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A Proven Different Approach to Teaching Linear Circuits

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Abstract

At the University of Denver we have taught circuits for eighteen years to electrical (EE), mechanical (ME) and computer engineering (CpE) sophomores using a considerably different approach. Our course covers most of the traditional topics but with different emphasis and organization. We introduce design and evaluation right from the beginning with students designing circuits to meet constraints within the first several lessons. We introduce the operational amplifier as another linear circuit element early and fully integrate it throughout the course. DC circuits are designed using voltage and current dividers to deliver specified currents, voltages or power; interface circuits are designed when neither the source circuit nor the load circuit is alterable; and instrumentation systems are created to interface transducers to a particular output device. A major departure from most circuits courses occurs in our approach to dynamic circuits. We begin by introducing a separate block on signal waveforms including singularity functions, exponentials, sinusoids and their combinations. This better prepares the student for finding solutions of first- and second-order circuits using the classical differential equation approach. The most significant departure from tradition occurs when Laplace transforms are introduced immediately after the classical treatment of circuit differential equations. This arrangement allows the concepts of sinusoidal steady-state response, network functions, frequency responses, impulse response, step responses, and convolution to be treated within a common framework. We have found that beginning students achieve a real understanding of transient and steady-state responses more rapidly by this method than the classical phasor-first approach. The Laplace transform early approach actually saves classroom time because students quickly master classical phasor analysis when it is presented as a logical outgrowth of an overall theme. We spend a block of time on mastering how to design circuits to achieve a desired transfer function. Since there are often several competing solutions, learning how to choose between the various solutions depending on different constraints is another key feature of our course. Finally, we spend a block of time designing both active and passive filters (Butterworth, Chebyshev, First-order Cascade) – real applications. Students learn how to select the best filter type based on various real scenarios. Computer simulations and an accompanying lab add additional realism to the course. In sum students become highly motivated because they know how to actually design circuits. The emphasis on design and Laplace transforms prepares them well for Electronics, Signals and Systems, Controls and Instrumentation courses. This approach has been successfully applied to the circuits courses taught at the USAF Academy.

Introduction

Linear circuits are ubiquitously taught to all electrical and computer engineers. It is also often a required course for numerous other engineering disciplines, mechanical and bio engineers most notably. Although there are numerous variants to how circuits are currently taught the most common approach is to teach linear circuits by beginning with dc circuits, introduce circuit theorems, then possibly teach dependent sources and the operational amplifier, introduce inductors and capacitors followed by first-order RL and RC circuits, then transition to ac circuits using phasor analysis. Subsequently there appears to be two major approaches. Some will teach frequency response and three-phase power using only phasor analysis, while others will introduce Laplace transforms and do ac circuits using Laplace analysis.

Up to the early 1990's essentially all circuits courses that were taught solved only analysis problems – that is, circuit problems were usually constructed so that students determined an output of a circuit given one or more inputs. There was only one acceptable solution to the problem. In the early 1990's the Accreditation Board for Engineering and Technology (ABET) began emphasizing the importance of design in the curriculum. What ABET sought to influence were programs wherein students had some experience with design before they attempted their capstone design project. Although design was usually added to other than circuits courses, a few brave circuits instructors began to add some design content to their courses. Some circuits texts began to include some design problems. Today including design content in the first and/or second circuits course is still far from being universally adopted. Many students, especially those in non-electrical/computer engineering programs, view linear circuits as uninteresting, difficult and unrewarding. After eighteen years teaching circuits with a different approach, we believe that our methods yield a more efficient and exciting method of teaching circuits. Furthermore, students appear to like this method more than the classical approach, they learn more and are better prepared to pursue subsequent courses.

Our basic philosophy

The philosophy we espouse is to deliver a course that would involve students more in the learning process. We believe that students connect more with what they are learning if they can see that what they are doing is actually practical. That is, they see usefulness to what they are learning. In understanding human learning we turned to Bloom's Taxonomy of Educational Objectives[1]. We felt that by having students master higher level thinking skills would engage them intellectually and make learning more rewarding. Coupling design skills, for example, to a laboratory program would then permit the students to see that they could actually build circuits that would perform in the manner they wanted. In addition, since different students will solve design problems differently it is natural to ask which design is the better. We felt that students should be able to determine which solution is the best considering given constraints. We added elements to the course that have students compare and evaluate designs. This effort is called *Evaluation* in Bloom's Taxonomy and represents the highest level of cognitive learning.

