"Software for New Directions in Undergraduate Circuits Instruction"

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Abstract Many universities have dedicated personal computing environments supporting their engineering curricula. A typical arrangement allows students to use a variety of software tools for writing reports, performing complex analysis and simulations, and illuminating abstract concepts. In an electrical engineering department, the sophistication of these tools might range from spreadsheets and word processors, to industrial-strength computer-aided engineering systems for designing integrated circuits, and modeling processes for fabricating such circuits. While commercial engineering software tools can provide a high degree of realism to the curriculum, they don't necessarily lend themselves to the broader objectives of classroom instruction. **Commercial tools generally provide powerful analytic and problem-solving capability, but fail to present an integrated view of concepts**. Hence, there is a need for point tools serving the pedagogical needs of individual courses within an overall curriculum. This paper identifies key features that can be used to compare software tools for the introductory circuits courses, and then describes features of a new software tool for students and faculty in the undergraduate circuits course sequence.

I. Background

Circuits courses provide a foundation for undergraduate electrical engineering education, and are often taken by other engineering majors to satisfy curriculum requirements. In many accredited degree programs one or two courses cover, as a minimum, the fundamentals of Ohm's Law, Kirchhoff's Laws, time-domain (transient) analysis, power, sinusoidal steady-state response, Bode plots, Fourier series, Fourier transforms, and Laplace transforms, and spectral concepts. These courses typically focus attention on linear circuits having resistors, capacitors, inductors, opamps, independent voltage and current courses, controlled sources, and transformers, with primary attention to step and sinusoidal input signals.

Today's classroom and computer technologies offer new solutions to the challenges that confront students and instructors in engineering. Software tools now support the curriculum, and many students learn to use them early in their studies. The availability of powerful personal computers linked to classroom video projection systems creates an opportunity for faculty to broaden the scope of their instruction on-the-fly, with a high level of audience interaction and exploration. With software tools, examples can be explored freely, and students can address "what-if" questions immediately. Students gain valuable reinforcement for their understanding of abstract concepts by seeing physical, practical effects on the screen, under their control.

Given this scope of subject matter and available technology**, how, then, might one evaluate the applicability of software tools to the task of teaching circuits**?

II. Software Support for the Circuits Instructor

Because analysis of even elementary circuits is mathematically intensive, time-consuming and often tedious, instructors can be tempted to use only canned, tried-and-true, examples in the classroom. The risk of making a mistake in a calculation in a live classroom exercise, together with the pressure to cover what seems like an enormous amount of material in a shrinking amount of time, can entice an instructor to choose the safe, attractive path of familiar examples in a narrow domain of circuits and input signals. On the other hand, the abstract concepts in circuit theory can be better understood if students are encouraged to entertain questions about the subject matter, and if they can witness and engage in such probing as part of their experience in the classroom. But the numerical calculations supporting an exposition of concepts in circuit theory limit the range of probing that can occur. **A software tool for introductory circuits should allow the instructor to establish and change component values and signal sources quickly, and immediately display results, without a significant risk of mistake.**

III. Software Support for the Circuits Laboratory

Hardware laboratories can play a key role in a circuits curriculum by providing hands on experience with actual circuits and instruments. But the availability, security, and reliability of equipment can limit a student's access to resources. Labs might be locked after hours, or they might be serving other functions. Individual instruments might be broken, and components might be in short supply. Even if equipment is available, the allowed range of operation of the hardware might limit the student's exploration of a circuit. Or personal safety might be a limiting factor. On the other hand, **a software environment for exploring circuits should provide a virtual laboratory that does not ordinarily impose restrictions of safety, reliability and access to the student**. A virtual kilovolt source will not vaporize a virtual circuit or endanger a real student!

IV. Software Support for the Self-Study Environment

It is commonplace for students to study in "wired" environments, where they have access to personal computing resources and the internet**. Software tools for introductory circuits should be compatible with the low-cost of a personal computing environment, and be user-friendly enough to allow students to not only solve homework problems, but to safely explore circuit-theoretic concepts on their own**. Certainly, an individual personal computer might fail to operate, but a student will have an easier time finding a replacement for a PC in the dormitory than a replacement for a power supply. **Software tools should also enable the student to "capture" the results in electronic or hardcopy format, and imbed them in a report, and/or email them to the instructor.**

V. Support for Building Intuition

The "safe" paradigm of canned examples can send a mixed message to students: "**Develop your intuition, but don't explore circuits**." This could explain why students deal with the mathematics of capacitors and inductors, but fail to understand their physical role in a circuit, and cannot anticipate the behavior of a circuit containing these elements. It seems self-evident that working problems to pass an exam does not necessarily build intuition, and solving individual problems does not integrate concepts. It seems desirable, then, that software tools support a student's need to gain intuition in their foundation courses, where study habits and attitudes towards subject matter are formed. **Software tools should support an interactive mode of inquiry in which an instructor asks questions that lead the development of a student's intuition about the physical behavior of a circuit, and then demonstrates the effect in real time, or has the student explore the question outside the classroom**. For example, when an instructor poses a question about the effect of increasing the value of a feedback capacitor in an opamp filter, some of the students might believe that the output voltage will become oscillatory, others might disagree. A discussion could sort out reasoned answers from guesses. A demonstration could not only reveal the circuit's behavior, but could also reveal the effect of incrementally changing one or more components, individually or as a group. To further reinforce the experience, the instructor can assign the task of formally analyzing the circuit to confirm that the observed behavior is consistent with theory.

Circuit theory combines time-domain analysis and frequency domain analysis, and the relationship between concepts in the two domains can be difficult to grasp and appreciate. **Interactive software tools should expose and illuminate the relationship between the time-domain and frequency-domain models of circuit behavior**. Without exploration**, circuits courses can bog down in theory and abstractions, and leave students with an undeveloped intuition about circuit behavior**. This is especially true for students who are taking circuits as an elective outside the field of their major.

Software tools that solve individual problems do not necessarily reveal relationships between concepts in circuits. For example, a tool that displays a time domain response of a circuit but does not illustrate the circuit's pole-zero pattern in the same display misses an opportunity to connect abstract concepts to physical behavior. **Software tools for teaching circuits should illuminate relationships between concepts and do so in an integrated visual display**.

VI. Features of the Circuit Works Software Environment

Having identified a number of criteria for evaluating software tools for the introductory circuits courses, this paper will now describe and discuss the main features of *Circuit Works*[1], a new software environment for exploring the time and frequency domain properties of basic circuits.

