EMC Course Notes 2024

Introduction to Electromagnetic Compatibility

Introduction to EMC

In a world where electronic devices play a key role in day-to-day activities, most people are familiar with the concept of electromagnetic interference (EMI). Many can even cite examples of EMI impacting the operation of phones, computers, medical devices, automobiles or aircraft. Nevertheless, EMI problems tend to be viewed as rare occurrences. Few people outside of the electronics industry appreciate the time and effort required to ensure that electronic devices are compatible with today's electromagnetic environment.

Electromagnetic compatibility (EMC) is broadly defined as the state that exists when all electronic devices in a system function without error in their intended electromagnetic environment. Virtually all electronic devices must meet EMC requirements before they can be marketed or sold. The electromagnetic noise emanating from most devices is carefully measured and regulated. Many products are also subjected to strong external fields or voltage transients to ensure they can operate normally in noisy environments.

To a knowledgeable design engineer, meeting EMC requirements is no different than meeting functional, thermal, or safety requirements. It's simply a matter of being aware of the requirements as well as the steps necessary to ensure compliance. With a well-thought-out design, most products have no trouble meeting their EMC requirements. However, while most product designers understand the importance of addressing functional, thermal and safety requirements early in the development cycle, it's not uncommon for the first attempts to address EMC issues to occur after a product fails its first EMC compliance test. At that point, design options tend to be limited. EMC "fixes" can (and often do) delay development schedules and increase product cost.

Many companies, especially those with short product development cycles, recognize the importance of addressing EMC early. They rely on engineers who understand what it takes to design EMC-compliant products. For these companies, EMC testing is a formality. Their products tend to be more reliable and lower-cost than similar products that had to be "fixed" after failing an EMC test.

As one might expect, engineers that understand electromagnetic compatibility principles and can apply them to product design tend to be in high demand. They possess a skill-set that includes a basic understanding of electromagnetic field theory, as well as a familiarity with real-world circuits, components and systems. They understand the importance of electrical ground and recognize that ground and current-return are different concepts. They know that the physical layout of a system is important, and that circuit behavior is often governed by component interactions that do not appear in circuit schematics. Basically, the engineers who understand what it takes to design EMC-compliant products are those who understand the concepts described in these course notes and have learned to apply them to real-world product designs.

Elements of an EMC Problem

There are three essential elements to an EMC problem as illustrated in Figure 1.1. There must be a source of electromagnetic energy, a receptor (or victim) that cannot function properly due to interference from the source, and a path that couples the interfering energy from the source to the receptor. Each of these three elements must be present for the interference to occur. Electromagnetic compatibility problems are generally solved by identifying at least two of these elements and eliminating (or attenuating) one of them.

Lightning	Cables	Integrated Circuit
RF Transmitter	Antennas	RF Receiver
High Speed Data Trace	Common Ground	High Speed Data Trace
Electric Motor	Power Lines	Cell Phone
Arc Welder	Parasitic Capacitance	Electronic Controls
Video Display	Parasitic Inductance	Video Display

Figure 1.1. The three essential elements of an EMC problem

For example, there have been several documented cases of EMI causing nuclear power plants to go into an emergency shut-down. In at least one case, the noise was a spurious voltage spike in a ventilation flow sensor circuit. In another case, it was a neutron flux sensor. In both cases, the first element identified was the victim circuit (a sensor). In both cases, the last leg of the coupling path was conducted noise on the sensor cable.

Since it’s only necessary to eliminate one of the three elements, in both cases, it was possible to solve the problem with noise suppression on the sensor cable. It wasn’t strictly necessary, but in both cases the likely source was also identified. The apparent source of the flow sensor malfunction was the keying of wireless handsets operated by plant personnel. The source of the flux sensor interference was noise generated by actuation of relays in another circuit.

In another documented case, an aerial tramway car suddenly accelerated as it approached the terminal slamming into a guard fence, shattering windows, and throwing passengers to the floor. The source of the tramway problem was thought to be transients on the tramway's power. The coupling path was presumably through the power supply to the speed control circuit, although investigators were unable to reproduce the failure so the source and coupling path were never identified conclusively. The receptor, on the other hand, was clearly shown to be the speed control circuit and this circuit was modified to keep it from becoming confused by unintentional random inputs. In other words, the solution was to eliminate the receptor by making the speed control circuit immune to the electromagnetic phenomenon produced by any source.

Potential sources of electromagnetic compatibility problems include radio transmitters, power lines, electronic circuits, lightning, lamp dimmers, electric motors, arc welders, solar flares and just about anything that utilizes or creates electromagnetic energy. Potential receptors include radio receivers, electronic circuits, appliances and anything that utilizes or can detect electromagnetic energy.

While the receptor is often the first element identified, the key to solving an interference problem is often the coupling path. There are only four mechanisms for coupling electromagnetic energy from a source to a receptor. These are:

1. Conducted (common impedance coupling)
2. Inductively coupled (magnetic field coupling)
3. Capacitively coupled (electric field coupling)
4. Radiated (electromagnetic field coupling)

Methods for attenuating the coupling vary greatly depending on the coupling mechanism. Fortunately, with a little investigation, the correct mechanism can often be quickly identified, allowing the investigator to determine the appropriate countermeasures.

In some situations, the coupling between the source and receptor involves more than one of these coupling mechanisms. For example, conducted from the source to Point A, then field-coupled from Point A to Point B, then conducted again from Point C to the receptor. In a situation like this, there are multiple opportunities to attenuate the coupling.

A Brief History of EMC

In the late 1880's, the German physicist Heinrich Hertz performed experiments that demonstrated the phenomenon of radio wave propagation, thus confirming the theory published by James Clerk Maxwell two decades earlier. Hertz developed a spark in a small gap between two metal rods that were connected at the other end to metal plates, as shown in Figure 1.2. The spark excitation created an oscillating current on the rods resulting in electromagnetic radiation near the resonant frequency of the transmitting antenna. The receiving antenna was a loop of wire with a very thin gap. A spark in the gap indicated the presence of a time-varying field and the maximum spark gap length provided a measurement of the received field's strength.

