

Interactive Modules for Electric Circuits

**Mahmood Nahvi, Professor
California Polytechnic State University**

Abstract

Digital simulators are familiar tools in the undergraduate teaching and learning environments. In both inanimate and live forms, simulators are used as tools for design, concept development, demonstrations, and supplements to laboratory experiments. We have developed computer-based modules for the circuits, signals and systems courses that provide maximum man-machine interaction with minimum effort. For maximum learning effectiveness, the modules i) are specialized, ii) have reaction speed close to the real-time operation of the physical system and iii) use open-loop movement of finger and hand as opposed to closed sensory-motor loops for variable modification. This paper presents circuit modules covering resistive circuits, network theorems, amplifiers, RC-RL-RLC circuits, resonance, and energy and power. Each module focuses on a specific topic. It gives the user the choice of circuit and signals within a family and allows him/her to rapidly modify element values and initial states. Circuit variables such as voltages, currents, and power are displayed on the monitor. The modules, as an integral part of the courseware, can play an important role in helping students develop concepts, practice, analyze, simulate and design.

1. Introduction

Among tools and approaches used in undergraduate engineering education are a) paper/pencil exercises b) computational engines (e.g., mathematical tables, abacus, nomograms, slide rules, calculators, programmable computers), c) simulations, and d) laboratories. Traditionally, paper/pencil (a) and laboratories (d) carry the banner, Fig. 1-a. Contemporary approaches incorporate computational engines (b) and simulators (c) within the environment, Fig. 1-b^{1, 2}.

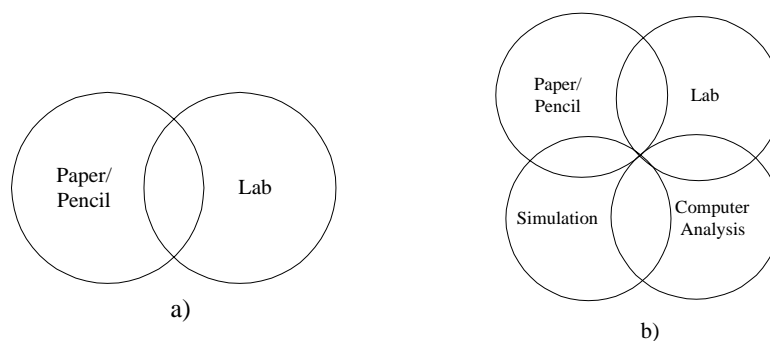


Figure 1 - Two Approaches to Undergraduate Engineering Education

For electrical engineering students, laboratories are very important. By working with physical circuits, devices and systems such as electrical and electronic components and measurement instruments, students get as close to a real-world engineering environment as possible. They acquire qualitative as well as quantitative skills and knowledge of the subject. Notions previously discussed using analytical tools and mathematical language become alive, often for the first time, in a laboratory environment. Laboratories have some drawbacks, however. For the university it is the monetary cost of running labs. For curricula designers and students, it is the pay-off in terms of preparation and set-up time versus the number of credit units gained. Computer-based simulators can retain many advantages of interactivity and hands-on experience while avoiding the above drawbacks. Good simulators can be effective and efficient learning and teaching tools. The present paper is concerned with such features.

2. Hands-on Learning Experience by Interactive Simulation

Hands-on learning experience by simulation is an alternative to full-scale laboratory experiments. Simulators are used to enhance lectures, supplement labs, and function as tutorial help. They offer tools for analysis, design, computation, training and education. They support *learning-by-doing* in that they build models of actual systems with the same external characteristics and explore their behavior or use them in design. For several reasons, digital simulators are popular tools in the undergraduate teaching and learning environments. They fall into two categories: i) inanimate (off-line) and ii) live (on-line, real-time). In the second category the discrete model of a system, programmed in computer hardware or software, is running in real-time with the results displayed through visual, auditory, or other channels. The computer continually senses the system's parameters just as in a real physical system and enters them into the equation. Such simulators may be running on a general-purpose computer or on a special purpose one, such as a digital signal processing board. Real-time simulators functionally resemble the real-time operation of the actual physical system, but they work within a synthetic virtual environment. These simulators have the following features: (1) They can be highly interactive. The system's parameters can be easily modified in real-time while the simulator is running; (2) They can create situations not possible within the actual physical environment; (3) They can present the user with the same real-time input-output signals that are encountered when one uses the real physical system, thus approaching a laboratory experience and even closely resembling or replacing it. The modules described in this paper aspire to that performance.

