A wire run through a noisy environment may pick up

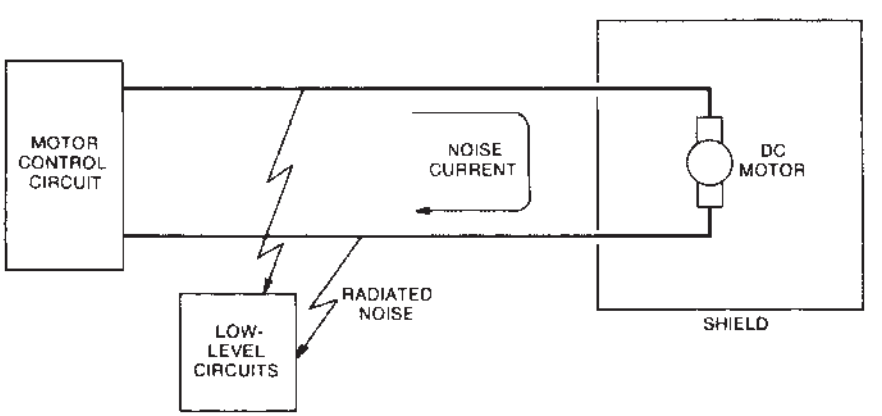

FIGURE 1-8. In this example, the noise source is the motor, and the receptor is the low-level circuit. The coupling channel consists of conduction on the motor leads and radiation from the leads.

noise and then conduct it to another circuit. There it causes interference. The solution is to prevent the wire from picking up the noise or to remove the noise from it by filtering before it interferes with the susceptible circuit.

The major example in this category is noise conducted into a circuit on the power supply leads. If the designer of the circuit has no control over the power supply, or if other equipment is connected to the power supply, it becomes necessary to decouple or filter the noise from the wires before they enter the circuit. A second example is noise coupled into or out of a shielded enclosure by the wires that pass through the shield.

1.13.2 Common Impedance Coupling

Common impedance coupling occurs when currents from two different circuits flow through a common impedance. The voltage drop across the impedance observed by each circuit is influenced by the other circuit. This type of coupling usually occurs in the power and/or ground system. The classic example of this type of coupling is shown in Fig. 1-9. The ground currents 1 and 2 both flow through the common ground impedance. As far as circuit 1 is concerned, its ground potential is modulated by ground current 2 flowing in the common ground impedance. Some noise, therefore, is coupled from circuit 2 to circuit 1, and vice versa, through the common ground impedance.

Another example of this problem is illustrated in the power distribution circuit shown in Fig. 1-10. Any change in the supply current required by circuit 2 will affect the voltage at the terminals of circuit 1 because of the common impedances of the power supply lines and the internal source impedance of the power supply. A significant improvement can be obtained by connecting

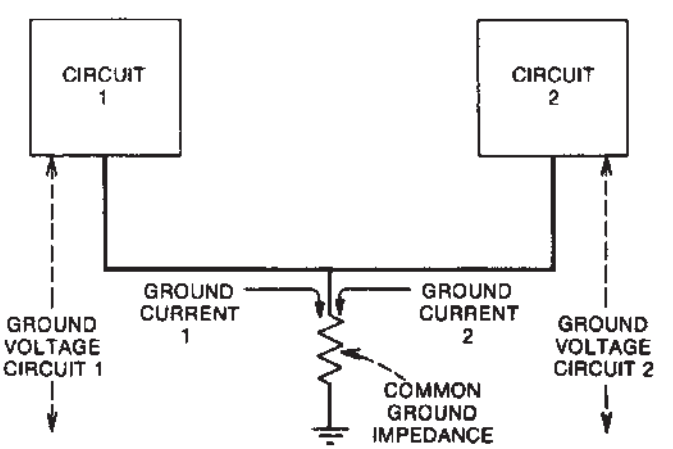

FIGURE 1-9. When two circuits share a common ground, the ground voltage of each one is affected by the ground current of the other circuit.

