A MATLAB-Based Virtual Laboratory for Teaching Introductory Quasi-Stationary Electromagnetics

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Abstract—This paper reports the realization of a MATLAB-based electromagnetic-fields virtual laboratory, and experimentation in the teaching of undergraduate Introductory Electromagnetics courses. The choice of the developing environment is discussed in the light of authoring issues and user advantages. The virtual laboratory is described in terms of its functionalities, and a selection of examples is illustrated, showing its actual didactic use. The software architecture produced, including the Web interface, is briefly described and the possible extensions or different uses of the environment realized discussed. The positive response from students in a two-year classroom experience is reported, and future developments are outlined.

Index Terms—Education, e-learning, electromagnetics, multimedia learning resouces, simulation in engineering education, virtual laboratory, Web-based delivery environments.

I. INTRODUCTION

THERE is a widespread opinion among students (and teachers) that electromagnetics is a difficult subject, especially at the undergraduate introductory level [1], [2]. This difficulty is normally attributed to three main reasons: 1) the subject relies heavily on vector mathematics and is perceived as somewhat abstract; 2) the few examples that can be solved on the blackboard are highly idealized and, therefore, do not easily provide physical insight; and 3) at the introductory level, motivation of students through realistic examples supporting the theory with laboratory work is difficult.

The spectacular growth of computer simulation in electromagnetic analysis and design over the last two to three decades has been considered by many teachers as a unique opportunity for reversing such a situation. Several different tools and experiences have been reported [3]–[5]. Nevertheless, the author states that, contrary to what has happened in other areas (for example, circuit and systems education), the systematic use of simulation in teaching electromagnetics is still the exception and not the rule.

Apart from some conservative attitudes toward such a well-structured and traditional subject, this situation is probably motivated by the lack of a standard reference in electromagnetic-fields simulation for education, and often the proposed tools do not appear to be general enough to really compete with the traditional chalk-and-blackboard approach.

In this scenario, a significant novelty has been presented by the development and wide diffusion of general-purpose mathematical software packages, such as MATLAB [6], MATHCAD [7], or MATHEMATICA [8], which are all modern mathematical tools characterized by powerful function libraries, friendly user interfaces, and (most important) "open" structure of the programming environment. This novelty has been considered by some authors as a cornerstone in the teaching of electromagnetics, and examples of the integration of these environments into traditional courses are reported [9].

In this paper, the author describes the work being carried on at the University of Naples FEDERICO II, Naples, Italy, in realizing a MATLAB-based virtual laboratory on electric and magnetic fields and introducing it in courses in the electrical engineering curriculum at different levels. A virtual laboratory, to parallel the theoretical lessons with a well-balanced supply of guided and free examples, is not a new idea [5]. If it is realized by means of a general-purpose, wide-diffusion, and "open" mathematical programming environment, this approach allows some of the criticism about using specialized tools [9] to be overcome and gives a more robust background to the instructor in developing the study cases and examples. On the other hand, the open structure of the environment can be exploited to offer the student different levels of interaction and understanding. Finally, this kind of choice provides a modern conception of didactic resource production and maintenance.

After discussing certain general authoring issues and the specific possibilities offered in this context by the MATLAB developing environment (Section II), some examples of the EM virtual laboratory that have been developed are given. They illustrate how the laboratory works (Section III) and what the possible extensions and different utilizations are of the proposed implementation (Section IV). Some insight into the architecture is also provided (Section V), and in Section VI, the author's experience in terms of the advantages and effectiveness of the tool in students' training is discussed.

II. SOME ISSUES REGARDING AUTHORING A MATLAB-BASED VIRTUAL LABORATORY

Any author who has embarked on the enterprise of building self-consistent "courseware" to integrate his or her traditional teaching with simulations and multimedia has experienced how the production of any "electronic" learning material is extremely time consuming. Although the possibilities offered by this developing technology in education grow more attractive each day, before starting to work, one must try to answer some basic practical questions concerning the diffusion and availability of the hardware and software required of the user (student), the relative difficulty and time expenditure for the creation of the resources, the possibility of reusing and easy maintenance of the resources

in the future, and the relative effort for enlarging the base of examples and cases. Finally, one is advised nowadays to consider the problem of Web integration and delivery of the resources [10].

Several solutions and strategies are available; each one responds, for better or worse, to the points mentioned. The author reports, in this paper, his experience in using the MATLAB environment, showing how this choice can positively answer most of the questions raised. More generally, in the area of electrical engineering education, there is increasing diffusion of the idea of producing additional didactic material based on MATLAB and its numerous specific toolboxes; for example, a certain number of books on electric and electronic circuit analysis with MATLAB [11] or systems and control theory [12] have been published. Much less is presently available on the part of electromagnetics education, probably for the reasons previously discussed. Nevertheless, in this area also, the situation is evolving [13].