***Circuit Works* is a Windows™-based interactive software packag**e for computing a circuit's time and frequency domain responses and displaying conceptual relationships between fundamental properties of basic electrical circuits. A notable feature of the software environment is that it presents an integrated display of s-domain, frequency domain, and time domain concepts in circuits. This presentation can reinforce the classroom experience of the student by displaying abstract concepts and related physical behavior. The *Circuit Works* display format reveals how variations in a circuit's component values affect the circuit's response in the time and frequency domains, and helps students visualize and appreciate relationships between such important concepts as frequency-domain Bode plots, s-domain pole-zero patterns, and time-domain waveform responses. As a classroom tool, the *Circuit Works* software environment lets teachers reinforce their classroom lectures by easily generating displays of circuit concepts - on the fly, in real time.

Setting up the Circuit: The starting point for all activity in *Circuit Works* is the circuit that is to be analyzed. The system includes a library of 100 basic circuits ready for use. A mouse-click selects a circuit. *Circuit Works* allows the user **to assign up to two independent sets of component values to the same circuit**, effectively creating two circuits whose time domain and frequency domain properties can be compared. The labels of the primary and secondary values are automatically presented in the parameter display window and are distinguished by their color. ***Circuit Works* automatically updates the screen displays when an initial condition, a component value, or a parameter of the input signal changes.**

Circuit Works has many user-friendly features. For example, the tool will issue a warning and ignore an attempt to simulate a circuit whose components have not been assigned values. It also includes on-line documentation and hypertext help files.

Mouse clicks select the circuit's input signals and the voltage or current that is to be observed. The voltage across a capacitor and the current in an inductor can be assigned initial conditions. *Circuit Works* includes a family of 20 periodic signals and 15 aperiodic input signals that may be used to create voltage and current sources driving the circuit. Figure 1a shows a signal in the periodic sub-library, and Figure 1b shows a signal from the aperiodic sub-library.

The set of parameters needed to specify the waveform of an aperiodic signal in the *Circuit Works* signal library may include the following:

A	Amplitude
Δ	Pulse width
ω_o	Sinusoidal frequency
ϕ	Phase angle
τ	Turn-on delay time (postpones application of source)
σ	Exponential decay factor ($\sigma > 0$ for decay)

Circuit Works includes switched, damped, sinusoids having the form: $f(t) = Ae^{-\sigma(t-\tau)} \sin(\omega_o(t-\tau) + \phi)\, u(t-\tau)$, where u(.) is the unit step, ω_o is the radian frequency, σ is the damping factor ($\sigma > 0$ for decay, $\sigma < 0$ for growth), and ϕ is the phase angle. The turn-on delay time parameter, $\tau \geq 0$, determines when the source is applied to the circuit. For $0 \leq t \leq \tau$ the source is assumed to be off. The parameter Δ acts as a pulsewidth in signals having a finite duration.

Pole-Zero Patterns: ***Circuit Works* automatically displays the pole-zero pattern of a circuit's input-output transfer function** after component values have been assigned and an output voltage or current has been selected. Figure 2 shows the result of zooming the display of a pole-zero pattern. The display is automatically updated when the value of a component is changed. **The pole-zero pattern can be displayed for the primary circuit, the secondary circuit, or both circuits in a superimposed, color-differentiated format**. In each case, the numerical value of the location of each pole and zero is displayed.

<u>Frequency Response</u> (Bode Plots): ***Circuit Works* automatically displays the circuit's pole-zero pattern and its frequency domain Bode plots** (magnitude and phase). The user has control of the range of frequencies over which the plots are displayed. The Bode plot can be displayed for primary, secondary, or both circuit values. The plot can also be displayed in a zoom format. The Bode plot and the spectra plot can be displayed simultaneously, and, likewise, the display of the Bode plot and the output waveforms can also be displayed simultaneously. **Note: the screen images produced by *Circuit Works* can be captured in a variety of formats for imbedding within reports**.

Figure 3 illustrates the screen contents displayed by *Circuit Works* for a series RC circuit, assigned primary and secondary component values, and an initial capacitor voltage. Primary and secondary responses are both displayed. The Bode plots were made over a range from 0 to 1200 radians/sec (the pole farthest from the origin is at s = -1000 on the real axis). The pole-zero patterns and Bode plots of the transfer function between the source voltage and the capacitor voltage, displayed simultaneously for two choices of components, clearly shows the effect of changing the value of the capacitor from 1μF to 5μF. **The primary circuit, having the smaller capacitor, exhibits a higher bandwidth and has its pole farther from the origin**. (The actual on-screen displayed results are color coded to distinguish the primary and secondary results and to associate them with their component values.)

If the Bode responses are displayed for both the primary and secondary component values, the "zoomed" display will show the magnitude and phase plots in semi-logarithmic format over two decades of frequency, and the vertical axis is normalized by a scale factor. The center frequency, ω_M, for the plot is selectable.

<u>Time-Domain Analysis</u>: ***Circuit Works* automatically computes and displays time-domain waveforms of the voltages and currents in a circuit**, including: i. The zero-input response (ZIR) to initial conditions, ii. **zero-state response** (ZSR) to an applied source, with zero initial conditions, and iii. the **initial-state response** (ISR) to an applied source and arbitrary initial conditions. It also presents the **superposition** of the ZIR and ZSR waveforms to form the ISR waveform. An instructor can immediately display a circuit's response to an impulse or a step function, pulses of various shapes, damped sinusoids, and other input signals. The user interface allows the instructor to choose from a built-in library of parameterized periodic and aperiodic signals and quickly generate time domain responses of the voltages and currents in the circuit. In seconds, the parameters of the waveform of the input signal can be changed, and the results displayed. Or a different signal can be chosen as the input or the output.

Figure 5 shows the ZIR of a series RLC circuit in which the primary set of components produces an overdamped response to the initial voltage and inductor current. Figure 6 shows the response for the secondary set of components. The response is underdamped, i.e. the poles of the transfer function do not reside on the real axis and are near the j-axis. The time-domain response is oscillatory. For comparison, Figure 7 shows the superimposed responses for both sets of components. (Notice the location of the primary and secondary poles in the s-plane, and the initial conditions on the capacitor voltage and the inductor current.)

The capacitor voltage has an initial value of 5 volts (after de-scaling by the value of the scale factor, Y_s). In the overdamped circuit the capacitor voltage decays to zero in approximately 5.48

secs, while in the underdamped circuit the voltage oscillates and decays to zero in 80 secs. These decay times can be computed from the location of the circuit's poles, or they can be measured on the displayed waveforms.
Figure 8 illustrates the sensitivity of the capacitor voltage to a change in the value of the resistor. It is apparent that decreasing the size of the resistor causes the response to become oscillatory. The basis for this effect can be described analytically in a circuits course, where a formal relationship can be established between the values of a circuit's components and the location of its poles. The display is shown in "zoomed" format. Figure 9 shows the ZSR of the capacitor voltage to a step input current source in a parallel RLC circuit. Figure 10 shows the ISR of the circuit to initial conditions and a step input current source signal.

