Student Projects for an Electromagnetics Course

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Abstract

The course on electromagnetics, which is a mainstay of many electrical engineering programs, is typically taught in the junior year as a theory course without a lab. Several abstract and difficult concepts are introduced and often, even good students, will leave the course having mastered the mathematics but with little intuition about how the theory they know relates to the physical world of engineering. Concepts introduced include movement of charge, capacitance, inductance, static magnetic fields, and electromagnetic waves.

In the electromagnetics course at the University of Evansville, projects have been introduced to help students relate the theory from class to the real world. Projects are completed outside of the classroom and open project labs provide access to lab equipment at all hours. Projects are done in teams of two and each team typically does three projects over the semester. This paper describes seven projects which have been used in the course to illustrate concepts. Student feedback is presented along with practical implementation strategies for success.

The six projects are:

1. **Capacitive Rain Gauge**: Students design a gauge that is sensitive to the fluid level in the gauge. This gauge is based on the principle that capacitance is dependent on the dielectric constant of the material between two conductors.

2. **Transmission Line Characteristics**: Students must calculate characteristic impedance and propagation speed of a coaxial cable based on measured dimensions.

3. **DC Electric Field Probe**: Students design a non-contact probe that can detect the presence and polarity of a static (or slowly varying) electric field in air.

4. **AC Current Meter**: Students design a non-contact AC current meter.

5. **Metal Detector**: Students design a metal detecting device based on mutual inductance.

Introduction

A course in electromagnetics is a fundamental requirement for nearly all electrical engineering programs. The course is typically taken at the beginning of the junior year – after students have completed the prerequisite math and physics courses. Topics include: Introduction to electromagnetic field theory, Maxwell's equations, divergence, Poisson's and Laplace's equations, conductance and capacitance, Stokes' theorem, retarded potentials, the Poynting theorem and skin effect.

The course is most often a lecture course but a few programs have traditional labs to go with it. An internet survey of 25 universities where information was readily available indicated that only 2 of the 25 had a required lab for the course. The electromagnetics course at the University of Evansville has long been a traditional lecture course. Over the years, some software has been introduced, usually MATLAB®, for use in producing graphs, doing simulations, and solving problems that are tedious by hand. There have been few senior design projects using...
emotronics and little student interest. Projects have been introduced in an effort to stimulate interest and demonstrate the many practical applications of the theory.

The Projects

Each project is chosen with three ideas in mind: First it is important that the project illustrate some topic for which the theory is presented in the course. Second, the student must be able to make use of the theory in the project as part of its design. The project should not be only peripherally related to the idea being presented. Finally, the project needs to be simple enough that an undergraduate student who has completed courses in circuits and electronics with labs, can complete the project in about two-weeks. The project below meet these guidelines.

**Project 1: Capacitive Rain Gauge**

This project illustrates capacitance and its relationship to the dielectric constant. When students take the electromagnetics course they are already familiar with capacitors from the course in circuits and electronics but they have never had to think much about a dielectric. For this project, students are expected to construct a container which will catch rain water in such a way that the volume of water will alter the capacitance of a home-made capacitor. In its simplest form, the container is two cylinders where the smaller one fits inside the larger one. Both cylinders are made of some conductive material and become the two sides of a capacitor. The cylinders are electrically isolated from one another and the rain water fills in the space between the cylinders thereby altering the measured capacitance. Students can measure the capacitance by making the capacitor the frequency determinant in an oscillating circuit and measuring the change in frequency by counting cycles over a fixed period of time.

One strength of this project is that it connects basic electromagnetic principles to an open-ended design project. Below is an outline of the various stages of the project.

*Identification of a solution*

There are many potential ways to build an electronic rain gauge. In an effort to highlight the entire design process students could be asked to brainstorm various ways to electrically and remotely make measurements of fluid levels. Solutions may include a float with potentiometer, sonar, etc. We now impose the constraint that we want to exploit the high dielectric constant of water to design our rain gauge. Since the dielectric constant has a strong effect on the electric field intensity and no effect on magnetic fields, we need to find a geometry that lends itself to large electric fields. The obvious solution is a capacitor.

