

# 1 Background and Motivation

## 1-1 Introduction

Electromagnetics is both the oldest and most basic of all the branches of electrical engineering. Stated simply, electromagnetics deals with four questions: what is electricity, how does it behave, what can it do, and how can we control it. So fundamental are the questions that it addresses that it is not an exaggeration to say that electromagnetics is at the heart of everything that is done with electricity. As a result, an understanding of electromagnetics is essential in order to fully understand the operation of many (if not most) electrical devices and effects.

At its most basic level, electromagnetics concerns itself with the forces that charged particles exert upon each other. These forces are important for two reasons. The first is that they determine how electric charges and currents distribute themselves in electrical devices. The second is that it is these forces that make electricity useful to us, since these forces make other things move and allow us to detect the presence of charges and currents. Indeed, applications such as telecommunications, electrical machines, and computers would not be possible were it not for these forces.

Although there are many applications where electromagnetic forces are our primary interest (as in the case of electric motors), we are usually more interested in how these forces cause the charges and currents in circuits and devices to distribute themselves. For instance, in the case of electrical computing, electronic memory is accomplished by moving packets of charge into discrete locations in semiconductor chips and later sensing their presence (or absence). Similar processes are used in a large number of applications, whereby information is stored or transmitted by controlling the flow of charges throughout a system or device. Examples include radio, television, radar, sound reproduction, among many others.

Possibly the most useful and remarkable property of electricity is its ability to produce effects between two devices or circuits when there is no material connection between them. This is unlike mechanical systems, which must always have some sort of mechanical linkage in order for there to be any effect. Electricity is capable of producing measurable effects over very large distances, even through great distances in vacuum. This allows us to routinely use electricity in such applications as wireless communications, radar, remote sensing, as well as many others. The key to accomplishing these applications is an understanding of the physical quantities that are responsible for these interactions: electric and magnetic fields. Once these concepts are understood, the range of applications in electrical devices and systems is limited only by our imagination, our knowledge of the properties of materials, and our manufacturing ability.

## 1-2 A Little History

Electrical systems and devices are so common in our lives that it is difficult to envision an age when electricity and magnetism were simply mysterious curiosities. But up until the early 1800's, that is exactly what they were. How these phenomena were discovered, understood, and harnessed is one of the greatest feats in the history of science and engineering.

"Electromagnetics" is a word that was coined in the late 1800's to denote a newly discovered phenomenon that was the combination of what previously had been thought to be completely separate phenomenon: electricity and magnetism. Electric effects were the first to be discovered. History records that the ancient Greeks discovered that when an amber rod was rubbed with fur, the amber would attract bits of dust, straw, and other small objects. Nearly two thousand years passed before William Gilbert realized in the early 1600's that this same effect could be observed when rubbing a variety of substances. It is he who coined the term "electric", using the Greek word for amber, elektron. About the same time, Niccolo Cabeo also discovered that the electric effect could result in both attractive and repulsive forces between electrified (i.e., charged) objects.

The first indications that electricity can move from one place to another came from experiments conducted by Stephen Gray in 1729. He found that when two objects were connected by a tube, both could be electrified when only one was rubbed. This discovery led J.T. Desaguliers in 1739 to the discovery of a class of materials he called conductors that pass electricity easily.

As interesting as these discoveries were, they did not explain how these electric effects occurred. This started to change in the mid 1700's when a number of investigators began to suspect that the forces between charges could be described as an inverse-square law that was similar to the universal gravitational law, proposed by Sir Isaac Newton in the late 1600's. Although Benjamin Franklin, Joseph Priestley, John Robison, and Henry Cavendish all made significant contributions to the discovery of this law, it was Charles Augustin de Coulomb who attracted the most attention, so we now call this law Coulomb's law of force. The discovery of this law was the first step towards finding a comprehensive theory of electromagnetics.