Guglielmo Marconi learned of Hertz's experiments and improved upon them. In 1895, he developed the wireless telegraph, the first communications device to convey information using radio waves. Although the significance of his invention was not initially appreciated, the U.S. Navy took an interest due to the potential of this device to enhance communication with ships at sea.

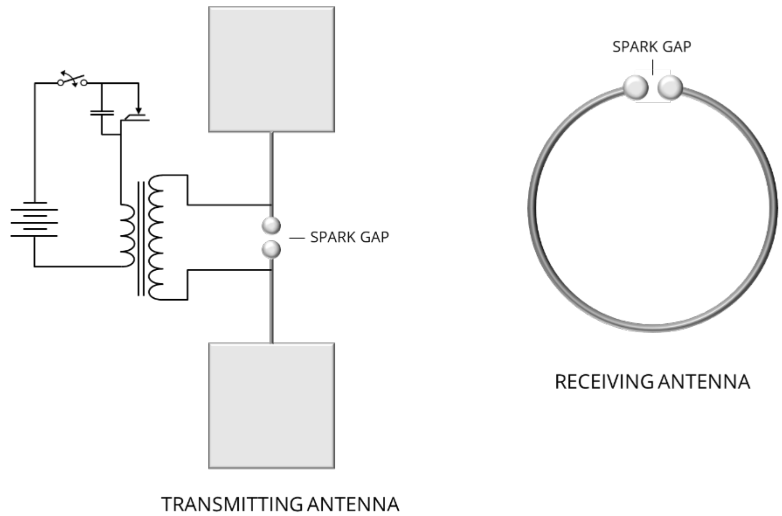

Figure 1.2. Early antennas constructed by Heinrich Hertz

In 1899, the Navy initiated the first shipboard tests of the wireless telegraph. While the tests were successful in many ways, the Navy was unable to operate two transmitters simultaneously. The reason for this problem was that the operating frequency and bandwidth of the early wireless telegraph was primarily determined by the size, shape, and construction of the antenna. Receiving antennas were always “tuned” (experimentally) to the same operating frequency as the transmitting antenna, however the bandwidth was difficult to control. Therefore, when two transmitters were operating simultaneously, receivers detected the fields from both to some extent and the received signal was often unintelligible. This early electromagnetic compatibility problem came to be referred to as Radio Frequency Interference (RFI). As the popularity of the wireless telegraph grew, so did the concern about RFI.

In 1904, U.S. president Theodore Roosevelt signed an executive order empowering the Department of Commerce to regulate all private radio stations and the Navy to regulate all government stations (and all radio stations in times of war). Different types of radio transmitters were assigned different frequency allocations and often were only allowed to operate at certain times to reduce the potential for RFI.

By 1906, various spark-quenching schemes and tuning circuits were being employed to reduce the bandwidth of wireless transmitters and receivers significantly. However, it was the invention of the vacuum tube oscillator in 1912 and the super heterodyne receiver in 1918 that made truly narrow-band transmission and reception possible. These developments also made it possible to transmit reasonably clear human speech, which paved the way for commercial radio broadcasts.

The period from about 1925 to 1950 is known as the golden age of broadcasting. During this period, the popularity of radio soared. As the number of radios proliferated, so did electromagnetic compatibility problems. RFI was a common problem because the regulations governing intentional or unintentional interference with a commercial radio broadcast were lax, and more people had access to radio equipment. To alleviate this problem, the Federal Communications Commission (FCC) was established in 1934 as an independent agency of the U.S. Government. It was empowered to regulate U.S. interstate and foreign communication by radio, wire, and cable. FCC regulations and licensing requirements significantly reduced the number of radio frequency interference problems.

However, due to the increasing number of radio receivers being located in homes, the general public was introduced to a variety of new EMC problems. Unintentional electromagnetic radiation sources such as thunderstorms, gasoline engines, and electric appliances often created bigger interference problems than intentional radio transmitters.

Intra-system interference was also a growing concern. Super heterodyne receivers employed their own local oscillator, which had to be isolated from other parts of the radio's circuitry. Radios and phonographs were lumped together in home entertainment systems. Radios were installed in automobiles, elevators, tractors, and airplanes. The developers and manufacturers of these systems found it necessary to develop better grounding, shielding, and filtering techniques in order to make their products function.

In the 1940's many new types of radio transmitters and receivers were developed for use during World War II. Radio signals were not only used for communication, but also to locate ships and planes (RADAR[1]) and to jam enemy radio communications. Because of the immediate need, this equipment was hurriedly installed on ships and planes, often resulting in severe EMC problems.

Experiences with electromagnetic compatibility problems during the war prompted the development of the first joint Army-Navy RFI standard, JAN-I-225, “Radio Interference Measurement,” published in 1945. Much more attention was devoted to RFI problems in general, and techniques for grounding, shielding and filtering in particular. Electromagnetic compatibility became an engineering specialization in a manner similar to antenna design or communications theory.

In 1954, the first Armour Research Foundation Conference on Radio Frequency Interference was held. This annual conference was sponsored by both government and industry. Three years later, the Professional Group on Radio Frequency Interference was established as the newest of several professional groups of the Institute of Radio Engineers. Today, this group is known as the Electromagnetic Compatibility Society of the Institute of Electrical and Electronics Engineers (IEEE).

During the 1960's, electronic devices and systems became an increasingly important part of our society and were crucial to our national defense. A typical aircraft carrier, for example, employed 35 radio transmitters, 56 radio receivers, 5 radars, 7 navigational aid systems, and well over 100 antennas. During the Vietnam War, U.S. Navy ships were often forced to shut down critical systems in order to allow other systems to function. This alarming situation focused even more attention on the issue of electromagnetic compatibility. Outside the military, an increasing dependence on computers, satellites, telephones, radio and television made potential susceptibility to electromagnetic phenomena a very serious concern.

The 1970's witnessed the development of the microprocessor and the proliferation of small, low-cost, low-power semiconductor devices. Circuits utilizing these devices were much more sensitive to weak electromagnetic fields than the older vacuum tube circuits.

[1] RADAR is an acronym for Radio Detection And Ranging.

As a result, more attention was directed toward solving an increasing number of electromagnetic susceptibility problems that occurred with these circuits.

