Electric Power Systems Education for Multidisciplinary Engineering Students

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New challenges associated with power and energy and a rapidly retiring workforce have created a great demand for power and energy engineers from across engineering disciplines. Within this context, the Power and Energy Institute of Kentucky, a multidisciplinary engineering institute offering certificates in power and energy at the University of Kentucky has been created. A motivating observation guiding this educational program is that exposure to multidisciplinary ideas within the power and energy field will better prepare engineers from all disciplines for the types of multidisciplinary problems that they will encounter in their careers. As part of this program, a senior-/graduate-level course in electric power system fundamentals was created. This course is a core course within the power and energy program and is an option for undergraduate students and a requirement for graduate students studying within the program, including those who are not electrical engineers. Therefore, this course is intended for engineering students studying electrical engineering as well as those studying in other engineering disciplines. The fundamental challenge associated with this course is how to achieve the correct balance between sufficient technical rigor for an upper-level electrical engineering student and appropriate level for students with little electrical engineering coursework, a challenge that is significantly different than those experienced in teaching lower-level engineering courses to students in different disciplines. The ways in which this challenge has shaped course outcomes, prerequisites, textbook selection, and course structure are presented. Course assessment data (including exam-based assessment of outcomes and student self-assessment) as well as anecdotal evidence of how well this challenge is being met are discussed and analyzed. In particular, the performance of electrical engineering students and students from other engineering disciplines is compared for the various course outcomes. Lessons learned from offering this course are presented.

I. Introduction

New challenges associated with power and energy and a rapidly retiring workforce have created a great demand for power and energy engineers from across engineering disciplines. In 2010, the Power and Energy Institute of Kentucky (PEIK) was established with funding from the Department of Energy to respond to these challenges. A motivating observation guiding this program is that exposure to multidisciplinary ideas within the power and energy field will better prepare engineers from all disciplines for the types of multidisciplinary problems that they will encounter in their careers.

PEIK is a multidisciplinary engineering educational institute offering certificates in power and energy at both the undergraduate and graduate levels. As part of both certificate programs, students are required to take coursework from a set of core courses. These courses include public policy and economics, electric power generation, and electric power system fundamentals. These courses are intended to provide students with a broad view of the relevant issues in power and energy. Students pursuing the undergraduate certificate in power and energy are required to select one of the three core courses, but students pursuing the graduate certificate are required to complete all three. The electric power system fundamentals course is discussed herein. The electric power system fundamentals course is largely focused on electrical engineering, but it is a required course for students from other engineering disciplines seeking the graduate certificate in...
power and energy. This creates the fundamental challenge associated with this course: how to achieve the correct balance between sufficient technical rigor for an upper-level electrical engineering student and appropriate level for students with little electrical engineering coursework. This challenge is significantly different than those experienced in teaching lower-level engineering courses to students in different disciplines. In particular, in lower-level engineering courses, the material is at a low enough level that students from different engineering disciplines each have approximately the same prerequisite knowledge.

Herein, the ways in which this challenge has shaped course outcomes, prerequisites, textbook selection, and course structure are presented. Course assessment data (including student self-assessment and exam-based assessment of outcomes) as well as anecdotal observations of how well this challenge is being met are discussed and analyzed. Lessons learned from offering this course are presented.

II. Course Design

The primary challenge associated with the design of this course was finding the correct balance between technical rigor (it is a senior-/graduate-level course) and accessibility to students that are not studying electrical engineering. This challenge has been the primary driver for many decisions related to the design of the course as related below.