Like the electric properties of amber, the magnetic properties of a mineral called lodestone were also known to the ancients, who knew that it could attract iron and would point towards north when allowed to float on water. As time progressed, several other materials were found to possess similar characteristics. Also, they discovered that "artificial" magnets could be made from naturally occurring ones. The first quantitative theories of magnetism were advanced in the eighteenth century. In 1750 John Michell theorized that permanent magnets have north and south poles that attract or repel each other according to an inverse square law that is similar to the Coulomb's law of force.

The pace of discovery of both the electric and magnetic effects quickened with the onset of the nineteenth century. In the year 1800, Volta developed the first chemical battery, which consisted of strips of dissimilar metals, immersed in a weak acid electrolyte. This invention enabled the flow of steady currents and fostered numerous experiments involving chemical effects, heating, and material studies. One of the most important series of experiments was performed by George Simon Ohm in 1826, where he showed that when a constant voltage is applied to a conductor, the resulting current is proportional to the conductor's cross sectional area and inversely proportional to its length. This is Ohm's law, which is one of the most important laws of circuit theory.

The first evidence that electric and magnetic phenomena are related came from Hans Christian Oersted, who, in 1819, discovered that a steady current could move a compass needle, just as a

permanent magnet can. This was closely followed by André-Marie Ampère's discovery that electric currents exert attractive and repulsive forces on each other. Ampère discovered that the force exerted by current segments varies inversely with the square of the distance between them and perpendicular to the line that connects them. We call this law Ampère's law of force, which is the magnetic analog of Coulomb's law of force.

Another important experimental connection between electric and magnetic effects was discovered by Michael Faraday in 1831. He conducted an experiment whereby two insulated wires were wrapped around an iron core. Faraday found that when the current in one winding was switched, a voltage was induced in the other. This discovery of transformer action led Faraday to a series of experiments in which he was able to conclude that a voltage is produced in a circuit whenever a time-varying magnetic field is present - either because the current is time-varying, or because the circuit or source are in motion. We call this Faraday's law of induction (often simply called Faraday's law).

With the discovery of Faraday's law, the stage was set for the development of a complete theory of electromagnetism. This was accomplished by James Clerk Maxwell, a professor of experimental Physics at the Cambridge University. In 1873 he published *A Treatise on Electricity and Magnetism*. In this work, he proposed that just as time-varying magnetic fields can produce electric fields, the opposite is also true. Adding this conjecture to what was already known about electricity and magnetism, Maxwell produced his now famous system of equations - called Maxwell's equations. These equations relate electric and magnetic fields to each other and their sources. In addition to his work in electromagnetics, Maxwell is also known for several other contributions to physics, including thermodynamics (where a set of equations also bears his name) and the first workable theory of the rings of Saturn.

The definitive experimental verification of Maxwell's theory came in 1886 through a series of experiments conducted by Heinrich Hertz. These experiments showed that electromagnetic waves can be propagated, reflected, and focused, just as light waves can. This discovery completely validated Maxwell's theory and ushered in the era of modern electromagnetic theory and applications.

### 1-3 Engineering Applications of Electromagnetics

One might think that engineering applications of electromagnetics occurred only after Maxwell's theories were presented and Hertz validated them with his experiments. The fact is, however, that there was a thriving electrical industry before the complete theory of electromagnetics was laid out. This activity started around 1834 with the introduction of the telegraph by Charles Wheatstone, William Cook, and Samuel Morse, among others. The first undersea telegraph cable was laid in 1851, and nearly one hundred thousand miles of cable had been laid world wide by 1885. Also invented before Hertz's experiments were the telephone (1876) and the electric light bulb (1879).

The most dramatic application of the new electromagnetic theory came in 1901 when Guglielmo Marconi sent the first wireless telegraph signals across the Atlantic Ocean. The next two

decades saw a host of developments in antennas, amplifying devices, and modulation techniques, culminating in the first commercial radio broadcasts in the early 1920's. Television soon followed in the early 1930's, followed by radar in the late 1930's.