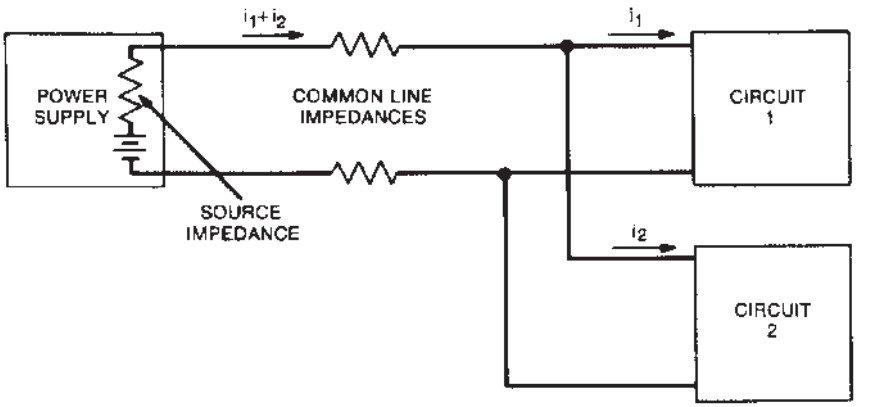

FIGURE 1-10. When two circuits share a common power supply, current drawn by one circuit affects the voltage at the other circuit.

the leads from circuit 2 directly to the power supply output terminals, thus bypassing the common line impedance. However, some noise coupling through the power supply's internal impedance will remain.

1.13.3 Electric and Magnetic Field Coupling

Radiated electric and magnetic fields provide another means of noise coupling. All circuit elements, including conductors, radiate electromagnetic fields whenever a charge is moved. In addition to this unintentional radiation, there is the problem of intentional radiation from sources such as broadcast stations and radar transmitters. When the receiver is close to the source (near field), electric and magnetic fields are considered separately. When the receiver is far from the source (far field), the radiation is considered as combined electric and magnetic or electromagnetic radiation.*

1.14 MISCELLANEOUS NOISE SOURCES

1.14.1 Galvanic Action

If dissimilar metals are used in the signal path in low-level circuitry, a noise voltage may appear from the galvanic action between the two metals. The presence of moisture or water vapor in conjunction with the two metals produces a chemical wet cell (galvanic couple). The voltage developed depends on the two metals used and is related to their positions in the galvanic series

* See Chapter 6 for an explanation of near field and far field.

TABLE 1-13. Galvanic Series.

	ANODIC END (Most susceptible to corrosion)		
Group I	1. Magnesium		13. Nickel (active)
			14. Brass
	2. Zinc		15. Copper
	3. Galvanized steel		16. Bronze
Group II	4. Aluminum 2S	Group IV	17. Copper-nickel alloy
	5. Cadmium		18. Monel
	6. Aluminum 17ST		19. Silver solder
			20. Nickel (passive)[a]
	7. Steel		21. Stainless steel
	8. Iron		(passive)[a]
	9. Stainless steel		
Group III	(active)		22. Silver
	10. Lead-tin solder	Group V	23. Graphite
	11. Lead		24. Gold
	12. Tin		25 Platinum
			CATHODIC END (Least susceptibility to corrosion)

[a]Passivation by immersion in a strongly acidic solution.

shown in Table 1-13. The farther apart the metals are on this table, the larger the developed voltage. If the metals are the same, no potential difference can develop.

In addition to producing a noise voltage, the use of dissimilar metals can produce a corrosion problem. Galvanic corrosion causes positive ions from one metal to be transferred to the other one. This action gradually causes the anode material to be destroyed. The rate of corrosion depends on the moisture content of the environment and how far apart the metals are in the galvanic series. The farther apart the metals are in the galvanic series, the faster the ion transfer. An undesirable, but common, combination of metals is aluminum and copper. With this combination, the aluminum is eventually eaten away. The reaction slows down considerably, however, if the copper is coated with lead-tin solder because aluminum and lead-tin solder are closer in the galvanic series.

The following four elements are needed before galvanic action can occur:

1. Anode material (higher rank in Table 1-13)
2. Electrolyte (usually present as moisture)
3. Cathode material (lower rank in Table 1-13)
4. Conducting electrical connection between anode and cathode (usually present as a leakage path)

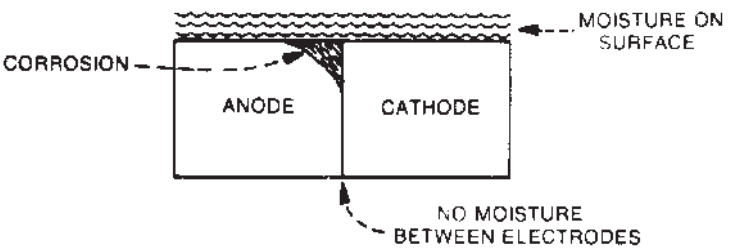

FIGURE 1-11. Galvanic action can occur if two dissimilar metals are joined and moisture is present on the surface.