A. Course Content and Outcomes

The course is intended to cover the wide breadth of the electric power systems area; it is the only course in electric power systems that some of the students will ever take. However, it is not intended to be a survey course in which many topics are described in very little detail. Therefore, the course is focused on providing sufficient detail for students to be able to work problems, while sacrificing depth on advanced topics. For example, transmission line modeling, including short-, medium-, and long-line representations, is covered, but not the electromagnetic calculations associated with determining distributed line parameters. In practice, most transmission line parameters are calculated using commercial power system software, and this was judged to be an acceptable sacrifice. Similarly, the nonlinear equations that describe the power flow problem are derived and explained, and some small examples in which hand calculation is possible are solved. However, numerical techniques for solving such systems of nonlinear equations (e.g., Gauss-Seidel and Newton-Raphson methods) are omitted. Again, most power flow calculations are performed in commercial power system software. A summary of topics covered and omitted in this course is presented in Table I. This strategy results in a significant overlap with other upper-level power systems courses offered at the University of Kentucky. In particular, the authors estimate that approximately 70% of the content of two other courses is covered in the PEIK electric power system fundamentals course. The other two courses cover many of the advanced topics that are omitted, but the students in the fundamentals course have working knowledge of the main topic areas. This is part of an intended curricular realignment in which the basic ideas are moved into this course and more advance ideas are covered in a subsequent course. Presently, the main power systems courses are taught independently without any prerequisite relationship. Structured in this way, this course can serve as an entry point to other more advanced power systems coursework in the eventual realignment.
Table I. Summary of topics covered and omitted.

<table>
<thead>
<tr>
<th>Topics covered</th>
<th>Topics omitted</th>
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<tbody>
<tr>
<td>Three-phase power fundamentals</td>
<td>Transmission line parameter calculation</td>
</tr>
<tr>
<td>Transformers</td>
<td>Transmission line transient operation</td>
</tr>
<tr>
<td>Per-unit representation</td>
<td>Node elimination</td>
</tr>
<tr>
<td>Transmission line steady-state operation</td>
<td>Power flow solutions</td>
</tr>
<tr>
<td>Power flow problem and formulation</td>
<td></td>
</tr>
<tr>
<td>Symmetrical faults</td>
<td></td>
</tr>
<tr>
<td>Symmetrical components</td>
<td></td>
</tr>
<tr>
<td>Unsymmetrical faults</td>
<td></td>
</tr>
<tr>
<td>System protection</td>
<td></td>
</tr>
<tr>
<td>Power system controls</td>
<td></td>
</tr>
<tr>
<td>Transient stability</td>
<td></td>
</tr>
</tbody>
</table>

In order to make the course accessible to nonelectrical engineering students, phasors, complex power, and three-phase power are reviewed during the first couple of sessions. This is probably valuable to the electrical engineering students as well. Transformers are taught next, followed by transmission lines. The power flow problem is discussed next. Then the course shifts towards fault analysis. Balanced, three-phase faults, the method of symmetrical components, and unbalanced faults are taught. System protection is covered next. Afterwards, load-frequency control and economic dispatch are presented. A section on modern trends in power systems is driven by the graduate students in the course. Finally, transient stability using the swing equation is presented.

The course learning outcomes are as follows. A student who has successfully completed this course should be able to:

1. Perform basic calculations associated with the steady-state operation of balanced three-phase circuits.
2. Solve problems involving the basic principles of transformers, transmission lines, and the power-flow problem.
3. Perform basic fault analysis and have some knowledge of system protection.
4. Solve basic problems involving power system control, including economic dispatch, and power system stability.
5. Describe modern trends, including distributed generation and smart grid applications.

B. Prerequisites

Determining appropriate prerequisites for this course was challenging. Electrical engineering students have required coursework in circuits that covers topics like phasors, complex power, transformers, and polyphase power. They have also been required to take a course in electromechanical energy conversion that reviews these topics. Electrical engineering students in this course should be very comfortable with these topics. On the other hand, students from other engineering disciplines are only required to take a service course in electrical circuits for nonelectrical engineers. This course covers some of these topics, but not in the same detail as the courses for electrical engineers. Civil engineering students are not even required to take the
service course in electrical circuits. Their only exposure to these topics is in their physics courses.

Ultimately, it was decided that graduate or engineering (upper-level) standing and the electrical engineering circuits sequence, the electrical circuits service course, or the equivalent was a suitable prerequisite requirement. This requirement includes the tacit assumption that students that are unfamiliar with circuits will need to spend additional time to develop their competency in these areas.