The issue of availability and diffusion of the environment is easily addressed since MATLAB is now extremely widespread, at least in universities for research and education, and very often officially adopted as a standard tool in an increasing number of engineering disciplines. At the same time, a second goal is fulfilled: the reduced effort required for students to familiarize themselves with this environment is very often preserved for other courses and, eventually, professional use. From the teacher's point of view, as well, such a choice is often synergic to the scientific work, resulting in reduced time needed to create new examples and case studies, competing with pencil and paper.

The problem of future maintenance of the produced resources is also solved for two main reasons. First, because of the macro functions structure, one can update or modify single blocks relatively easy, instead of rewriting a great part of the code. Second, the great effort made by the producer in the backward compatibility of the successive version of the software allows a costless upgrade, often with some of the functionalities enhanced.

Finally, from version 5.2, MATLAB provides a well-integrated common gateway interface (CGI) for a Web server, which allows easy deployment of any MATLAB-based application via the World Wide Web, eventually interfacing multimedia and other resources. This improved version provides the opportunity for the user to run simulations remotely, without the need for licensed software or appropriate hardware.

Apart from these general considerations, for those who are familiar with the major features of the MATLAB environment, one can easily imagine how the calculus and graphics capabilities can be used in developing examples in vector field analysis. Analytical and numerical solutions of canonical field configurations can easily be implemented, and the results can be well depicted by the high graphical capabilities of the environment. Plenty of cases can be easily developed in the standard MATLAB environment based on analytical solutions, and simple "ad hoc" numerical models can be implemented when analytical solutions are not directly available.

Much more sophisticated possibilities are offered by the use of the MATLAB partial differential equation (PDE) toolbox [14], which provides a powerful and flexible environment for the study and solution of two-dimensional PDEs. The package, described in [15], is intended 1) to define the PDE problem, in terms of geometry, boundary conditions, and coefficients, 2) to define a triangular mesh over the considered geometry, 3) to discretize the equations by the finite-element method (FEM) and numerically solve them by producing an approximation to the solution, and 4) to visualize results by means of specialized graphic tools. Clearly, this tool significantly enlarges the possibilities in designing examples and case studies. Moreover, the PDE toolbox results are fully visible and available to the MATLAB environment, allowing the variables and the source files to be accessed directly and to further manipulate the solution to calculate quantities that are not expressly provided. For the sake of completeness, the author is compelled to mention that a similar but more powerful (full three-dimensional) environment is available as FEMLAB [16]. It could, in principle, be used for didactic purposes as well.

III. A VIRTUAL LABORATORY FOR STATIC AND QUASI-STATIONARY EM FIELDS

The electric- and magnetic-fields virtual laboratory realized and presented in this paper is the convergence of previously developed simulations into a specifically designed multimedia Web environment. The actual novelty of the realization is that it is based on MATLAB both as a simulation environment and as a Web server, allowing a remote Web interfacing by the student without any need for private software licenses. Another point is its "open structure" design where different authors can integrate material quite easily. In the following, first described are the overall environment and the user interface, then the content of the virtual laboratory, and finally some technical aspects of its realization.