In addition to traditional radiated electromagnetic susceptibility (RES) problems due to intentional and unintentional radio frequency transmitters, three classes of electromagnetic susceptibility problems gained prominence in the '70s. Perhaps the most familiar of these is electrostatic discharge (ESD). An electrostatic discharge occurs whenever two objects with a significantly different electric potential come together. The “shock” that is felt when a person reaches for a metal doorknob after walking across a carpet on a dry day is a common example. Even discharges too weak to be felt, however, are capable of destroying semiconductor devices.

Another electromagnetic susceptibility problem that gained notoriety during the '70s was referred to as EMP or Electromagnetic Pulse. The military realized that a high-altitude detonation of a nuclear warhead would generate an extremely intense pulse of electromagnetic energy over a very wide area. This pulse could easily damage or disable critical electronic systems. To address this concern, a significant effort was initiated to develop shielding and surge protection techniques that would protect critical systems in this very severe environment.

The emergence of a third electromagnetic susceptibility problem, power line transient susceptibility (PLT), was also a direct consequence of the increased use of semiconductor devices. Vacuum tube circuits generally required huge power supplies that tended to isolate the electronics from noise on the power line. High-speed, low-power semiconductor devices on the other hand were much more sensitive to transients and their modest power requirements often resulted in the use of small low-cost supplies that did not provide much isolation from the power line. In addition, the low cost of these devices meant that more of them were being located in homes and offices where the power distribution is generally not well regulated and is relatively noisy.

The emphasis on electromagnetic susceptibility during the 1970's is exemplified by the number of task groups, test procedures, and product standards dealing with susceptibility that emerged during this decade. One organization established in the late 70's known as the EOS/ESD Association (EOS is an acronym for electrical overstress) deals exclusively with the susceptibility problems mentioned above.

Another change that occurred during the 60's and 70's was the gradual displacement of the term RFI by the more general term EMI or Electromagnetic Interference. Since not all interference problems occurred at radio frequencies, this was considered to be a more descriptive nomenclature. EMI is often categorized as radiated EMI or conducted EMI depending on the coupling path.

Two events in the 1980's had significant, wide-ranging effects on the field of electromagnetic compatibility.

- The introduction and proliferation of low-priced personal computers and workstations.
- Revisions to Part 15 of the FCC Rules and Regulations that placed limits on the electromagnetic emissions from “computing devices.”

The proliferation of low-priced computers was important for two reasons. First, a large number of consumers and manufacturers were introduced to a product that was both a significant source and significant receptor of electromagnetic interference. Secondly, the availability of low-cost, high-speed computation spurred the development of a variety of numerical analysis techniques that have had an overwhelming influence on the ability of engineers to analyze and solve EMC problems.

The FCC regulations governing EMI from computing devices were phased in between 1980 and 1982. They required all electronic devices operating at frequencies of 9 kHz or greater and employing "digital techniques" to meet stringent limits regulating the electromagnetic emissions radiated by the device or coupled to the power lines. Virtually all computers and computer peripherals sold or advertised for sale in the U.S. must meet these requirements. Many other countries established similar requirements.

In the 1990's, the European Union adopted EMC regulations that went well beyond the FCC requirements. The European regulations limited unintentional emissions from appliances, medical equipment and a wide variety of electronic devices that were exempt from the FCC requirements. In addition, the European Union established requirements for the electromagnetic immunity of these devices and defined procedures for testing the susceptibility of electronic systems to radiated electromagnetic fields, conducted power and signal line noise, and electrostatic discharge.

The impact of these regulations was overwhelming. At a time when the market for computers was growing exponentially, many of the latest, most advanced designs were being held back because they were unable to meet government EMC requirements. Companies formed EMC departments and advertised for EMC engineers. An entire industry emerged to supply shielding materials, ferrites, and filters to computer companies. EMC short courses, test labs, magazines, and consultants began appearing throughout the world. The international attention focused on EMC encouraged additional research. Significant progress was made toward the development of more comprehensive test procedures and meaningful standards.

In the past 30 years, several technology trends have had a profound impact on the relevance of EMC and the tools available to ensure it. The emergence of the *Internet of Things* has resulted in exponential growth in the number of electronic systems that need to function reliably in increasingly complex electromagnetic environments. More systems rely on wireless communications and satellite location services. Autonomous vehicles, medical devices, aircraft, industrial robots and many other products depend heavily on the reliable operation of their electronics to ensure the safety and welfare of the people who use them. There is now much less room for error when it comes to specifying meaningful EMC requirements and designing products that are guaranteed to meet those requirements.

Fortunately, the past 30 years have also resulted in significant breakthroughs to aid engineers in their efforts to anticipate and correct potential EMC problems. Aided by increasingly sophisticated electromagnetic modeling tools, researchers have developed a much better understanding of the coupling mechanisms responsible for EMC issues. Models have been developed that can anticipate worst-case scenarios and assist with the development of products that are guaranteed to meet their EMC requirements. There have also been significant technology advancements related to the components and materials available to reduce or eliminate unwanted electromagnetic coupling. Examples include new lightweight and low-cost shielding materials, thinner and more effective absorbing materials, smaller passive filter components, more effective transient suppression components and more sophisticated digital devices capable of reduced emissions and greater electromagnetic immunity.

The Future of Electromagnetic Compatibility

Today, the trends of the past 30 years are continuing. Computing devices are getting denser, faster, more complex, and more widespread. Wireless technologies continue to proliferate and evolve. Advances in electronics create new challenges for the EMC engineer. At the same time, advances in electromagnetic analysis and available design options are revolutionizing the methods used to ensure electromagnetic compatibility.

Government and industry regulations and test procedures related to electromagnetic compatibility continue to be introduced and updated on a regular basis. Nevertheless, the rapid pace of technical innovation basically ensures that regulations alone will never be sufficient to guarantee the safety and compatibility of electronic systems. This makes it more important than ever to address electromagnetic compatibility issues early in the design, rather than “fixing” a product after it fails to meet a given requirement.

Working with Decibels

If you want to communicate effectively with EMC engineers, it’s important to get comfortable with decibels (dB). Decibel notation is a convenient way of expressing ratios of quantities that may or may not span many orders of magnitude. It is also used to express the amplitude of various signal parameters such as voltage or current relative to a given reference level.