Many different capacitor geometries will work for this project. The simple coaxial geometry mentioned previously gives the student an opportunity to make very close comparisons of initial calculations of capacitances to those of the final product. The equation for ideal coaxial capacitor ($C$) is:

$$C = \frac{2\pi\varepsilon h}{\ln\left(\frac{b}{a}\right)}$$
Here $\varepsilon$ is the total permittivity, $h$ is the axial height, and $b$ and $a$ are the outer and inner radii respectively. We take advantage of the fact that when the capacitor is empty (air filled) the permittivity is $\varepsilon \approx \varepsilon_0$ since the dielectric constant (relative permittivity) is $\varepsilon_r \approx 1$. As the capacitor space between the conductors is filled with water the total capacitance can be viewed as the parallel combination of a water filled capacitor (dielectric constant $\varepsilon_r \approx 80$) of height $z$ with an air filled capacitor of height $h - z$. The result is the sum of two regions.

$$C = \frac{2\pi(80)\varepsilon_0 z}{\ln\left(\frac{b}{a}\right)} + \frac{2\pi\varepsilon_0 (h - z)}{\ln\left(\frac{b}{a}\right)} = \frac{2\pi\varepsilon_0}{\ln\left(\frac{b}{a}\right)} (79z + h)$$

We plainly see from this equation that the total capacitance is strongly dependent on $z$, the height of the water.

**Construction of the Capacitor**

Before construction begins the constraints of the systems should be carefully considered. Clearly the height of the rain gauge is determined by reasonable amounts of rainfall. 30 cm should be sufficient. The selection of $b$ and $a$ are perhaps not so obvious. To maximize the sensitivity of the rain gauge we need to maximize $dC/dz$. This would be maximum when the denominator is minimum. Since the outer radius $b$ must be greater than the inner radius $a$, $dC/dz$ is maximum when $b$ almost the same as $a$. In other words, the gap between the conductors should be as small as possible. Of course, there is a practical lower limit on the size of the gap based on the fact that it must be sufficiently large to collect water without surface tension or splash affecting the collection of water.

Additionally the inner and outer conductors should be coated with a thin insulator so that the water does not conduct current. The conductivity of pure (deionized) water is very low, but dissolved impurities greatly affect the conductivity. To minimize the effect of impurities the water should not directly contact either conductor. However, the presence of a thick insulator (thick compared to the air gap) would greatly affect the calculation of the capacitance, but we can compensate if needed.

The best prototype we have built started with a ~1 cm thick plastic base. A hole was drilled in the center so that a bolt could be inserted through the bottom. The bolt was both to secure the center conductor and to provide an electrical attachment point. The inner conductor was a 50 cm diameter aluminum bar also cut to 30 cm long with one end tapped to accept the center bolt. The inner conductor was wrapped in a sheet of 25µm Mylar and the seam was sealed using clear packing tape. Epoxy was used at the joint between the inner conductor and the base to ensure it was water tight. The outer conductor was made of a 75 cm diameter aluminum pipe cut to 30 cm long. To insulate the inner surface we cut a sheet Mylar so that it just fit inside the pipe. Again the seam was sealed with clear packing tape. The now insulated pipe was attached to the plastic base using epoxy. An economy version of this could be made with PVC pipe and aluminum foil.

**Method of Measurement and Calibration**

The method used for measurement of capacitance can vary greatly. This is an area where instructors have a chance to allow much freedom. For the most part measurements can be made using an oscilloscope, but more elaborate display systems could be used. In my opinion, students benefit the most here when given a few starting guidelines and left to fill in the rest on their own.
One of the most accurate methods is to create a frequency sensitive system. There are many oscillator designs whose frequency depends on capacitance. One relatively simple setup would be to use a transistor driven multivibrator. A monostable multivibrator, for example, may use only one capacitor and usually has a square wave output. This makes frequency easily measurable by any digital device.

The frequency could also be measured from a driven LC tank circuit. The nice thing about this circuit is its relevance to electromagnetic phenomena. The oscillation due to the transfer of energy stored in the electric field to energy stored in the magnetic field and back makes its own nice little electromagnetic side project.

