2006-1241: ELECTRIC & MAGNETIC FIELDS, TRANSMISSION LINES FIRST?

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BIOGRAPHICAL INFORMATION

Dr. Mousavinezhad is an active member of ASEE and IEEE having chaired sessions in national and regional conferences. He is IEEE Region 4 Educational Activities Chair and member of the ASEE North Central Section Executive Board. He was the ECE Program Chair of the 2002 ASEE Annual Conference, Montreal, Quebec, June 16-19 and 2003 ASEE ECE Division Chair. Professor Mousavinezhad received ASEE/NCS Distinguished Service Award, April 6, 2002, for significant and sustained leadership. In 1994 he received Zone II Outstanding Campus Representative Award. He is also a Senior Member of IEEE, Recipient of the IEEE Third Millennium Medal, and Chair of the West Michigan Section. He has been a reviewer for IEEE Transactions including the Transactions on Education. His teaching and research interests include digital signal processing (DSP) and Bioelectromagnetics. He has been a reviewer for engineering textbooks including "DSP First" by McClellan, Schafer, and Yoder, published by Prentice Hall, 1998 and 2003. He was co-editor of ECEDHA Newsletter, national ECE department chairs organization. Hossein is a member of the Editorial Advisory Board of the international research journal Integrated Computer-Aided Engineering. Professor Mousavinezhad is the general chair of IEEE e IT (electro/information technology) Conferences, 2006 eit conference will be hosted by MSU.

Professor Mousavinezhad was founding general chair of the First IEEE Electro Information (eit) Technology Conference, June 8-11, 2000, in Chicago. The e IT conferences are bringing together researchers in the ECE field covering such ECE research topics as Wavelet Transforms, Soft Computing, Power & Energy, Intelligent Control, Wireless Communications, and Fuzzy Logic. Keynote/Invited speakers have included Drs. H. Adeli, M. Sloan, M. J. T. Smith, and L. Zadeh. He was part of the group promoting economic development in Michigan, MEDC, and was responsible for bringing Innovation Forums to Western Michigan University, January 21, 1999. These forums were a series of meetings and seminars focused on university and industry collaboration initiated by the Michigan Governor. The Forums were sponsored by the Kellogg and Dow Foundations and were designed for finding strategies to create more Hi-Tech jobs in the State. He was chair of the faculty senate (WMU) Graduate Studies Council, 2001-2003.

As part of his responsibilities as Professor and Chair of the ECE Department at Western Michigan University, he prepared ABET reports for the two programs offered by the Department (EE and CpE.), currently he serves as ABET program evaluator for both CpE and EE programs. The graduate programs offered by the Department grew between 1995 and 2004 and he was responsible for initiating the first MSEE program in 1987, a new ECE Ph.D. program was initiated in the Fall of 2002. In addition to administrative responsibilities, he has managed to teach undergraduate/graduate courses in his research areas of Digital Signal Processing, , wireless engineering and computer engineering seminar. He was co-PI for a DSP grant funded by NSF. He has received other NSF and government grants in addition to equipment grants from Texas Instruments in support of his teaching/research activities in the DSP field.

More information is available in his vita which can be accessed through the web (http://homepages.wmich.edu/~mousavin)

Electric & Magnetic Fields, Transmission Lines First?

Abstract

Many schools offer at least one required course in electrical engineering curriculum on electromagnetics (E&M). At Western Michigan University, a junior level course has been offered for a number of years. A few years ago, the topical coverage of course materials was re-designed so that students are introduced to transmission lines (an important application area) first before devoting time to cover such topics as electrostatics and magnetostatics. The author started teaching the course for the first time in Fall 2005 using a new textbook. There are pros/cons of covering applications areas (such as transmission lines) before a discussion of electric and magnetic fields (both static and dynamic.) There are recent textbooks that introduce transmission lines first. Because of the importance of wireless communications and antenna technology, there has been discussion among engineering educators that the subject of E&M is a fundamental area of study for all electrical engineering and perhaps computer engineering majors. So the question becomes how many E&M courses are needed? Most schools are offering one undergraduate course in this important area and perhaps a second elective course.

