

# Physics Education Research in an Engineering Context

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**Abstract.** We report on an ongoing investigation of student understanding in several introductory engineering courses at Hamburg University of Technology. Preliminary results from a first-year electrical engineering course indicate that many students did not gain a conceptual understanding of the material. Some students had difficulty interpreting graphical representations of information or displayed a lack of understanding of basic principles. Specific examples concerning load lines and three-phase systems are used to illustrate how general findings from physics education research can guide investigations of student understanding and the development of curriculum in an introductory engineering context.

**Keywords:** Physics education research, engineering, electric circuits, load lines, three-phase systems.

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## INTRODUCTION

In recent decades, Physics Education Research (PER) has helped identify many student difficulties with specific concepts in introductory physics. Results from many individual studies that focus on specific topics combine to support a number of general conclusions about the teaching and learning of physics that by now are widely accepted [1].

Many introductory engineering courses cover topics in which basic principles from physics are applied or extended. It therefore seems plausible that methods from physics education research could be successfully applied to investigate student understanding in introductory engineering.

At Hamburg University of Technology (TUHH), we have begun to follow this approach in several engineering disciplines. In this paper, we report on our study and illustrate how many of our findings are in good agreement with various general results from physics education research.

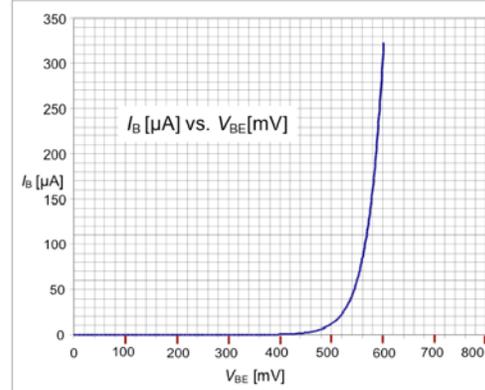
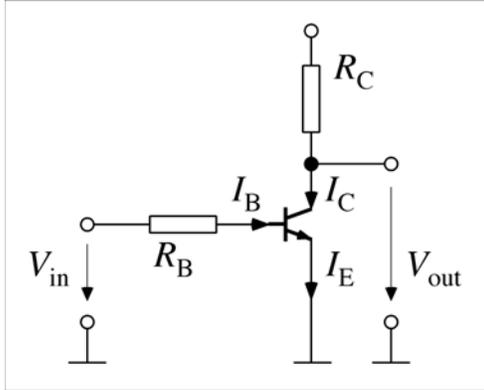
## ENGINEERING CONTEXT

So far, our work has mostly focused on two courses: *Fundamentals of Electrical Engineering*, which covers circuits and fields, and *Engineering Thermodynamics*, which covers the laws of thermodynamics and their applications in industrial processes. More recently we have also turned our

attention to a three-semester course in *Engineering Mechanics* that includes topics from *Statics*, *Mechanics of Materials*, and *Dynamics*. For the purpose of this paper, we focus on work done in the context of the electrical engineering (EE) course. Below, we briefly describe this course and then present some sample tasks used to probe student understanding.

## Description of EE Course

*Fundamentals of Electrical Engineering* is a two-semester course taken by general and electrical engineering majors. In the first semester, it covers DC circuits, static electric fields and stationary currents, and magnetic fields and induction. Since *Physics* is only a co-requisite for this course (and for these students does not include electricity and magnetism) instruction for all three topics begins at a level comparable to a typical calculus-based introductory physics course but includes methods and examples usually not seen in the context of physics (such as Thevenin's and Norton's theorems, and the concept of a magnetic circuit). In the second semester, the course covers AC circuits as well as nonlinear and active circuit elements. While building on basic concepts that are taught early in the first semester, coverage extends substantially beyond typical physics content, including such topics as three-phase systems, transistor circuits, and operational amplifiers (op amps).



**FIGURE 1.** Circuit diagram and base-current characteristic included in the examination problem on transistor circuits.

The course has an enrolment of about 150 students and follows a format that is frequently found at German engineering institutions. Three hours of lectures each week are supplemented by two hours of small-group recitation sections. Although the audience includes a considerable number of foreign students, the language of instruction (and of all the questions posed as part of this study) is German. Examinations take place during lecture-free time periods at the end of each semester. Since students who do not pass may re-take the exam two more times after subsequent semesters, the cohort of students taking a particular exam may include students who attended classes one or two years earlier. This situation severely limits the changes that can be made to the course at one time. Moreover, it complicates the task of determining whether a particular modification to the course has had any effect on student learning.

