Integration of COMSOL Multiphysics into an Undergraduate Electrical Engineering Curriculum

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Abstract

There is a need for multiphysics simulation in undergraduate electrical engineering curricula, however, many programs do not include this at the undergraduate level. This paper discusses the integration of multiphysics simulation into an undergraduate curriculum at the University of Pittsburgh for the purposes of educational enhancement and undergraduate research.

In this paper, we will discuss an internal grant award that was used to fund 60 student licenses of COMSOL Multiphysics to enhance the electrical engineering curriculum in the aforementioned manner. This is done over the course of three major objectives.

First, several modules that were developed over the summer of 2020 as part of a student special project. An undergraduate ECE student at the University of Pittsburgh developed a series of interactive modules which will have a video component to instruct junior electrical engineering students on how to use COMSOL Multiphysics as part of their required electromagnetics course. In these modules, students will learn about device geometry, material properties, simulations meshes, and simulation methods. Students will learn how to model energy storage devices such as parallel plate capacitors and energy transmission devices such as cylindrical conductors.

The second major objective is undergraduate research. In this paper, an undergraduate research project which took place over the summer of 2020 at the University of Pittsburgh as part of the Mascaro Center for Sustainable Innovation's undergraduate research program, will be discussed. In this project, undergraduate student researcher modeled an aluminum conductor, steel reinforced, transmission line conductor to verify its resistance, inductance, and capacitance. This model will be the basis for artificial intelligence application training of transmission line measurements.

The third major objective is to integrate this multiphysics tool into a junior level semiconductor device theory course and a senior level applications of fields and waves course. These courses have traditionally given students' difficulties due to the abstract and "hard to visualize" nature of the course. The implementation of COMSOL into these courses is discussed.

Introduction

Design should be at the forefront of the educational process for electrical engineering undergraduate students. Design has been defined as "a process by which human intellect, creativity, and passion are translated to useful artifacts" [1]. The National Academy of Engineering has stated several times that design is essential to improving student learning [2], [3], [4].

The EE program at the University of Pittsburgh, on the other hand, has traditionally been centered around theory when it comes to courses that rely heavily on physics. The three courses which this is most evident are electromagnetics, semiconductor device theory, an application of fields & waves. The first two are EE core courses and the latter is an elective course. Design in these courses can quite be difficult for students to grasp and appreciate because electromagnetic phenomena are difficult to see. One way to add a visual aspect to these electromagnetic phenomena is through the use a multiphysics simulation.

Professor's Robert Kerestes and Feng Xiong applied for an internal Innovation in Education Award at the University of Pittsburgh and received funding to purchase COMSOL Multiphysics and integrate it into the EE curriculum to rectify this.

This paper discusses the integration of COMSOL Multiphysics into an EE program through the use of energy related applications. This was made possible by the university's Innovation in Education Award. This paper details the award proposal, the implementation of COMSOL Multiphysics into an electromagnetics course through an undergraduate special project, an energy related undergraduate summer research using COMSOL Multiphysics, and a plan for integrating the tool into more of the EE curriculum at University of Pittsburgh and how it can be used for education and undergraduate research in sustainable energy.

Innovation in Education Award

The University of Pittsburgh has an annual Innovation in Education Award which faculty throughout the university can apply to. This program is set up to provide funding to catalyze innovative practices in teaching. The faculty authors proposed to acquire the multiphysics computer aided design (CAD) tool, COMSOL Multiphysics, and integrate this tool into EE curriculum, thus providing the opportunity for EE students to gain energy-based design skills in the classroom and in undergraduate research.