Introduction

At our university for a number of years we have offered a junior-level course, ECE 3610, Electromagnetic (E&M) Fields, 4 credit (semester) hours. Most students are electrical engineering (EE) majors but some computer engineer majors have expressed interest in the course. At the present time ECE 3610 is required for EE majors only. In Attachment 1 we present a more detailed description of the course including topics and learning outcomes. ECE 3610 has been offered previously with transmission lines first emphasis. We note that transmission lines are only one application area of the powerful subject of electromagnetics and we believe that it should be a requirement for all engineering majors, especially electrical/computer engineering, as is college physics. Other applications include waveguides, antennas, and microwave engineering. These applications are as critical as transmission lines, especially with the widespread use of wireless communications and smart antennas. The textbook by Schwarz was used for a number of years before changing to a new textbook in Fall 2005.

In addition to Schwarz's book[3], other books which use transmission lines first approach, include "Applied Electromagnetics" (Prentice Hall) by Dr. Ulaby of the University of Michigan. Another book is "Dynamic Electromagnetics" by Dr. Diament of the Columbia University. This book has a few chapters first but they do start with transmission lines before covering other application areas. One concern with transmission lines first approach is that students may not have a good feeling for vector quantities of electric and magnetic fields. There may have to be some coverage of basic wave concepts and vector fields before covering transmission lines. This will change the topical coverage slightly but will prepare students better to understand wave equations and other concepts associated with the transmission lines.

On the other hand, introducing transmission lines first has the advantage of motivating students with an important application area before encountering further details of electric and magnetic fields. Use of MATLAB in new textbook is very helpful for student understanding of the subject. We believe transmission lines should be covered as early as possible but some materials should be introduced before starting on transmission lines. This way we are emphasizing transmission lines and other important applications of electromagnetic fields before going into mathematical details of E fields, H fields and Maxwell's Equations. In addition to matlab, author uses MATHCAD and other resources which are available for teaching electromagnetics.

Transition from Circuits to Waves

Almost every engineering major takes an introductory course on circuit analysis. There are many excellent textbooks available in this fundamental subject area for engineering majors. In our school, the text by Alexander and Sadiku[1] is used for the first course and also the second on signals & systems (network analysis). Another textbook is the recent edition of basic engineering circuit analysis by Irwin and Nelms[2], including many examples of a Web-based tutorial. Assuming good coverage of fundamental concepts of circuit analysis typically consisting of resistive, first-order/second-order RC/RL and RLC circuits, AC voltages/currents, impedance and power relationships; the students will be ready to study such concepts and principles as impedance matching, lossless transmission lines, reflection coefficients, standing waves in a first electromagnetics course (assuming four hours of lecture per week.) There are a few other excellent references for the transmission lines first approach[4, 5, 6]. Reference 6 has suggested topics using transmission lines first approach and also uses MATLAB examples.

It is true for students as well as for some ECE faculty that the subject of electromagnetics is possibly the toughest mathematically oriented subject in the undergraduate curriculum for electrical engineering and some computer engineering majors. Basically there are four (4) major equations, MAXWELL'S EQUATIONS, which govern the behavior of time-varying (dynamic) electromagnetic fields and wave propagation. In most common form these equations are stated as:

$$\nabla \times \mathbf{E} = -\,\partial \mathbf{B}/\partial t \quad ; \quad \nabla \times \mathbf{H} = \mathbf{J} + \partial \mathbf{D}/\partial t \quad ; \quad \nabla \cdot \mathbf{D} = \rho \quad ; \quad \nabla \cdot \mathbf{B} = 0$$

where ρ is volume charge density (C/m^3), **J** is current density (A/m^2), **E** (V/m) and **H** (A/m) are electric and magnetic field intensities, respectively; and **D** (C/m^2) and **B** (T) are electric flux and magnetic flux densities, respectively. Bold quantities are vectors.

If (x.y,z) denotes a point in Cartesian (rectangular) coordinates, we can see that each function, e.g., electric field intensity vector, **E**, must be written as **E**(x,y,z,t). Considering the fact that in general there are three (3) components for this vector field, $E_x(x,y,z,t)$, $E_y(x,y,z,t)$ and $E_z(x,y,z,t)$, one can see that EM problems can become fairly complex to deal with mathematically.

