

EDN SERIES FOR DESIGN ENGINEERS

Electromagnetics Explained

A Handbook for Wireless/RF,
EMC, and High-Speed Electronics

Ron Schmitt



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1 INTRODUCTION AND SURVEY OF THE ELECTROMAGNETIC SPECTRUM

How does electromagnetic theory tie together such broad phenomena as electronics, radio waves, and light? Explaining this question in the context of electronics design is the main goal of this book. The basic philosophy of this book is that by developing an understanding of the fundamental physics, you can develop an intuitive feel for how electromagnetic phenomena occur. Learning the physical foundations serves to build the confidence and skills to tackle real-world problems, whether you are an engineer, technician, or physicist.

The many facets of electromagnetics are due to how waves behave at different frequencies and how materials react in different ways to waves of different frequency. Quantum physics states that electromagnetic waves are composed of packets of energy called photons. At higher frequencies each photon has more energy. Photons of infrared, visible light, and higher frequencies have enough energy to affect the vibrational and rotational states of molecules and the electrons in orbit of atoms in the material. Photons of radio waves do not have enough energy to affect the bound electrons in a material. Furthermore, at low frequencies, when the wavelengths of the EM waves are very long compared to the dimensions of the circuits we are using, we can make many approximations leaving out many details. These low-frequency approximations give us the familiar world of basic circuit theory.

THE NEED FOR ELECTROMAGNETICS

So why would an electrical engineer need to know all this theory? There are many reasons why any and all electrical engineers need to understand electromagnetics. Electromagnetics is necessary for achieving

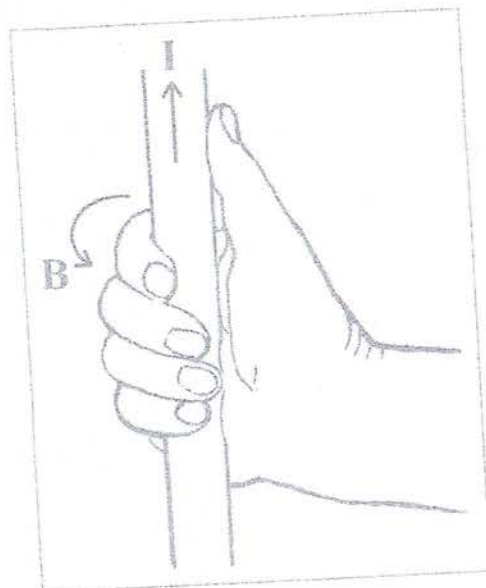
electromagnetic compatibility of products, for understanding high-speed digital electronics, RF, and wireless, and for optical computer networking.

Certainly any product has some electromagnetic compatibility (EMC) requirements, whether due to government mandated standards or simply for the product to function properly in the intended environment. In most EMC problems, the product can be categorized as either an aggressor or a victim. When a product is acting as an aggressor, it is either radiating energy or creating stray reactive fields at power levels high enough to interfere with other equipment. When a product is acting as a victim, it is malfunctioning due to interference from other equipment or due to ambient fields in its environment. In EMC, victims are not always blameless. Poor circuit design or layout can create products that are very sensitive to ambient fields and susceptible to picking up noise. In addition to aggressor/victim problems, there are other problems in which noise disrupts proper product operation. A common problem is that of cabling, that is, how to bring signals in and out of a product without also bringing in noise and interference. Cabling problems are especially troublesome to designers of analog instrumentation equipment, where accurately measuring an external signal is the goal of the product.

Moreover, with computers and networking equipment of the 21st century running at such high frequencies, digital designs are now in the RF and microwave portion of the spectrum. It is now crucial for digital designers to understand electromagnetic fields, radiation, and transmission lines. This knowledge is necessary for maintaining signal integrity and for achieving EMC compliance. High-speed digital signals radiate more easily, which can cause interference with nearby equipment. High-speed signals also more often cause circuits within the same design to interfere with one another (i.e., crosstalk). Circuit traces can no longer be considered as ideal short circuits. Instead, every trace should be considered as a transmission line because reflections on long traces can distort the digital waveforms. The Internet and the never-ending quest for higher bandwidth are pushing the speed of digital designs higher and higher. Web commerce and applications such as streaming audio and video will continue to increase consumer demand for higher bandwidth. Likewise, data traffic and audio and video conferencing will do the same for businesses. As we enter the realm of higher frequencies, digital designs are no longer a matter of just ones and zeros.

Understanding electromagnetics is vitally important for RF (radio frequency) design, where the approximations of electrical circuit theory start to break down. Traditional viewpoints of electronics (electrons

Figure 3.3 The right hand rule: the magnetic field (B) curls like the fingers of the hand around the current (I), which points in the direction of the thumb.



of reference, the charge is stationary, producing only an electric field. Therefore, the magnetic field is a relative quantity. This odd situation hints at the deep relationship between Einstein's relativity and electromagnetics, which you will learn about in detail in Chapter 6.

The magnetic field direction, clockwise or counterclockwise, depends on which direction the current flows. You can use the "right hand rule" for determining the magnetic field direction. Using Figure 3.3 as a guide, extend your hand flat and point your thumb in the direction of the current (i.e., current is defined as the flow of positive charge, which is opposite to the flow of electrons). Now curl the rest of your fingers to form a semicircle. The magnetic field will follow your fingers, flowing from your hand to your fingertips, or in other words, the arrow tips of the field will be at your fingertips.