Project Goals

The project goals for this award were as follows:

1. To purchase COMSOL Multiphysics and integrate it into electrical engineering curriculum making coursework more applicable and design focused
2. To develop a set of Open Educational Resource (OER) videos, along with the University Center for Teaching and Learning, training students on how to use COMSOL Multiphysics in the context of these courses
3. To implement analysis and design problems into EE courses which currently lack them using COMSOL Multiphysics
4. To strengthen instruction and assessment of Accreditation Board for Engineering and Technology (ABET) Criterion 3 (student outcomes) and Criterion 4 (continuous program improvement) by means of analysis and design using COMSOL Multiphysics

Courses Targeted

The project targeted two EE core courses and one EE elective courses which are based around applied electromagnetic physics, making design implementation difficult:

Semiconductor Device Theory – An EE core course which involves a study of electrical properties of solids, energy levels, semiconductor theory, diodes, bipolar junction transistors, field effect transistors
Electromagnetics – An EE core course which involves a study of static and dynamic electromagnetic fields in electrical and magnetic materials such as dielectrics, conductors, semiconductors and ferrite
Applications of Fields and Waves – An EE elective course (electronics concentration) which involves a study of electromagnetic waves and associated applications such as transmission lines, wave guides, antennas and radiation applications

Design Project

This section details the proposed project for the innovation in education award. The electromagnetics course, which is taught by the project director, Robert Kerestes of the ECE department, was to have at least two exercises (one electrostatic and one magnetostatic) which students would open electromagnetic device models and simulate them. In addition, the course was to have an additional open-ended energy-based design project. Students were to work in groups for this project and the instructor was to formulate these teams with diversity and inclusion being the top priority. This not only aligned with the University of Pittsburgh's commitment to diversity and inclusion, but it is proven that these teams will work more effectively [5]. The instructor was to include a short lecture module on diversity and inclusion and how it enhances engineering team effectiveness. In this design project, students were to:

- Choose between three predefined electromagnetic energy-based design problems
- Work in groups, effectively communicate with peers, and produce periodic status reports
- Construct their design using COMSOL and simulate this design using multiple different materials and boundary conditions
- Write a report on this design detailing; (1) a statement of the design problem and its constraints, (2) the behavior of the design for different materials used and different boundary conditions, (3) economic analysis of design in comparison with other design options, (4) global and ethical considerations in gathering materials in comparison with other design options
- Present their design to the rest of the class

Implementation of COMSOL Multiphysics

In the summer of 2020 Robert Kerestes recruited undergraduate ECE student, Anthony Popovski, to work on the implementation of COMSOL Multiphysics into the electromagnetics course. A series of teaching modules for COMSOL Multiphysics were developed for the ECE 1259 Electromagnetics course.

These modules are assigned in conjunction with in-class teaching such that topics covered in class are demonstrated in the modules. The goal was that at the end of the course and upon completion of the modules, the students will have a basic enough command of the software to model simple electromagnetic situations and perform relevant studies based on those models. These modules were not meant to provide a mastery of the software, but to give students some basic exposure.

Modules

Ten modules were developed for the purpose of instructing students how to approach and use COMSOL Multiphysics with the classkit license, as well as strengthen their understanding of electromagnetic concepts taught in class. The ten modules can be organized into three separate projects:

- Demonstration of Ampère's Law (Six Modules)
- Demonstration of Electric Fields and Shielding (Two Modules)
- Demonstration of Q and V Methods for Determining Capacitance (Two Modules)

These projects guide the student through the creation of 2D and 3D geometries, the assigning of material properties and physical boundary conditions, the performing of a study, and the analysis of the results.

Earlier modules provide more details and step-by-step instructions than later modules, as it is assumed that the student will have learned the reoccurring processes used in the modelling of these scenarios. The first five modules of the Demonstration of Ampère's Law project are the first modules to be taught, followed by the two electric fields modules, then the two capacitance modules, and finally the remaining Ampère's Law module. This order was selected because the simplistic model of the Ampère's Law project lends itself to novice users. In this electromagnetics course, electric fields are taught around the fifth week of the semester, followed by capacitance in the seventh week, and Ampère's Law in the eighth week. The final five modules are thus presented in their order to match the presentation of material in the class.

