Electromagnetic Foundations of Electrical Engineering

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J. A. Brandão Faria

Instituto Superior Técnico – Technical University of Lisbon, Portugal

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To the memory of my wife,
Fernanda Faria

'Let there be light', and there was light
Genesis 1:3

$$\begin{cases} \operatorname{curl}\mathbf{E} = -\dfrac{\partial \mathbf{B}}{\partial t} \\ \operatorname{div}\mathbf{B} = 0 \\ \operatorname{curl}\mathbf{H} = \mathbf{J} + \dfrac{\partial \mathbf{D}}{\partial t} \\ \operatorname{div}\mathbf{D} = \rho \end{cases}$$

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About the Author

J. A. Brandão Faria received his PhD degree and aggregate title in electrical engineering from the Instituto Superior Técnico of the Technical University of Lisbon, where, since 1994, he has been a Full Professor of Electrical Engineering teaching undergraduate and graduate courses in electromagnetics. His teaching activities also include lecturing courses at the Portuguese Air Force Academy.

Professor Brandão Faria was a senior scientist with the former Centro de Electrotecnia Teórica e Medidas Eléctricas where he served as President from 1994 until 2000. Since 2008, he has been at the recently created CIEEE (Center for Innovation in Electrical and Energy Engineering).

Professor Brandão Faria was the recipient of two Honorable Mentions awarded in 1994 and 2007 by the Portuguese State Department of Science and Technology, and by the Technical University of Lisbon, respectively. His areas of interest include electromagnetic field

problems, power lines, and wave propagation phenomena in multiconductor transmission lines. He is the author of two books on electrical engineering subjects, namely *Optica* and *Multiconductor Transmission-Line Structures*, and has published over 100 technical papers.

Professor Brandão Faria is a member of the Editorial Board of the *European Transactions on Electrical Power* (John Wiley & Sons, Ltd) and a senior member of the IEEE.

For more details follow the author's website link at:
https://fenix.ist.utl.pt:443/homepage/ist11545.

Preface

This book has been written bearing in mind not only my own students but also electrical engineering students in general, including European students now facing the challenges of the Bologna Reform.

The primary goal of this textbook, *Electromagnetic Foundations of Electrical Engineering*, is to provide undergraduate students taking courses in electrical engineering with a scientifically founded and unified basis of fundamental knowledge on electromagnetic field phenomena, which will enable them to grasp advanced topics and specialized applications that will be dealt with later in their courses, or that they will come across in their professional lives as engineers.

Several distinguishing features make this new textbook unique in its area. It is primarily a balanced foundations book with a broad scope. The emphasis is on basic principles, concepts and governing laws that can be used precisely by electrical engineering students pursuing studies in areas as diverse as power and energy systems, telecommunications, electronic circuits, control systems, bioengineering, etc. In order to reach and serve as large a readership as possible, bias towards specific areas has been deliberately avoided. Electrical engineering professionals (practitioners) with a need for a refresher course in electromagnetic foundations will also find the book a valuable asset.

A project-solving oriented posture is adopted to capture more easily the reader's interest. However, it is not my intention to provide ready-made recipes or rote procedures for students; my approach emphasizes problem solving as a thought process based on concepts and on concept linking. Right at the beginning of the book, a project portfolio is proposed and offered to students in order to capture their attention and trigger their curiosity (project solutions will be available separately). These projects tie together a diversity of knowledge components whose roots lie in different chapters in the text; this salient feature, it is hoped, will help readers understand the big picture, avoiding segmented perspectives. The key idea is to enable students' knowledge integration skills so that, after completing the book, they can solve the various problems and questions included in the proposed project portfolio. When they do, both the students and the book will have accomplished their goals.

In addition, in all chapters, several fully worked-out application examples are presented to illustrate the theory and concepts that have just been introduced and developed. End-of-chapter homework problems, intended to help guide students in their learning process,

are also included; these problems are of practical interest and focus on engineering applications.

The material covered in the book is assumed to be taught in the fourth or fifth semester of the first cycle of studies leading to a Master's degree. Its content, its smooth build-up, as well as its presentation and style, make it suitable for adoption in any top-tier university in the world.

