UNDERGRADUATE ELECTROMAGNETICS – MODIFIED CONTENT AND LABORATORY

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Abstract

Electromagnetics (EM) courses at the undergraduate level have traditionally covered static electric and magnetic fields with limited coverage of time-varying fields. There are many applications of the static fields, however, majority of the modern engineering applications involve the time-varying electromagnetic fields. The increasing speed of digital devices not only necessitates the time-varying approach but also introduces the issue of electromagnetic compatibility (EMC). Most of the present undergraduate curricula do not explicitly address EMC. Moreover, most of the EM courses taught at the junior level do not have a laboratory component associated with them. This paper elaborates on a new content for the undergraduate EM/EMC course and suggests potential topics for the associated laboratory.

1.0 INTRODUCTION

Most of the current undergraduate textbooks on electromagnetics follow a "classical pattern" when it comes to the content and format. This pattern has changed very little in the past 20 years, yet the electromagnetic phenomena have become of paramount importance in modern electrical engineering. Many of the current textbooks start with vector calculus, followed by static electric and magnetic fields, and then by time-varying Maxwell's equations leading to the electromagnetic waves and transmission lines theory [1-2]. Some of the textbooks present the transmission lines topics first, followed by a sequence of topics conforming to the pattern mentioned [3]. Modern topics related to electromagnetic compatibility are either absent [2] or marginally present [1]. There is a noticeable trend, however, in some texts, to include introductory EMC coverage [4-6]. While the coverage of EMC topics is increasing in [5-6], the traditional content is still retained, making it practically impossible to teach the subject in a single-semester format. Most undergraduate curricula devote just a single semester to the topics of electromagnetics. EMC is rarely taught within the EM course, and very few schools offer a dedicated EMC course at the junior or even senior level. Moreover, most of the junior EM courses do not have a laboratory associated with the course, making the topic very theoretical and of very limited practical application to the students.

This paper advocates an approach based on the topic sequence used by Rao [5], together with augmenting the course with a laboratory component and EMC aspects. The author suggests reducing the static electric and magnetic fields coverage to the absolute minimum and increasing the coverage of the time varying fields and their applications, including EMC. This approach is justified by the fact that most undergraduate engineering curricula discuss the static fields in the engineering physics course, which is a pre-requisite to the EM course. In addition, the author introduces the laboratory/demonstration component to the course and proposes several lab topics. The observations and suggestions in this paper agree with the opinions expressed in the preface of the 6th edition of Rao's "Elements of Engineering Electromagnetics" [5].

This paper is organized as follows. Section 2 presents the "classical" EM content and format. In Section 3, the alternative format is discussed. The topic of Maxwell's equations, electromagnetic waves and transmission lines is discussed in Section 4. Section 5 enumerates suggested laboratory activities. Conclusions are presented in Section 6.

2.0 CLASSICAL COURSE FORMAT

Most introductory electromagnetics textbooks follow a format, in which vector calculus, with some geometry is presented first. As an example, we will use the format utilized in [1] and elaborate on some variations:

1. Vector Algebra
2. Coordinate Systems and Transformation
3. Vector Calculus
4. Electrostatic Fields
5. Electric Fields in Material Space
6. Electrostatic Boundary-Value Problems
7. Magnetostatic Fields
8. Magnetic Forces, Materials, and Devices
9. Maxwell's Equations
10. Electromagnetic Wave Propagation
11. Transmission Lines

Chapter 11 is followed by the elective/advanced topics beyond the one-semester coverage.

Some textbooks [5] introduce vector calculus (Chapter 3, above) in the context of the EM topics (on the "as needed" basis. Other [3], begin the coverage with the transmission lines (Chapter 11, above) and then proceed to the static fields, followed by the time-varying topics. This approach is motivated by the fact that the transmission line theory can be explained in terms of circuit variables (voltage and current), instead of the field variables (field intensity and flux density). Moreover, the topic of transmission lines can be explained using the circuit theory without relying on the EM background. While this approach tries to bridge the circuit theory with electromagnetics, it does little towards student's comprehension of the subject.

