Practical Circuit Design in an Elementary Circuit Theory Lab

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A course in elementary circuit analysis is a common requirement in an electrical engineering curriculum. The course traditionally emphasizes fundamental DC and AC circuit theory concepts for resistive and reactive components and may introduce operational amplifiers (op-amps). Students learn Ohm's and Kirchoff's Laws, series and parallel relationships, and voltage and current division, as well as various circuit analysis techniques and theorems, such as nodal and mesh analysis, Thevenin and Norton equivalent circuits, superposition, and transient analysis. It is often the first required course in the curriculum, so students enter the course highly motivated and excited to finally begin their major area of study. It is also common for the theoretical rigor and tedium of the fundamentals to discourage some students, leading them to different courses of study. No doubt this is best for certain students, but it is also unfortunate if students who could succeed and become excellent electrical engineers do not only because they may not yet appreciate the value of fundamental circuit theory. This motivational problem can be a particular challenge at an institution like the U.S. Naval Academy, where the student is trained primarily as a naval officer and electrical engineering is a secondary pursuit.

To provide a rationale for learning the theoretical concepts required in the course, we have restructured our laboratories. In implementing new labs for the course, we've attempted to meet the following goals: 1) Labs should motivate students through greater emphasis on the practical merit of the fundamentals. Using typical devices, with which students are familiar, such as lamps, batteries, loudspeakers, etc, is helpful. 2) Insure that the labs are conceptually integrated with the course in a preconceived fashion. The labs should not merely be fun, but must reinforce the fundamental concepts. 3) Emphasize design using practical components. The use of lights and sound in an electrical engineering lab is not a new idea. However, when students are encouraged to be creative using components they are familiar with, the learning process is more relevant for them. This can be challenging in less advanced courses that have a theoretical orientation, but it is possible if the instructor is innovative.

Here we discuss four different designs that were done in the lab. In the first, students design a dimmer circuit for a lamp. The design process is made quite evident to the student, as the initial design is marginally adequate, requiring changes. The circuit is improved in following lab exercises as different circuit theory concepts are emphasized along the way. In later labs, other designs, such as a digital-to-analog converter with an op-amp or a camera flash simply aid in teaching fundamental concepts. In addition, we sometimes demonstrate slightly more advanced circuits that operate on the same principles as the ones designed by the students. This helps keep students motivated and interested in knowing how they can make improvements. The final design project, a bass and treble control circuit, emphasizes many of the concepts taught during the course, and provides continuity for the discussion of filters common in the second course of a circuit analysis sequence.

I. Dimmer

In an initial lab, students investigate Ohm's Law using resistors and a lamp. This helps students realize that common components can sometimes be modeled as resistances. The concepts of voltage division and current division are addressed in a following lab. Students use a potentiometer (or a rheostat) to design a dimmer for the lamp. From a practical standpoint, the circuit is unacceptable - the low impedance lamp loads the circuit excessively, so that the potentiometer controls the current through the lamp in a nonlinear fashion. Students, however, are simply excited that they can control the lamp this easily. Safety issues can be addressed at this point by specifying limits on the current in the circuit.

To improve the circuit, a common emitter bipolar junction transistor is placed between the potentiometer and the lamp, as in Figure 1. It is easy for the students to observe the improved control over the lamp brightness, and they quickly gain insight into the concept of loading. We found that the loading concept was understood and remembered well after this laboratory experience; students always were able to recall the advantage of using a high impedance load instead of a low impedance load.

There are other reasons to introduce transistors at this point. First, they are easy to model (in PSpice for example) and analyze using nodal or mesh analysis. In addition, many students already know the transistor is an important device, so it lends relevancy to the laboratory. This also provides justification for studying dependent sources, and current sources in particular. Finally, it is an opportunity to use transistors in a simple setting. Students may find them less intimidating in future courses.

The circuit in Figure 1 also provides a convenient transition to a discussion of circuit equivalence. It is easy for students to determine the Thevenin equivalent of the potentiometer control circuit by measuring the open circuit voltage and short circuit current at the base of the transistor. We chose to have the students measure these just as the lamp began to turn on, so that it was possible to actually observe how an equivalent circuit would behave using the Thevenin voltage and resistance instead of the potentiometer.