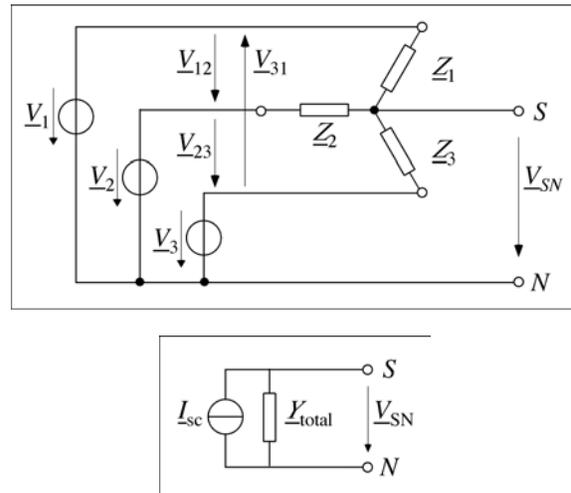
### Tasks for Probing Student Understanding

To probe student conceptual understanding, we use non-graded quizzes, examination tasks (including standard quantitative problems and qualitative questions) and multiple-choice questions asked during lecture (“clicker questions”). Below we describe two sample examination questions from the second semester of *Fundamentals of Electrical Engineering* and briefly outline a solution in each case.

#### *Sample examination questions from second-semester electrical engineering course*

One of the questions presented students with a circuit diagram for a simple transistor circuit and a graph of the base-current characteristic ( $I_B$  vs.  $V_{BE}$ ) as shown in Fig. 1. Among other tasks, students were asked to determine graphically the operating point of the transistor. This task required them to use the circuit data in the problem to draw a load line and then

find its intersection with the given characteristic curve. The load line, which is a graphical representation of the current-voltage relationship in the base-emitter junction imposed by the circuit external to the transistor, can be found by applying Kirchhoff’s voltage law (and Ohm’s law for  $R_B$ ). Although there is an algorithm that can be used, a conceptual understanding of simple DC circuits is helpful to arrive at the answer.



**FIGURE 2.** Circuit diagram for three-phase network and blueprint for Norton equivalent as given in the problem.

Another question that we used in our study concerned the three-phase circuit shown in Fig. 2. The three impedances ( $Z_1$ ,  $Z_2$ ,  $Z_3$ ) were of equal magnitude but different phase angle (i.e., one was purely resistive while the others had inductive or capacitive parts). Students were first asked to draw the phasors (vectors in the complex plane used to represent sinusoidally time-dependent quantities) for the three source voltages ( $V_1$ ,  $V_2$ ,  $V_3$ ) in a diagram containing the line voltages ( $V_{12}$ ,  $V_{23}$ ,  $V_{31}$ ). Next, the Thevenin and

Norton equivalents were to be found (i.e., the total impedance or admittance, the short-circuit current, and the open-circuit voltage needed to be determined for a given set of terminals). Finally, students were asked if the currents through the three load impedances would change if the terminals  $SN$  were short-circuited.

A correct answer required students to perform the following steps: draw three phasors at  $120^\circ$  angles that would correctly combine to form the given line voltages ( $\underline{V}_{12} = \underline{V}_1 - \underline{V}_2$ ), combine impedances in parallel, graphically or algebraically add (complex) currents, and apply the AC equivalent of Ohm's law. To answer the final task, students did not have to use any of their answers to the preceding parts. Instead, they only needed to recognize that the three load impedances are not identical, and that as a result their currents would not add to zero if  $SN$  were short-circuited.

## RESULTS

Many of the patterns of reasoning and student difficulties that we have observed in these courses so far mirror well established results in PER. Similarly, common strategies for helping students overcome typical difficulties in physics seem to have a good chance at being successful in engineering as well.

### General Findings from *PER* Relevant to Engineering Contexts

Research in physics education has led to a number of general conclusions about student understanding for which evidence can be found in student responses to questions from various areas of physics. While these generalizations are now common knowledge in physics education (and are therefore stated here without reference to specific sources), it is interesting to note that many of them seem to be valid for introductory engineering as well. Moreover, these ideas seem to have affected instruction in engineering to a much lesser degree than in physics.

#### *Failure To Form Conceptual Models*

When the examination question on the transistor circuit in Fig. 1 was first administered to about 150 students, about 60% of them did not even attempt to draw a load line (and, in most cases, then failed to answer any of the subsequent parts of this question). On a similar question given after modified instruction in the following year, about 10% of the students drew "load lines" with a positive slope. We interpret this as resulting from the students' failure to develop a qualitative understanding of the relationship

represented by the load line, such as "Increased load current results in greater voltage drop across internal resistance, thus leading to smaller terminal voltage."