The initial-state response of a linear circuit is the sum of its zero-input response and its zero-state response. *Circuit Works* can simultaneously display the individual waveforms of the ZIR, ZSR, and the ISR. Figure 11 shows the superposition of the ZIR and ZSR to form the ISR in a parallel RLC circuit.

<u>Sinusoidal Steady-State Response</u>: *Circuit Works* computes and display the waveform of the steady-state output signal of a circuit for a selected number of terms in its Fourier series. This feature reveals the incremental composition of the periodic output signal. Figure 12 shows the approximate steady-state response of the capacitor voltage in a series RC circuit to a squarewave input signal having a fundamental frequency of 6.28 radians/sec. Three terms were used in the Fourier series of the output signal. Figure 13 shows the same response when ten terms are used. By allowing the user to select the number of terms in the Fourier series, *Circuit Works* helps students understand the role of the Fourier series in circuit analysis.

Note: ***Circuit Works* automatically re-computes the Fourier series and displays the output waveform when a component value is changed**. This feature can be used to quickly explore the sensitivity of a circuit's steady-state response to a given component.

<u>Input – Output Spectra</u>: Circuit Works provides a framework for displaying the relationship between the Fourier spectra of circuit's input signal, the transfer function of the circuit, and the Fourier spectra of the output signal of the circuit. The system displays the Fourier series magnitude and phase spectra of steady-state responses to periodic signals, and the Fourier transform magnitude and phase spectra of responses to aperiodic signals. The spectra of a periodic input signal is represented by lines drawn to heights corresponding to the magnitude and phase of the signal's complex Fourier series coefficients. Spectral lines are displayed over a selectable frequency range from ω_L to ω_H. Figure 14 shows the magnitude spectrum of a biased rising sawtooth periodic input signal.

If the input signal is aperiodic, the magnitude and angle of its complex Fourier transform are plotted vs. ω over the range of the frequency axis determined by ω_L and ω_H, the limits of the Bode plot. Figure 15 shows the magnitude spectrum of a rectangular pulse signal.

Circuit Works automatically determines the spectra of the output signal from the spectra of the input signal and the transfer function of the circuit. The magnitude spectrum of the output signal is the product of the magnitude spectrum of the input signal and the magnitude of the circuit's transfer function. The angle spectrum of the output signal is the sum of the angle spectrum of the input signal and the angle of the transfer function.

In a flash *Circuit Works* can generate an integrated display of the circuit's Bode response and the input/output signal magnitude or phase spectra to show how the Bode response forms the magnitude and phase spectra of the output signal from the spectra of the input signal. Figure 16 shows the input/output spectra of a series RC circuit when the input signal is a periodic biased rising sawtooth signal. In this example, *Circuit Works* reveals how the spectral lines of the output of the secondary circuit undergo greater attenuation than those of the primary circuit. This effect can be related to the Bode response of the circuit.

Active and Passive Filters: The *Circuit Works* library includes first- and second-order active and passive filter circuits. Figure 17 shows a second-order, active highpass filter implemented in the library. Once a filter has been selected the other *Circuit Works* operations can be performed. When the bandwidth of a lowpass filter is high enough to pass the spectra of the input signal without significant distortion the output signal will be a reasonably good approximation of the input signal. Figure 18 shows how a series RC circuit filters an input squarewave for one set of components (secondary), but passes the input signal for another (primary). It is apparent that decreasing the value of the circuit's resistor increase the circuit's bandwidth.

Free Demonstration Software

A free demonstration version of *Circuit Works* is available at www.cktworks.com. Windows: Requires at least a 386 processor or better (486 recommended), 8MB of RAM, 4MB of disk space, VGA (minimum 800x600 resolution) or better, Windows 3.1 or Windows for Workgroups™ 3.11 running 386 Enhanced Mode, or Windows 95™, or NT-4™. A mouse is required. The software works with any laser, inkjet, or dot-matrix printer that is supported by a Windows device driver.

References

1. Circuit Works – CircuitWorks LLC, P.O. Box 8269, Colorado Springs, Colorado 80933-8269

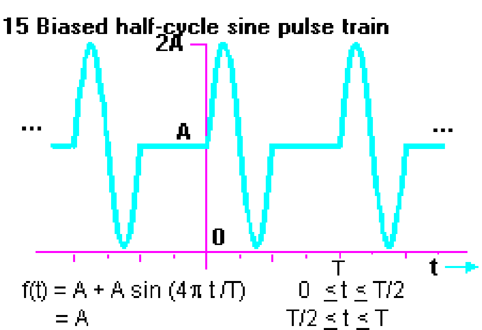

Figure 1a

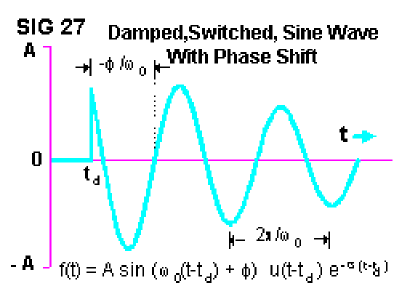

Figure 1b

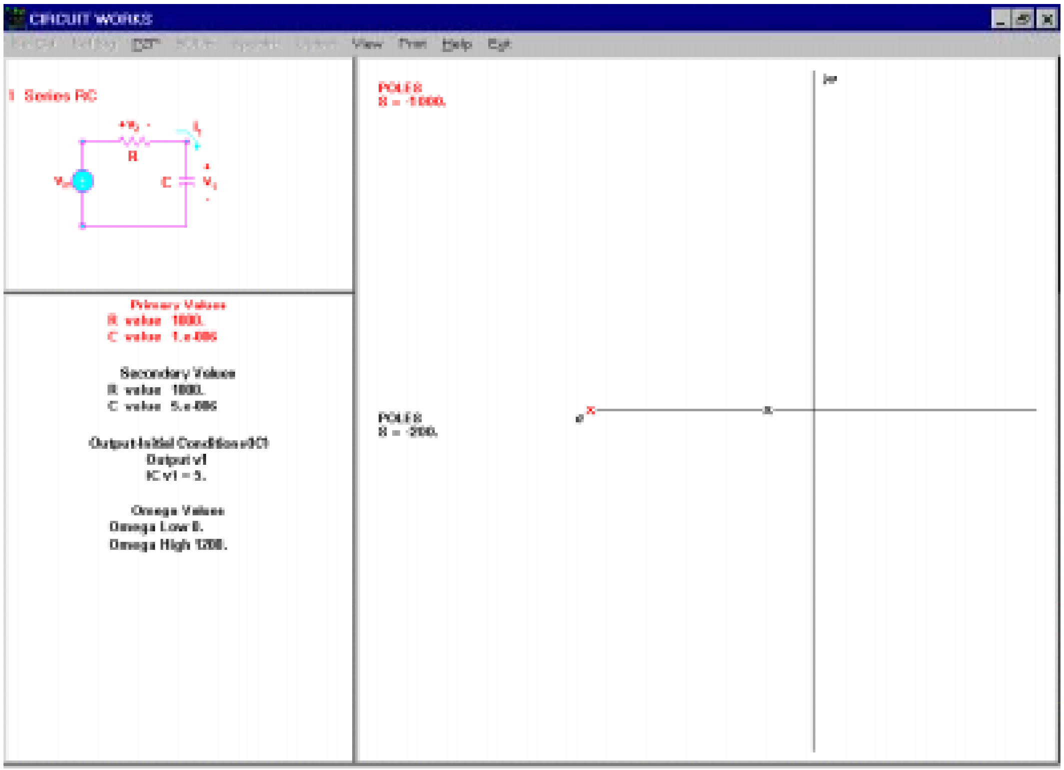

Figure 2 Screen display after zooming the display of both pole-zero patterns.