The source characteristics of real voltage and current sources can also be described using a similar circuit, shown in Figure 2. As the 20-V source is varied in this circuit, the current through lamp 1 is relatively constant. In contrast, the current in lamp 2 changes. The different behavior of the two lamps is easy to observe. Hence, the conceptual difference between a current source and a voltage source is emphasized. Also, since the current in lamp 1 is actually not precisely constant, students learn that a Norton equivalent circuit can be used to describe a real current source. The students also determine the source characteristic of a household battery by measuring the terminal voltage across two resistive loads and solving a set of simultaneous equations for the Thevenin equivalent circuit. Alternatively, the open circuit voltage and short circuit current can be measured, though the battery drains quickly with a short circuit as the load.

II. Digital-to-Analog Converter and Op-Amps

When using operational amplifiers, a variety of design applications are possible. We chose to have students design and build a simple three-bit digital-to-analog converter (DAC) as one part of an introductory lab exercise on op-amps. A common design uses a simple summing amplifier, one of the first op-amp configurations that students learn. It is not necessary to discuss the DAC in great detail; issues such as resolution and sampling can be addressed later in the curriculum. At this point, simply providing mathematical examples of binary digital to analog number conversion suffices. It also helps to provide some common examples where this circuit might be applied (compact disc player, modem, etc). For the three bit design, students were required to implement the function $|V_o| = V_1 + 0.5V_2 + 0.25V_3$, where the voltages V_1, V_2 and V_3 represent binary digital values. It is appropriate in this design to discuss specifications, as in maximum current or minimum tolerance, for example, which must be met in converting the digital input to analog values.

III. Camera Flash

In a lab on capacitor and inductor transients, a design exercise in which students build a camera flash is appropriate. In the first part of the lab, the students explore basic transient characteristics for RL and RC circuits using the oscilloscope. Later in the lab students analyze the circuit in Figure 3 to determine the time constants during the charging and discharging phases for the capacitor. For a design exercise, they were instructed to make changes to the circuit to make it operate as a camera flash. Various specifications could: 1) require a certain capacitor voltage 2) state the energy storage requirements of the capacitor 3) define capacitance values that may be used and 4) state the minimum time to charge the capacitor.

The camera flash design was quite popular with the students. Depending on the depth in which the material is covered, it could be designed from scratch. In our lab, however, time constraints prevented its completion during the lab, but students insisted that they be allowed back in the lab to build the circuit at another time. To motivate the students to consider alternative circuits that use similar concepts, we demonstrated the circuit in Figure 4 at the beginning of the lab. The bulb simply flashes repeatedly at the frequency of the square wave input. Many students were curious to know how they might implement such a circuit.

IV. Bass and Treble Tone Control

Oftentimes, filters are not discussed in the first semester of a circuit analysis course. However, by the end of the course students usually have enough knowledge to conceptually understand their basic operation. Hence, the final lab project of the course was to design a bass and treble tone control. The design integrates many of the concepts taught during the course, such as nodal analysis, loading, voltage division, op-amp circuits, complex impedance, and AC sinusoidal analysis.

Since the students are not introduced to the concept of filtering during this course, it was best to discuss the circuit operation only in the context of the frequency dependent impedance of the capacitor. The concepts were introduced initially in a lab on complex impedance. In that lab, students first use the oscilloscope to measure basic phase relationships between voltage and current for capacitors and inductors. In addition, they observe the behavior of the circuit in Figure 5 as the frequency varies from DC to 5kHz. It is readily apparent that lower frequencies are not heard from the speaker. Most students are able to relate this to the open (short) circuit behavior of the capacitor at low (high) frequencies. For the design project, students must add a bass filter to the circuit and use a single potentiometer to select between the bass and treble components of a signal. Though several circuits are possible, the most common and simplest design that students attempted is shown in Figure 6. Many also used inverting op-amps in the design. To encourage work outside the classroom, students were assigned briefcases that contain a prototype breadboard (proto-board), separate DC power supplies, a function generator, and a built-in speaker.

General specifications were given as follows: 1) The relationship between the input and output voltages $|\mathbf{V_{OUT}}/\mathbf{V_{IN}}|$ for the treble and bass circuits is defined at frequencies of 100Hz and 10kHz. No specification was given for the frequencies between 100Hz and 10kHz. 2) The maximum allowable currents throughout the circuit (with the exception of the speaker) are 10mA and the output voltage must be 1V or less, depending on the power rating of the speaker. 3) The potentiometer must control the volume in a linear fashion. 4) Only standard resistor and capacitor values must be used, with no greater than two in parallel or series.