3. Modules for Electric Circuits

At Cal Poly State University we have developed and used computer modules for circuits, signals and systems for the undergraduate electrical engineering curriculum, along with commercial software simulation packages. The work was supported by the National Science Foundation and carried out in collaboration with several institutions^{1,2}. Some aspects of the work have been reported previously^{3,4}. The modules are distinguished from commercial simulation packages in that they are optimized for specific problems. Each module has a set of notes that describe the subject in the traditional and analytical way with equations, examples and problems. Each module also includes a computer package specifically designed for the subject topic of that module. The software runs on a PC. Each module treats one subject, normally on a single screen.

The present paper describes the computer-based parts of the modules for the following topics, along with some of their working examples:

- i) Resistive circuits
- ii) Network theorems
- iii) Wheatstone bridge
- iv) Amplifiers
- v) RC, RL, and RLC Circuits
- vi) Resonance
- vii) Energy and power

Each module has a set of preconstructed circuits and signals that can be chosen by toggling through a software switch. Upon execution, a module (except the module on energy and power that contains eight screens) simultaneously displays a circuit diagram, input-output buttons, and display windows. Buttons are used to toggle among several circuits and input signals, enter, modify and display signal parameters, element values, and initial conditions, and display voltages and currents. Windows are used to display graphs, equations and numerical results. All variables and element values are accessed directly. Inputting a value is done by keystrokes, a single-step ballistic motion. This provides very short sequences of actions with rapid closures, hence frequent repetitions and modifications and examination of the consequences. The user can scroll between buttons by using the left-right keys ($\leftarrow \rightarrow$). The chosen button is identified by a red frame. The value of the chosen button can be incremented and decremented by the up-down scroll keys ($\uparrow \downarrow$). The value may also be entered directly from the keyboard. For direct entry, the button is cleared first by pressing the *enter* key, then typing in the desired value and pressing *enter* again. Toggling the *F1* key displays the *help* window and hides it. Pressing the *F2* key displays the window *about* the module. Pressing the *Esc* key exits the program.

Each module deals with one subject. For example, the RC module explores a circuit made of a resistor, a capacitor and an energy source. This provides the choice of five possible circuits with nine possible input signals all in a single module. Figure 2 displays an example of the RC module.