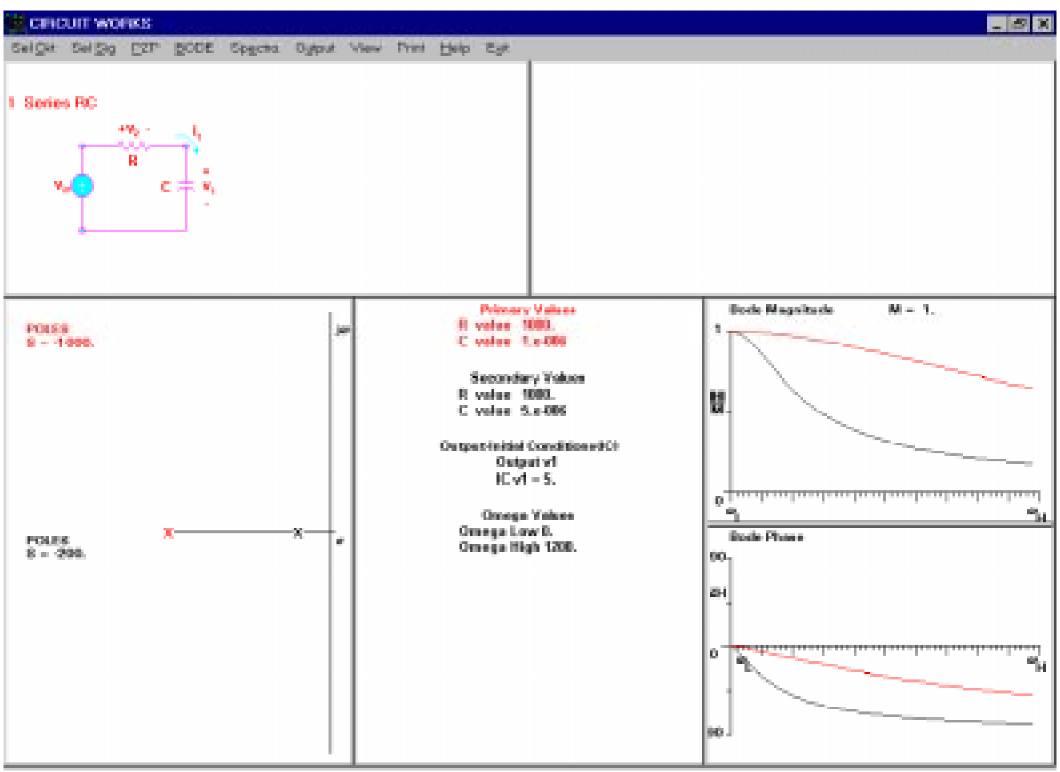

Figure 3 Screen display after selecting a circuit and assigning primary and secondary values to components.

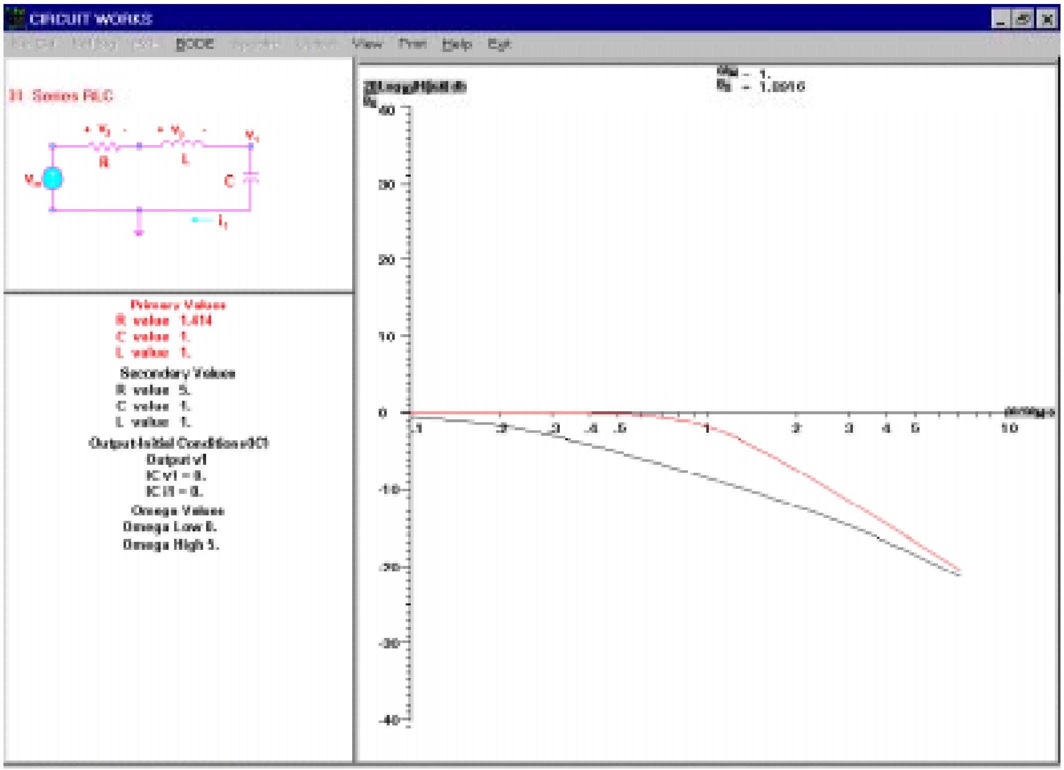

Figure 4 "Zoomed" Bode plots in semi-logarithmic format.