Another, perhaps more simple method is to simply use a step response to measure capacitance. Here we are just the decay rate (or possibly rise time) of an RC circuit. Calculation of capacitance can be very simple, but care must be taken to remove all unknown impedances. For example if using a function generator to generate a step the student must account for the output impedance of the generator. Perhaps the simplest way to correct for output impedance is to eliminate it. If an RC circuit using the rain gauge for the capacitance is charged to a constant voltage then “disconnected” the resistance of the system is clearly known. The capacitor could either manually disconnected with a switch assuming the RC time constant is sufficiently large or a high impedance transistor, such as a MOSFET, could be used to “disconnect” the RC circuit. This method is quite simple if using an oscilloscope as one could measure the time \( t_{1/2} \) for the signal to decay to half the original voltage and use the relationship:

\[
C = \frac{t_{1/2}}{R \ln(2)}
\]

Comparison of Theory to Observation and Identification of Potential Enhancements

This is a simple but important step as it brings the theory full circle. Students can be asked to identify sources of discrepancy between the initial calculations and the final design. This is also the time where student can be asked to discuss, or actually implement, full standalone designs that communicate with a microcontroller and somehow display the height of the water.

Variant of the Capacitive Rain Gauge

Physical construction of the capacitor used for the rain gauge can be time consuming especially if resources are limited. To address this issue students can be asked to design the capacitor on paper then focus on building the circuit and/or method used to measure the capacitance. Once students are ready to verify their methods they can measure the capacitance of an unknown “mystery” capacitor. This compressed variant still contains most of the electromagnetic theory and design elements.

Project 2: Transmission Line Characteristics.

Transmission lines embody a straightforward way to study electromagnetic waves. This project would typically come late in a first semester electromagnetic course or early in a second semester course once students have used Maxwell’s time dependent equations to form wave equations for electric and magnetic fields. The two conductors of a transmission line make electric field measurements simple since we only need measure the electric potential between the two conductors. Therefore, we need only derive a relationship between voltage and current,
which is much easier to measure than the relationship between electric and magnetic fields. The
time dependent voltage is, of course, related to the current through the characteristic impedance
$Z_0$. In a transmission line the solution to the wave equations give rise to a traveling wave with
velocity mostly dependent on the dielectric constant of the transmission line.

$$v = \frac{1}{\sqrt{\mu \varepsilon}} \approx \frac{1}{\sqrt{\mu_0 \varepsilon_0}} = \frac{c}{\sqrt{\varepsilon_r}}$$

It is easy to derive that there must be a forward transmitted and backward reflected wave at a
discontinuity in the characteristic impedance in order to conserve energy. We exploit this
consequence to calculate the attributes of the transmission line. This project can be conducted
under the pretext of a power company or communications company who want to locate faults in
their transmission lines.

**Characteristics**
Students are asked to find:
1. velocity of propagation in the transmission line,
2. length of the transmission line,
3. attenuation coefficient of the transmission line,
4. impedance of an unknown termination.

**Initial Conditions**
This project is best presented a laboratory project. In other words, the only equipment need is an
oscilloscope, function generator, transmission line, and various terminations for the line.
Students are given a long length of coaxial cable to use as the transmission line. The minimum
usable length depends on the equipment available. For example if using a 100 MHz oscilloscope
with a standard function generator, approximately 50 m of cable is needed. This project is
simplified by using 50 $\Omega$ coaxial cables terminated with BNC connectors, typically the same as
the lab equipment. Generally, students are given the characteristic impedance of the line, but it
could be calculated by analyzing the line with a known termination.

**Determination Method**
To derive the characteristics of the transmission lines students could use either a short pulse or
standing wave method using sinusoidal voltage. Both methods have their advantages and
disadvantages as will be discussed for each result. Generally, depending on the equipment used,
the pulse method is easier but the standing wave method leads to more accurate results.