The topics addressed in the textbook are confined to the teaching/learning cycle of a single semester, before which students are supposed to have already acquired the necessary basic skills in and knowledge of both mathematics and physics. Therefore, given the allotted time limitations, a very judicious choice of not only the subject matter, but also its methodological presentation, becomes an imperative and difficult task. In addition to these time limitations (typical lecture times do not globally exceed 40 hours per semester), another challenge faced by this book concerns the average preparation background of students. Although the panorama may change from country to country, my own teaching experience indicates that a great deal of caution may be needed. Taking it for granted that students have already mastered key concepts in electromagnetism can be the first step to failure. Even worse, I have seen in many cases that students have been exposed to some misleading ideas, meaning that additional efforts aimed at deconstructing some preconceived or pre-acquired concepts cannot be avoided for the sake of a sound lifelong preparation.

The book is organized into four parts containing several chapters. The starting point is Maxwell's equations. From them, the fundamental laws and principles governing static and time-varying electric and magnetic fields are derived. Results are subsequently particularized for slow time-varying electromagnetic field problems (steady-state sinusoidal circuit analysis and transient phenomena) and for rapid time-varying electromagnetic field problems (electromagnetic waves and transmission-line theory).

The presentation of the book's subject matter starts with very simple phenomena and proceeds, chapter by chapter, to consider progressively difficult topics. Although the material is arranged in traditional chapter form, a unique approach with this book is that its topics are not tightly compartmentalized. Matter belonging to advanced chapters is frequently built upon preceding topics, taking advantage of existing similarities among the governing equations and making use of contact points that may exist among different concepts. This approach not only contributes to a unified vision of the book's content, but also allows students to correlate apparently distinct topics, enabling them to develop a correct frame of thought where knowledge integration is a prominent objective.

Students using this book are expected to attain a level of competence that will enable them easily to follow up advanced classes taught subsequently in their courses, namely electromagnetic waves, radiation, antennas, microwaves, optics, instrumentation and measurement, electromagnetic compatibility, electrical machines, power systems analysis, etc.

The subjects dealt with throughout the book obey the school of thought traditional to top-tier universities: rigorous concepts, solid ideas, clear introduction of approximations, use of deductive methodology and rejection of ready-made recipes. This approach is seasoned with a friendly presentation of all topics aimed at drawing the students' attention to the central issues under discussion. In addition, special emphasis is placed on the examination and criticism of a few aspects where wrongly preconceived ideas are suspected to exist.

Formal demonstrations of certain results and theorems are absolutely necessary; however, in some instances they will be avoided or alleviated whenever possible. In fact, some results

will be derived by simply invoking duality principles or by making use of existing analogies with previously treated subjects; this methodology not only saves time, but also contributes yet again to the global goal of knowledge integration.

The organization and style of this book reflect my experience as a faculty member of the Instituto Superior Técnico (IST)[1] – the School of Engineering of the Technical University of Lisbon.

[1] The IST is a European higher education establishment belonging to the CLUSTER (Consortium Linking Universities of Science and Technology for Education and Research) network, which includes Universitat Politècnica de Catalunya – Barcelona, Technische Universität Darmstadt, Eindhoven University of Technology, Institut National Polytechnique de Grenoble, Universität Karlsruhe (TH), École Polytechnique Fédérale de Lausanne, Imperial College London, Université Catholique de Louvain, Kungl Tekniska Högskolan (KTH) – Stockholm, Politecnico di Torino, and TKK Teknillinen Korkeakoulo (formerly Helsinki University of Technology), as well as Ecole Polytechnique Montreal (Canada), Georgia Tech (USA), Tomsk Polytechnic University (Russia) and Tsingua University Beijing (China).

For Electrical Engineers/Practitioners

As mentioned above, the main target of this book is the university population (students and faculty staff) concerned with electrical engineering studies. However, it is widely recognized today that any practitioner must keep up to date with new developments in their area of expertise. This means lifelong learning. Despite a university education, the skills and knowledge acquired there by practitioners may be insufficient for a professional career spanning several decades. What is more, corporate policies regarding employment quite often impose very rapid and dramatic changes on the tasks assigned to employees, who in many cases have to retrain for a new line of work.

Electrical engineering technology is evolving at a very rapid pace in almost all of its branches and, therefore, it is virtually impossible for anyone to be able to stay on top of all of its novel developments (which, they too, will soon become obsolete). The only thing that really remains stable and imperishable is the foundations of electrical engineering. These foundations can provide practitioners with a refreshing of the key concepts and theories underlying their professional activities, or even open doors to a new start in a different area.