In the engineering community, there has been a lot of discussion regarding the use of mathematical tools and software packages (such as MATLAB and MATHCAD) and the time/place for their introduction into the curriculum. We can easily see that these tools can be very beneficial for the study of electromagnetics. Care should be taken when introducing such powerful tools and the understanding of basic laws of Coulomb's, Gauss's, Faraday's and Ampere's before students use these software packages in problem solutions. Our present text uses MATLAB as well as online resources (such as EMAG Solutions). The author also uses MATHCAD during lecture presentations and when solving examples and homework solutions.

Course topics

Since students have taken prerequisite courses (circuits, vector analysis, differential/integral calculus and physics) the author starts teaching the course by an introduction and overview of electromagnetic spectrum and briefly discusses applications such as wireless communications (cell phones), biomedical instrumentation, transmission lines (as examples of guided EM waves), microwaves and antennas. Many applications involve time-varying fields but the course starts first with a discussion of electric fields (Coulomb's Law), at the same time covering concepts needed in the later treatment of waves such as charge density, current density, and electric flux density (vector). In addition to Cartesian (rectangular) coordinate systems, students use Cylindrical and Spherical systems as they need them; and study divergence theorem (Gauss's Law) and gradient (electric potential function). They learn about electric potential energy and compare this to the problem of capacitance (something they learned in circuits). Throughout the course, the author tries to show the analogy between fields and voltage/current concepts that they are familiar with. This analogy will be emphasized again in the study of transmission lines (both loss-less and lines with loss). They are also introduced to Poisson's and Laplace's equations with brief mention of boundary value problems. In some schools there is a second electromagnetics course with more emphasis on time-varying fields, boundary value problems, antennas, waveguides and microwave engineering. The author has taught a first year graduate (ECE 5600, Time-Varying Fields) course which can be taken (elective) by advanced undergraduates as well.

Following coverage of electric fields due to charge distributions, students next learn about magnetic fields due both to natural sources (earth's) and those generated by electric currents. After studying Biot-Savart's Law, we discuss Ampere's Circuital Law and show examples including coaxial cable. Here they study curl and apply Stokes's theorem to solve for magnetic field intensity vector. This is followed by the discussion of magnetic materials, magnetic flux density and the B-H characteristics (hysteresis loop). At this point students are introduced to the four basic equations of electromagnetics involving divergence and curl of the electric field; divergence and curl of the magnetic field. These (Maxwell's) Equations are encountered again in the study of time-varying fields and Helmholtz wave equation. Obviously these equations are essential for any study involving EM applications but students get a good feeling for these fundamental laws starting with basic laws of physics such as Coulomb's and Ampere's Laws.

Magnetic circuit examples such as solenoids and toroids are discussed next and we point out that they will have more detailed studies of magnetic circuits in the subsequent power (electromechanical) systems courses.

Having a basic understanding of electric and magnetic fields, we next bring in the time dependence by studying dynamic fields. They are familiar with **J** and ρ (current and charge densities) and now they study their relationship (continuity equation). With time varying fields and wave fundamentals, students then study Faraday's Law and the interdependence between electric and magnetic fields. Maxwell's Equations and propagation of transverse electromagnetic (TEM) waves are studied in detail and the concepts of propagation constant, phase/attenuation constants and propagation velocity are introduced. Time-Harmonic dependence and fields analysis using phasors (again familiar from circuits course) are used to solve Maxwell's Equations. Plane waves, intrinsic wave impedance and Helmhlotz (wave) equation are studied in loss-less and media with losses. Many practical problems including loss tangent, good conductors, skin depth are studied next. The power propagation, **E x H,** Poynting theorem are covered for plane wave propagation.