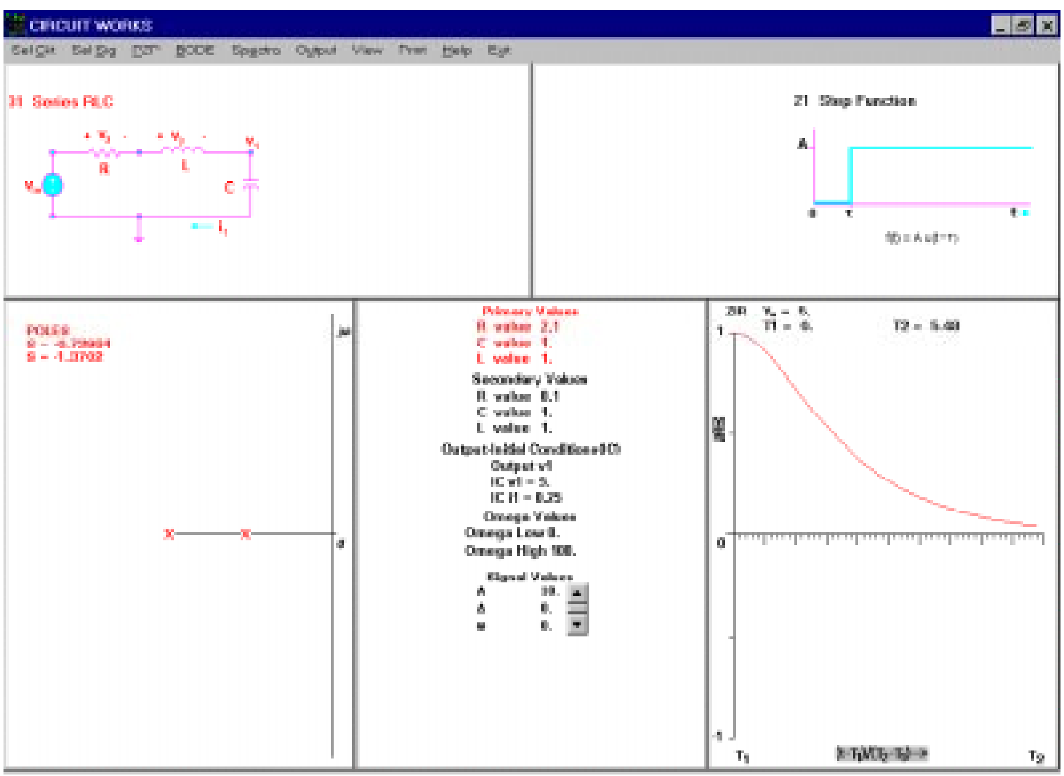

Figure 5 Zero-input response of the capacitor voltage to initial conditions in an overdamped series RLC circuit.

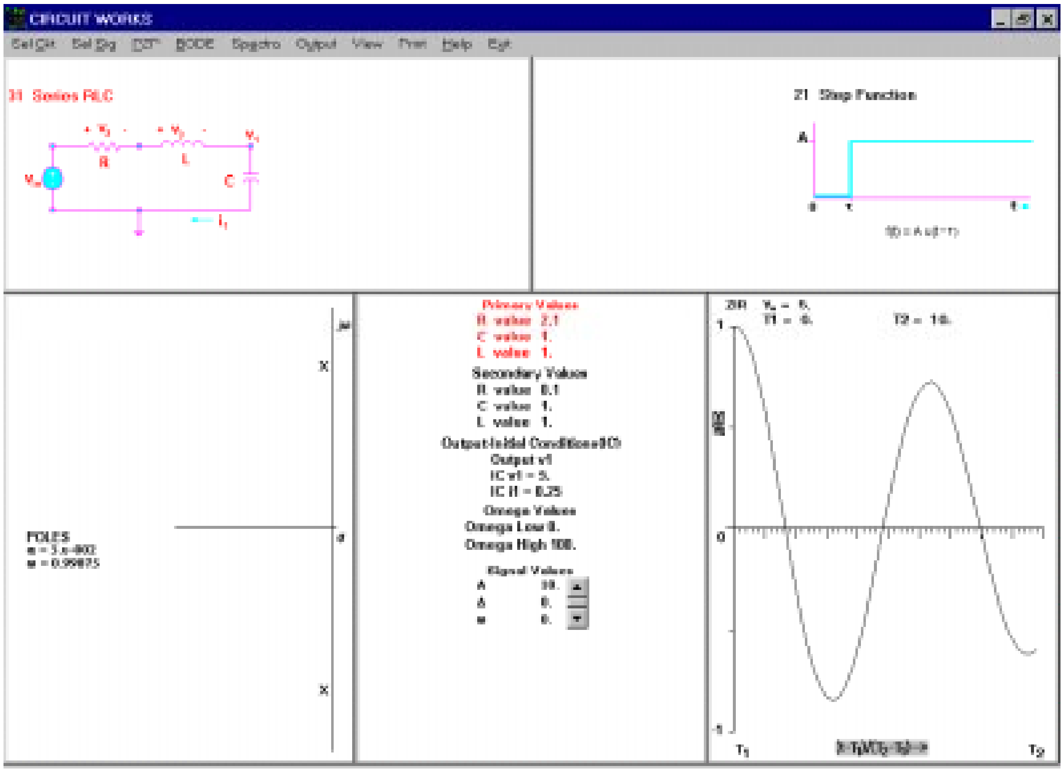

Figure 6 Zero-input response of the capacitor voltage to initial conditions in a underdamped series RLC circuit.

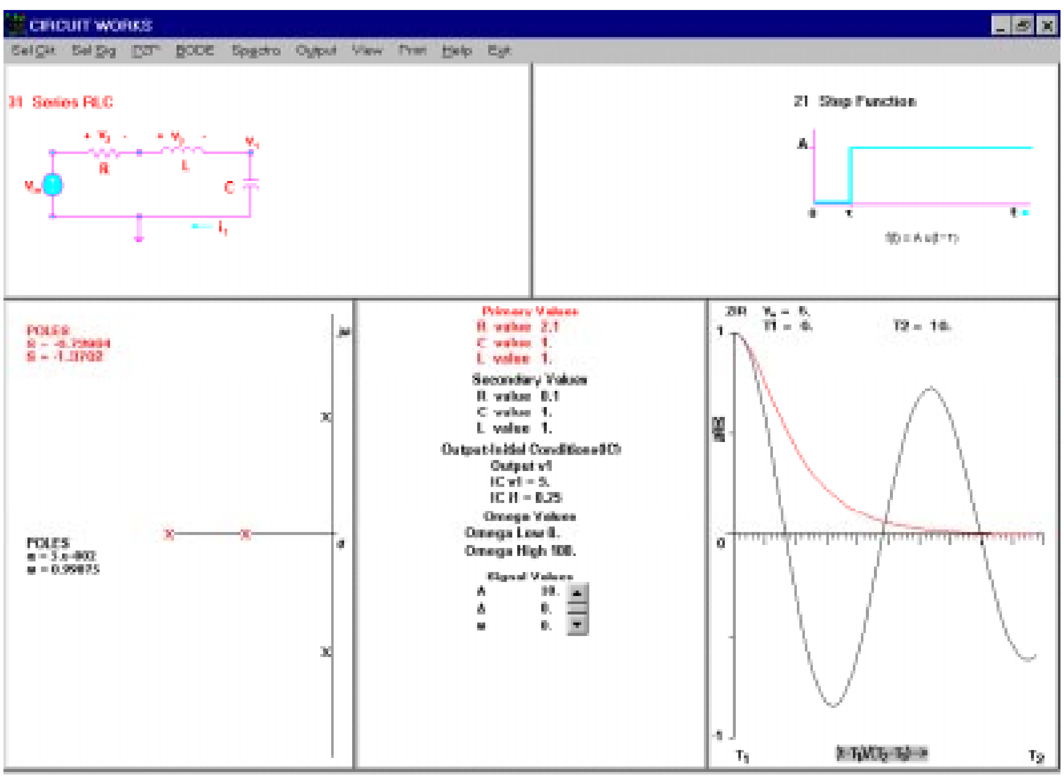

Figure 7 Comparison of series RLC circuit responses for an overdamped primary circuit and underdamped secondary circuit.