Module Example: Energy Storage Device Modelling – Capacitor

One of the modules developed demonstrates the modelling of an energy storage device such as a capacitor. Demonstration of the Q and V methods for Determining Capacitance project guides the student through the modeling of 3D capacitors and finding their capacitance. The first module is focused on the Q method. It begins with a review of the Q method and the design of a 1 nF parallel plate capacitor with an air as the gap dielectric material.

The student assumes a charge Q on each plate of a parallel plate capacitor and solves for the electric flux density **D** using Gauss's Law (1), and subsequently the electric field intensity **E** (2).

$$\psi = \boldsymbol{D} \cdot d\boldsymbol{S} \tag{1}$$

$$\boldsymbol{D} = \epsilon \boldsymbol{E} \tag{2}$$

The definition of voltage (3) is then used and divided by the initial assumed Q to find the capacitance.

$$V = -\int \boldsymbol{E} \cdot d\boldsymbol{L} \tag{3}$$

The student is guided to create a 2D axisymmetric component with Electrostatics physics and a stationary study. Rectangles are used to create a geometry that will be half of the cross section of the final capacitor. Copper and air material properties are assigned to the component and gap areas, respectively. A terminal domain condition is added to the physics and a voltage of 1 V is assigned to the upper plate of the capacitor. A ground boundary condition is added to the physics and is assigned to the lower plate perimeter. The study is computed, and the student can observe the default 2D and 3D rotated electric potential plots. A global evaluation is added that measures the Maxwell Capacitance of the model.

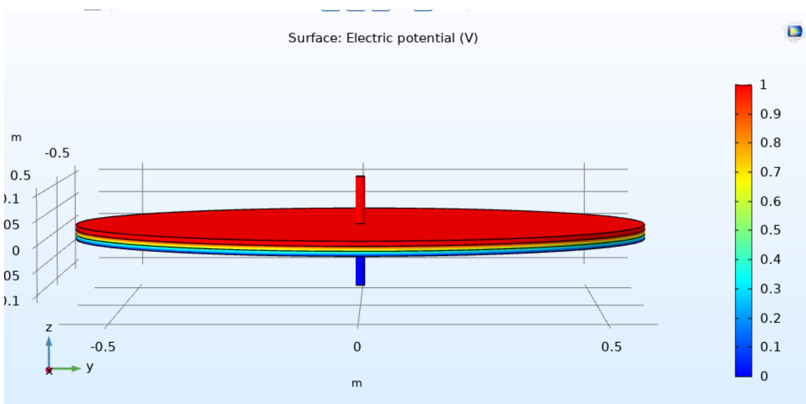

Figure 1: Realized model of the parallel plate capacitor

The second module is focused on the V method. It begins with a review of the V method and the design of a cylindrical capacitor with given geometric parameters and the calculation of the capacitance. Due do the complexity of the derivation, the capacitance equation (4) is given.

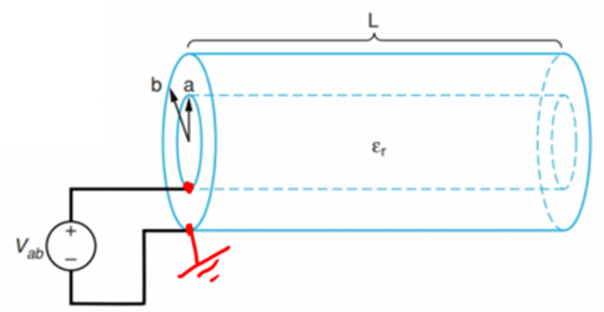

Figure 2: Cylindrical capacitor model

$$C = \frac{2\pi L\varepsilon}{\ln\left(\frac{b}{a}\right)} \tag{4}$$

The student is guided to create a 3D component with Electrostatics physics and a stationary study. A layered cylinder is created with copper and air material properties assigned to the inner and outer layers of the cylinder, respectively. A terminal boundary condition is added to the physics, and a voltage of 1 V is assigned to the inner cylinder perimeter. A ground boundary condition is added to the physics and is assigned to the outer cylinder perimeter. The default electric potential plot is generated.