C. Textbook Selection

For an upper-level power systems course, a textbook like that of Grainger and Stevenson\cite{7} might be selected. However, because of the need to make the course accessible to nonelectrical engineering students, the textbook of Glover, Sarma, and Overbye\cite{8} was selected. This textbook is self-contained in that all of the preliminary material on phasors, complex power, and three-phase power are described. This is an advantage in such a course. It allows electrical engineering students to review this material, but more importantly, it allows the nonelectrical engineering students to learn the material. The textbook of Grainger and Stevenson is used in other courses at the University of Kentucky, and it is recommended as supplemental material in the fundamentals course. However, the use of a self-contained text for the course for those without an electrical engineering background has been beneficial.

Another advantage of the textbook is its incorporation of the PowerWorld solver into examples and problems. The PowerWorld solver is an excellent pedagogical tool. It allows students to examine more complex systems that cannot be addressed by hand. It is only available for Microsoft Windows. In order to ensure that students can use the student version to solve problems, students are permitted to work in groups.

D. Assignments

Homework assignments are given each week. These assignments allow the students to practice using the concepts discussed in class. The homework assignments are weighted more heavily than might be typical in a higher level course, but they do serve to keep students engaged in the material. This also serves to deemphasize exams slightly, which is advantageous to the nonelectrical engineering students in the class.

Previously, homework assignments and quizzes were alternated weekly. The quizzes were replaced with only homework assignments when the course enrollment became too large to manage the quizzes efficiently every second week. This was largely due to the size of the classroom, the number of quizzes to be distributed, and the amount of class time this takes. It is possible that this could be improved through alternative methods of quiz administration (e.g., online quizzes), but student feedback on a homework-only system in teacher/course evaluations has been unanimously positive.

E. Exams

There are three exams during the semester and a final exam. The exams focus on the learning outcomes described above. Student note sheets are permitted during the exams; this serves to
help the nonelectrical engineering students in the course. In particular, they are not penalized for not having memorized certain concepts that electrical engineering students would have already memorized. Instead the exams focus on the course material. While it is always valuable to make exam expectations clear, in this course, doing so makes the exam preparation less daunting for nonelectrical students. They can focus their attention and are more likely to meet the instructor’s expectations. This also limits any potential for a performance gap due to nonelectrical engineers being less able to approach less familiar problems outside of their disciplines.

It has been observed that nonelectrical engineering students tend not to fare as well as electrical engineering students on the first exam, but they continually improve through the course of the semester as the topics become more familiar to them and the course moves beyond the material with which the electrical engineering students are already familiar.

F. Presentations

The graduate students in the course are required to select a recent research paper on power systems, read it, critique it, and make a presentation. This presentation is intended to provide an overview of the main contribution of the paper as well as a critique of the paper. Summarizing the research of others, critiquing this research, and presenting clearly are important skills for graduate researchers. Many of the graduate students in the course are in their first semester of graduate study, and this exercise provides important practice for them. Likewise, these presentations allow many modern topics in power systems research to be introduced to the students in the class and discussed.

Originally, each student presented during class time. However, the graduate enrollment in the course reached a point at which this was no longer feasible. Instead, a day-long event is organized in which all of the graduate students present to the instructor, other graduate students, and any undergraduate students that attend. The instructor selects several of the presentations based on quality and coverage of topics to be presented during class time. This has allowed for higher quality presentations during class time and more extensive discussion in class.