A power ratio, $P_2{:}P_1$, in decibels is simply calculated as,

$$\text{Power ratio in dB} = 10\log\left(\frac{P_2}{P_1}\right). \tag{1.1}$$

For example, if we are comparing a 10-watt received power to a 5-watt specification, we could say that the received power exceeded the specification by,

$$10\log\left(\frac{10\text{ watts}}{5\text{ watts}}\right) = 3\text{ dB}. \tag{1.2}$$

If the impedance associated with two power levels is constant, then the power is proportional to the voltage (or current) squared. In this case, we can also express voltage (or current) ratios in dB,

$$10\log\left(\frac{P_2}{P_1}\right) = 10\log\left(\frac{V_2}{V_1}\right)^2 = 20\log\left(\frac{V_2}{V_1}\right), \tag{1.3}$$

or,

$$10\log\left(\frac{P_2}{P_1}\right) = 10\log\left(\frac{I_2}{I_1}\right)^2 = 20\log\left(\frac{I_2}{I_1}\right). \tag{1.4}$$

Decibels can also be used to express ratios of power densities or electromagnetic field strengths. For example, if the electric field strength incident on a composite surface is 3 V/m and the reflected field strength is 1 V/m, the ratio of incident to reflected field strength is,

$$20\log\left(\frac{3\text{ V/m}}{1\text{ V/m}}\right) \approx 10\text{ dB}. \tag{1.5}$$

Antenna or amplifier gains are usually reported in dB; so are cable or filter losses. An amplifier that receives a 1-watt signal and produces a 100-watt signal has a gain of,

$$10\log\left(\frac{100}{1}\right) = 20\text{ dB}. \tag{1.6}$$

A cable whose input signal has an amplitude of 3.0 volts and whose output signal has an amplitude of 2.8 volts exhibits a gain of,

$$20\log\left(\frac{2.8}{3.0}\right) = -0.6\text{ dB} \tag{1.7}$$

or a loss of,

$$20\log\left(\frac{3.0}{2.8}\right) = 0.6\text{ dB}. \tag{1.8}$$

Note that the inverse of any ratio is expressed by changing its sign in dB. A ratio of 1 is 0 dB. Complex numbers, phase or negative values cannot be expressed in dB.

Quiz Question

A signal traveling one kilometer in a coaxial cable loses one-half its voltage. Express the,

a.) input-to-output voltage ratio
b.) input-to-output power ratio
c.) input-to-output voltage ratio in dB
d.) input-to-output power ratio in dB.

Of course, the input-to-output voltage ratio is 2:1, while the input-to-output power ratio is $(2)^2$:$(1)^2$ = 4:1. The voltage ratio expressed in dB is $20\log\left(\frac{2}{1}\right) = 6\text{ dB}$. The power ratio is $10\log\left(\frac{4}{1}\right) = 6\text{ dB}$. This illustrates one of the primary advantages to expressing gains or losses in dB. As long as the impedance is constant, it is not necessary to specify whether a ratio is power or voltage when it is expressed in dB. A 6 dB gain unambiguously means the power has quadrupled whether the original measurement was voltage, current or power. On the other hand, if we were simply to say that one signal was *twice as strong* as another, it would not be clear whether it had twice the power or twice the voltage.

Example 1-1: Specifying ratios in dB

Specify the following ratios in dB:

200 μV/m : 100 μV/m	$20\log\left(\frac{200}{100}\right) = 6 \text{ dB}$
300 mV : 100 mV	$20\log\left(\frac{300}{100}\right) = 9.5 \text{ dB} \approx 10 \text{ dB}$
400 mA : 100 mA	$20\log\left(\frac{400}{100}\right) = 12 \text{ dB}$
500 μA/m : 100 μA/m	$20\log\left(\frac{500}{100}\right) = 14 \text{ dB}$
2 μW : 1 μW	$10\log\left(\frac{2}{1}\right) = 3 \text{ dB}$
3 mW : 1 mW	$10\log\left(\frac{3}{1}\right) = 4.8 \approx 5 \text{ dB}$
5 mW : 1 mW	$10\log\left(\frac{5}{1}\right) = 7 \text{ dB}$

Expressing Signal Amplitudes in dB

Signal amplitudes can also be expressed in decibels as a ratio of the amplitude to a specified reference. For example, a 100-microvolt signal amplitude can also be expressed as,

$$20\log\left(\frac{100\,\mu\text{V}}{1\,\mu\text{V}}\right) = 40 \text{ dB}(\mu\text{V}). \tag{1.9}$$

The units in parentheses following the "dB" indicate that the quantity being expressed is an amplitude relative to the given reference value.

Quiz Question

Express the following signal or field amplitudes in their normal units,

a.) 6 dB(μV)
b.) 20 dB(μA)
c.) 20 dB(A)
d.) 100 dB(μV/m)
e.) 100 dB(μW).

Each of the quantities above is simply converted as follows:

$$\text{a.)}\, 6\text{ dB}(\mu\text{V}) = 20\log\left(\frac{\text{X}}{1\,\mu\text{V}}\right) \rightarrow \text{X} = 10^{6/20}\,\mu\text{V} = 2\,\mu\text{V} \tag{1.10}$$

$$\text{b.)}\; 20\text{ dB}(\mu\text{A}) = 20\log\left(\frac{\text{X}}{1\,\mu\text{A}}\right) \rightarrow \text{X} = 10^{20/20}\,\mu\text{A} = 10\,\mu\text{A} \tag{1.11}$$

$$\text{c.)}\; 20\text{ dB}(\text{A}) = 20\log\left(\frac{\text{X}}{1\text{ A}}\right) \rightarrow \text{X} = 10^{20/20}\text{ A} = 10\text{ A} \tag{1.12}$$

$$\text{d.)}\; 100\text{ dB}(\mu\text{V/m}) = 20\log\left(\frac{\text{X}}{1\,\mu\text{V/m}}\right) \rightarrow \text{X} = 10^{100/20}\,\mu\text{V/m} = 10^{5}\,\mu\text{V/m} \tag{1.13}$$

$$\text{e.)}\; 100\text{ dB}(\mu\text{W}) = 10\log\left(\frac{\text{X}}{1\,\mu\text{W}}\right) \rightarrow \text{X} = 10^{100/10}\,\mu\text{W} = 10^{10}\,\mu\text{W}\,. \tag{1.14}$$

Using Decibels

Why bother expressing signal amplitudes in dB? After all, there is never any ambiguity concerning whether a quantity is a power or voltage when the amplitude and its units are provided. The real power of working in dB is calculating ratios.