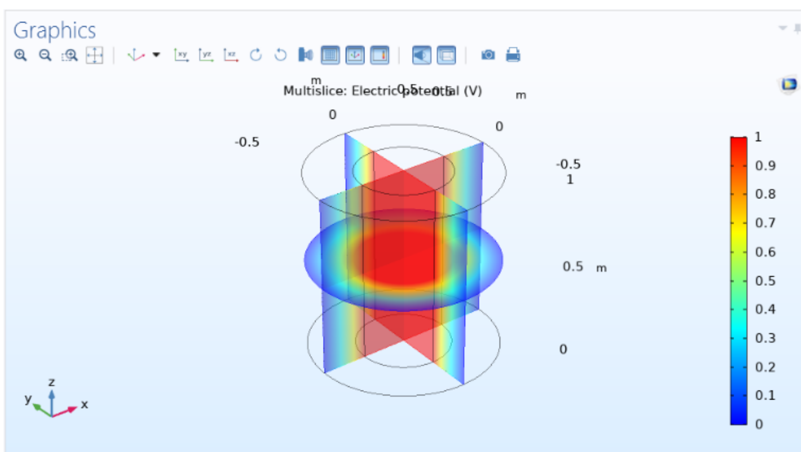

Figure 3: Electric potential plot of cylindrical capacitor model

A global evaluation is added that measures the Maxwell Capacitance of the model. The capacitance will match the desired value calculated at the beginning of the module.

Undergraduate Research Project on Transmission Line Modelling

For COMSOL Multiphysics to become fully immersed into the EE curriculum, a research component was added. As a research 1 institution, University of Pittsburgh has a research focus in all educational endeavors. Every summer the Mascaro Center for Sustainable Innovation holds a summer undergraduate research program where the focus of the research should be in sustainable engineering. As part of this program, Robert Kerestes recruited ECE student, Evan Gzesh to participate in this program and focus on multiphysics modelling of energy transport devices such as aluminum conductor, steel reinforced (ACSR) transmission lines. This section details this undergraduate research project.

Description of Model

The following figure shows the spacing diagram for the overhead transmission line that was used in the study.

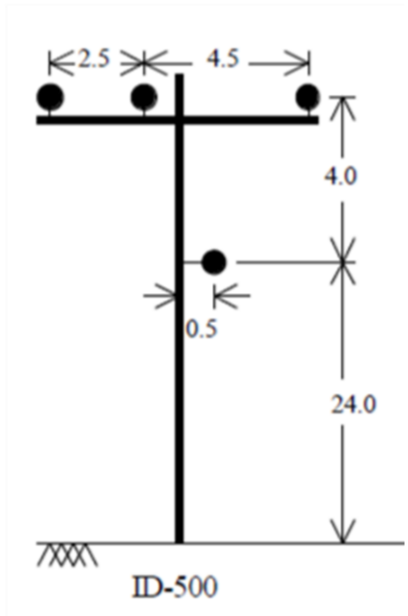

Figure 4: Conductor Spacing in Feet [6]

This standard configuration uses aluminum-conductor-steel-reinforced (or ACSR) cables. ACSR cables consist of steel strands in the center surrounded by strands of aluminum. The aluminum strands conduct the majority of the current due to the metal's high conductivity, and the steel center reinforces the cable.

The overhead phase conductors use the "Dove" ACSR cable, and the neutral conductor uses the "Penguin" ACSR cable. Conductor information is presented in the table below.

For the analytical calculations, the cables were modeled as simple cylindrical conductors. Shown below are the detailed cross-sectional geometry of each cable used in the COMSOL model.