The electric- and magnetic-fields virtual laboratory, as designed and realized, could actually be considered a general learning environment with online, interactive, EM-field simulations. A specific user interface was designed for the delivery of the resources that were in an early version based on MATLAB itself [17]. In the present version, a general Web interface was developed, described in the following. A "first page" screenshot of the virtual laboratory as currently available is reported in Fig. 1. Several different subwindows can be distinguished to integrate different kinds of resources (simulations, text, pictures, PowerPoint presentations, video and audio streaming, self-evaluation tests, etc.), with the opportunity of directly browsing among the available simulation examples and all the associated multimedia resources. Four independent windows are provided: one (top left) for streaming video, another (bottom left) for browsing into the material, another (top right) for general information and eventually pictures, and a fourth (bottom right) for showing different resources, simulation results, etc. On the top is a menu bar where, after a certain topic has been chosen in the browsing window (by selecting the appropriate folder–subfolder path up to the single example), the user can choose the resource language (for multilanguage resources), the progressive level (beginner, intermediate, advanced, etc.), and other associated resources on the subject (menu "more"); can visualize associated multimedia (menu "media"); and, finally,
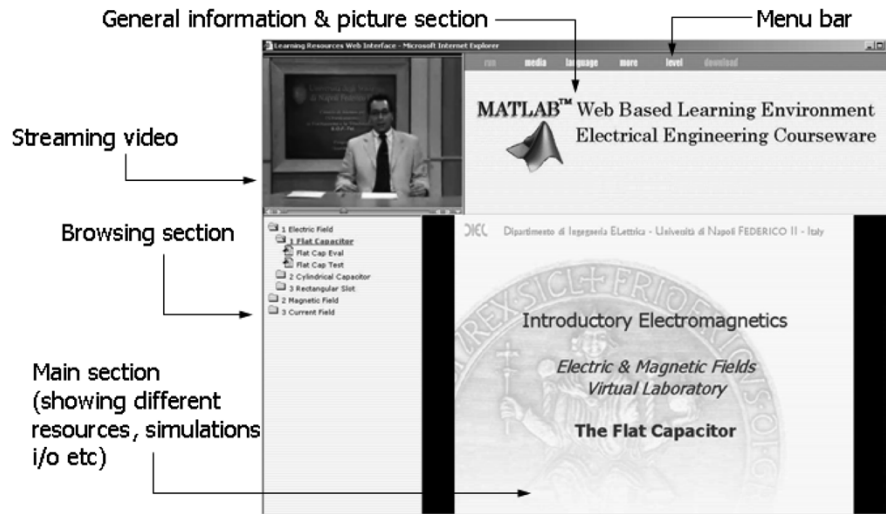
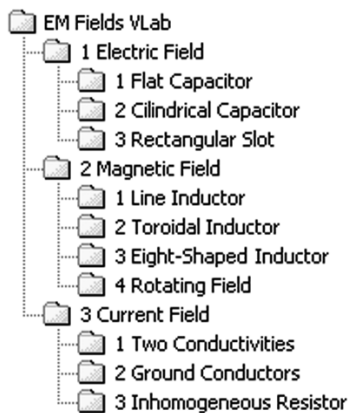Fig. 1.   Screenshot of the first page Web interface of the virtual laboratory.

Fig. 2.   List of available topics and examples as visualized in the browsing window of the virtual laboratory.

can run interactive simulations (menu "run") or eventually download the corresponding source files (menu "download").

The web server provides for the execution of the simulation and creation of the output page in hypertext markup language (html) style. A full demonstration of the interface and the virtual laboratory itself can be viewed at the website address www.elettrotecnica.unina.it/multimedia.

The actual content of the virtual laboratory, in terms of simulation examples, is fully available at the browsing window of the interface. In Fig. 2, the list of topics presently available is reported.