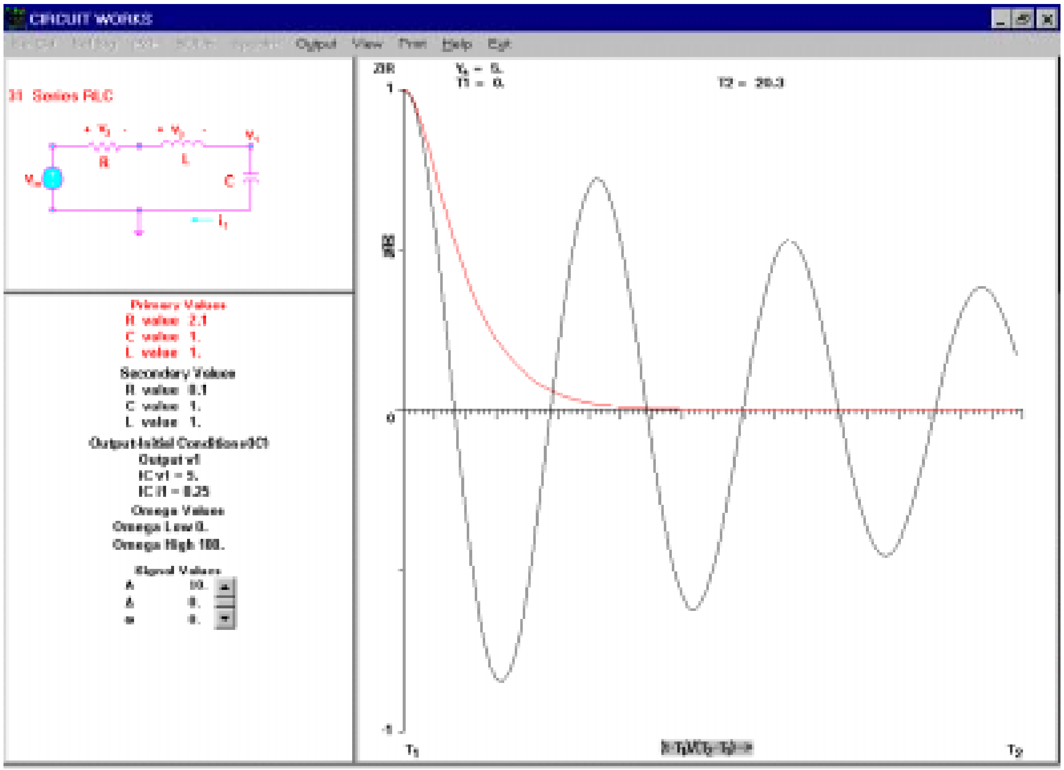

Figure 8 “Zoomed” display of the zero-input response of the capacitor voltage to initial conditions in a series RLC circuit, overdamped primary circuit, underdamped secondary circuit.

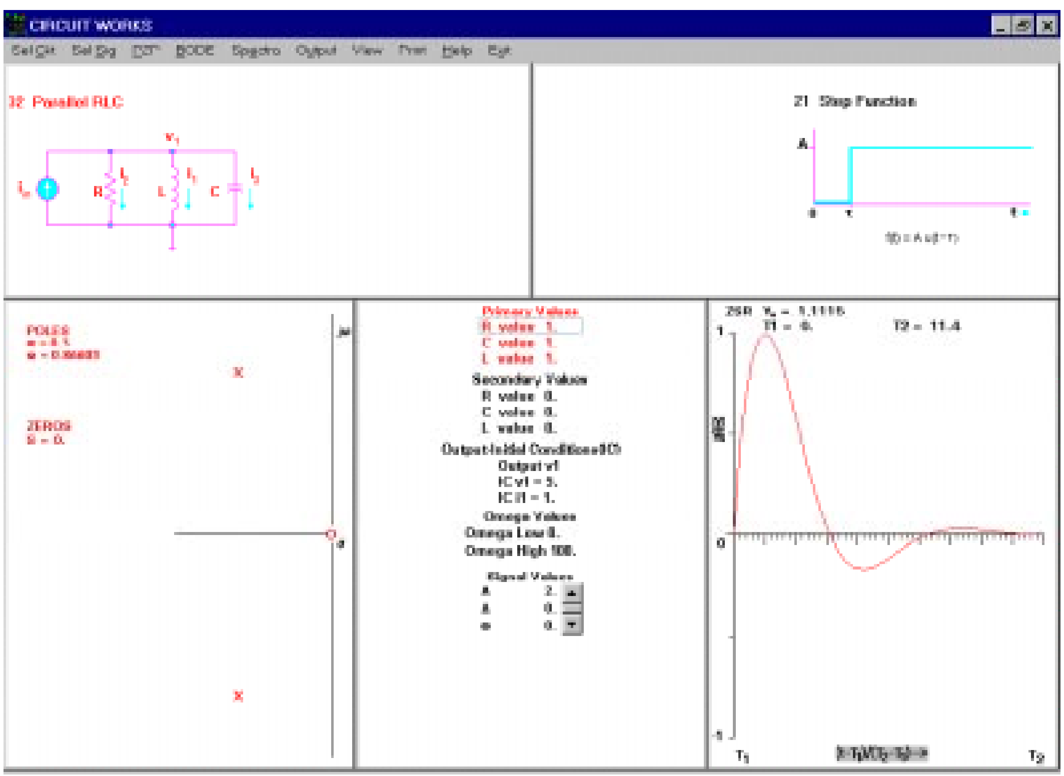

Figure 9 Zero-state response of the capacitor voltage to a step input in a parallel RLC circuit.