	Conductor Name	Aluminum Strands	Steel Strands	Total Diameter
Phase A, B, C	"Dove"	26	7	0.927in
Neutral	"Penguin"	6	1	0.563in

Table 1: Conductor Data

For the analytical calculations, the cables were modeled as simple cylindrical conductors. Shown below is the detailed cross-sectional geometry of each cable used in the COMSOL Model.

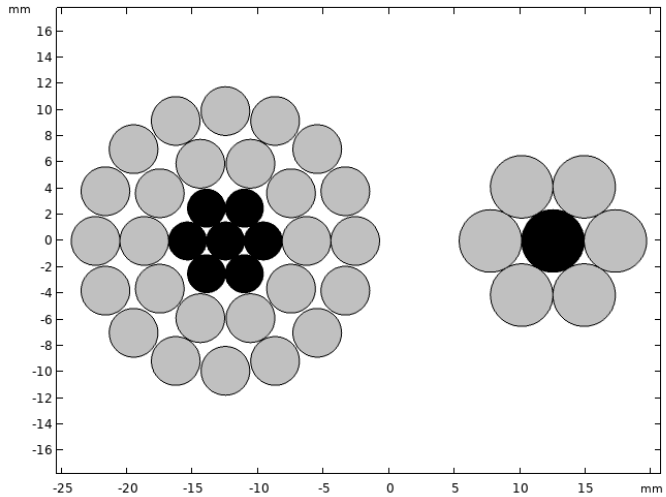

Figure 5: "Dove" cable (left) and "Penguin" cable (right)

Study Example: Transmission Line Shunt Admittance

This section details the shunt admittance study that was conducted. In addition to shunt admittance, series impedance was also studied.

The shunt admittance of a distribution line results from the capacitive coupling between phases and from the phases to ground. The effect is a displacement current that flows from phase to phase and from each phase to ground. For an actual distribution line, shunt current could be found by comparing current-sensor data at two separate points along the line. Since capacitance is a function of conductor spacing, a disturbance along that portion of the line - such as a tree branch striking one of the phases - would manifest as a sudden change in shunt current due to the geometric displacement of the conductors.

The first step towards analytically calculating three-phase shunt current was finding the phase capacitance matrix $\boldsymbol{C_P}$. The matrix $\boldsymbol{C_P}$ is a three-by-three matrix that, when multiplied by a three-by-one vector containing the voltage of each phase, yields the charge stored on each phase for a 1-meter length of cable.

$$q_P = \begin{bmatrix} q_a \\ q_b \\ q_c \end{bmatrix} = \mathbf{C_P} V_P = \begin{bmatrix} \mathrm{C_{aa}} & \mathrm{C_{ab}} & \mathrm{C_{ac}} \\ \mathrm{C_{ba}} & \mathrm{C_{bb}} & \mathrm{C_{bc}} \\ \mathrm{C_{ca}} & \mathrm{C_{cb}} & \mathrm{C_{cc}} \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \tag{5}$$

$\boldsymbol{C_P}$, was calculated by first replacing the earth plane with a set of below-ground image conductors. These image conductors are identical to the overhead conductors but are mirrored over the horizontal axis and carry an opposite charge [7].

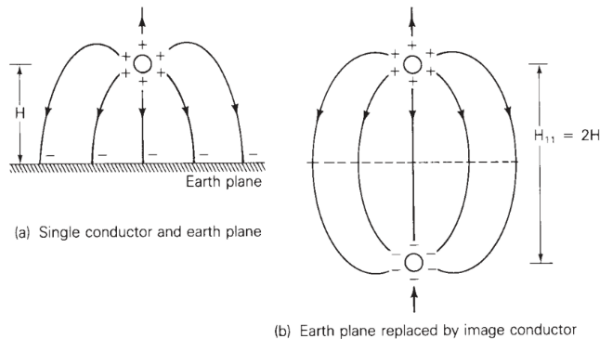

Figure 6: . Overhead Conductor and Below-Ground Image Conductor [7]