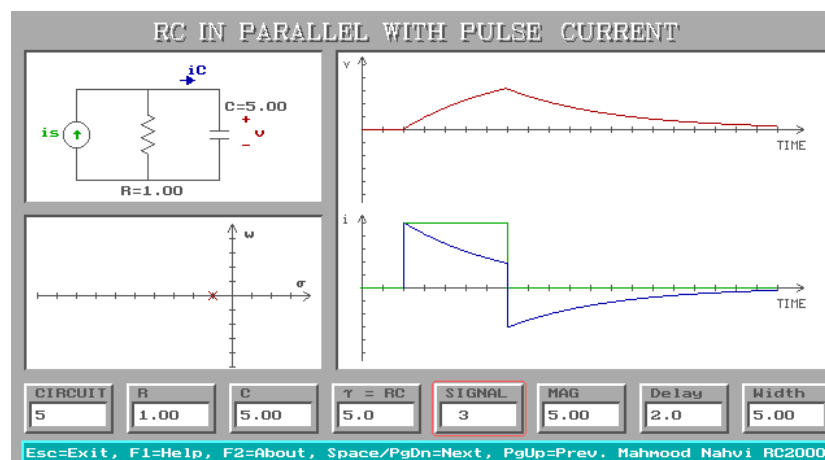


Figure 2 - A Practical Current Pulse Charges a Capacitor

The module gives the user the ability to rapidly modify element values and initial states. Voltages and currents are displayed on the monitor. The user can examine the behavior of various RC circuits in response to various inputs or initial conditions. The user can also examine various designs, to achieve desired behaviors. The module provides a balance of analytical approach and qualitative understanding. The user can develop a qualitative understanding of the circuit performance, the role of the capacitor, the resistor, initial values, exponential change, time constants, final values, and asymptotic variations. This is a very desirable feature for EE students, which would require much more time and effort if approached through paper/pencil and analytical/mathematical exercises alone.

4. Design Considerations for Interactivity

In running the modules, the user visually observes the outcome on the computer monitor and interacts with the simulator through a keyboard, a mouse, or other devices manipulated by hand. The roles of sensorimotor, decision, and computational processes involved in this type of interaction have been discussed previously^{3,4}. For more details of man-machine interfacing see references 5 and 6. Figure 3 shows a simplified schematic diagram of such a man-computer interaction loop. Each side of the loop has three segments: a) input interface, b) output interface, and c) processing (computation/modeling/decision making).

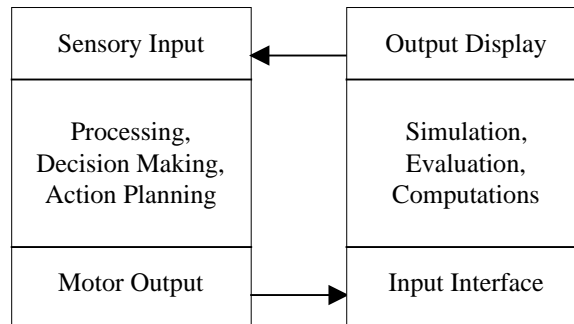


Figure 3 - A Simplified Model of Man-Computer Interaction

The human side of the loop involves noticing computer displays, processing and decision making, and sensorimotor coordination for providing input to the computer. The operator's side often involves open or closed paths with delays ranging from fractions of a second in reaction time for striking a key, to several seconds in implementing a sequence of pointings by the mouse to adjust a parameter, pull down a menu item, or drag an object on the screen to a certain location. The time needed by the computer to process the model and display the results introduces delay in the loop.

The following important considerations were taken into account in the design of the modules:

- i) For maximum efficiency and speed of operation, parameters are entered through ballistic motor acts such as keystrokes and scrolling. The feedback in this type of motion is internal with very short delays and is similar to automatic feedback in a regulator or stabilizer loop. From the

man-machine interaction point of view, the control is more like an open loop. Such motor acts take shorter time, do not require position or force control, and require less effort and concentration.

ii) The response time, i.e., the delay from the time the user enters a command until the time the simulator's responses are displayed, is kept at the minimum level, often less than a human's simple reaction time. This makes the simulation close to real-time and harmonious with the operator's sensory-decision-motor acts.

iii) Circuit parameters and input-output variables are displayed simultaneously. The operator views the computer monitor and by his/her short term visual memory maintains immediate and simultaneous access to the displayed information. In a physical circuit the interaction between its elements and input is often instantaneous. Simulation of a circuit generally involves a set of input, output, models, and states that are related to each other at every moment. Their display is likewise instantaneous and coordinated at all times to reflect this relationship.

iv) A total simulation contains many small steps, which we call mini-runs. In a mini-run the human operator enters the input command through the keyboard to control the simulation. The computer operates on the input and displays the output on the monitor. The operator examines the display and decides on the next input. The cycle is then repeated. In a sense, mini-runs constitute the building blocks of man-machine interaction. Mini-runs are exploratory steps, repeated many times to simulate many conditions. A mini-run may seem a small step but, as it consumes time and effort to set up and examine its results, is the main contributor to the operating *cost* of a simulator as an educational tool. Two factors contribute to the operating cost of a mini-run: a) its response time and b) the effort or burden it puts on the sensorimotor system of the operator. The cost of a mini-run is smaller under open-loop motor acts and simultaneous observation of all results. The modules are designed with the above factor in mind.