Previously, we mentioned comparing a 10-watt receiver to a 5-watt specification. In Equation (1.2), we showed that the receiver was 3 dB over the specification. In this case, if the powers had been expressed in dB(W),

$$10\text{ W} = 10\log\left(\frac{10\text{ W}}{1\text{ W}}\right) = 10\text{ dB}(\text{W}) \tag{1.15}$$

$$5\text{ W} = 10\log\left(\frac{5\text{ W}}{1\text{ W}}\right) = 7\text{ dB}(\text{W})\,. \tag{1.16}$$

We could have calculated the ratio as,

$$10\text{ dB}(\text{W}) - 7\text{ dB}(\text{W}) = 3\text{ dB}\,. \tag{1.17}$$

Rather than dividing amplitudes to determine the ratio, we can simply subtract amplitudes expressed in dB(•). Again, as long as the impedance is constant, it will not matter whether we are working with units of power, voltage or current.

Example 1-2: Specifying ratios in dB

Specify the following ratios in dB:

46 dB(μV/m) **:** 40 dB(μV/m) → 46 dB(μV/m) - 40 dB(μV/m) = 6 dB

50 dB(mV) **:** 40 dB(mV) → 50 dB(mV) – 40 dB(mV) = 10 dB

52 dB(mA) **:** 40 dB(mA) → 52 dB(mA) - 40 dB(mA) = 12 dB

54 dB(μA/m) **:** 40 dB(μA/m) → 54 dB(μA/m) - 40 dB(μA/m) = 14 dB

3 dB(μW) **:** 0 dB(μW) → 3 dB(μW) - 0 dB(μW) = 3 dB

7 dB(mW) **:** 0 dB(mW) → 7 dB(mW) - 0 dB(mW) = 7 dB

dBm

One of the most common units expressed in decibels is dB(mW) or dB relative to 1 milliwatt. This is almost always written in the abbreviated form, dBm (i.e., without the "W" and without the parentheses). Many oscilloscopes and spectrum analyzers optionally display voltage amplitudes in dBm. Since dBm is a unit of power, we must know the impedance of the measurement to convert dBm to volts. For example, a voltage expressed as 0 dBm on a 50-Ω spectrum analyzer is,

$$\begin{aligned}
&0 \text{ dBm} = 10\log\left(\frac{\text{X}}{1\text{ mW}}\right) \quad \Rightarrow \quad \text{X} = 1\text{ mW} \\
&\text{X} = \frac{|V|^2}{50\ \Omega} \qquad (1.18) \\
&V = \sqrt{(1\text{ mW})(50\ \Omega)} = 0.2236 \text{ volts}.
\end{aligned}$$

Example 1-3: Specifying voltages in dBm

Specify the following voltages in dBm assuming they were measured with a 50-Ω oscilloscope:

$$1\ \mu\text{V} \quad \rightarrow \quad \frac{(1\ \mu\text{V})^2}{50} = 2\times10^{-11}\text{ mW} \quad \rightarrow \quad 10\log\left(\frac{2\times10^{-11}}{1}\right) = -107 \text{ dBm}$$

$$2\ \mu\text{V} \rightarrow \frac{(2\ \mu\text{V})^2}{50} = 8\times10^{-11}\ \text{mW} \rightarrow 10\log\left(\frac{8\times10^{-11}}{1}\right) = -101\ \text{dBm}$$

$$10\ \mu\text{V} \rightarrow \frac{(10\ \mu\text{V})^2}{50} = 2\times10^{-9}\ \text{mW} \rightarrow 10\log\left(\frac{2\times10^{-9}}{1}\right) = -87\ \text{dBm}$$

$$1\ \text{V} \rightarrow \frac{(1\ \text{V})^2}{50} = 20\ \text{mW} \rightarrow 10\log\left(\frac{20}{1}\right) = 13\ \text{dBm}$$

$$2\ \text{V} \rightarrow \frac{(2\ \text{V})^2}{50} = 80\ \text{mW} \rightarrow 10\log\left(\frac{80}{1}\right) = 19\ \text{dBm}$$

$$10\ \text{V} \rightarrow \frac{(10\ \text{V})^2}{50} = 2000\ \text{mW} \rightarrow 10\log\left(\frac{2000}{1}\right) = 33\ \text{dBm}$$

In this example, we can see that doubling the voltage adds 6 dB (e.g., 13 dBm + 6 dB = 19 dBm) and increasing a voltage by a factor of 10 adds 20 dB. This is true no matter what units of voltage are used and is another example of why it is often convenient to work with decibels.

EMC Regulations and Testing

Virtually every country in the world regulates the electromagnetic compatibility of electronic products marketed or sold within its borders. Organizations such as the *International Electrotechnical Commission* (IEC) and the *International Organization for Standardization* (ISO) develop and maintain standards and test procedures for evaluating the EMC of electronic products. Professional trade organizations, such as the IEEE and SAE also develop EMC standards.

The specific EMC requirements that apply to any given product depend on the product's function, application, and market. Regulations pertaining to EMC can differ significantly from one country to another: or from one industry to another. For example, in the U.S., most commercial computer equipment is subject to conducted and radiated emissions requirements but has no immunity requirements. Medical devices in the U.S. are generally subject to both emissions and immunity requirements, while automotive electronics are mostly exempt from federal EMC requirements. In Europe, on the other hand, nearly all electronic devices are subject to some form of EMC requirement.

In addition, many electronics companies have their own EMC test requirements to ensure that their products will perform reliably in the field, as well as comply with all applicable legal requirements. Products used by the military are typically subject to military EMC standards that, in many cases, can be considerably more stringent than commercial EMC requirements.

EMC tests are generally divided into two categories, emissions, and immunity. Emissions tests measure electromagnetic noise emitted from a product. Immunity tests measure the susceptibility of a product to external sources of electromagnetic noise. The following sections briefly introduce important types of EMC testing.