The next step was to calculate the primitive potential coefficient matrix (inverse of capacitance). This primitive matrix gave the relationship between the charge on each conductor (including N number of neutral conductors), and the voltage on each conductor.

$$\begin{bmatrix} V_{an}\\ V_{bn}\\ V_{cn}\\ \hline 0\\ \vdots\\ 0\end{bmatrix} = \left[\begin{array}{c|c} \overbrace{\begin{matrix} P_{aa} & P_{ab} & P_{ac}\\ P_{ba} & P_{bb} & P_{bc}\\ P_{ca} & P_{cb} & P_{cc}\end{matrix}}^{\mathbf{P}_A} & \overbrace{\begin{matrix} P_{an1} & \cdots & P_{anN}\\ P_{bn1} & \cdots & P_{bnN}\\ P_{cn1} & \cdots & P_{cnN}\end{matrix}}^{\mathbf{P}_B} \\ \hline \underbrace{\begin{matrix} P_{n1a} & P_{n1b} & P_{n1c}\\ \vdots & & \\ P_{nNa} & P_{nNb} & P_{nNc}\end{matrix}}_{\mathbf{P}_C} & \underbrace{\begin{matrix} P_{n1n1} & \cdots & P_{n1nN}\\ & & \\ P_{nNn1} & \cdots & P_{nNnN}\end{matrix}}_{\mathbf{P}_D}\end{array}\right] \begin{bmatrix} q_a\\ q_b\\ q_c\\ \hline q_{n1}\\ \vdots\\ q_{nN}\end{bmatrix} \tag{6}$$

The elements of this primitive matrix were given by the following equation, where D_{km} is either the distance between conductor *k* and conductor *m*, or the radius of conductor *k* when *k* equals *m*. H_{km} is the distance between conductor *k* and image *m*.

$$P_{km} = \frac{1}{2\pi\varepsilon} \ln \frac{H_{km}}{D_{km}} \tag{7}$$

Finally, the four submatrices, $\mathbf{P_A}$ through $\mathbf{P_D}$, were used to calculate the phase capacitance matrix $\mathbf{C_P}$, as shown below

$$\mathbf{C_P} = (\mathbf{P_A} - \mathbf{P_B}\mathbf{P_D^{-1}}\mathbf{P_C})^{-1} = \begin{bmatrix} 0.983 & -0.329 & 0.122\\ -0.329 & 10.391 & -0.208\\ -0.122 & -0.208 & 0.930\end{bmatrix} \times 10^{-9}\, F/m \tag{8}$$

Since current is the time-derivative of charge, the shunt admittance matrix $\mathbf{Y_P}$ was calculated by multiplying $\mathbf{C_P}$ by $j\omega$

$$\mathbf{Y_P} = j\omega\mathbf{C_P} = \begin{bmatrix} j3.706 & -j1.241 & -j0.461\\ -j1.241 & j3.917 & -j0.783\\ -j0.461 & -j0.783 & j3.506\end{bmatrix} \times 10^{-7}\, S/m \tag{9}$$

The shunt current I_s was then calculated by multiplying the admittance matrix by the phase voltage vector, as shown below. These calculations assume a nominal balanced phase voltage of $7.2\text{kV}_{\text{RMS}}$.

$$I_s = \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = \mathbf{Y}V_p = \begin{bmatrix} \mathrm{Y_{aa}} & \mathrm{Y_{ab}} & \mathrm{Y_{ac}} \\ \mathrm{Y_{ab}} & \mathrm{Y_{bb}} & \mathrm{Y_{bc}} \\ \mathrm{Y_{ac}} & \mathrm{Y_{bc}} & \mathrm{Y_{cc}} \end{bmatrix} \begin{bmatrix} 7.2 \\ 7.2e^{-j2\pi/3} \\ 7.2e^{j2\pi/3} \end{bmatrix} kV \tag{10}$$

To compute these results in COMSOL, the Electric Currents physics interface was used. This model configuration is illustrated and described below.