In summary, the modules employ input and output interfacing methods and computational tools, which increase simplicity, consistency, ease of use, short response time, and quick display of graphical and numerical feedback data. Mouse use is avoided as much as possible. The burden on the user is reduced by making motor acts open-loop as much as possible, the computer response time as close to real-time operation of the physical circuit as possible, and the display of the results as simultaneous and parallel as possible. Thus, modules are strongly application-specific, specialized for strong and frequent interaction and approach real-time operation of the simulated circuit.

5. Examples

In this section, we present sample examples of circuit modules.

Resistive Circuits - There are seven modules for resistive circuits with up to three sources and four resistors. Each source can be either a voltage or a current source. The module can implement any of the eight possible source combinations. One example is shown in Figure 4 with two sources and three resistors. Another example is shown in Figure 5 with three sources and five resistors.

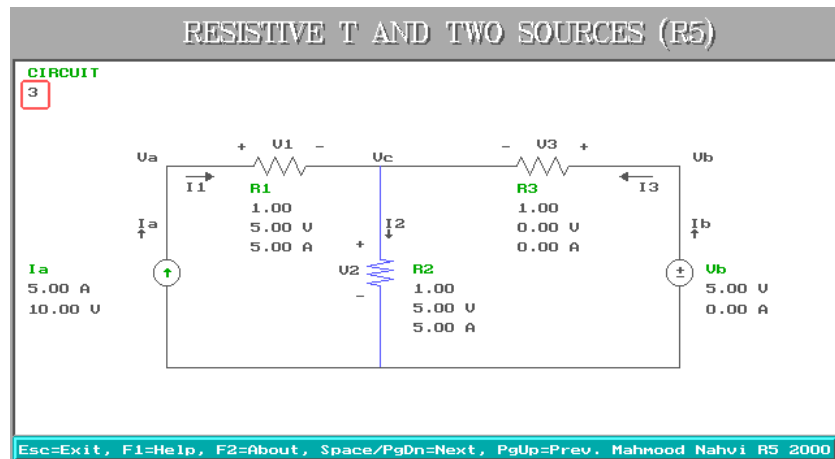


Figure 4 - A Resistive Circuit with Two Sources

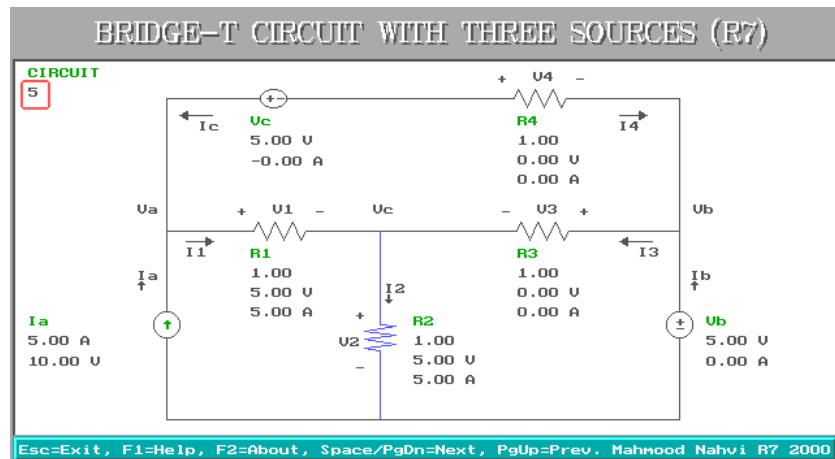


Figure 5 - A Resistive Circuit with Three Sources

Network Theorems - Resistive modules may be used to explore network theorems such as Thevenin's, Norton's, superposition, and maximum power transfer theorem. The resistor load is identified by assigning blue color to its schematic.