Galvanic action can take place even if moisture does not get between the anode and the cathode. All that is needed is some moisture on the surface where the two metals come together, as shown in Fig. 1-11.

As observed in Table 1-13, the metals of the galvanic series are divided into five groups. When dissimilar metals must be combined, it is desirable to use metals from the same group. Usually metals from adjacent groups can be used together if the product is to be used in a fairly benign indoor environment.

Other methods of minimizing corrosion between two dissimilar metals are as follows:

- Keep the cathode material as small as possible.
- Plate one of the materials to change the group that the contact surface is in.
- Coat the surface, after joining to exclude surface moisture.

1.14.2 Electrolytic Action

A second type of corrosion is caused by electrolytic action. It is caused by a direct current flowing between two metals with an electrolyte (which could be slightly acidic ambient moisture) between them. This type of corrosion does not depend on the two metals used and will occur even if both are the same. The rate of corrosion depends on the magnitude of the current and on the conductivity of the electrolyte.

1.14.3 Triboelectric Effect

A charge can be produced on the dielectric material within a cable, if the dielectric does not maintain contact with the cable conductors. This is called the triboelectric effect. It is usually caused by mechanical bending of the cable. The charge acts as a noise voltage source within the cable. Eliminating sharp bends and cable motion minimizes this effect. A special "low-noise" cable is available in which the cable is chemically treated to minimize the possibility of charge buildup on the dielectric.

1.14.4 Conductor Motion

If a conductor is moved through a magnetic field, a voltage is induced between the ends of the wire. Because of power wiring and other circuits with high-current flow, stray magnetic fields exist in most environments. If a wire with a low-level signal is allowed to move through this field, then a noise voltage will be induced in the wire. This problem can be especially troublesome in a vibrational environment. The solution is simple: prevent wire motion with cable clamps and other tie-down devices.

1.15 USE OF NETWORK THEORY

For the exact answer to the question of how any electric circuit behaves, Maxwell's equations must be solved. These equations are functions of three space variables (x, y, z) and of time (t)—a four-dimensional problem. Solutions for any but the simplest problems are usually complex. To avoid this complexity, an approximate analysis technique called "electric circuit analysis" is used during most design procedures.

Circuit analysis eliminates the spatial variables and provides approximate solutions as a function of time (or frequency) only. Circuit analysis assumes the following:

1. All electric fields are confined to the interiors of capacitors.
2. All magnetic fields are confined to the interiors of inductors.
3. Dimensions of the circuits are small compared with the wavelength(s) under consideration.

What is really implied is that external fields, even though actually present, can be neglected in the solution of the network. Yet these external fields may not necessarily be neglected where their effect on other circuits is concerned.

For example, a 100-W power amplifier may radiate 100 mW of power. These 100 mW are completely negligible as far as the analysis and operation of the power amplifier is concerned. However, if only a small percentage of this radiated power is picked up on the input of a sensitive circuit, it may cause interference.

Even though the 100 mW of radiated emission is completely negligible to the 100-W power amplifier, a sensitive radio receiver, under the right conditions, may be capable of picking up the signal thousands of miles away.

Whenever possible, noise-coupling channels are represented as equivalent lumped component networks. For instance, a time-varying electric field that exists between two conductors can be represented by a capacitor connecting the two conductors as shown in Fig. 1-12. A time-varying magnetic field that