With reference to present utilization for an introductory course, the virtual laboratory is structured in three sections: electrostatics, magnetostatics, and stationary current field, with some examples of different difficulty levels. Currently, a tenth of the examples of interactive simulations are fully available, with a reference time of 15–20-hour lessons for its delivery, including some theoretical recalls for each one. Each example has several associated didactic resources as PowerPoint presentations, text, etc.
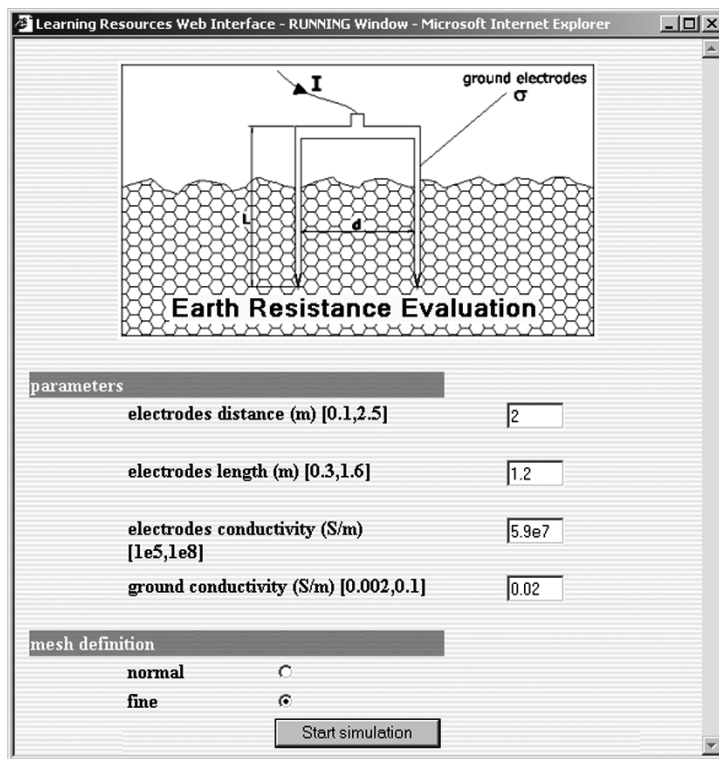
Parts of the simulations are realized in the standard MATLAB environment; others are based on the PDE toolbox. Some examples (more often when realized with PDE) have the main goal of illustrating the field configuration and some significant properties of the analyzed structures. Others are designed with the double purpose of analyzing and gaining insight into a specific problem, as well as familiarizing students with simulation problems and numerical techniques. In a third category of examples, the goal is to illustrate the relationships of geometry and material properties versus some global parameters, such as resistance, capacitance, or inductivity. A fourth category shows fields animations. In the following, a sample for each section is described with the goal of explaining how in practice the virtual laboratory works, what the major pedagogical ideas behind it are, and finally how it can be used or eventually expanded by other authors.
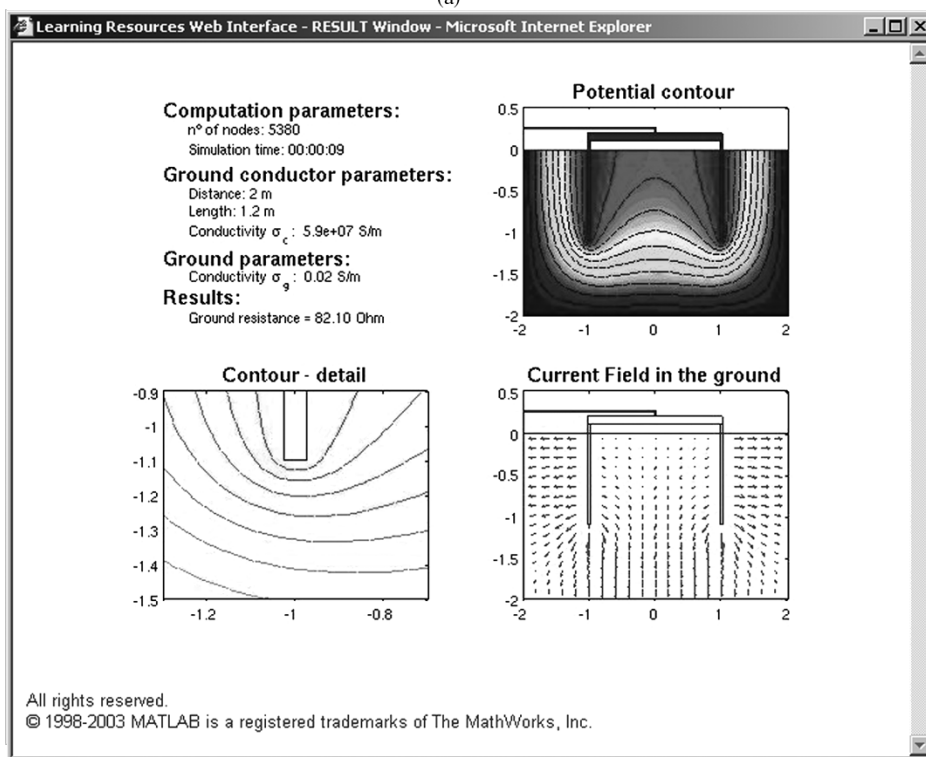
A. Examples of Realistic Design Components by PDE

As mentioned previously, an important advantage of a simulation approach is to show the students realistic applications, stimulating both interest in the subject and sensitivity to realistic parameters and geometries. By the use of the PDE toolbox, building complex field configurations is quite easy and not very time consuming. In this way, one can build a library of examples to show the most common canonical field configurations in real components, such as capacitors of different shapes, inductors, resistors, insulators, and transmission lines. The PDE simulations are fully integrated with the MATLAB environment, and further manipulation of the solutions are available to the teacher and the student.

To demonstrate this idea, the author takes an example from the current field folder, namely the grounding conductor analysis. With reference to a structure of two cylindrical grounding conductors in a conducting ground [Fig. 3(a)], the earth resistance is evaluated for a set of parameters chosen by the student, such as the electrode's length, distance, and conductivity, and the surrounding ground conductivity. After the simulation, the potential and field distribution is also shown with other associated information [Fig. 3(b)].

Fig. 3. Grounding conductors example: (a) input window and (b) output window.