Wireless communication is probably the most conspicuous application of electromagnetics, since it involves the propagation of electromagnetic waves through air or space. But Maxwell's electromagnetic theory has been equally important in the development of a host of other engineering applications. This should come as no surprise, since electromagnetics is the comprehensive theory of what electricity is and how to control it. Other devices and systems in which electromagnetic theory played an important part in their development include: the vacuum tube (1906), the magnetron (a high frequency amplifier and oscillator used in microwave systems; 1940), the transistor (1950), the laser (1960), fiber optic systems (late 1970's). In fact, it is safe to say that electromagnetic theory has been an essential ingredient in the development of every electrical device or system that we now take for granted.

Some of the major engineering applications of electromagnetics can be classed into the following areas:

**Semiconductor devices:** Electromagnetic theory and quantum semiconductor theory are the keys to understanding how charges and currents are manipulated within semiconductors.

**High speed circuits:** Ordinary circuit theory is fine for low frequency circuits, but this theory breaks down when the circuit dimensions and frequency reach the point where propagation delay times can no longer be ignored. This is particularly true for microwave circuits and high speed digital circuits.

**Antennas:** These devices launch and capture electromagnetic waves, so electromagnetic theory is essential to their operation. Even though antennas have been used for decades, recent advances in wireless communication systems have created the need for smaller and more efficient antennas.

**Electro mechanical machines:** The forces that currents (and sometimes charges) exert on each other are used to make machines and devices that are capable generating forces and torques.

**Fiber optic systems:** Since the development of low loss optical fibers in the 1970's, the number of fiber optic communication links has grown steadily, to the point where fiber optic transmission is now the standard in many industries. Electromagnetic theory is used to describe light propagation on the fibers, as well as the operation of the laser diodes and detectors.

**Bioelectronics:** In many respects, the human body can be considered as a massive collection of electrical circuits. This understanding has spawned the bioelectronics industry, which supplies instruments and systems that measure and modify various biological functions in humans and animals. Electromagnetics plays an essential part in understanding how these instruments interact with the body.

Electromagnetic interference (EMI) and compatibility (EMC): Even when a circuit or system is not intended to radiate or receive energy, these effects may still occur. This is particularly troublesome when digital and analog circuits are present in the same device, since the high current levels and fast switching times of the digital circuits often radiate unwanted energy towards the analog circuits. These problems can be controlled by using electromagnetic techniques.

Superconductors: When cooled below their critical temperature, superconductors exhibit zero resistance and repel magnets. The discovery of high temperature superconductors has rekindled interest in using superconductors in a number of engineering applications, including power transmission and magnetic levitation.

#### 1-4 In This Text . . .

The goal of this text is to lay out the electromagnetic theory in the context of its engineering applications. This discussion starts with a review of vector calculus, which is the best "language" for describing electromagnetic effects. This is followed by a chapter that presents an overview of electromagnetic effects and Maxwell's equations. This chapter is intended to provide a broad view of the relationship between electric and magnetic fields and the sources that produce them. From there, the next three chapters discuss various aspects of low frequency electric fields when magnetic effects are negligible. This followed by three chapters that discuss low frequency magnetic fields when electric effects are negligible. Chapter 10 begins the transition from low frequency electromagnetic effects to high frequency effects, where electric and magnetic fields are completely interdependent. In this chapter, Maxwell's equations are described in detail for both transient and time harmonic cases.

The final four chapters of this text discuss four electromagnetic topics that are important to the operation of high frequency devices and systems designed and used by electrical engineers. The first topic is transmission lines, which are used transport signals and energy in electric circuits. The second topic is plane waves, which are the waves launched into space by sources such as antennas and lasers. The third topic is waveguides and cavities. Like transmission lines, waveguides are also used to transport signals and energy. A common example of waveguides is optical fibers, which are commonly used in communication systems. The final topic is radiation and antennas. In this chapter, the general theory of how sources radiate is discussed, and many practical aspects of antennas are discussed. Although mechanical systems are, in theory, coupled by gravity, this coupling is so weak as to render it essentially useless in most applications.