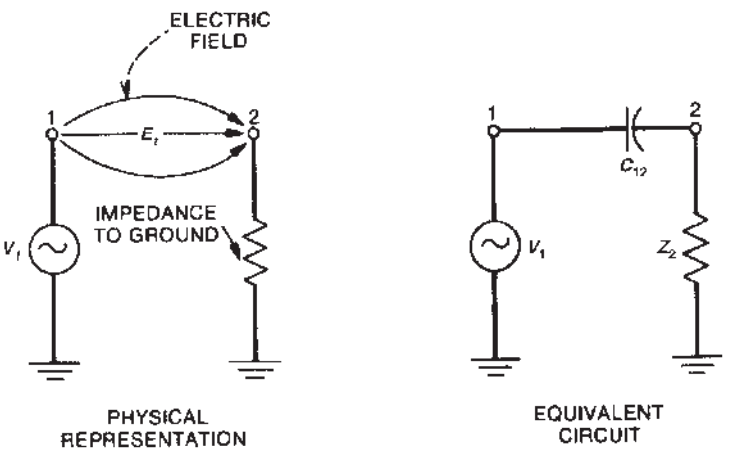

FIGURE 1-12. When two circuits are coupled by an electric field, the coupling can be represented by a capacitor.

couples two conductors can be represented by a mutual inductance between the two circuits as shown in Fig. 1-13.

For this approach to be valid, the physical dimensions of the circuits must be small compared with the wavelengths of the signals involved. Wherever appropriate, this assumption is made throughout this book.

Even when this assumption is not truly valid, the lumped component representation is still useful for the following reasons:

1. The solution of Maxwell's equations is not practical for most "real-world" noise problems because of the complicated boundary conditions.
2. Although lumped component representation will not produce the most accurate numerical answer, it does clearly show how noise depends on the parameters of the system. On the other hand, the solution of Maxwell's equations, even if possible, does not clearly show such parameter dependence.
3. To solve a noise problem, a parameter of the system must be changed, and lumped circuit analysis clearly points out the parameter dependence.

In general, the numerical values of the lumped components are extremely difficult to calculate with any precision, except for certain special geometries. One can conclude, however, that these components exist, and as will be shown, the results can be very useful even when the components are only defined in a qualitative sense.

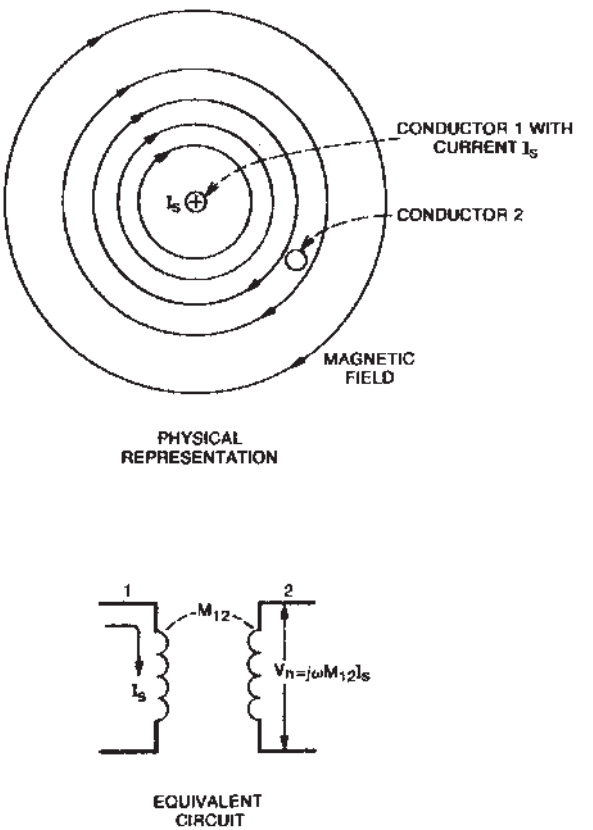

FIGURE 1-13. When two circuits are coupled by a magnetic field, the coupling can be represented as a mutual inductance.

SUMMARY

- Designing equipment that does not generate noise is as important as designing equipment that is not susceptible to noise.
- Noise sources can be grouped into the following three categories: (1) intrinsic noise sources, (2) man-made noise sources, and (3) noise caused by natural disturbances.
- To be cost effective, noise suppression must be considered early in the design.
- Electromagnetic compatibility is the ability of an electronic system to function properly in its intended electromagnetic environment.
- Electromagnetic compatibility has two aspects, emission and susceptibility.
- Electromagnetic compatibility should be designed into a product not added on at the end of the design.