B. Analysis of Simple Field Configurations With Analytical and Numerical Solutions Compared

Let us now take an example from the electrostatic folder, such as the study of a rectangular slot with assigned potential at the boundaries. On such kinds of problems, a simple numerical approach can be introduced to the students (either during regular lessons or as a specific resource associated to the simulation) and comparison to the analytical solution or to different numerical formulation results can be proposed to them. Therefore, the assumption is that the students are aware of the possible analytical solution by rectangular harmonics series expansion, which is first implemented in the example. Because of rectangular geometry, one may easily discretize the Laplace equation with fi-
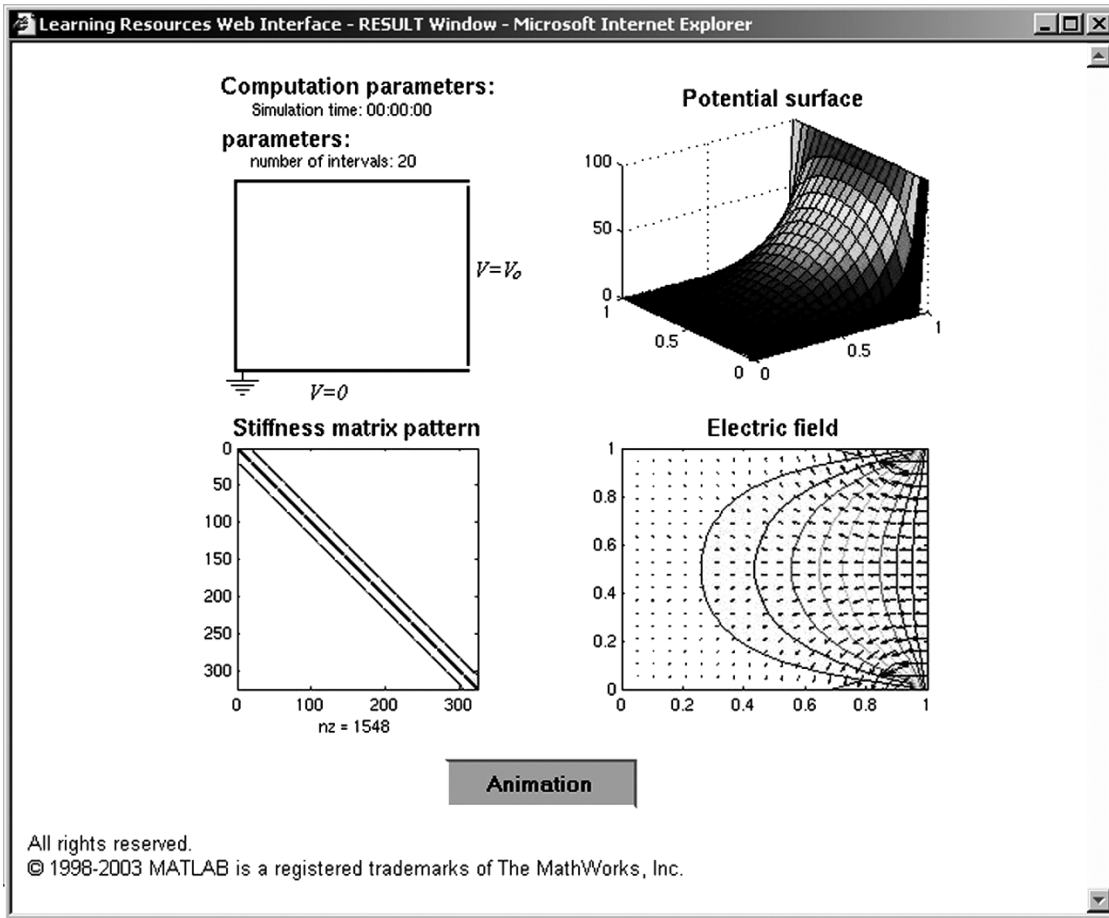
Fig. 4. Output window for the example of a rectangular conducting slot solved with a finite-difference formulation.

nite differences and impose boundary conditions. When an algebraic equation system is obtained from the original partial derivative equations, a solution can be obtained by direct or indirect methods, and the numerical solution can be easily compared with the analytical solution obtained by harmonic expansion.

In this case, the output window (Fig. 4) will show the solution, in terms of potential and field, according to the chosen formulation. The availability of built-in postprocessing and graphic tools for the solution allows the field structure in some detail to be easily shown, as well as zooming the critical points like edges and corners, etc. Moreover, a comparison between different formulations, additional information such as the simulation time, and the picture of the stiffness matrix occupation or the animation of a solution by a relaxation technique are all available as output.