Such readers will find in the book not only the necessary electromagnetic basics, but also a vast collection of useful illustrative application examples and problems that will help them solidify their knowledge. A key feature of this book, which I believe can attract their attention and interest, is a project portfolio that precedes the presentation of the theory. It includes a series of elaborated projects (focusing on engineering problems) that tie together the multiple topics dealt with throughout the book. If, after reading the project portfolio, practitioners feel unsure about how to solve the proposed projects, then they will have a strong additional reason to acquire this book.

For Students

The material presented in the book is built on a substrate of knowledge already provided by the basic sciences of mathematics and physics. Students are supposed to be acquainted with certain topics, such as linear algebra, differential equations, integral calculus, vector analysis and complex functions. If students still have difficulties with these topics, they may have to recap them in order to refresh their skills.

This book is not a treatise on electricity and magnetism – its scope is far less ambitious. Its content can be delivered in a single-semester course, and is aimed to provide a scientifically founded and unified basis of fundamental knowledge on electromagnetic field phenomena that will help students follow up more advanced subjects covered in their courses. Topics are introduced in a systematic and friendly manner, proceeding from the simpler to more difficult ones, using a slow build-up process. In addition, a series of application examples and homework problems have been prepared to help students through the learning process. The fact that the book is partitioned into chapters does not imply that some of them can be skipped. Because the subject matter is deeply interrelated, students must try to adhere to the normal chapter sequence, otherwise they may be wasting their time or fail to get an integrated comprehensive view of the electromagnetic phenomena.

At the beginning of the book there is a project portfolio which includes examples of problems that students may encounter during their life in electrical engineering. These projects were conceived so as to merge a variety of knowledge components from different chapters in the text. Students may start by skimming through the proposed project themes just to get an idea of what the book is about and, also, to realize what will have to be learned. Once students have finished reading the book they should return to the project portfolio and try to solve the proposed projects. If they succeed, it will mean that their goals have been accomplished, and they should be confident about their newly acquired skills. Project solving is a well-proven methodology in any learning process. But students should be aware that they themselves, not the instructor, are supposed to do that job. Let us use an analogy to remind students that no one can learn to ride a bicycle by seeing others do it – practice is required to develop the skill.

A final word: do not believe people who say that learning is fun. Learning involves a lot of hard work and persistent effort, especially when the subjects being studied are of an abstract kind. Do not be worried when difficulties arise, do not give up, recap and recap again until the source of difficulty is clearly identified, and then debate the issue

with fellow students or ask the instructor for assistance. Further, I will gladly help (brandao.faria@ieee.org). Fun comes only at the end of the process, after many hours of struggle. The moment when students realize they have been empowered with valuable new knowledge and become intellectually richer, then, and only then, will they really experience the feeling of fun.

For Instructors

The failure or success of delivering a university course (any course) relies mainly on the pedagogical skills and scientific preparation of the instructor in charge. A good book can help a lot, but, just by itself, it is not a guarantee of success.

The present book on the electromagnetic foundations of electrical engineering has been conceived in order to assure that its subject matter is presented in a coherent and logical arrangement. In addition, application problems and final work projects have been prepared to guide the students through the learning process.

The content of this textbook has been tested and subjected to proof for many years with thousands of students. I bear witness not only that lectures have been well received and enjoyed by those students, but also that their final exam success rate has been high (around 80 %).

From my own experience three recommendations stand out. When teaching a given subject, the scientific preparation level of the instructor must be several notches above the one that would strictly be required for lectures, otherwise instructors may find it difficult to answer unexpected questions raised by more advanced students. A second aspect has to do with the utilization of audiovisual aids: they should be used very sparingly and prudently, otherwise students may become ‘disconnected’. Finally, as far as project solving is concerned, students should be provided with orientation guidelines and have their mistakes corrected, not have problems solved for them, otherwise they will hardly be able to assess their own skills correctly.

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Now a retired Emeritus Professor with the Technical University of Lisbon, Professor Borges da Silva superbly guided my teaching and research activities for two decades. His thorough and very rigorous approach to electrical engineering subjects made him a role model for me. The writing of this book would never have become possible without the long-lasting influence he has had on me.

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Last but not least, I would like to strongly emphasize my endless heartfelt gratitude and love to my deceased wife Fernanda, who, despite her terminal illness, never failed to back me up in this enterprise.