Conducted Emissions Testing

Conducted emissions tests generally measure the noise voltage that a device puts on its power inputs. The noise voltage is measured in the frequency domain using a spectrum analyzer or an EMI test receiver. These tests employ a device called a *Line Impedance Stabilization Network (LISN)*[2], that provides a stable impedance for the measurement while also protecting the receiver from noise and potentially large power voltages coming from the power supply.

For power line measurements, the LISN is placed between the power source and the device under test (DUT)[3] as illustrated in Figure 1.3. The voltage is measured from each power phase to system ground. The most common LISN impedance is 50 Ω for power line measurements. Standards that require conducted emissions testing of *communication* lines typically call for a 150-Ω LISN.

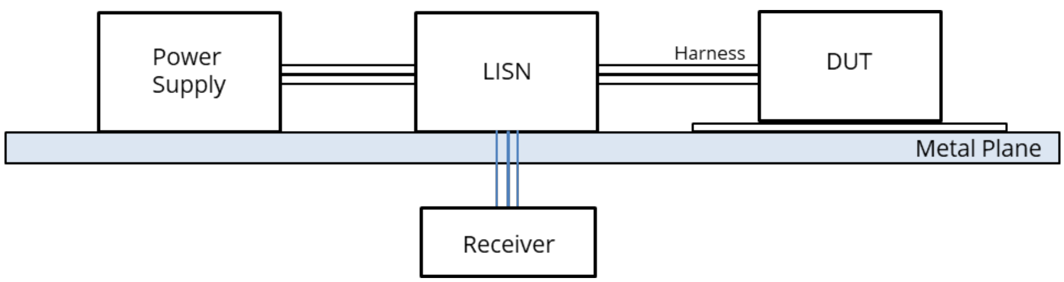

Figure 1.3. Conducted emissions test set-up.

Figure 1.4 shows a 50-Ω LISN schematic. The 50-μH inductor and 1-μF capacitor attenuate any high-frequency noise coming from the power source. The 0.1-μF capacitor protects the receiver from the low-frequency power voltage. Limits are typically specified in μV or dB(μV) and are rms values. There may be different limits for peak, quasi-peak and average power measurements. Peak, quasi-peak, and average detectors are described in Chapter 4.

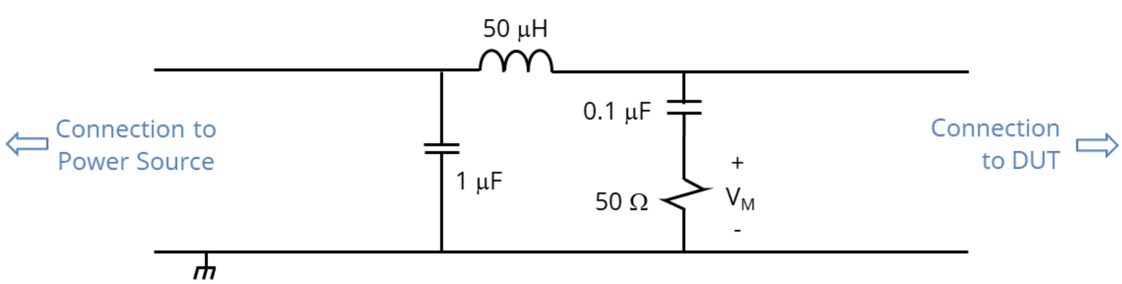

Figure 1.4. Schematic of a 50-Ω LISN.

[2] Some standards refer to the LISN as an Artificial Mains Network (AMN).
[3] Some standards refer to the test object as the EUT (Equipment Under Test) rather than DUT.

Radiated Emissions Testing

Radiated emissions testing is normally performed by placing an antenna at a given test distance from the DUT as illustrated in Figure 1.5. This is usually done in an open field or in a shielded semi-anechoic room. Electromagnetic emissions picked up by the antenna are measured using a spectrum analyzer or EMI test receiver. If the measured field strength at any frequency is above the specified limit, the product is non-compliant. Limits are typically specified in μV/m or dB(μV/m) and are rms values. Like conducted emissions measurements, there may be different limits for peak, quasi-peak and average power measurements.

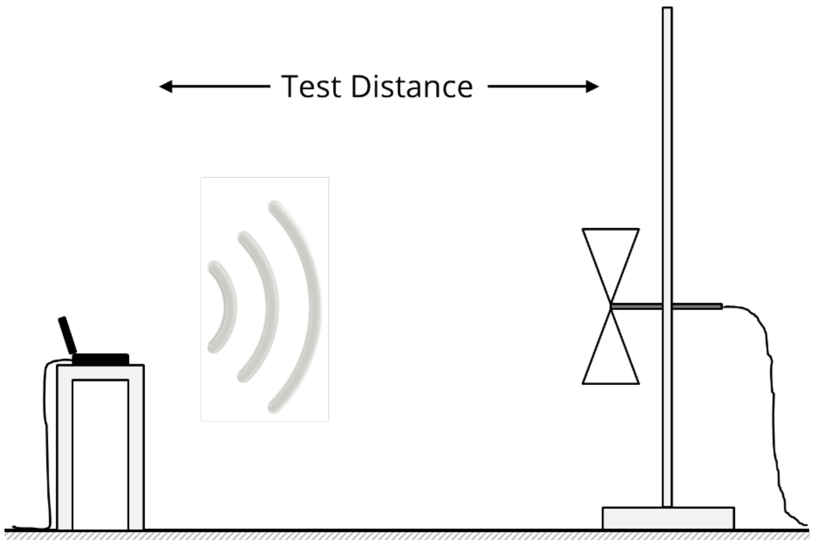

Figure 1.5. Radiated emissions test set-up.

At frequencies below 30 MHz, the receiving antenna is typically a rod antenna (electrically short monopole). Biconical antennas are generally used between 30 MHz and 200 MHz. Log periodic arrays or large horn antennas may be used from 200 MHz to 1 GHz, and horn antennas are typically used above 1 GHz.

Radiated Immunity Testing

Radiated immunity testing is generally performed using a transmitting antenna that is placed at a given test distance from the DUT as illustrated in Figure 1.6. This is normally done in a shielded semi-anechoic room. The DUT is subjected to an electric field at various frequencies. Generally, the product must function without error when subjected to a specific minimum field strength.