The traditional approach to linear circuits introduces phasors before Laplace transforms. This time-honored method is based using phasors to develop ac circuit analysis, frequency response, steady-state power, and polyphase circuit analysis. Laplace transform theory, if taught at all in circuit courses, is often left to the last few weeks of the second course. Our experience is that students find the challenge of first learning phasor analysis about the same as learning Laplace analysis. The advantage of treating Laplace analysis first is that once mastered it makes learning phasor analysis easy – much easier than learning Laplace analysis after having first mastering phasor analysis. The basic problem with the phasor-first method is that most students never make the connection between phasor analysis and the transient and steady-state concepts developed through Laplace analysis. They rarely see that phasor analysis is just a special case of Laplace analysis and that phasors are a simplifying tool for treating the sinusoidal steady-state.

Our approach to teaching linear circuits

Our course begins much like traditional courses with dc circuits. However, immediately after the basic theorems we have added a lesson on signal transfer and a lesson on interface circuit design. These two lectures occur just after eight lectures on fundamentals. The lesson on signal transfer prepares students to know that circuits have limitations on how much voltage, current or power can be delivered to a load. Interface circuit design enables students to deliver to a fixed load from a fixed source a requisite voltage, current or power providing, of course, that the maximum possible signal limit is not exceeded. In this section we also begin a discussion of loading – what it is, when it is a bad thing and when it is a good thing. A suitable laboratory exercise is to have students design an interface circuit to deliver a certain voltage, current or power ±10% to a fixed load using a limited set of resistors, for example. As simple as this exercise is it begins to build confidence early that the student can design. Who has created the best design vis-à-vis a set of constraints begins providing insight into the highest level of learning – *Evaluation*.

Since we do a lot of design in our course the Op-amp becomes an essential tool. We develop student understanding of Op-Amp behavior as follows. We begin with two lessons on dependent sources including analysis of a dependent source circuit with feedback. Then we have a lesson on the BJT transistor – using a piecewise linear model as a simple demonstration of the use of modeling active circuits with dependent sources. This prepares us to transition to studying the Op-Amp. We use four lectures in teaching about the Op-Amp. We focus on its use as a premier design tool. We cover cascading Op-Amps and raise the issue of loading again – including the use of the Follower. We have students practice interfacing transducers to Op-Amps as part of an instrumentation system. In designing instrumentation systems we begin with a desired transducer and its characteristic and finish with a working circuit that produces the desired output. We show students how to design both a weighted summer D/A and an R-2R D/A. Determining which D/A approach is better continues to introduce students to making choices.

An instrumentation laboratory exercise using a strain gage, photocell or thermocouple as the sensor and asking the students to design an instrumentation system to produce a desired output is a very useful laboratory effort especially for the non-electrical/computer engineers.

Before introducing ac circuits we spend four lectures on introducing basic signals – the singularity functions (impulse, step, ramp), the exponential, the sinusoid, and combinations of such (window function, charging exponential, damped ramp, damped sinusoid, etc.) We also introduce partial indicators of signals like peak, peak-to-peak, average and root-mean-square values. Introducing signals just before capacitors and inductors helps students understand the nature of time-varying signals without the added complications of derivatives and/or integral relationships.

Capacitors and inductors are developed traditionally in two lectures along with two simple Op-Amp applications (integrators and differentiators). Following we combine these energy-storage devices with resistors to introduce first-order and second-order circuits. Students quickly realize after six lectures that classical solution of second-order linear differential equations with step, exponential or sinusoidal inputs are quite challenging to solve. While the responses yield signals like those they studied in earlier lectures, the solutions tend to be lengthy and time-consuming. Certainly there must be an easier way they lament. This sets them up for Laplace transforms. Classical solutions to time-domain behavior of circuits (transients) are very important for students to develop first-hand since it will help them to understand circuit responses when studied again using Laplace transforms.

A traditional lab exercise will have students plotting the response of a second-order RLC circuit and witnessing the changes in the response as the resistor, for example, is varied. We prefer to give students a set of constraints and have the students design a circuit to meet the constraints. For first-order circuits we specify the initial value, final value and a time-constant, while we add rise time, settling time, and leave off the time constant for second-order design challenges. This exercise becomes quite challenging if a second-order circuit solution is necessary and the overshoot is also constrained.