- Most electronic equipment must comply with EMC regulations before being marketed.
- EMC regulations are not static but are continually changing.
- The three major EMC regulations are the FCC rules, the European Union's regulations, and the military standards.
- The following products are temporarily exempt from the FCC requirements:
  - Digital electronics in transportation vehicles
  - Industrial control systems
  - Test equipment
  - Home appliances
  - Specialized medical devices
  - Devices with power consumption not exceeding 6 nW
  - Joystick controllers or similar devices
  - Devices with clock frequencies less than 1.705 kHz, and which do not operate from the AC power line
- Virtually no products are exempt from the European Union's EMC requirements.
- Electromagnetic compatibility should be a major design objective.
- The following three items are necessary to produce an interference problem:
  - A noise source
  - A coupling channel
  - A susceptible receptor
- Three important characteristics of noise are as follows:
  - Frequency
  - Amplitude
  - Time (when does it occur)
- Metals in contact with each other must be galvanically compatible.
- Noise can be reduced in an electronic system using many techniques; a single unique solution to most noise reduction problems does not exist.

PROBLEMS

1.1 What is the difference between noise and interference?

1.2 a. Does a digital watch satisfy the FCC's definition of a digital device?
b. Does a digital watch have to meet the FCC's EMC requirements?

1.3 a. Does test equipment have to meet the technical standards of the FCC's Part 15 EMC regulations?
b. Does test equipment have to meet the non-interference requirement of the FCC's Part 15 EMC regulations?

1.4 a. Who is responsible for meeting the technical standards of the FCC's EMC regulations?
   b. Who is responsible for meeting the non-interference requirement of the FCC's EMC regulations?

1.5 Are the FCC's or the European Union's Class B radiated emission limits more restrictive:
   a. In the frequency range of 30 to 88 MHz?
   b. In the frequency range of 88 to 230 MHz?
   c. In the frequency range of 230 to 960 MHz?
   d. In the frequency range of 960 to 1000 MHz?

1.6 a. Over what frequency range, below 500 MHz, does the maximum difference exist between the FCC's and the European Union's Class B radiated emission limits?
   b. What is the magnitude of the maximum difference over this frequency range?

1.7 a. Over what frequency range does the FCC specify conducted emission limits?
   b. Over what frequency range does the FCC specify radiated emission limits?

1.8 a. What are the essential requirements for a product to be marketed in the European Union?
   b. Where are the essential requirements defined?

1.9 By what process are commercial EMC regulations made public?

1.10 What is the *major* difference between the FCC's EMC requirement and the European Union's EMC requirements?

1.11 What additional emission requirements does the European Union have that the FCC does not?

1.12 Your company is in the process of designing a new electronic widget to be marketed in the European Union. The widget will be used in both residential and commercial environments. You review the most current list of harmonized product specific EMC standards, and none of them apply to widgets. What EMC standards (specifically) should you use to demonstrate EMC compliance?

1.13 To be legally marketed in the European Union, must an electronic product be compliant with the harmonized EMC standards?

1.14 In the European Union, what are the two methods of demonstrating compliance with the EMC directive?

1.15 Which of the following EMC standards are legal requirements and which are contractual?
   - FCC Part 15 B
   - MIL-STD-461E

- 2004/108/EC EMC Directive
- RTCA/DO-160E for avionics
- GR-1089 for telephone network equipment
- TIA-968 for telecom terminal equipment
- SAE J551 for automobiles

1.16 What are the official journals of the following countries: the United States, Canada, and the European Union?

1.17 In the United States, does medical equipment have to meet the FCC's EMC requirements?

1.18 What are the three necessary elements to produce an interference problem?

1.19 When analyzing the characteristics of a noise source, what does the acronym FAT stand for?

1.20 a. Which of the following metals is the most susceptible to corrosion: cadmium, nickel (passive), magnesium, copper, or steel?

b. Which is the least susceptible to corrosion?

1.21 If a tin plate is bolted to a zinc casting, because of galvanic action, which metal will be corroded or eaten away?

REFERENCES

2004/108/EEC. Council Directive 2004/108/EEC Relating to Electromagnetic Compatibility and Repealing Directive 89/336/EEC, *Official Journal of the European Union*, No. L 390 December 31, 2004, pp. 24–37.

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*, IEEE, July 17, 1992.