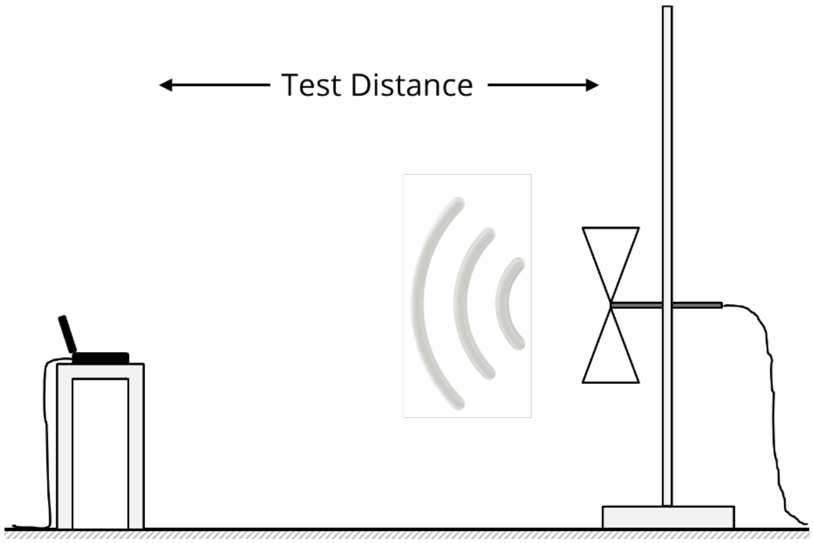

Figure 1.6. Radiated immunity test set-up.

Dwell time is an important parameter of the test. The DUT must be illuminated at a given frequency long enough to run through all of its operating states. Tests may require continuous wave (CW) sources that essentially emit a sine wave and/or modulated sources that simulate interference from intentional transmitters.

Due to the difficulty of generating strong radiated electric fields at low frequencies (e.g., below 100 MHz), low-frequency radiated immunity tests are often performed by placing the DUT in some type of waveguiding structure, such as a TEM or GTEM cell[4].

For radiated immunity tests, limits are typically specified in V/m and are rms values. Test procedures may specify different field strength levels corresponding to the severity of the failure. For example, at 10 V/m, behavior that is merely annoying may be ok; while product behavior that affects operator safety may need to meet a much more stringent field-strength requirement. Field strength levels are also typically different in different frequency bands depending on the EM environment where the product is likely to be used.

While swept-frequency, electric-field immunity is the most common type of radiated immunity testing, there are other radiated immunity tests that evaluate magnetic field immunity and transient field immunity.

Finally, it is important to note that international immunity standards have not kept up with the rapid introduction of new transmitter technologies and protocols. Many companies have their own internal radiated immunity test procedures designed to guarantee that their products won't be interfered with by newer phone models, near-field transmitters and other interference sources not covered by international standards.

Transient Immunity Testing - Switching

Transient immunity tests are primarily designed to emulate the noise created when the current to inductive loads is switched off. As illustrated in Figure 1.7, a transient generator produces voltage spikes with a specified amplitude and duration. These voltage transients

[4] The TEM (Transverse ElectroMagnetic) cell and GTEM (Gigahertz Transverse ElectroMagnetic) cell are transmission line structures with expanded dimensions to allow the placement of test devices inside.

are coupled to the wiring harness of the equipment under test (EUT). The EUT must continue to operate normally, or with acceptable errors, in the presence of the coupled transients.

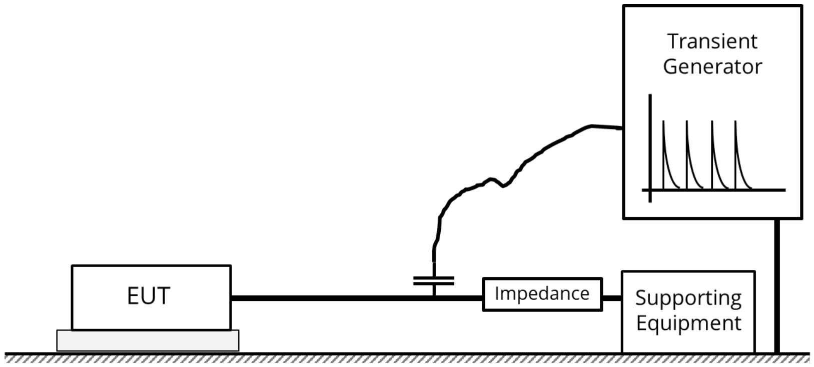

Figure 1.7. Transient immunity test set-up.

Different standards specify different coupling networks. In addition to the capacitive coupling illustrated in the figure, transients may be coupled through a direct connection or through a transformer. The injected voltage and current waveforms depend on the coupling network and the EUT impedances. The coupled waveforms generally look very different from the source waveforms in the specification.

Transient Immunity Testing - Lightning

There is no international standard for lightning testing that involves striking the product with a massive air discharge. Lightning immunity testing is performed by injecting high-energy transients on the cables attached to certain component inputs, as illustrated in Figure 1.8. The voltage waveform of the transient source and/or the current injected is specified and monitored. For communication cables, the end of the cable opposite the EUT is connected to transient-protected supporting equipment. For power lines, the end of the cable opposite the EUT is connected to an LISN.

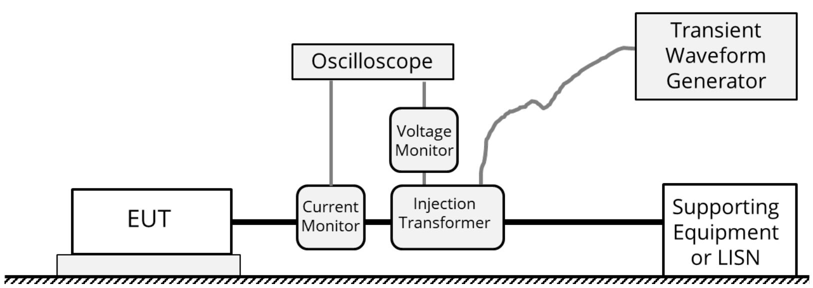

Figure 1.8. Lightning immunity test set-up.