We depart radically from traditional approaches to circuits at this juncture. We introduce Laplace transforms immediately following classical solutions of first- and second-order circuits. We develop the Laplace transform and show how differential equations that describe first- or second-order circuits can be solved easier using s-domain algebra rather than classical differential equation techniques. We introduce the students to pole-zero diagrams. At this point in the course students still need to determine the desired differential equation and that still causes some problems. Then we show how to transform circuits directly into the s-domain thereby avoiding finding the differential equation altogether. Students find this technique easy and very appealing. We then solve these transformed circuits by applying all of the circuit theorems taught in dc circuits. We return to pole-zero diagrams and look at the nature of the response associated with the location of poles and zeros. We even, albeit briefly, discuss the concept of stability. We can relate the location of the poles and zeros to the second-order classical solutions studied earlier. Students have no difficulty understanding what happens to the circuit response as the poles are moved around. After eight lessons – four learning the basics of Laplace transform theory and four applying circuit theorems using Laplace techniques – the students are ready to use what they learned to do more practical problems.

After students are comfortable analyzing circuit problems using Laplace transform techniques we introduce the concept of the transfer function. Students see what the transfer function is and how it describes circuit behavior. We use the transfer function to do transient analysis (step and impulse response of circuits) and sinusoidal steady state analysis. Once students see the role of the transfer function in the response behavior of circuits we turn to showing them how they might design a circuit from a transfer function. We show them how to partition a transfer function into modules than can be easily designed using basic building blocks – voltage and current dividers, and inverting and non-inverting Op-Amp circuits. The concern here, of course, is that circuits must follow the chain rule and not load each other. Using the Op-Amp follower to isolate voltage-divider stages, for example, is discussed. We cover this material in four or five lectures. Exam questions usually require students to create an efficient design for a given transfer function. Evaluation questions are easily constructed wherein a given transfer function is offered with several competing designs. After validating that all designs actually work students are asked to select the design the best fits the stated criteria and to explain their choice.

We feel that teaching frequency response flows best if done immediately after learning about transfer functions. We usually spend two lectures on first-order circuits, one on second-order circuits and two on Bode diagrams. Once students know what a first-order filter transfer function looks like, they can and do design first-order circuits to meet low-pass, high-pass, band-pass (cascaded first-order circuits) and band-reject (summed first-order circuits) responses. We also have students using first-order circuits design solutions to meeting simple filter requirements based on Bode diagrams. In this case they derive a transfer function from the Bode diagram (only real poles) and then design a circuit that produces the desired transfer function.

At this point in our course we have developed all the tools to be able to apply them to do some serious design. There are several ways one can go forward depending on the ultimate goal of the course.

If learning about power is important then one can return to the sinusoidal steady-state analysis and derive the phasor analysis approach. It would take only six or seven lectures to cover phasor analysis and polyphase power circuits. Studying power systems including analyzing single and three-phase systems and designing for a specific power factor or matching three-phase loads to a line become possible. Three additional lectures could cover coupled coils and transformers. Two-ports and Fourier Transforms could also be added depending on the length of the term and the emphasis placed on various other topics.

If learning about filters is important then one can do two or three lectures on Fourier Series and then spend four or five lesson on multipole filter analysis. At DU we choose this path since our students use filters extensively in subsequent design courses. We teach students how to design multipole filters using the first-order cascade design approach as a reference. We then develop the Sallen-Key prototypical filter. Using this prototype we show them how to design Butterworth and Chebyshev multipole filters using either equal-R equal-C, or unity-gain realizations. Competing solutions are discussed considering both frequency domain and time domain considerations and limitations.

A typical lab would create a scenario that requires the students to determine the type of filter that would satisfy the criteria best and the order of the filter to attain the desired roll-off. Student then must simulate their solution and if that works build and test their solution in the lab. Exam questions typically offer a scenario and present the students with competing solutions. Students need to analyze each solution and determine which best fits the problem.

At DU after studying filters three lessons are devoted to sinusoidal-steady-state analysis using phasors and two lessons are devoted to coupled coils and transformers. The remaining lessons are scattered at salient parts of the course and are primarily used for student evaluations.

Our philosophy regarding the use of software tools is simple. Use whatever software tools make the most sense to solve the problem at hand. Throughout the course software tools are applied to assist the students in their analysis of their designs. Electronic Workbench® (pSpice), Excel® and MathCad® are used extensively in the linear circuits course at the University of Denver. At the USAF Academy we use OrCad® (pSpice) and Matlab®.