CAN/CSA-CEI/IEC CISPR 22:02. *Limits an Methods of Measurement of Radio Disturbance Characteristics of Information Technology Equipment*, Canadian Standards Association, 2002.

CISPR, Publication 22. "Limits and Methods of Measurement of Radio Interference Characteristics of Information Technology Equipment," 1997.

Code of Federal Regulations, Title 47, Telecommunications (47CFR). Parts 1, 2, 15, 18, and 68, U.S. Government Printing Office, Washington, DC.

EMCAB-1, Issue 2. Electromagnetic Compatibility Bulletin, "Immunity of Electrical/Electronic Equipment Intended to Operate in the Canadian Radio Environment (0.014–10,000 MHz)." Government of Canada, Department of Communications, August 1, 1982.

EN 61000-3-2. *Electromagnetic Compatibility (EMC)—Part 3-2: Limits—Limits for Harmonic Current Emissions (Equipment Input Current ≤ 16 A Per Phase)*, CENELEC, 2006.

EN 61000-3-3. *Electromagnetic Compatibility (EMC)—Part 3-3: Limits—Limitation of Voltage Changes, Voltage Fluctuations and Flicker in Public Low-Voltage Supply*

Systems, for Equipment with Rated Current ≤ 16 A Per Phase and Not Subject to Conditional Connection, CENELEC, 2006.

European Commission. *Guidelines on the Application of Council Directive 89/336/EEC on the Approximation of the Laws of the Member States Relating to Electromagnetic Compatibility*, European Commission, 1997.

FCC. "Commission Cautions Against Changes in Verified Computing Equipment." Public Notice No. 3281, April 7, 1982.

FCC. "United States and Canada Agree on Acceptance of Measurement Reports for Equipment Authorization," Public Notice No. 54795, July 12, 1995.

FDA. Guide to Inspections of Electromagnetic Compatibility Aspects of Medical Device Quality Systems, US Food and Drug Administration, Available at http://www.fda.gov/ora/inspect_ref/igs/elec_med_dev/emc1.html. Accessed September 2008.

GR-1089-CORE. *Electromagnetic Compatibility and Electrical Safety—Generic Criteria for Network Telecommunications Equipment*, Telcordia, November 2002.

Heirman, D. N. "Broadcast Electromagnetic Environment Near Telephone Equipment." IEEE National Telecommunications Conference, 1976.

Janes, D. E. et al. "Nonionizing Radiation Exposure in Urban Areas of the United States." *Proceedings of the 5th International Radiation Protection Association*. April 1977.

MDS-201-0004. *Electromagnetic Compatibility Standards for Medical Devices*, U.S. Department of Health Education and Welfare, Food and Drug Administration, October 1, 1979.

MIL-STD-461E. *Requirements For The Control of Electromagnetic Interference Characteristics of Subsystems and Equipment*, August 20, 1999.

MIL-STD-889B. *Dissimilar Metals*, Notice 3, May 1993.

RTCA/DO-160E. *Environmental Conditions and Test Procedures for Airborne Equipment*, Radio Technical Commission for Aeronautics (RTCA), December 7, 2004.

SAE J551. *Performance Levels and Methods of Measurement of Electromagnetic Compatibility of Vehicles and Devices (60 Hz to 18 GHz)*, Society of Automotive Engineers, June 1996.

SAE J1113. *Electromagnetic Compatibility Measurement Procedure for Vehicle Components (Except Aircraft) (60 Hz to 18 GHz)*, Society of Automotive Engineers, July 1995.

TIA-968-A. *Telecommunications Telephone Terminal Equipment Technical Requirements for Connection of Terminal Equipment to the Telephone Network*, Telecommunications Industry Association, October 1, 2002.

FURTHER READING

Cohen, T. J., and McCoy, L. G. "RFI–A New Look at an Old Problem." *QST*, March 1975.

Gruber, M. ed. *The ARRL RFI Book*, Newington, CT, American Radio Relay League, 2007.

Marshman, C. *The Guide to the EMC Directive 89/336/EEC*, IEEE Press, New York, 1992.

Wall, A. " Historical Perspective of the FCC Rules For Digital Devices and a Look to the Future," 2004 *IEEE International Symposium on Electromagnetic Compatibility*, August 9–13, 2004.