**Velocity of propagation**
Typically the velocity of propagation, $v$, would already be known, but in the interest of being
thorough we can find the phase velocity in one of two ways. If the dielectric is know we can use
the equation above. Otherwise, we can empirically measure the phase velocity from a sample of
transmission line of known length. In this case, since both ends of the transmission line are
available we can measure the velocity using short lengths. To do this, students can run a signal
cable from a function generator to one channel of an oscilloscope. The signal is connected to the
first channel with a $T$-connector and the sample cable to be test is connected to the same $T$. Note
that to avoid unwanted reflection the oscilloscope input impedance should be set to 1 M$\Omega$. The
other end of the sample line is connected to a second oscilloscope channel and terminated with
50 $\Omega$ (some oscilloscopes have the option to do this internally). A pulse (any shape will do) is
fed into the transmission line by the function generator. We then observe the delay in channel two compared to the first. For minimum error, students should use the location of half the maximum voltage to find the time of flight. The phase velocity is obviously the length of the cable divided by the time of flight. Note that frequency dispersion will occur in longer lengths of cable if using sharp-edge signal like a square wave. This could be discussed as an error source. Typical phase velocities for 50 Ω coax is about 70% of the speed of light.

Transmission Line Length

Since is it proposed to students that they work for a power company, or similar, where having access to both ends of a transmission line is not practical the process for finding the length differs slightly from the process from finding the velocity. Finding the length of the transmission line is supposed to mimic locating a fault in an existing line. To do this we take advantage of the fact that any impedance mismatch will generate a reflected wave. Therefore, the transmission line is connected to the function generator and oscilloscope as outlined above except the load end is not connected to the second channel. The procedure below assumes that impedance at the end of the transmission line is an open circuit (load impedance \( Z_L = \infty \)), but it could be done for any sufficiently large impedance mismatch.

Pulse method

This method uses a short pulse, with a pulse width small compared to the round trip transit time of the transmission line (i.e. for a 50 m line the pulse width should be less than 500 ns). From this method we should observe the round trip time of flight, \( \tau \), from the difference in the time that the incident pulse enters the transmission line and the time of the reflected pulse as it returns. Again, to minimize the error mark the time from half of the maximum. The length, \( d \), can now be found by

\[
d = \frac{v}{2\tau}
\]

Standing wave method

This method utilizes a continuous sinusoidal input signal. When the sinusoidal traveling wave reflects of the discontinuity at the end of the transmission line the superposition of the incident and reflected waves create a standing wave. The resulting standing wave has a maximum amplitude where the incident and reflected waves are in phase and minimum when they are 180 degrees out of phase. These minima and maxima occur periodically along the length of the transmission line. The location of these extrema are related to the length of the transmission line. For example 2 successive minima are separated by a distance of \( \lambda/2 \), where \( \lambda \) is the wavelength in the transmission line.

\[
\lambda = \frac{v}{f}
\]

Here \( v \) is the velocity of propagation in the transmission line and \( f \) is the source frequency. Since we do not have the ability to probe the transmission line at various locations we instead adjust the source frequency until we find the lowest frequency voltage minimum. Assuming the transmission line is terminated with an open circuit (load impedance \( Z_L = \infty \)) then the lowest frequency voltage minimum should occur at

\[
d = \frac{\lambda}{4}
\]

from the end of the transmission line. This method will work as long as the transmission line is terminated with a resistance greater than the characteristic impedance (\( R_L > Z_0 \)). If the
termination is a resistance less than the characteristic impedance \((R_L < Z_0)\) the lowest frequency minimum will be located at
\[
d = \frac{\lambda}{2}
\]
from the end of the transmission line.

**Attenuation Coefficient**

Determination of the attenuation coefficient comes from the knowledge of the length of the transmission line with along measured attenuation of the return signal with respect to the source signal. Rigorously speaking the attenuation coefficient (along with the velocity of propagation) is a function of the input frequency. For simplicity we will ignore the frequency dependence at this time. The equation for voltage attenuation in the transmission line a function of distance \(z\) is given by
\[
V_{out} = \Gamma V_{in} e^{-az}.
\]
Here were are defining \(V_{out}\) and \(V_{in}\) to be the voltage of reflected and incident signals measured at the entrance to the transmission line. The attenuation coefficient \((\alpha)\) is most easily found when the reflection coefficient \(\Gamma = 1\), which occurs when the load impedance \(Z_L = \infty\). The distance the signal travels \((z)\) is the round trip distance in the transmission line, which is twice the length \((z = 2L)\). If we now solve for \(\alpha\) we find
\[
\alpha = \frac{\ln \left(\frac{V_{in}}{V_{out}}\right)}{2L}.
\]