A limited number of textbooks deviate from the traditional approach described above, and the content and sequence of topic varies between the authors. One excellent example of such textbook is [5], which the author of this paper uses in his courses.

3.0 ALTERNATIVE COURSE FORMAT

Few authors deviate from the classical format in order to include modern topics, which are becoming of paramount importance to any electrical engineering graduate. As an example, we will use the format utilized in [5]:

PART 1 Essential Elements for Electrical and Computer Engineering

1. Vector and Fields
2. Maxwell's Equations in Integral Form
3. Maxwell's Equations in Differential Form, and Uniform Plane Waves in Free Space
4. Fields and Waves in Material Media
5. Electromagnetic Potentials and Topics for Circuits and Systems
6. Transmission-Line Essentials for Digital Electronics

PART 2 Essential/Elective Elements

In this format, the coverage of static fields is reduced, discussed on as-needed basis in the context of Maxwell's equations. This allows for the discussion of the introduction of important time-varying applications, which, otherwise could only be done in a cursory manner. Section 6.7 in [5] is devoted to the topic of crosstalk on transmission lines, important EMC aspect of digital electronics. Chapter 6 lends itself to many practical laboratory experiments, suggested in Section 5 of this paper, which help students bridge the gap between the theory and practice of electromagnetics.

4.0 MAXWELL'S EQUATIONS, WAVES AND TRANSMISSION LINES

In most textbooks, [6] for example, Maxwell's equations are derived for arbitrary time variations of the electric and magnetic fields. Usually, they are presented in the familiar form:

$$\nabla \times \mathbf{E}(x, y, z, t) = -\frac{\partial \mathbf{B}(x, y, z, t)}{\partial t} \quad (1)$$

$$\nabla \times \mathbf{H}(x, y, z, t) = \mathbf{J}(x, y, z, t) + \frac{\partial \mathbf{D}(x, y, z, t)}{\partial t} \quad (2)$$

where ***E*** is the electric field intensity; ***B***, the magnetic flux density; ***H*** the magnetic field intensity; ***J***, the current density; and ***D***, the electric flux density.

In (1) and (2) the time dependence of EM fields is arbitrary. Many texts proceed with the assumption that the fields are time harmonic, that is, they vary periodically or sinusoidally with time. Not only is sinusoidal analysis of practical value, it can be extended to most waveforms by Fourier transform techniques. Sinusoids are easily expressed in phasors, which are more convenient to work with.

In the phasor form (1) and (2) can be expressed as:

$$\nabla \times \mathbf{E}_s = -jw\,\mathbf{B}_s \quad (3)$$

$$\nabla \times \mathbf{H}_s = \mathbf{J}_s + jw\,\mathbf{D}_s \quad (4)$$

Equations (3) and (4) lead to the electromagnetic wave equations:

$$\nabla^2 \mathbf{E}_s - g^2 \mathbf{E}_s = 0 \quad (5)$$

$$\nabla^2 \mathbf{H}_s - g^2 \mathbf{H}_s = 0 \quad (6)$$

where g is the *propagation constant* of the medium. The wave equations (5) and (6) lead to the corresponding voltage and current equations:

$$\frac{d^2 V_s}{dz^2} - g^2 V_s = 0 \quad (7)$$

and

$$\frac{d^2 I_s}{dz^2} - g^2 I_s = 0 \quad (8)$$

The solutions of the linear homogeneous equations (7) and (8) are

$$V_s(z) = V_0^+ e^{-g z} + V_0^- e^{g z} \quad (9)$$

and

$$I_s(z) = I_0^+ e^{-g z} + I_0^- e^{g z} \tag{10}$$

where $V_0^+, V_0^-, I_0^+, I_0^-$ are wave amplitudes; and the + and – signs, respectively, denote wave traveling in the +z and –z directions.