V. Conclusion

In implementing these labs, it is clear that motivation has improved relative to previous semesters. Students occasionally stayed late in the lab to test ideas beyond what was expected in the lab exercises. This is significant given the rigid time structure of the military environment. For the design project, many students came to the lab with their designs already built on the proto-board, and were often interested to learn ways their designs might be improved.

Though it may sometimes be necessary for students to follow rote procedures in the laboratory, a rigid structure can stifle student creativity and excitement. Students grasp the fundamental concepts better when they are motivated to explore the boundaries. This is can be true even in courses that traditionally have a theoretical emphasis if the design process is encouraged in ways that are relevant yet challenging.

Bibliography

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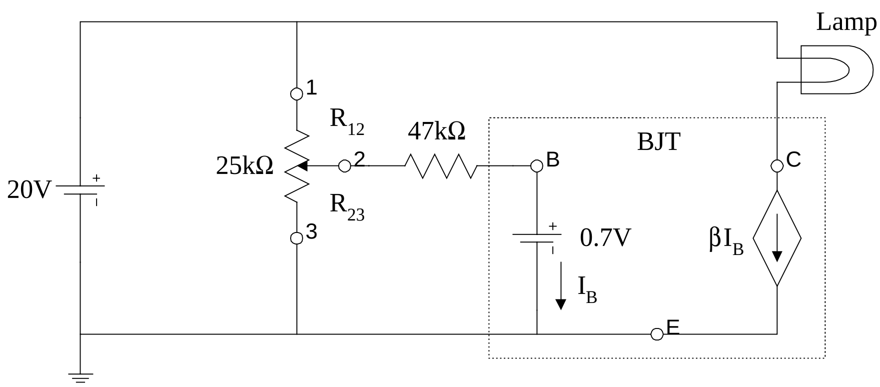

Figure 1: An improved dimmer control circuit.

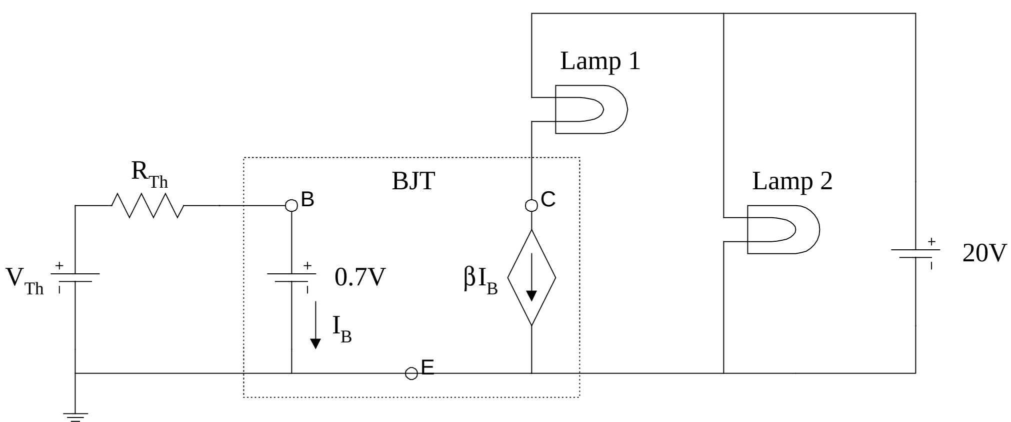

Figure 2: Circuit demonstrates the Thevenin equivalent circuit for the dimmer control. The source characteristic for the current source can be explored by varying the 20-V source.

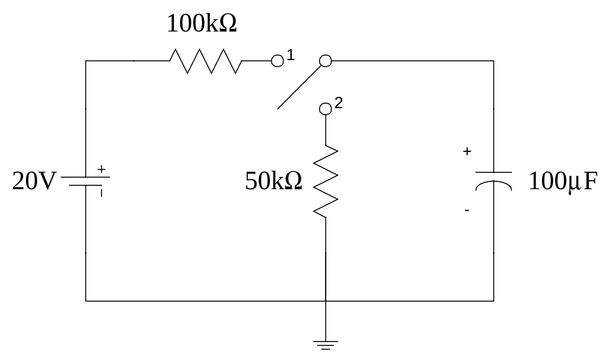

Figure 3: Circuit used to analyze transient behavior of capacitive circuit.