Despite (or maybe because of) its extreme simplicity, this kind of example has proved really helpful for students to familiarize themselves with a discretization process, compare some general-purpose "built-in" and "ad hoc" algorithms for the calculation of the solution, etc. In this way, instructors easily expose the students to problems, such as the computational efficiency and the relative precision of different solution algorithms, understanding the problem of manipulating sparse matrixes, or looking at the banded structure of the finite-differences matrix formulation. Finally, animation of the ongoing process in

searching solutions, as, for example, with relaxation techniques, can be easily provided.

C. Field Animations

The possibility of showing animation of significant time-varying field configurations each time is extremely important from the didactic point of view. In fact, the absence of a dynamic representation has normally been recognized as the most unsatisfactory point to gain real insight in the traditional approach. To illustrate the possibilities offered on this point, an example is taken from the magnetic field folder, where the study of a rotating electrical machine is considered. After a certain number of parameters have been selected by the student (number of phases to be fed, type of sequence, number of time steps, etc.) and the simulation launched, the results of the simulations are shown (Fig. 5) and the dynamics of the rotating field is visualized in a movie (full animation is available at the virtual laboratory Web address www.elettrotecnica.unina.it/multimedia).

D. Self Evaluation

Implementing self-evaluation schemes with, for example, multiple-answer questionnaires, etc., to be included in the virtual laboratory is quite straightforward. With reference to each example (eventually with all the associated resources),
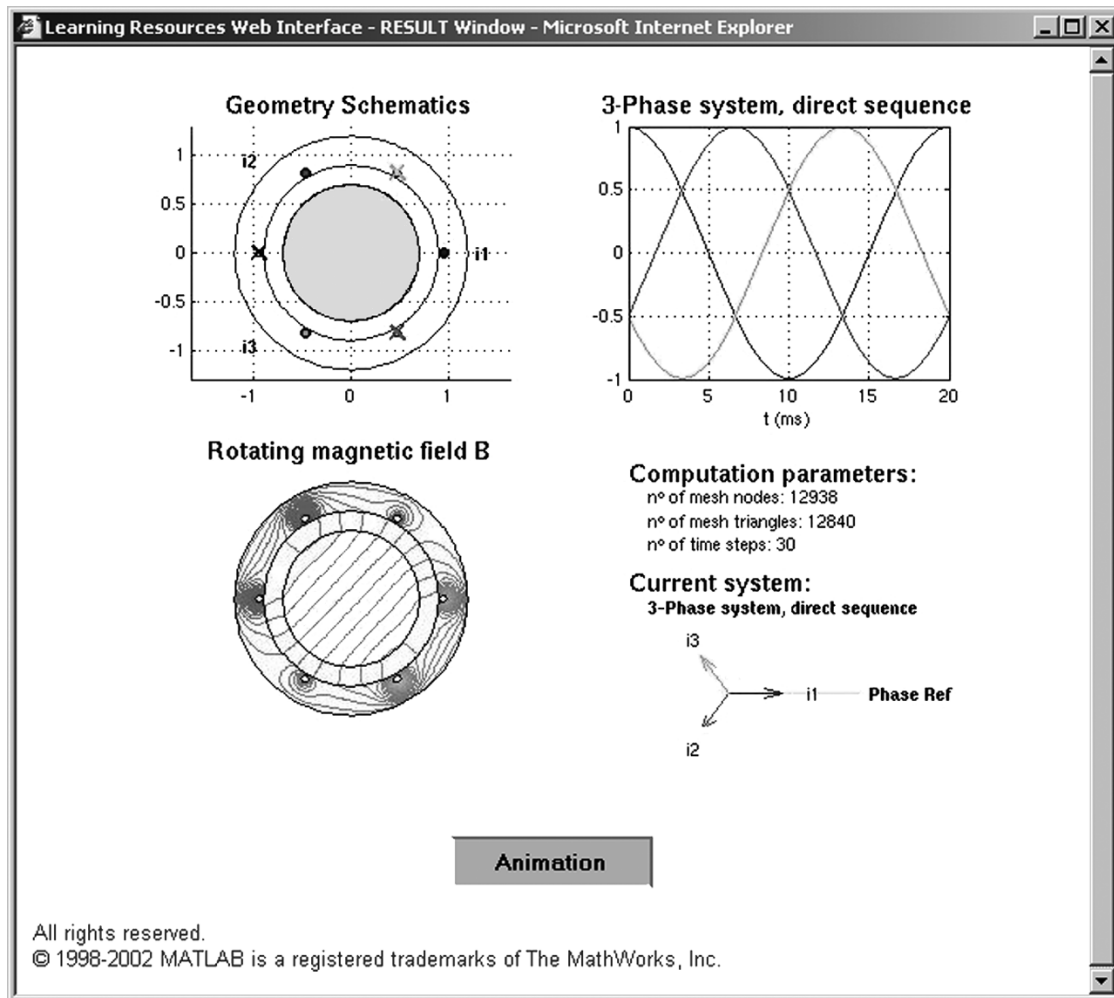
Fig. 5.   Rotating magnetic field in a three-phase asynchronous motor example.

a self-evaluation test can be prepared by the author. After the students work on the example, they can run the test, have results in terms of evaluation of their comprehension, and be given suggestions on specific topics to be improved. This procedure can be most easily integrated in the proposed architecture by including additional m-files, representing each test in the proper folder corresponding to the considered example.