Wheatstone Bridge - A module is specifically designed for resistive Wheatstone bridge. An example is shown in Figure 6.

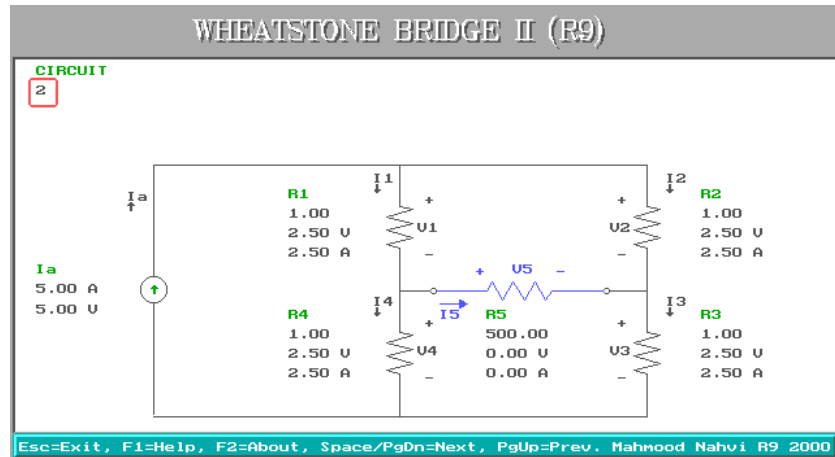


Figure 6 - Wheatstone Bridge With Load

Amplifiers - There are seven modules for circuits containing amplifiers, including op amps. Many effects of input and output impedances and feedback can be studied using amplifier modules. One example is shown in Figure 7.

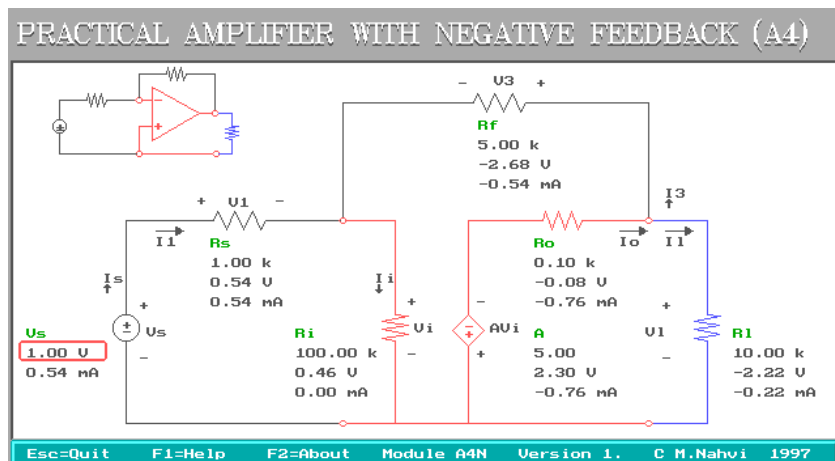


Figure 7 - A Practical Amplifier With Negative Feedback

RC Circuits - The RC, RL, and RLC modules represent first-order and second-order dynamical systems. For each circuit, input-output pairs are defined and poles of the network function are displayed in a window. An example of the use of the RC module was presented in Figure 2. The circuits of Figures 8 and 9 can be used to present design challenges to students. In Figure 8, capacitor voltage is to be kept at a constant DC level. In Figure 9, an input signal is required to drive the capacitor voltage to its final steady-state value within a finite time.