In the case of the pulse method, \(\alpha\) can be determined directly by observing \(V_{out}\) and \(V_{in}\) on an oscilloscope. For the standing wave method \(V_{out}\) and \(V_{in}\) cannot be observed directly, but they can be calculated from the voltage amplitudes at the extrema.
\[
V_{in} = \frac{V_{max} + V_{min}}{2} \quad V_{out} = \frac{V_{max} - V_{min}}{2}
\]

**Termination Impedance**

The final portion of this project students are asked to find the value on an unknown termination impedance. To complete this task many of the transmission line characteristic found previously will need to be reassembled. We can use the relationship of \(V_{out}\) and \(V_{in}\) reported in the previous section along with the knowledge the reflection coefficient \(\Gamma\) can be expressed in terms of the characteristic impedance \(Z_0\) and load impedance \(Z_L\)
\[
\Gamma = \frac{Z_L - Z_0}{Z_L + Z_0}
\]
to find
\[
Z_L = Z_0 \frac{1 + \Gamma}{1 - \Gamma} = \frac{V_{in} e^{-\alpha z} + V_{out}}{V_{in} e^{-\alpha z} - V_{out}}
\]

**Project 3: Electric Field Probe.**

Creating a non-contact static (DC) electric field probe is fairly simple in execution. Though this project only requires a small number of components to complete it pulls together several core
concepts from electromagnetic, circuits, and transistor theory. The key to making this project work centers on identifying that the DC impedance of space is relatively high. Note that we are referring to the DC impedance which is infinite for vacuum and very high for standard temperature and pressure conditions, which is not to be confused with the characteristic impedance of free space of 377 ohms. Students must recognize that the input impedance for an electric field probe must also be very high otherwise the probe will effectively “short” the electric field. A JFET transistor is well suited for this task. We further take advantage of the fact that the conduction channel from the drain to the source of the transistor is partially open when the gate is unbiased (floating). This allows the transistor to be sensitive to input polarization. In other words, if we use the output of the transistor to drive a resistive load, an unbiased gate will yield an intermediate voltage. The sample circuit shown in figure 1a, uses an n-channel JFET. Therefore, as the voltage of gate decreases, or becomes negative with respect to the source, the conduction channel closes and the voltage across the output resistor goes down. As the voltage of the gate increases the conduction channel opens and the voltage across the output resistor goes up. We can then feed this signal into two separate comparator circuits: one inverting and one non-inverting. The output of these comparator are coupled to LEDs in order to display the polarity of the field. Students can experiment with various ways to set the comparator thresholds, but a circuit in figure 1b shows a method for creating self-calibrating thresholds.

![Figure 1: (a) Electric field probe based on an n-channel JFET. (b) A modification to the electric field probe using a self-calibrating threshold.](image)

One last consideration is the probe itself. Obviously this circuit is sensitive to noise due to its high input impedance. Care should be taken to shield the circuit from electric field everywhere except the active portion of the probe. This can be effectively achieve by creating a probe from a section of coaxial cable with the outer conduction stripped back a short distance. In this sense it is the polarity of the electric field between the inner and outer conductors that will be detected. For best results the rest of the circuit should be placed in a shielded metal enclosure.

**Project 4: AC Current Meter.**

This project uses the AC current measurement to reinforce three core areas of electrical engineering.
1. Electromagnetics: Students must understand the relationship of current, magnetic fields, and electromotive force (emf) in order to make a current meter.

2. Optimization: In practice making a probe to detect current can be as simple as placing a loop of wire near the current to be measured. As an added layer of complexity, students can be asked to create a probe that is relatively insensitive to the position of the current that we wish to measure while also being insensitive to neighboring currents and magnetic field that we do not wish to affect the measurement.