IV. POSSIBLE EXTENSIONS AND DIFFERENT USAGES

The list of resources presently available in the virtual laboratory has been based on the classroom examples as developed (and delivered) in a two-year experience of an introductory course on Static and Quasi-Static Fields at the University of Naples FEDERICO II. Currently, a new set of examples are being designed to accompany an advanced course in CAD Elements for Electromagnetic Fields that is planned to be activated. It is therefore interesting to also discuss some possible developments of the proposed ideas, to enlarge the potential audience eventually to other disciplines and topics. Before that, some of the major reasons for the choice of MATLAB have to be recalled. They can be listed as open source environment, availability of a PDE toolbox, vector analysis macro functions, full

availability of PDE solutions for postprocessing, simple and effective graphical capability, and, finally, the possibility of Web integration.

An important point in enlarging the nature and scope of examples offered to students is the full availability of any solution (eventually a PDE one) for postprocessing. In fact, this feature permits direct calculation of global parameters (resistances, capacitance, inductivities, per-unit length parameters in transmission lines, etc.) or other quantities after the field configuration of a prescribed structure has been evaluated. This calculation can be provided by the instructor preparing the examples or left for further analysis by the student when a better level of understanding of the theory is reached. One can thus imagine evaluating secondary quantities, such as forces and stresses over the analyzed structures, by postprocessing the PDE solution, etc.

A second aspect in eventually enlarging the scope of the architecture presented is directly related to the open source structure of the environment. This structure allows (in principle) the student to enter the simulation code, directly modifying and/or enriching it with new features or building new examples from old ones, etc. This scenario is of course only suited to advanced courses.

Now consider the entire structure of the virtual laboratory, which also provides different potential usages (maybe in

contexts that are somewhat different from traditional university curricula). All the examples and their related resources (video–audio explanations, text and presentations, Web links, etc.) can be designed for different progressive levels and interconnected in a sort of hypertext-type structure. Apart from the technical aspects of such structure for the creation and delivery of the resources (to be analyzed in the next section), one finds it interesting to describe how some material can be recognized and included in the structure. Until now, the key role in the process is taken from the simulation example. One example (or a series of examples) that is meaningful to the educational goal must be defined. This example is prepared as a MATLAB code, defining a set of proper inputs (significant parameters) and outputs (graphs, additional computed quantities, general information, etc.). During this preparation, a level of difficulty can be assigned to the example or the same example can be viewed from different perspectives at different levels of difficulty, which have to be defined. Finally, additional information can be gathered from text, presentations, audio–visuals, etc. This additional resource can often be retrieved from existing ones, possibly from the Web.

Once the process has been completed, one can easily integrate the material into the Web server for its delivery and future maintenance. An ad hoc protocol that the author has developed (to be described in the next section) allows one to establish Web interfacing of the simulation code from the input–output point of view and the relationship between all the resources associated with the example. Therefore, the entire virtual laboratory grows as new examples are introduced and duly related to the structure.

The resources, as well as the corresponding links available, are shown according to the instructor's defined difficulty level, once the user provides his or her selection. In this way, a personalization of the educational path is possible, both by the *a priori* choice of the desired difficulty level and, more directly, by the choice of the sequence of links in the resources exploration.

Except for copyright problems from institutions and single authors, the proposed structure is, in principle, well suited to an integrated use by many different authors who may interact at the entire virtual laboratory level, at the single example level, or at the single associate resource level. In particular, the "download" option (not presently activated for external use owing to copyright problems) allows one to obtain remotely the source code of examples and all the associated resources.

V. Some Insight Into the Software Architecture

The overall design of the project has been based on a few ideas with the goal of integrating the MATLAB simulations in a unique Web interface with as many different associated resources as possible. Apart from the simulations, many standards for supplementary resources are supported, such as Word and pdf text, all major picture formats [Joint Photographic Experts Group (JPEG), Graphic Interchange Format (GIF), Portable Network Graphics (PNG), Microsoft Bitmap (BMP), etc.], PowerPoint and HTML-Java presentations, QuickTime for video and audio streaming, and Moving Picture Experts Group (MPEG) and Advanced Visual Interfaces (AVI) formats

for nonstreaming audio–video. All these standards can be freely chosen by authors to complete and enrich the proposed simulations, although they are not required for their completion.