This conceptual model had not been very strongly emphasized in the course. After deriving the load line equation and pointing out the relevance of the open-circuit voltage and short-circuit current, the lecturer presented three examples in some detail but did not make any additional effort to help students develop the kind of qualitative understanding stipulated above. The results suggest, however, that for many students this development is unlikely to happen spontaneously.

#### *Difficulty Interpreting and Applying Graphical Representations of Information*

In their responses to the examination question on the three-phase circuit in Fig. 2 about 15% of the students drew circuit symbols for sources or loads on their arrows in the phasor diagram. This observation suggests that a number of students in the course still fail to distinguish between two different (but frequently used) graphical representations at the time of the final exam. Moreover, virtually none of the students (less than 2%) attempted a graphical solution for finding the total admittance or the short circuit current. Students also did not use diagrams to plan or check their algebraic solutions.

As has been shown in various contexts in physics, students often have difficulty interpreting graphical representations of information. Students tend to avoid graphical means of solving problems even when these may be simpler or faster than alternative methods. Finally, relating graphical and algebraic representations of the same information to each other (as would be necessary in order to use one method for checking a solution obtained by the other) seems to present a particular challenge to many students.

#### *Lack of Understanding of Basic Ideas and Principles*

About 15% of the students taking the examination that included the three-phase circuit question arrived at incorrect results for the total admittance of the circuit due to difficulties with basic ideas in circuit analysis. These included confusion between series and parallel connections, a failure to distinguish between impedance and its inverse (admittance), and incorrect application of Ohm's law. Another 10% of the students inappropriately added the three source voltages (which always add to zero due to their phase relationship) and then concluded that the short-circuit current would be zero. It is likely that these students had not yet mastered the distinction between current and voltage, which would include an understanding of when either type of quantity can be added.

While this result, like the others above, will not be surprising to physics education researchers, it does not seem to be widely recognized in the engineering disciplines that many student difficulties with more advanced topics (and engineering applications) often have their roots in a lack of understanding of basic ideas and principles.

*Conceptual Difficulties  
Associated with Vector Quantities*

In their responses to the last part of the three-phase circuit question, a number of students claimed that the currents would not change since the “impedances are symmetric except for their phase angles.” Apparently, these students had difficulty recognizing that vector quantities of the same magnitude but different direction are not equal. It is interesting to note that similar difficulties have been observed in the context of vector quantities in mechanics (e.g., velocity and momentum). More generally, we conclude that when using vector quantities in engineering contexts, students are likely to encounter the same difficulties as in introductory physics.

### **Use of *PER*-based Strategies for Instructional Materials in Engineering**

For more than a decade, results of physics education research have strongly affected curriculum development in physics. While there exists now a variety of research-based materials, many of these use, implicitly or explicitly, similar instructional strategies. Below, we illustrate how we have used some of these in designing collaborative-group worksheets for *Fundamentals of Electrical Engineering*.

*“Making Qualitative Predictions  
before Carrying Out Calculations”*

In an activity on load lines, we ask students to consider a non-ideal voltage source that can be connected to different loads. Before calculating specific values, students predict the general shape of the graph of  $I_{\text{load}}$  vs.  $V_{\text{terminal}}$ . Later, students predict how the load line would change if the source voltage were increased or the internal resistance decreased.

*“Relating Graphical, Verbal, and Algebraic  
Representations of the Same Relationships”*

After drawing a load line for the given circuit, students are asked to interpret the  $I$ - and  $V$ -axis intercepts of the graph (beyond stating the terms “short-circuit current” and “open-circuit voltage”).

They are also asked to spell out the general circuit law that is expressed in the equation of the load line.

*“Relating Different Ways of Reasoning  
to Obtain the Same Answer”*

In an activity on three-phase systems, students consider Y- and  $\Delta$ -connected loads made up of identical resistances. After finding the magnitudes and phases of the various voltages and currents, students are asked to compare the power dissipated in the two configurations. Subsequent questions help students recognize that this question can be answered by considering either the source or the load side of the circuit.

### **Preliminary Assessment of Instructional Strategies**

Responses to two different examination questions on transistor circuits that were given after the activities had been implemented indicate that these strategies can help improve student learning. While the fraction of blank responses decreased from about 60% to below 20%, there was a corresponding increase of correct answers from below 30% to about 55%. There is evidence that the frequency of some typical errors was also reduced. After the second iteration of the load-line worksheet, only 2 out of about 150 students drew a line that had a positive slope.

## **CONCLUSIONS**

Preliminary results from our study of student learning in introductory engineering courses indicate that methods from physics education research can be successfully applied to probe student understanding in these courses. Furthermore, our results suggest that research-based strategies for instruction in physics also have some merit for teaching introductory engineering.

## **ACKNOWLEDGMENTS**

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