III. Experience and Lessons Learned

The electric power system fundamentals course has been offered each fall semester since 2010. For the purposes of the discussion that follows, students studying computer engineering within the electrical and computer engineering are not distinguished from electrical engineering students. Students from biosystems and agricultural engineering, civil engineering, manufacturing systems engineering, materials science and engineering, mechanical engineering, mining engineering, and public policy and administration have taken the course. The enrollment levels for the course are shown in Figure 1. It can be seen that the majority of the students that take the course (86%) are electrical engineering students. Most of the nonelectrical engineering students are graduate students, but there have been two undergraduate students in the course. There has been consistent growth in the course (including in the numbers of nonelectrical engineering students). Tuition scholarships have been offered in the past to allow students to pursue the graduate certificate, which requires this course. The composition of graduate student enrollment has been externally influenced by the distribution of these scholarships among the engineering disciplines. The decline in nonelectrical engineering enrollment in 2013 is due to the
number of power and energy scholarships that were awarded to nonelectrical engineering students in that year. However, a number of nonelectrical engineering students are beginning to take the course for reasons other than as a requirement of their scholarships.

![Historical course enrollment](image)

The students assess their achievement (between 1 and 5) with respect to the course learning outcomes via the teacher/course evaluations each semester. The text from the teacher/course evaluation is shown in Table II. The results of this student self-assessment are shown in Figure 2. It can be seen that these assessments are fairly flat, but some trends can be observed. Initially, some of the course outcomes that are treated later in the semester had worse assessments than those treated earlier. As experience was gained offering the course, the treatment of these outcomes resulted in increased student self-assessment of their mastery of these outcomes. In particular, the fifth outcome, which has to do with understanding modern trends in power systems, has improved with each offering of the course until 2013. In 2013, the treatment of the fifth outcome in a fewer number of in-class presentations seems to have reduced the students’ confidence in their ability to understand modern power system trends. This decline is not noted in the exam-based assessment of outcomes presented below. Unfortunately, the teacher/course evaluations do not allow the data to be differentiated by student major.

### Table II. Teacher/course evaluation text.

<table>
<thead>
<tr>
<th>Course Outcomes</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
<th>2013</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ability to perform basic calculations associated with the steady-state operation of balanced three-phase circuits.</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Ability to understand the basic principles of transformers, transmission lines, and the power-flow problem.</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Ability to perform basic fault analysis and have some knowledge of system protection.</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Ability to know the basics of power system control, including economic dispatch, and have a basic understanding of power system stability.</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
</tbody>
</table>
• Ability to understand modern trends, including distributed generation and smart grid applications.

Figure 2. Student self-assessment of course outcomes. The numbers of students responding in each year are 16 in 2010, 24 in 2011, 27 in 2012, and 47 in 2013.

The instructor of the course is also responsible for assessing student performance with respect to the course outcomes. This measure is constructed by averaging the scores on exam questions related to each of the course outcomes. Example questions related to each outcome are presented in Table III. The results of exam-based assessment of course outcomes are shown in Figure 3. It can be seen that there is considerable variability from one year to the next in terms of student performance. Also, there are some discrepancies between the student and exam-based assessments. For example, it seems that students generally consider themselves to be better with the first objective, which involves basic calculations with three-phase circuits, than the instructor finds them to be during the exams. Also, the dip in student confidence with modern power system trends observed in 2013 in Figure 2 and attributed above to a change in student presentation format was not observed by the instructor in student exam performance. The exam-based assessment results for only the graduate students are shown in Figure 4. It is possible to consider the nonelectrical engineering students separately with the exam-based assessments. The exam-based assessment results for only the nonelectrical engineering students are shown in Figure 5. It can be seen that similar trends exist. In order to compare the performance of the nonelectrical engineers with their peers, the values in Figure 5 are normalized by the values in Figure 3 and presented in Figure 6. In this figure, it can be seen that there are certain outcomes in which the nonelectrical engineering students perform better than the electrical engineering students. This is likely due to the fact that almost all of the nonelectrical engineering students are graduate students. The graduate students in the course generally tend to outperform the undergraduate students in the course. In order to compare the nonelectrical engineering students with the graduate students in the course, the values in Figure 5 are normalized by the values in Figure 4 and presented in Figure 7. Interestingly, the set of outcomes in which the nonelectrical engineering students perform better than the class as a whole varies each year. However, they generally seem to do relatively better with outcomes that are covered later in the semester.
Table III. Sample exam questions to assess course outcomes.