The types of waveforms injected depend on how and where the EUT is installed. Military and aerospace lightning transients are typically applied in multiple strokes spaced tens of milliseconds apart; and/or in multiple bursts, where each burst consists of multiple transients spaced about a millisecond apart.

Most automotive and consumer products are not subjected to lightning immunity testing. Lightning tests are typically limited to products that connect to the telephone network or to communication cables that extend long distances.

Electrostatic Discharge Testing

Electrostatic discharge testing simulates the effect of a charged person or device making contact and discharging to the DUT. Electric charge stored in a capacitor is discharged to the DUT through a resistance. A simple ESD simulator schematic is shown in Figure 1.9. Larger capacitances result in higher energy discharges. Lower resistances result in higher peak currents.

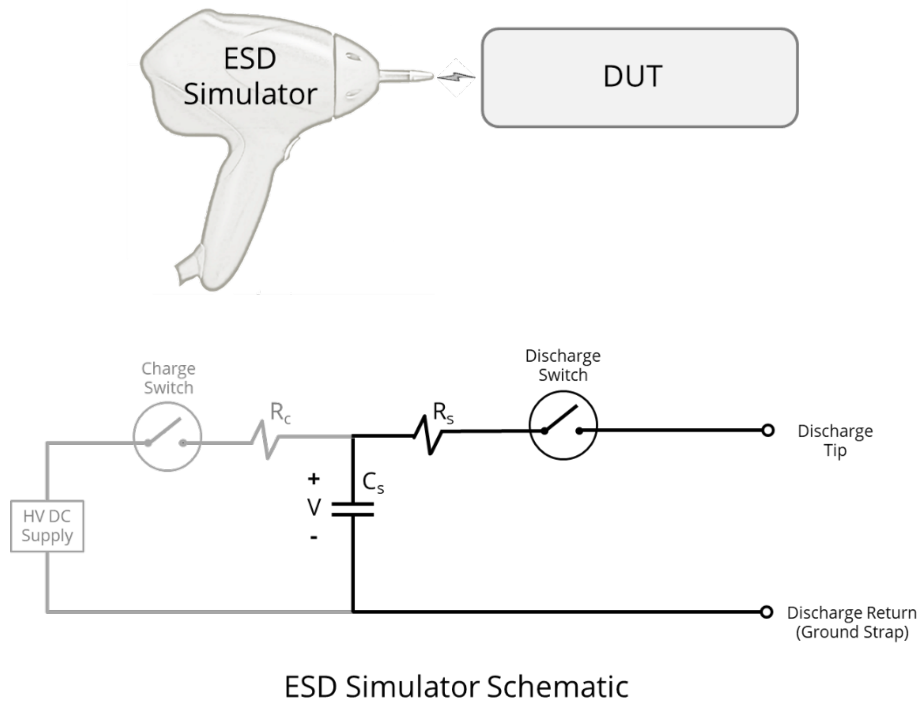

Figure 1.9. Electrostatic discharge testing.

Table-top products are typically tested on a non-conducting table with a metal top. Floor standing products are tested over a metal floor. Tests can be conducted by bringing the simulator close to various points on the DUT until a discharge occurs (air discharge); or by making metal-to-metal contact between the simulator and the DUT before triggering the simulator (contact discharge).

ESD test limits generally depend on the type of failure observed. The limit may be low for non-critical, self-correcting errors (e.g., ~2,000 V). On the other hand, critical errors such as damage to the DUT or shut-down of an important system are usually unacceptable, even at the highest simulator voltage.

Bulk Current Injection Testing

Bulk current injection testing is intended to simulate radiated interference at long wavelengths where the noise is most likely to be coupled to the EUT through the wiring harness. The basic test set-up is illustrated in Figure 1.10. A current injection probe is used to transformer-couple RF currents onto a wiring harness attached to the EUT. The equipment must perform without error when subjected to a specified level of current.

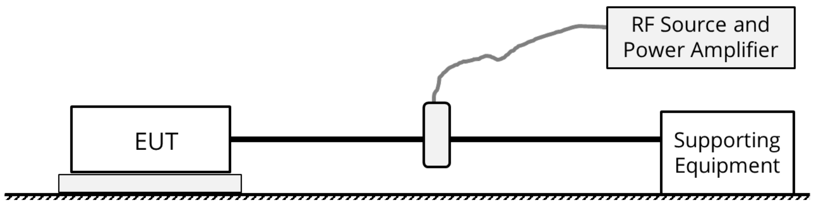

Figure 1.10. Bulk current injection test set-up.

Most consumer products are not subjected to bulk current injection testing, but it is commonly required for automotive and aerospace applications where components are likely to be connected through long wiring harnesses.

There are generally two categories of BCI tests that differ in the method used to determine when the specified injection current has been achieved. These categories are s*ubstitution* and c*losed-loop*. The substitution method performs a preliminary calibration test using a 50-Ω calibration fixture in place of the EUT, harness and support equipment. The forward-power from the transmitter required to produce the specified current at each test frequency is recorded. The test is then repeated with the EUT in place. Instead of monitoring the current, the test is performed with the same forward power that produced that current in the calibration fixture. The closed-loop method monitors the current injected on the wiring harness directly using another current probe. Closed-loop methods may or may not also have a forward-power limit determined by a pre-measurement calibration.

When testing components that are not grounded through their chassis, some BCI procedures allow a ground wire to bypass the current injection probe at low frequencies to give the current some place to go. Others do not allow the ground wire, basically requiring the current to be injected into an open circuit. This results in very strong electric fields between the EUT and the metal table-top.

Power Dips, Drops and Transients

The power distribution system in many environments such as factories, homes and vehicles can be very noisy. For example, in a typical home, it would not be uncommon to see occasional voltage spikes as high as several hundred volts or severe drops in the voltage that last several milliseconds. Products must be able to endure these power fluctuations without exhibiting any unacceptable behavior.

Specific requirements for immunity to power bus voltage fluctuations depend on the environment where the product will be used. The test procedure typically involves inserting test equipment between the DUT and its power source. Power line transients are injected in a manner similar to lightning or EFT transients. Brief power line dips are typically introduced by shorting the power input through a resistance for few milliseconds. Longer power line drops are performed by removing the power or reducing the power line voltage for a specified period.