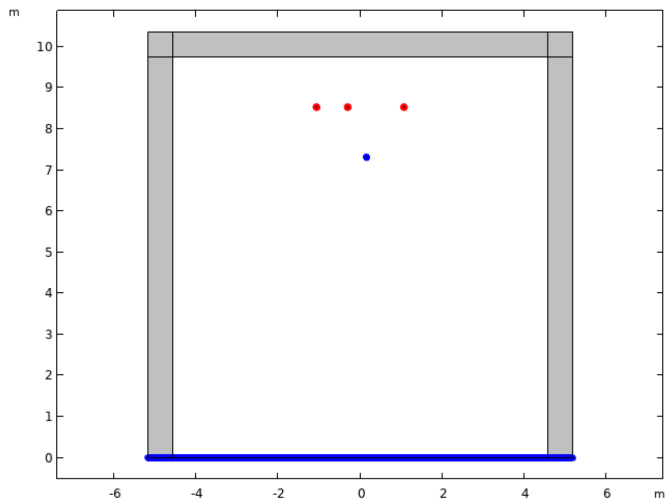

Figure 7: COMSOL Model Configuration for Shunt Current Calculation

Each phase conductor, shown in red, was set as a terminal with its prescribed phase voltage. The neutral conductor is grounded, as was the lower boundary of the modeling domain representing earth. The grounded boundaries are shown in blue. The left, right, and top outer boundaries were extended out to infinity. To do this, an infinite element domain is used, shown in gray.

The results of both the analytical and COMSOL calculations are shown in the table below.

	Analytical Results (μA/m)	COMSOL Results (μA/m)
I_a	$-4.862 + j32.809$	$-4.812 + j32.648$
I_b	$29.308 - j20.218$	$29.156 - j20.095$
I_c	$-26.745 - j13.123$	$-26.624 - 13.077$

The COMSOL results match the analytical results to roughly the second significant digit. This indicates that the COMSOL model was valid for calculating shunt current.

The final step to test the validity of the solutions was to calculate the power consumed by the three-phase line due to the shunt current. This is equal to the sum of each phase voltage times its corresponding shunt current. The total real power consumed should be zero since the shunt current is due exclusively to capacitive effects.

	Analytical Results (mVA/m)	COMSOL Results (mVA/m)
S_a	$-35.01 - j236.22$	$-34.65 - j235.07$

S_b	$20.55 - j255.53$	$20.34 - j254.14$
S_c	$14.45 - j214.01$	$14.31 - j213.09$
S_{total}	$\mathbf{0.00 - j705.77}$	$\mathbf{0.00 - j702.30}$

The total real power consumed by the line was zero watts per meter for both the analytical results and the COMSOL results, as expected. Additionally, the total complex power consumed due to shunt current for the analytical and COMSOL results matched one another to roughly the second significant digit. This further indicated that the COMSOL model is sufficiently accurate for calculating shunt current.

Plan Going Forward

Due to the COVID pandemic, it was not possible to use COMSOL Multiphysics during current semester. Many students took classes virtually and the licenses are only good for on-campus work. However, this will change in the very near future. The electromagnetics course will run again in the Summer 2021 semester and the school's supercomputing center can help out with using the software remotely. The COMSOL modules that were developed will be part of the course and the design project will also be a major focus of the course.

There will also be new undergraduate research opportunities to use COMSOL Multiphysics to model several pieces of equipment in the University of Pittsburgh's power systems laboratory. This would include modelling battery energy storage systems and out renewable energy systems.

Lastly, students will use COMSOL Multiphysics in both the semiconductor device theory class and the applications of fields and waves class in the fall. Students will use the software to solidify their knowledge and visualize some of the abstract phenomena which are not possible to see.

The faculty involved will collect data on all three courses and use that data in the continuous improvement process for the courses.

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