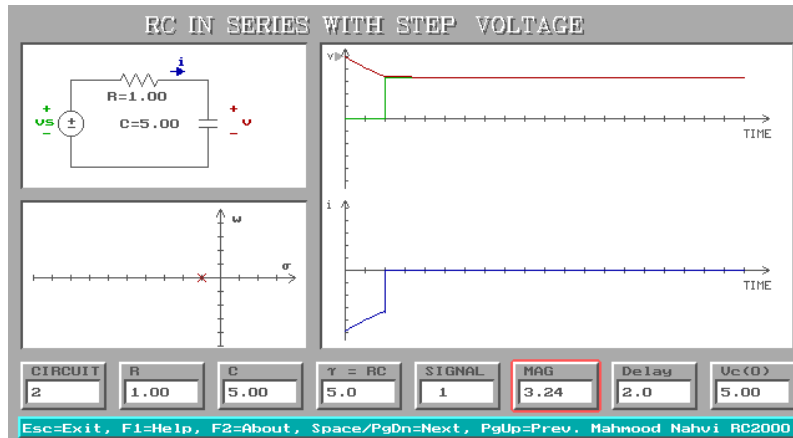


Figure 8 - Keeping The Capacitor Voltage Constant

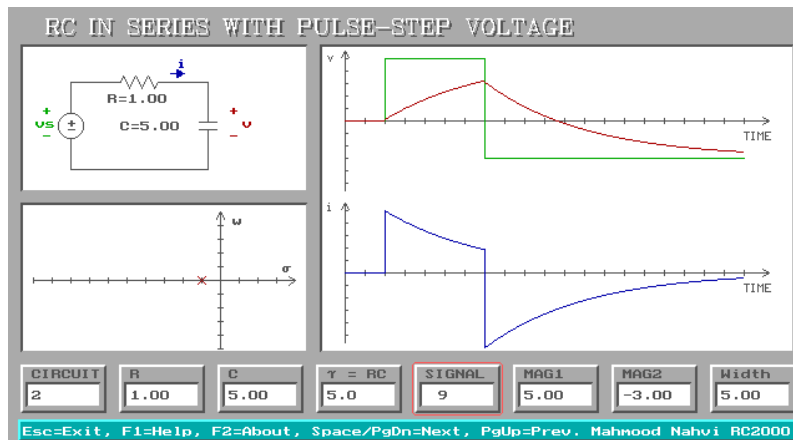


Figure 9 - Charging a Capacitor by a Pulse-Step Voltage

RL Circuits - The RL module is similar to the RC module. An example is shown in Figure 10.

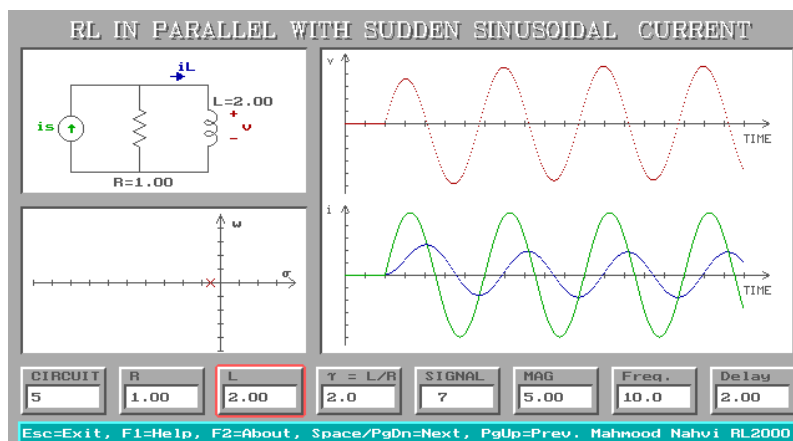


Figure 10 - Division of a Suddenly Applied AC Current

RLC Circuits - Two examples of the use of the RLC module are shown in Figures 11 and 12.