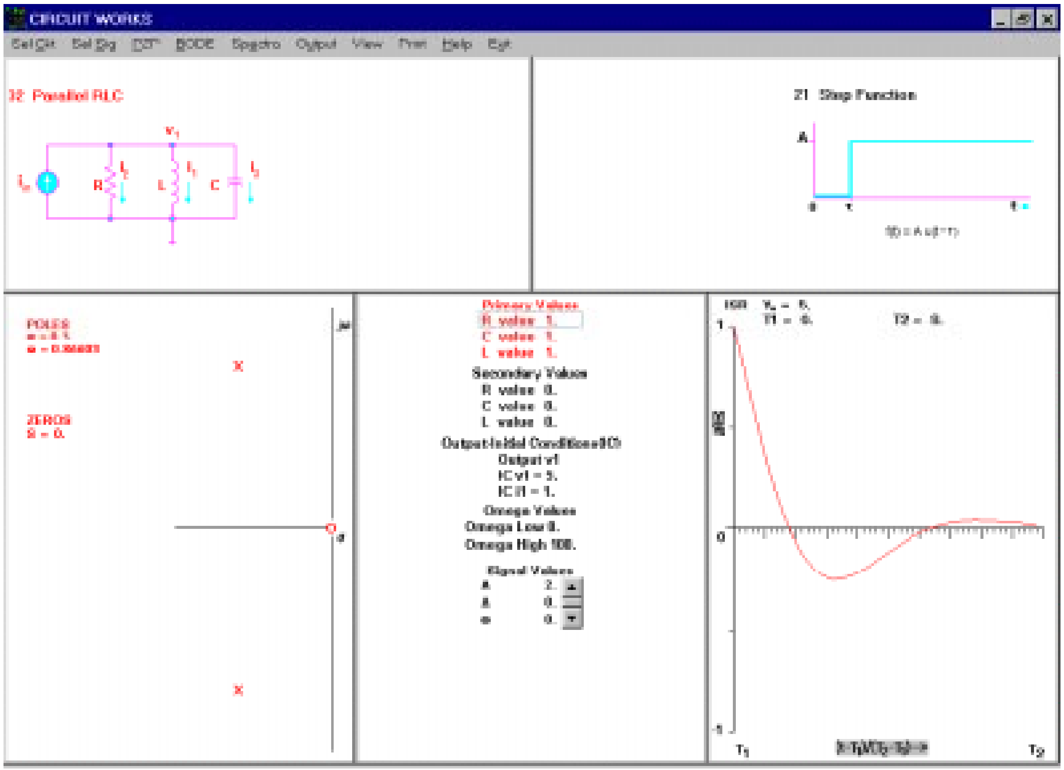

Figure 10 Initial-state response of the capacitor voltage to a step input current source in a parallel RLC with initial stored energy.

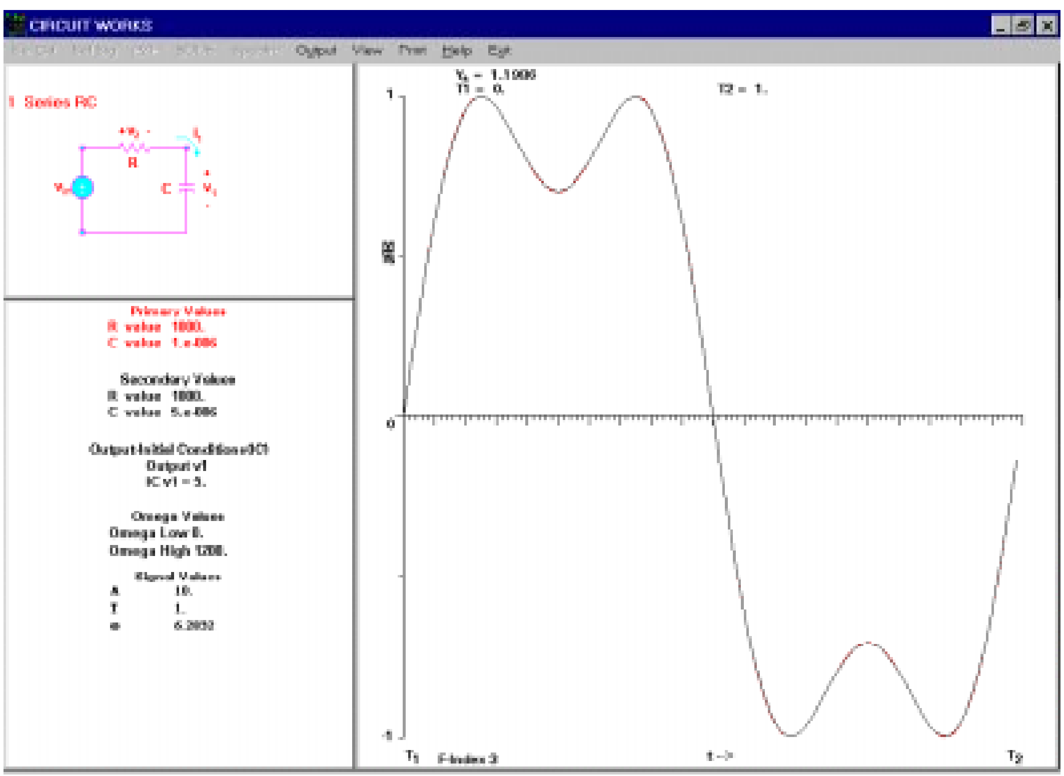

Figure 12. Screen display showing the (zoomed) approximate steady-state response of the capacitor voltage to a squarewave input signal, using three Fourier series terms.