While this approach is fully justified by the practical applications of Maxwell's equations, it is very esoteric and hard-to-understand for the students. Alternative approach is presented in [5] where the Maxwell's equations and subsequent topics of electromagnetic waves leading to transmission lines equations are derived and explained in time domain first. That is, the phasor approach and the corresponding phasor-domain solutions are postponed until the time-domain approach is investigated. This "tangible" approach is crucial for the "comfort level" needed by students to proceed with the abstract versions when switching to phasor form.

Time-domain wave equations, derived from (1) and (2) are

$$\frac{\partial E_x}{\partial z} = -\frac{\partial B_y}{\partial t} = -m_0 \frac{\partial H_y}{\partial t} \tag{11}$$

$$\frac{\partial H_y}{\partial z} = -\frac{\partial D_x}{\partial t} = -e_0 \frac{\partial E_x}{\partial t} \tag{12}$$

The solutions of these equations are:

$$E_x(z,t) = Af\left(t - z\sqrt{m_0 e_0}\right) + Bg\left(t + z\sqrt{m_0 e_0}\right) \tag{13}$$

$$H_y(z,t) = \frac{1}{\sqrt{m_0 / e_0}}\left[Af\left(t - z\sqrt{m_0 e_0}\right) - Bg\left(t + z\sqrt{m_0 e_0}\right)\right] \tag{14}$$

or alternatively,

$$\mathbf{E}(z,t) = \begin{cases} Af\left(t - \dfrac{z}{v_p}\right)\mathbf{a}_x & for \quad z > 0 \\ Bg\left(t + \dfrac{z}{v_p}\right)\mathbf{a}_x & for \quad z < 0 \end{cases} \tag{15}$$

$$\mathbf{H}(z,t)=\begin{cases}\frac{A}{h_0} f\left(t-\frac{z}{v_p}\right)\mathbf{a}_y & for \quad z>0 \\ -\frac{B}{h_0} g\left(t+\frac{z}{v_p}\right)\mathbf{a}_y & for \quad z<0\end{cases} \tag{16}$$

Rao, in [5], presents an excellent discussion of these time-domain solutions, and explains their physical interpretation. This explanation is crucial in facilitating students' understanding of the topic. It is only after this explanation, lacking in many texts, the Rao proceeds to the phasor analysis. At this point students are quite capable of understanding the abstract, yet computationally very convenient phasor approach.

5.0 LABORATORY COMPONENT

Most of the EM courses taught at the junior level do not have a laboratory component associated with them. In this section we suggests potential topics for the associated laboratory:

1. Examine the proper method of measuring the line capacitance, inductance, impedance and a balanced line.

2. Investigate the properties of electromagnetic waves along a transmission line and to understand electromagnetic wave propagation in a material medium.

3. Determine the effects of shielding versus non-shielding on wave propagation, attenuation, partial and reflection.

4. For a two-wire transmission line, demonstrate the properties of propagation, impedance matching, reflection and standing waves.

5. Investigate the properties of magnetic waves along a transmission line when using a continuous transmission line compared to a transmission line comprised of multiple sections using connectors and bulk heads between the transmit and receive ends of the cable.

6. Investigate the properties of magnetic waves along a transmission line using a function generator for simulated input versus a real world RS-422 driver (Tx and Rx) input.

7. Investigate the properties of power along a transmission line and to understand the affects transmission lines have on power. To understand the electrical power characteristics, such as frequency, amplitude and line loss, when transmitting AC and/or DC voltage across a particular distance using transmission lines.

6.0 CONCLUSION

In this paper a modification to the prevailing EM course format is proposed. After presenting the existing course format, the author suggests reducing the static fields coverage to the absolute minimum and increasing the coverage of the time varying fields and their applications, including EMC. The new course format is elaborated upon, together with the suggested laboratory/demonstration component of the course.

7. 0 REFERENCES

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