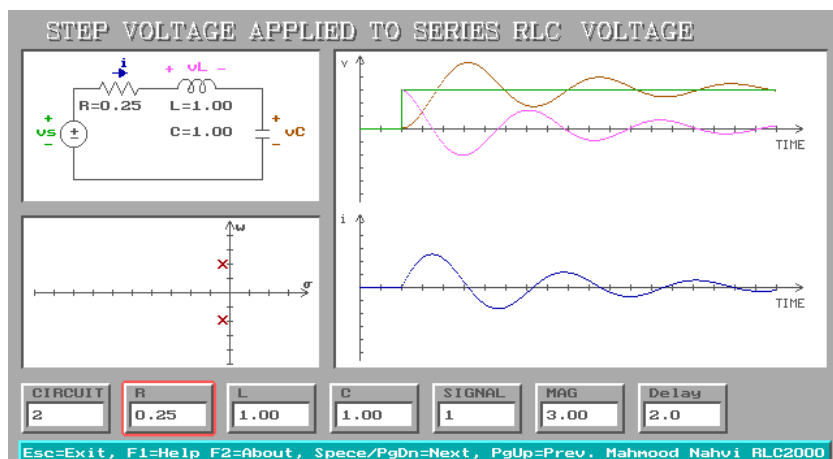


Figure 11 - Response of a Series RLC Circuit to a Step Voltage

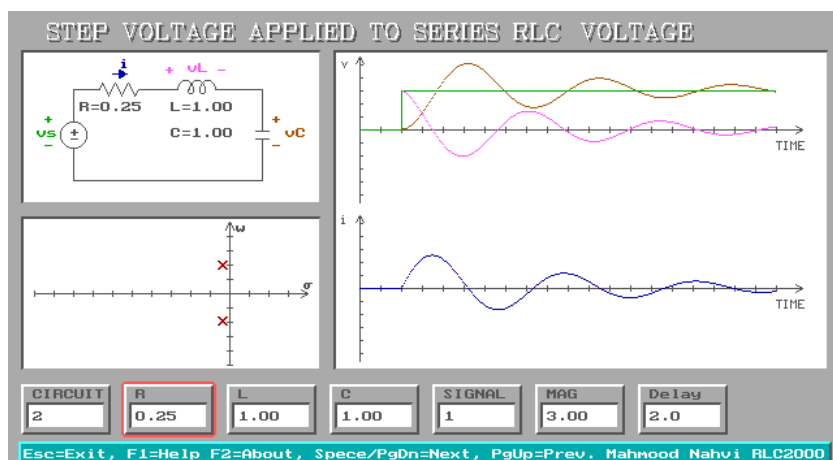


Figure 12 - Response of a Parallel RLC Circuit to a Pulse Current

Resonance - The subject of the module is resonance in parallel and series RLC circuits.

AC Power - In Figure 13, $v = V\sqrt{2} \cos(2\pi ft)$ and $i = I\sqrt{2} \cos(2\pi ft + \theta)$ are the terminal voltage and current of a linear circuit under AC steady state, respectively. V and I are *rms* values. θ is the phase of the impedance of the circuit, showing the phase-lag of the current with reference to the voltage. V , I and θ are adjustable, but the frequency is fixed. The instantaneous power delivered to the circuit is

$$p = vi = VI \cos \theta (4\pi ft + \theta)$$

Positive values of p correspond to energy entering the circuit (red color). Negative values of p correspond to energy leaving the circuit (light green color). Set $V = 5V$ and $I = 5A$. Note how

$p(t)$, P , Q , and S change for $-90^\circ < \theta < 90^\circ$. Compute $p(t)$, P , Q , and S for $\theta = -90^\circ, -60^\circ, -45^\circ, -30^\circ, 0, 30^\circ, 45^\circ, 60^\circ, 90^\circ$ and compare with values shown on the screen.