With the knowledge of electromagnetic fields, Maxwell's equations and other important concepts and theorems, students are ready to study both loss-less and transmission lines with losses. We discuss circuit model of transmission lines and derive the associated wave (Telegraphist's) equations. These equations are compared to previous Helmholtz's equations derived from Maxwell's equations. With time-harmonic dependence we discuss characteristic impedance and power transmission. With the terminated transmission lines we study problems involving reflection coefficients and voltage standing wave ratio (VSWR). Input impedance and reflection coefficient and impedance matching calculations using the Smith Chart are discussed next. Additional topics are then discussed at the conclusion of the course (time permitting), including transients on transmission lines, pulse response, dispersion, waveguides, antennas and introduction to microwave engineering.

Lecture Examples

Because of the mathematical nature of the subject, it is useful to introduce examples and work problems following the lecture materials which usually deal with theorems and laws important in the electromagnetics. We include a few examples in the paper with additional examples provided during the presentation.

Example 1. Consider a finite line of charge of length ℓ and linear charge density of ρ_L (C/m^2) along the z-axis. For a differential element of charge $dQ = \rho_L dz$, one can compute the electric force exerted on the charge q located at a distance ρ (cylindrical coordinates ρ,ϕ,z are used here) from the line using Coulomb's law as

$dF_y = q\ dQ \cos\alpha/(4\pi\varepsilon_0 R^2)$ ($\varepsilon_0 = 8.854 \times 10^{-12}$ F/m is the free space permittivity) where α is the angle from the y-axis and $R^2 = \rho^2 + z^2$. With $\cos \alpha = \rho/R$ and integrating to get total force (also utilizing the symmetry of the problem)

$F_y = 2 \int q \rho_L \rho \, dz /(4\pi\varepsilon_0 R^3)$ where integration is from $z = 0$ to $z = \ell/2$.

$F_y = q \rho_L \rho I /(2\pi\varepsilon_0)$ with integration $I = \int dz/(\rho^2 + z^2)^{3/2}$ with the same limits. Evaluating this integral using MATHCAD:

$$\int_0^{\frac{L}{2}} \frac{1}{\left(\rho^2 + z^2\right)^{1.5}} dz \rightarrow \frac{L}{\left(4.\cdot\rho^2 + L^2\right)^{\frac{1}{2}} \cdot \rho^2}$$

$F_y = [q \rho_L \rho /(2\pi\varepsilon_0)][\ell/(\rho^2\sqrt{(4\rho^2 + \ell^2)})] = q \rho_L \ell/[2\pi\varepsilon_0\rho\sqrt{(4\rho^2 + \ell^2)}]$

Dividing by q we get the electric field:

$E_y = \rho_L \ell/[2\pi\varepsilon_0\rho\sqrt{(4\rho^2 + \ell^2)}]$

Finally, if we take the limit as $\ell \rightarrow \infty$ we get the expression for the electric field of an infinite line of charge,

$E_y = \rho_L /(2\pi\varepsilon_0\rho)$. In vector form and using cylindrical coordinates the electric field vector can be written as

$\mathbf{E} = \rho_L /(2\pi\varepsilon_0\rho)\, \mathbf{a}_\rho$ where $\mathbf{a}_\rho$ denotes the unit vector in the radial direction. We note that in many textbooks results are obtained for an infinite line, a problem that seems to be difficult for students to visualize.

Example 2. (Transmission Line Example.) Consider a loss-less transmission line of length l = 100 meters terminated in a load impedance of $Z_T = 50 + j50\Omega$. The line has per unit parameters of L = 100 nH/m and C = 50 pF/m and is operating at a frequency of f = 1 MHz. Here we present solution using MATHCAD:

$f := 1 \cdot 10^{6}$ $\omega := 2 \cdot \pi \cdot f$

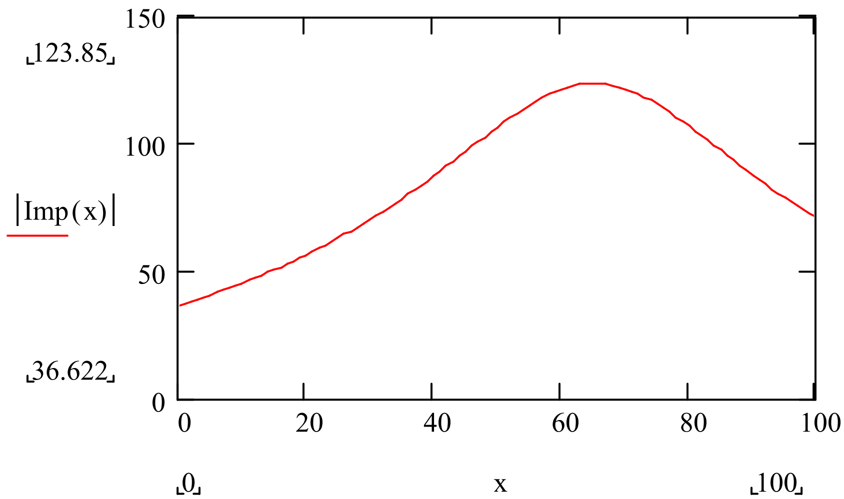
$L := 100 \cdot 10^{-9}$ $C := 50 \cdot 10^{-12}$

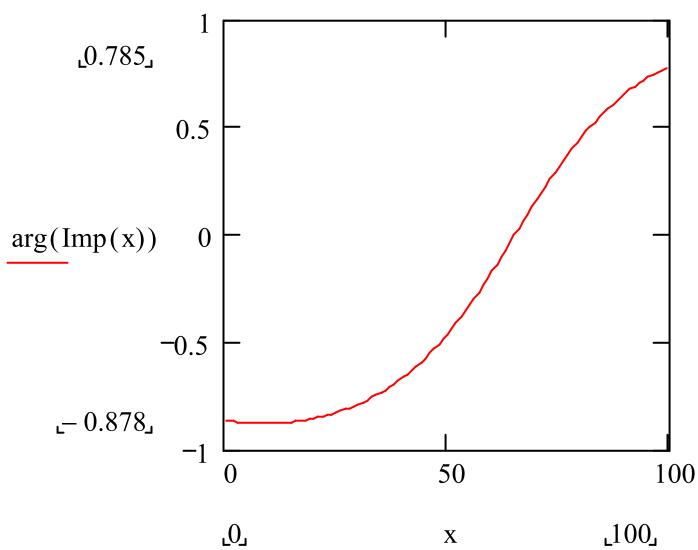
$j := \sqrt{-1}$ $Z_T := j \cdot 50 + 50$

$Z_0 := \sqrt{\frac{L}{C}}$ $v := \frac{1}{\sqrt{L \cdot C}}$

$x := 0, 1 .. 100$ $\beta := \frac{\omega}{v}$ $l := 100$

$$\mathrm{Imp}(x) := Z_0 \cdot \left[\frac{Z_T + j \cdot Z_0 \cdot \tan[\beta \cdot (l - x)]}{Z_0 + j \cdot Z_T \cdot \tan[\beta \cdot (l - x)]} \right]$$





Conclusions

Electromagnetics is a fundamental area of study for electrical, electronic and communication systems engineering students. With the widespread use of wireless communication systems and smart antenna technology, it will also be important for computer engineers and possibly other engineering majors to have a basic understanding of this important subject matter. Because of mathematical complexities, students usually shy away from this course but new tools are becoming available for instruction and also some educators feel that with covering applications areas (such as transmission lines) first students can be attracted to this important subject area of electromagnetic fields. The author feels that, especially for EE (and possibly CPE) majors; one needs a rigorous treatment of the theory and principles of the subject matter, followed by using modern tools (such as MATLAB, MATHCAD, MATHEMATICA) for solving problems, exercises and class examples. Since this is the first academic year that the author is teaching the undergraduate EM course at Western Michigan University, we still need to wait to get more assessment results. However we have noted that enrollment in the course has increased, especially when comparing Spring 2006 to Spring 2005. This can be an indication that students are attracted to this important subject area of Electrical (and Computer) Engineering. Finally, the Spring 2006 class is given a library assignment where they are asked to do some research in the topic of magnetic levitation (MAGLEV) transportation systems and submit a written report. Again the assessment results of this learning outcomes are pending as the final version of this paper was being prepared.