3. Basic circuit theory: The emf in a wire loop is natively proportional to the time derivative of the magnetic field and in turn the time derivative of the current. This relationship is fine as long as the user is willing to do some post measurement integration to determine the true current. Alternately, the current probe can be turned into part of a self-integrator circuit so that the output is directly proportional to the current.

As stated above this project in its easiest form only requires that students exploit the relationships that

\[ V_{emf} = -N \frac{\partial}{\partial t} \oint_{\text{surface}} B \cdot dS, \]

where \( V_{emf} \) is the emf voltage induced by the magnetic field \( B \) that penetrates the surface \( S \) of a coil of wire with \( N \) turns. The magnetic field can be found approximately a the field from a long straight filament of current

\[ B = \frac{\mu I}{2\pi r}, \]

where \( I \) is the magnitude of the current in a region of space with permeability \( \mu \) at a distance of \( r \).

We clearly see that the magnitude of the signal is determined by several factors including where the probe (coil) is placed relative to the object current we wish to measure. By experimenting with various geometry students may find that by passing the object current through the center of a toroidal coil that the magnitude of the signal is relatively insensitive to the position of the object current as long as the current passes somewhere through the center of the toroid. We can further improve performance by running one of the leads of the coil back along the axis of the toroid as shown. This will make the probe insensitive to currents that do not pass through the center of the toroid. This configuration is sometime referred to as a Rogowski coil.

Finally, processing the signal to obtain the true current requires that we integrate the signal over time. This can be done post measurement or we make the probe self-integrating by adding a small resistance parallel to the coil. The integration will be valid for times that are short compared to the \( L/R \) time constant of the circuit, where \( L \) is the inductance of the probe coil itself.

**Project 5: Metal Detector.**
Metal detection can be done in a variety of different ways. Here we will outline two basic methods for metal detection. Both methods rely on the modification of the inductance of a circuit in the presences of a metallic object. Both detection scenarios rely on the fact that conducting materials have a diamagnetic response in the presence of an AC magnetic field. This
diamagnetic response will lower the effective inductance of any coil that is near the metallic object. This turns out to be true even for ferromagnetic conductors like iron as the diamagnetic response is higher for most frequencies.

**Method 1—Mutual Inductance**

This method is perhaps the more primitive of the two. Two coils, a source coil and a detection coil, are placed close to one another (like the primary and secondary coils of a transformer). The source coil is driven with a voltage of some predetermined frequency. The optimal frequency depends on the physical attributes of the coil but is not terribly important. An emf is induced in the detection coil. Care should be taken that the diameter of the detection coil is less than or equal to the diameter of the source coil. As the mutual induction goes down in the presence of a metallic object so will the amplitude of the emf product on the detection coil. This amplitude change can easily be visualized by converting the output AC signal to DC using a rectifier bridge and a low pass filter. Once the output has been converted to DC the signal can be fed into a comparator with an adjustable threshold and displayed with an LED.

**Method 2—Self Inductance**

This method requires only one coil and relies on the fact that the self-inductance of a coil will diminish in the presence of a metallic object. If the inductance of the coil is made to be part of an oscillator circuit then the oscillation frequency will change in the presence of a metal. If the output of oscillator is fed into a frequency to voltage converter as shown we can again use a comparator and LED to flag the presence of a metal. Alternatively, the oscillator output can be used to drive a speaker such that the tone of the sound is proportional to the size and/or location of the metallic object. We found that by measuring the frequency with a microcontroller that this method was sensitive enough to distinguish between common US coins.

**Conclusions**

Measuring the effectiveness a project based class for electromagnetics is not an easy task. We implemented a traditional method for measuring effectiveness by giving exit surveys. On average, students were more positive about the projects than lectures and homework. We feel this does not truly measure the effectiveness of the projects. As such, we also selected small groups of volunteers to take short periodic competency exams. These exams are designed to measure how well students can apply core concepts from the course. The oral exams always show a dramatic improvement shortly after the completion of a project. We feel this is more persuasive evidence that the project based course is a more effective learning tool than a traditional lecture course.