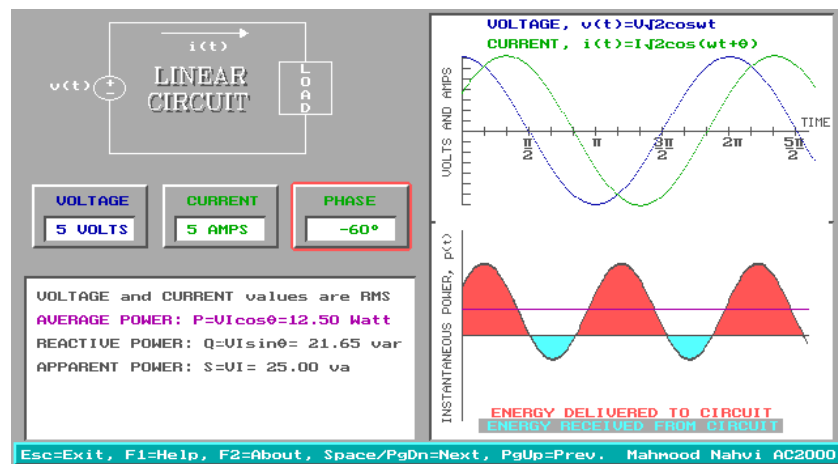


Figure 13 - AC Power in an Impedance

6. Discussion: Qualitative Understanding of Circuit Behavior

In addition to quantitative analysis methods, it is desirable and important that students develop a qualitative understanding of circuit behavior and be able to predict it under various input conditions. This is sometimes called having a *feel* or *intuition* for the problem. It helps to choose the best approach amongst various possible solution methods. Circuit simulation modules discussed in this paper are efficient tools for developing such a qualitative understanding. Quantitative/analytical solutions using paper/pencil methods can lead to a qualitative understanding, but at a much greater cost than simulation by these modules. By analytical solutions, the student learns how to write the node and mesh equations, eliminate variables, produce differential equations, use solution methods such as the Laplace transform, and find the response. The recipe is the same whether the circuit is simple or complex, contains one loop or many loops. For this method to lead to an intuitive understanding a large number of problems of the same class are solved and their universals are derived to construct a qualitative mental image (students' demand for a larger repertoire of problems and the increasing number of end-of-chapter problems available in circuit textbooks testify to the above). The simulation modules discussed in this paper do not teach students how to write the node and mesh equations and solve them (although they indirectly help in the analytical approach by providing numerical answers). They continually solve the circuits and make the results available to the student (both quantitatively and qualitatively, in real-time or frozen on the screen). Through easy manipulation of variables, this cycle can be repeated quickly and, if needed, in real-time. This enables the user to accumulate many observations, examine various conditions, test and verify hypotheses, and finally construct a conceptual model of the problem and its solution at a remarkably low cost.

Effective learning requires comprehensive representation of the situation (the circuit, inputs and outputs, the problem to be analyzed, acceptable solutions). The qualitative understanding of a problem helps students develop such a comprehensive representation. It makes students aware that there are many ways to apply their knowledge (i.e., choose the solution). While two or more

solution methods may lead to the same result and answer, each may have different features and attributes. Some are clearly more elegant, more illuminating, simpler, more efficient, or more accurate and, therefore, preferable to others. By limiting the circuit to a relatively few parts, the circuit module can also be used as design tools at the entry level for a class of circuit designs, which rely on intuition and intelligence rather than on an analytical and technical background.

7. Conclusions

Circuit modules discussed in this paper can be used as tools for exploration, tutorials, structured lectures, presentations, testing, and design. They can reinforce both analytical and laboratory approaches to the teaching and learning of the fundamentals of electric circuits. Because of their ease of parameter manipulation and a response time that can approximate the real-time operation of physical circuits, the modules provide the student with a broad spectrum of observations and examinations not easily available in the laboratory or by analytical approaches.

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Mahmood Nahvi
Electrical Engineering Department
Cal Poly State University, San Luis Obispo, CA 93407
Phone: (805) 756-2308; Fax: (805) 756-1458
E-mail: mnahvi@calpoly.edu; Homepage: <http://www.ee.calpoly.edu/~mnahvi>