MAGNETIC DIPOLES

Now, consider a current that travels in a loop, as shown in Figure 3.4. The magnetic field is a toroidal (donut-shaped) form. The magnetic field

7 THE HIDDEN SCHEMATIC

Typically, schematic diagrams show resistors, capacitors, inductors, and wires as ideal components. In many cases, components can be considered as ideal. However, at high frequencies such approximations are often no longer valid. The frequency-dependent departures from ideality are mainly due to parasitic capacitances and parasitic inductances. Electromagnetic theory dictates that any two conductors will have a capacitance between them and that any conductor used for carrying current will have inductance. Parasitic capacitance and inductance create reactive impedance that varies with frequency. For a capacitor, the impedance is $Z_c = -j/2\pi fC$. At DC, capacitive impedance is infinite—an open circuit. Capacitive impedance decreases with frequency. For an inductor, impedance is $Z_L = j2\pi fL$. At DC, inductive impedance is zero—a short circuit. Inductive impedance increases with frequency. These parasitic impedances cause real components to behave differently at high frequencies. The parasitic impedances of components are present in every real component but are typically not shown in their schematic symbols, hence the phrase *hidden schematic*.

In addition to the frequency-dependent parasitic elements, there exist other non-ideal characteristics of components. All conductors, including wires and component leads, have a non-zero resistance. At times this resistance must be accounted for in the design process. The characteristics of all components also vary with temperature. Components made from different materials will often display varying degrees of sensitivity to temperature. Temperature dependence must be accounted for in any real-world design. Finally, individual components will vary from the nominal value. The amount by which a component can be expected to vary from the nominal value is called *tolerance*.

THE NON-IDEAL RESISTOR

There are three common types of resistors: carbon resistors, wire-wound resistors, and metal film resistors. Carbon resistors are inexpensive

signals, but also limits radiation effects caused by the high-frequency ringing signal.

CONDUCTED VERSUS INDUCED VERSUS RADIATED INTERFERENCE

In EMC literature and EMC regulations the mechanisms of electromagnetic interference are divided into two categories, conducted and radiated. Historically, this categorization has been used in the regulations and, unfortunately, it continues today. I use the word "unfortunately" because both near-field coupling and far-field radiation are lumped under the term *radiated emissions*. While experts in electromagnetics are quite familiar with the difference between near-field coupling and far-field emissions, the vague terminology in EMC regulations tends to confuse those who are trying to learn the basic concepts. As I explained in Chapter 5, near-field energy is stored, not radiated. Furthermore, when you couple to the near-field of a circuit, you not only pick up unwanted electromagnetic energy, you also alter the operation of that circuit by extracting and/or redirecting energy that was otherwise being stored in the neighboring air. The Yagi-Uda antenna, as discussed in Chapter 11, exemplifies this phenomenon; it is constructed by placing two unconnected wires in the near field of a dipole antenna. This confusing EMC emissions terminology leads people to say ridiculous things like, "preventing 60Hz radiation." Radiation at 60Hz is never encountered on Earth because you must be over a thousand miles from the source to even get to the edge of the near field. Interference at 60Hz is caused by near-field coupling. In general, large stray fields can often be eliminated by using uniform transmission lines and by avoiding transmission line discontinuities.

I use the terms *induced interference* for near-field coupling and *radiated interference* for far-field radiation. This distinction is not purely academic. There are many practical differences between how induced and radiated interference occurs. Recall how electromagnetic shields behave in different types of fields. In the near field, electric fields are reflected by a thin metallic shield quite well, whereas magnetic fields readily penetrate metallic shields unless the shield is several skin depths thick. The far-field behavior of shields is different from both magnetic and electric near-field behavior.

Similar effects occur in how circuits pick up near-field electromagnetic energy. Whereas radiated waves always maintain the impedance of air and are therefore always electromagnetic, near-field waves are

usually dominated by one component, electric or magnetic. Circuits will pick up radiated energy if they contain antenna-like elements: loops or dangling monopole or dipole antennas. The most energy will be absorbed when the circuit impedance is matched to the self-impedance (feeding impedance) of the antenna. Induced energy coupling has different characteristics. *High-impedance circuits are very susceptible to interference from electric near fields, and low-impedance circuits are very susceptible to interference from magnetic near fields.* Furthermore, circuits with unconnected metal conductors of large size are more susceptible to electric fields, and circuits with large loops are more susceptible to magnetic fields. Both types of induced interference increase when the two circuits are brought closer together.

From these facts, you can conclude that if you want to create a magnetic field meter, you should use a loop or multiturn coil of wire, connected to a current amplifying circuit that has very low impedance. Coupling to a magnetic field can be thought of as coupling to a series voltage source, with series source inductance. The source inductance is the mutual inductance of the two circuits. If you want to create an electric field meter, you should use a metal plate or dangling wire that is connected to a high-impedance voltage amplifier. Coupling to an electric field can be thought of as coupling to a shunt current source, with a parallel source capacitance. The source capacitance is the mutual capacitance. Near fields that are equal in electric and magnetic fields can be thought of as a superposition of electric and magnetic fields; that is, they do not give rise to any new behavior.

The induced interference is also dependent on frequency. The energy in the near field is, perhaps surprisingly, mostly independent of frequency. However, the effects induced into a second circuit are proportional to how fast the field changes (i.e., proportional to the time derivative of the field). High-frequency signals and signals with rapid rise times do not create larger energy in the near field, but they do cause larger induced currents and voltages in any nearby circuits. To summarize, near-field interference increases with larger fields, higher frequencies, and shorter distances.

The equivalent circuit for capacitive coupling (induced interference) and the resulting induced circuit voltage are shown in Figure 12.3. The analogous results for magnetic coupling are shown in Figure 12.4.

The third type of interference is *conducted interference*. Conducted interference consists of unintended signal energy that leaves a product through its cables. For example, high-frequency energy can couple to the power supply and escape the product by traveling out on the power cord. From that point the interference energy can couple to other prod-

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