Acknowledgement

The author would like to thank Dr. Dean R. Johnson, ECE associate Professor, Western Michigan University, for his support and encouragement during preparation of this paper. I also would like to thank Tina Hong, Dave Wakstein and Marc Gravelin of MATHSOFT for their continued support.

ATTACHMENT 1

ECE 3610: Electromagnetic Fields

Required Course

Catalog Data: Static and time-varying electric and magnetic fields, plane waves, guided waves, transmission lines, radiation and antennas.
Credit: 4 hours
Prerequisites: MATH 2720, MATH 3740, ECE 2100 and PHYS 2070

Textbook: S. M. Wentworth, Fundamentals of Electromagnetics with Engineering Applications, Wiley, 2005

Reference Materials:

1. W. H. Hayt, Jr. and J. A. Buck, Engineering Electromagnetics, seventh edition, McGraw-Hill, 2006
2. F. T. Ulaby, Electromagnetics for Engineers, Prentice Hall, 2005
3. J. A. Edminister, Electromagnetics, 2nd edition, McGraw-Hill, Schaum's Outline Series, 1993.

Course Coordinator: Dr. S. Hossein Mousavinezhad, Professor, ECE

Instructor (Fall 2005): Dr. S. Hossein Mousavinezhad, Professor, ECE

Prerequisites by Topic:

1. Basic knowledge of electric and magnetic fields
2. Vector and multivariate calculus
3. Linear algebra
4. Differential equations
5. Electric circuit theory

Course Objectives and Learning Outcomes:

This course develops the students' ability: (objectives include list of relevant EE program outcomes)

1. to use source integrals for fields due to distributed sources(**a**,e,k);
2. to obtain differential equation solutions by analytical and numerical methods(**a,**e,k);
3. to apply boundary conditions at interfaces between different media(**a,**e);
4. to understand the electric potential and its relationship with the electromagnetic fields(**a**,e,k);
5. to understand spatial and time dependencies and other properties of fields(**a**,e,k);
6. to understand power computation, transmission and reflection for plane waves, for transmission lines and other wave guides(**a**,e,k);
7. to understand impedance matching on transmission lines(**a**,e,k);
8. to understand Maxwell's equations and their wave solutions in conductors and insulators(**a**,e,k);
9. to understand superposition of plane waves and polarization(**a**,e,k);
10. to develop a basic understanding of magnetic circuits(**a**,e,k); and
11. to develop an awareness of the range of applications of electromagnetic fields(g,h,**i**,j)

Topics:

1. Electrostatic Field (8 classes)
2. Magnetostatic Field (8 classes)

3. Good Conductors (2 classes)
4. Time-Varying Fields (6 classes)
5. Plane Waves (6 classes)
6. Maxwell's Equations (8 classes)
7. Transmission Lines (10 classes)
8. Guided Waves and Antennas (2 classes)

Evaluation:

1. Examinations (90%) 2. Homework Assignments (10 %)

Communication Skills:

Students write short reports on some applications of electromagnetics providing references.

Contribution to Professional Component:

ABET professional component as estimated by faculty member who prepared this course description:
Engineering Topics: 4 credits or 100%

Relation of Course to Program Outcomes:

EE program outcomes: **a**,e,g,h,**i**,k

Person who prepared this description and date of preparation:

Prepared by: S. Hossein Mousavinezhad Date: January 9, 2006

Bibliography

[1]. "Fundamentals of Electric Circuits," by Alexander and Sadiku, second edition, McGraw-Hill, 2004.

[2]. "Basic Engineering Circuit Analysis," by Irwin and Nelms, 8th edition, John Wiley, 2005.

[3]. "Electromagnetics for Engineers," by Steven E. Schwarz, Oxford University Press, 1990.

[4]. "Fundamentals of Applied Electromagnetics," by Fawwaz Ulaby, Prentice Hall, 2001 Media Edition.

[5]. "Dynamic Electromagnetics," by Paul Diament, Prentice Hall, 2000.

[6]. "Fundamentals of Electromagnetics with Applications," by Stuart Wentworth, John Wiley, 2005.