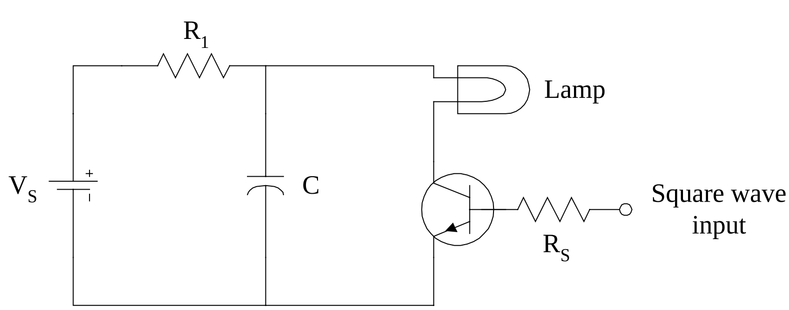

Figure 4: Circuit used to demonstrate periodically flashing bulb.

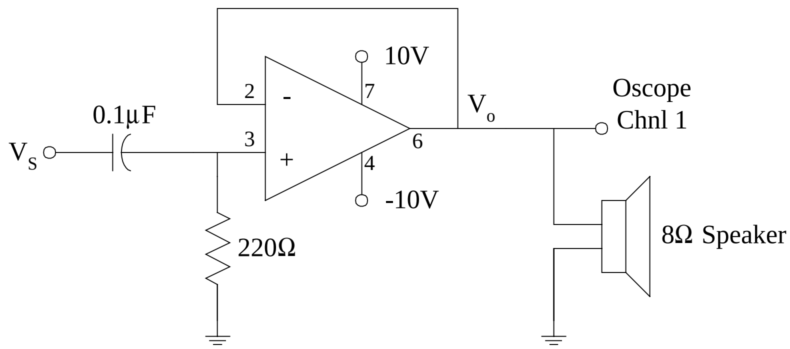

Figure 5: High pass filter used in treble tone control circuit.

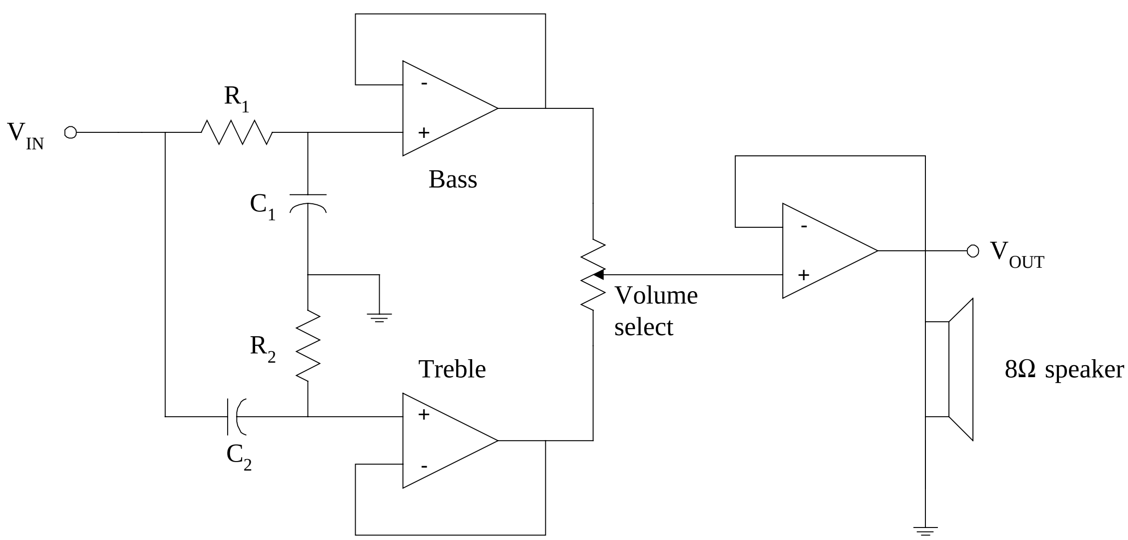

Figure 6: Common treble and bass tone control circuit design.