Results of teaching the course using our pedagogy

At the University of Denver, all of the major evaluations in linear circuits, such as, the mid-term exam and the final, are divided into two parts. The first part tests student retention of basic topics such as applying circuit theorems, performing a Laplace transformation, or solving a circuit for a transfer function. Testing of the first part is at the lower level of Bloom's Taxonomy (Knowledge, Comprehension and Application) and evaluates the ability of students to know and apply circuit tools. The second part tests the students' ability to integrate ideas, do design and evaluation, and apply concepts to new problems. These problems test at the upper level of the Taxonomy (Analysis, Design and Evaluation). Both parts are weight equally. Since we began keeping records in 1998 for this study there were from 35 to 45 students every term. The students were roughly evenly divided between electrical, mechanical and computer engineering majors. The course is criteria-based and the grades are not curved. Student performance has averaged between a C+ and B- every year – the desired performance range. Student critiques have been very positive throughout this period. Performance of these students in subsequent courses like *Signal and Systems*, *Electronics*, *Engineering Application III* (Instrumentation) and *Controls* has been excellent. At DU design is spread throughout all four years in numerous courses so it is not possible to attribute the students' strong design skills to any one course. Nevertheless, it is readily apparent that students know how to design simple circuits whenever they occur in subsequent design-based courses without regard to their engineering discipline.

With all educational innovations there is a question as to whether comparable results can be achieved in a different institutional setting. In the present case the answer appears to be yes. For the two most recent academic years the first named author has been a visiting professor at the USAF Academy. There he was involved in teaching the basic circuits course – in the traditional manner in 2002 and in the manner reported in this paper in 2003. The Academy course involves a diverse set of students (all engineering and Physics majors plus a few others) and a large enrollment (116 students and four instructors in the Fall of 2002, and 189 students and six instructors in the Fall of 2003). Historically the course had been taught in the traditional phasor-first manner with no design or evaluation. Lab and computer exercises typically involved verifying circuit theorems or validating the predicted response of a given circuit. All testing was done at the lower level of Bloom's taxonomy. While there were no problems in delivering this course, students taking the follow-on courses, especially the power course, the electronics sequence and the second circuits course, were not well prepared to deal with more advanced topics especially problems involving design and evaluation. Retention and/or understanding of many desired circuits concepts were lower than desired.

For the Fall term of 2003 the course was completely redesigned to follow the pedagogy discussed in this paper. Lab and computer exercises were fashioned to emphasis design and evaluation. Topical emphasis and testing were created to cover both the lower and higher levels of Bloom's Taxonomy. Traditional expectations would suggest that such a course would be much more challenging. Yet student performance in the course actually improved and student critiques were also considerably more positive. A comparison between the Fall 2002 offering (traditional approach) and the Fall 2003 offering (the different approach) is shown in Table 1. While it is too early to tell whether students will perform better in follow-on courses, the level of student achievement and confidence appears to have significantly improved. The follow-on redesigned *Electric Circuits and Systems II* course will be offered in Fall 2004.

Major	**Fall 2002 (Traditional Approach)**		**Fall 2003 (Different Approach)**	
	Number of Students	GPA in Circuits	Number of Students	GPA in Circuits
Aero	3	2.96	52	3.14
Astro	9	3.43	25	3.21
Civil	18	2.35	27	2.28
Computer	7	3.06	10	3.01
Electrical	14	3.24	20	3.17
Environmental	2	1.00	3	2.43
Engr Mech	6	2.73	7	3.28
Mechanical	21	2.68	12	3.06
Systems	0	-	9	2.82
Physics	12	3.50	11	3.44
Others	24	2.23	13	2.64
Course Overall	116	2.75	189	2.98

Table 1. Comparison of student performance in EE231 Electric Circuits and Systems I

Conclusion

Eighteen years of teaching linear circuits at DU and two years at USAF Academy have provided ample evidence of improved student performance using our approach to teaching circuits. Techniques include including more design, having students evaluate competing designs, have students design, simulate and build practical circuits, and teaching ac circuits using Laplace transforms before phasors. Applying these techniques have contributed to better prepared and more motivated students – regardless of the engineering discipline they are pursuing. A textbook titled *The Analysis and Design of Linear Circuits* has been authored and used to help deliver this pedagogy. It currently is in its fourth edition (Wiley, 2004).

Bibliography

[1] Krathwohl, D.R. and B.S.Bloom, *Taxonomy of educational objectives. Handbook 1. Cognitive Domain*, 1984a. New York: Longman.

Biographies

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