All the material—the example m-files (for the simulations) and the associated audio, video, text and picture, or presentations resources—is organized in a folder/subfolder structure, with additional embedded links that realize a hypertext. The Web application allows one to show the tree structure of the resources, to execute the simulations according to the user-defined parameters demonstrating the corresponding results, and to run the application needed for the fruition of the associated resources.

The implementation of this architecture is quite straightforward once a simple (and specifically designed) meta-language has been defined for the integration of the resources. On the basis of the information in m-file comments rows, or in additional specific info.txt files, the Web application enables all the resources to be shown and controlled. In addition, specific commands are defined in order to pass data from the user to the MATLAB session, with a general protocol that has been defined in order to handle scalar or matrix variables, numerical or Boolean, etc. The MATLAB Web server provides for the simulation and the creation of the output page as a single MATLAB figure that is passed to the Web environment as a JPEG image. A specifically written instructions block (webIO.m) which needs to be added to each example folder is launched by the MATLAB Web server CGI, providing the verification of proper input variables range and type, launching in turn the specific simulation routine, obtaining the relative output, and finally converting the output MATLAB figure creating the JPEG picture for the Web interface.

The actual implementation of the architecture has to be considered merely as a "case study," whereas the design ideas are quite general and can be implemented in different ways. On the other hand, this implementation, apart from being functionally satisfying, appears to be very simple and, consequently, well suited for further development and extensions.

VI. Discussion and Conclusion

An actual implementation of an electric- and magnetic-fields virtual laboratory has been presented entirely based on MATLAB simulations and fully Web interfaced. This virtual laboratory has been developed and experiments have been performed in classroom teaching at the University of Naples FEDERICO II. The purpose of building the virtual laboratory with a large diffusion environment has been discussed in detail, showing the advantages in terms of the actual realization, and the possible extensions and different uses. The author has illustrated, by means of a choice of examples, the major pedagogical ideas developed and different possibilities in the use of the tool. Moreover, this paper briefly described "how to do it" from the technical point of view since the design was based on open-structure software and well-diffused standards in the hope that this information will be of some help to those wishing to build up similar environments.

The main advantages from the student point of view and from the teacher–author point of view have been described; these

are related to the high-level programming, large availability of mathematical and graphics functions, the dedicated field analysis toolbox, well-supported Web integration of the simulations, and other associated didactic resources.

From the teacher's point of view, a systematic use of such a tool can significantly improve the realization of didactic resources associated with the course, both qualitatively and quantitatively, without the need for large time investments on specific software technologies, yet with a great possibility of the integration of resources produced by different authors.

The virtual laboratory has been tested for two years in a basic electrical engineering course in an "old" curriculum in electrical engineering, where for the first time applications of electric and magnetic fields have been presented after the physics course. The classroom time spent on the virtual laboratory was 20%, whereas the remainder of the time consisted of traditional teaching. From experience, the tool realized has proven to be very effective for early exposure of the students to realistic application and simulation in electromagnetic fields. The excitement of discovery, even in introductory courses, has stimulated the students' sensitivity to a critical use of simulation in engineering analysis and design. An extremely good response from students has been observed both in their enthusiastic liking for the virtual laboratory in giving insight into theoretical subjects and in the level of actual comprehension of the same topics as compared with students who attended the course in previous years (without the laboratory), as shown in the examinations' results.

On the basis of such positive response for the "new" curriculum, a more advanced course has been planned, entitled Elements of CAD for Static and Quasi-Static Fields. It will be firmly based on the virtual laboratory, and the development of a new class of examples is in progress. In evaluating this new tool, the author plans to use self-evaluation tests (described in a previous section), implementing a tracking scheme on the Web to follow each student's learning path to assess the effectiveness of the tool with reference to specific educational goals.

This scheme will be complemented by a student's satisfaction questionnaire, to be completed after the course and before examinations. Finally, this new course (with the virtual laboratory), as well as all other courses of the new curriculum, will be subject to independent assessment from the university with a quantitative comparison among courses within the same faculty.

The proposed approach of integrated, Web-delivered virtual laboratories can be easily extended to other disciplines, especially where a large base of MATLAB simulations is already available, and to a context different from university classrooms.

Finally, this kind of approach requires a profound revision of the didactic model, course programs, and overall curricula, at least for engineering education in general.

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