<table>
<thead>
<tr>
<th>Outcome</th>
<th>Sample question</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>Two balanced three-phase loads are connected in parallel. They are supplied by a 240-V source. The first draws 12 kW at a 0.95 lagging power factor. The second draws 8 kW at a 0.9 leading power factor. (a) Calculate the complex power provided by the source. (b) Calculate the a-phase source current assuming the phase of the a-phase line-to-neutral voltage is zero.</td>
</tr>
<tr>
<td>2</td>
<td>A 64-mile (medium length), three-phase line has a distributed series impedance of $z = 0.06 + j0.36 \Omega/\text{mile}$ and a distributed shunt admittance of $y = j1.2 \times 10^{-5} \text{S/\text{mile}}$. (a) Calculate the A and B parameters of the ABCD matrix. A load at the receiving end draws 100 MVA at 0.9 lagging when the receiving end voltage is 115 kV. (b) Calculate the sending-end line-to-line voltage magnitude.</td>
</tr>
<tr>
<td>3</td>
<td>A system has sequence networks with the Thévenin equivalent circuits shown below at the location of a fault, where $Z_0 = j0 \text{pu}$, $Z_1 = j0.15 \text{pu}$, $Z_2 = j0.2 \text{pu}$, and $\tilde{V}_F = 1.05 \angle 0 \text{pu}$. Calculate the sequence components $\tilde{I}_0$, $\tilde{I}_1$, and $\tilde{I}_2$ for a bolted line-to-line fault in this location.</td>
</tr>
<tr>
<td>4</td>
<td>The generator in the figure is operating in steady state, with $p_m = p_e = 1 \text{pu}$ and $\delta_0 = 20^\circ$. A three-phase fault occurs at point F, faulting bus 1. Calculate the critical clearing angle $\delta_{cr}$ for breakers B1 and B2 so that the power angle does not exceed the maximum value $\delta_3 = 156.7566^\circ$. Place a box around the answer.</td>
</tr>
<tr>
<td>5</td>
<td>Describe a current research trend that was described in class presentations. Discuss why it is important and what you learned.</td>
</tr>
</tbody>
</table>
Figure 3. Exam-based assessment of course outcomes. The number of students assessed in each year are 21 in 2010, 28 in 2011, 38 in 2012, and 58 in 2013.

Figure 4. Exam-based assessment of course outcomes for graduate students. The number of graduate students assessed in each year are 15 in 2010, 19 in 2011, 21 in 2012, and 18 in 2013.
Figure 5. Exam-based assessment of course outcomes for nonelectrical engineering students. The number of nonelectrical engineering students assessed in each year are 3 in 2010, 6 in 2011, 7 in 2012, and 5 in 2013.

Figure 6. Normalized exam-based assessment of course outcomes for nonelectrical engineering students. The number of nonelectrical engineering students assessed in each year are 3 in 2010, 6 in 2011, 7 in 2012, and 5 in 2013. The number of students assessed in each year are 21 in 2010, 28 in 2011, 38 in 2012, and 58 in 2013.
There are some lessons that can be learned from the experience offering this course. One subject that needs to be carefully evaluated is the position of such a course within the electric power systems curriculum. The course presently overlaps heavily with other power systems courses. It is possible that this overlap could be exploited to streamline the power curriculum and make better use of instructional resource, but this issue was not considered when the course was developed. On the other hand, the requirement for the course to be accessible to students from other engineering disciplines was carefully considered. This allowed the course to be structured to facilitate this requirement. For the electric power system fundamentals course, this requirement has shaped course outcomes, prerequisites, textbook selection, and course structure, and the requirement has been met. Students regularly comment on their teacher/course evaluations that they never felt like they could do so well in an electrical engineering course. This success is largely due to the ways in which the requirement was addressed in the development of the course and will likely improve the capabilities of these engineers to address the power and energy challenges of the future.