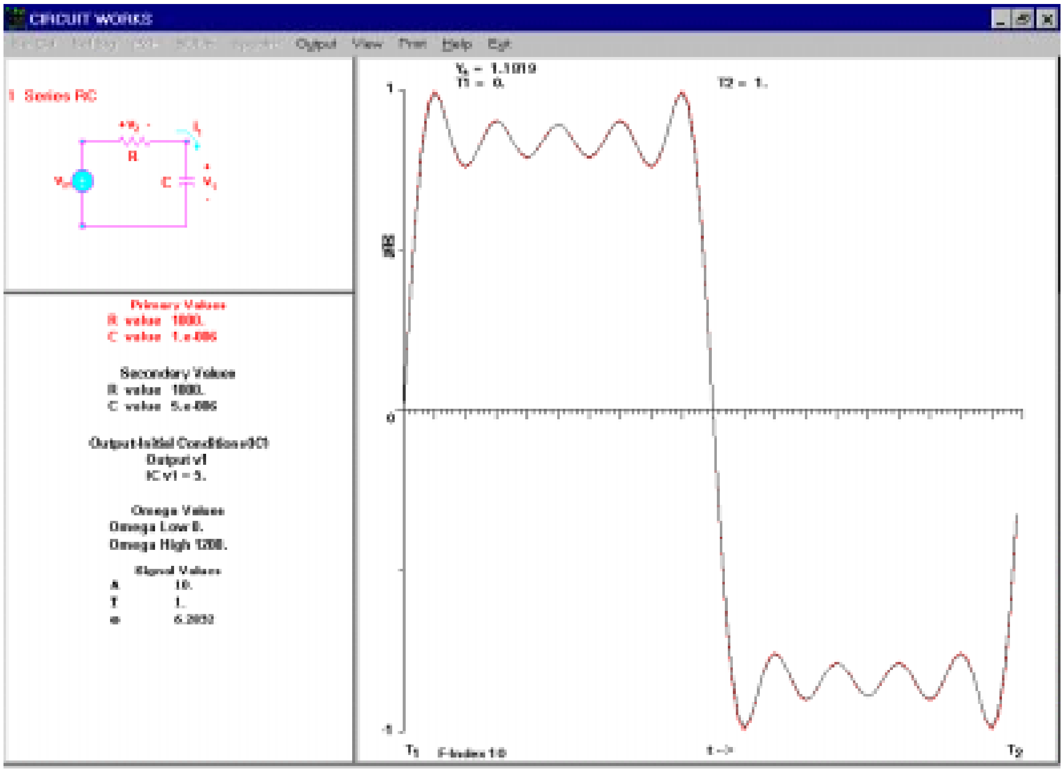

Figure 13. Screen display showing the (zoomed) approximate steady-state response of the capacitor voltage to a squarewave input signal, using ten Fourier series terms.

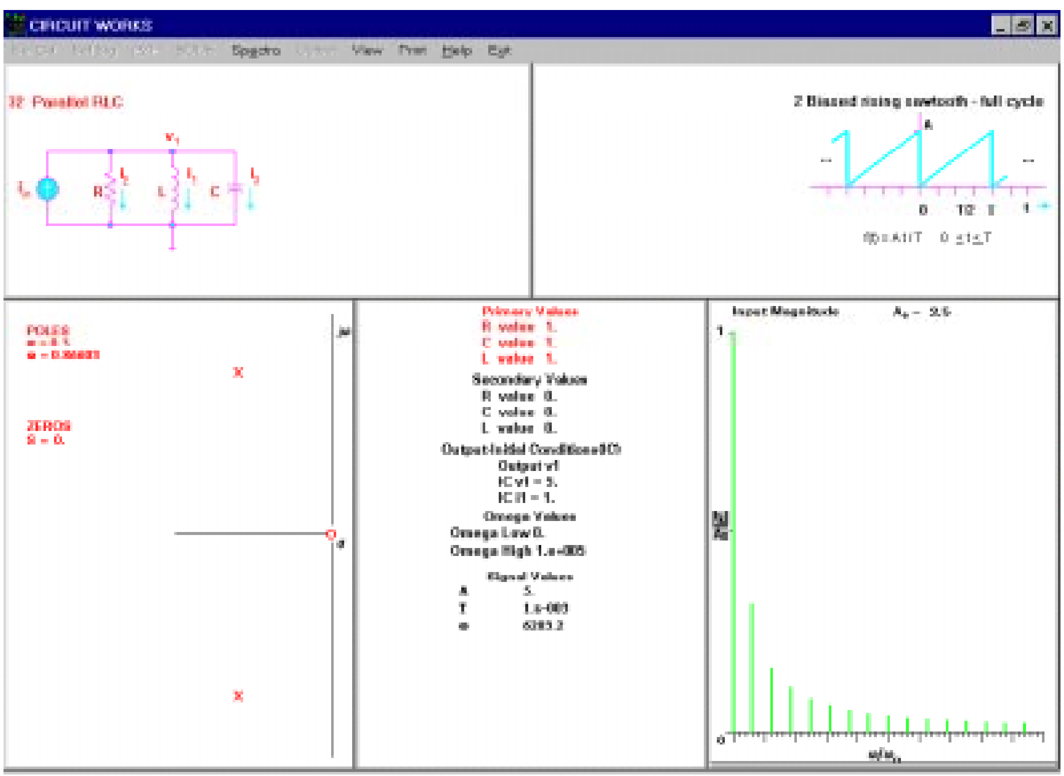

Figure 14. Magnitude spectrum of a periodic input signal.

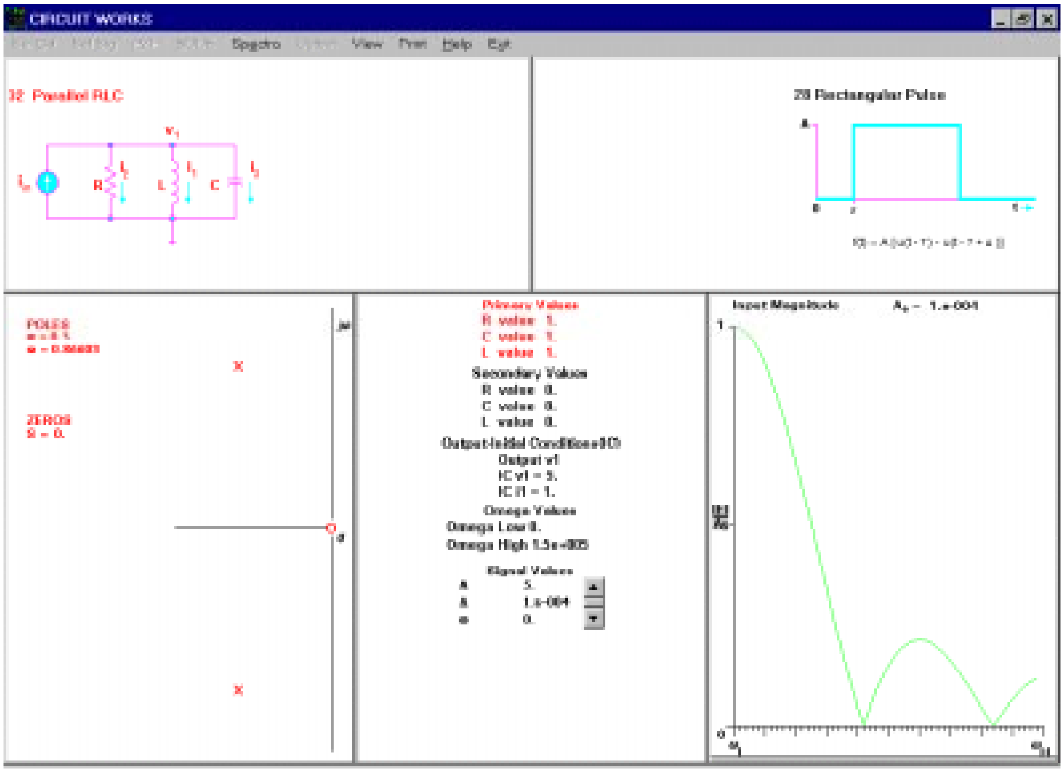

Figure 15. Magnitude spectrum of a rectangular pulse (aperiodic) input signal.

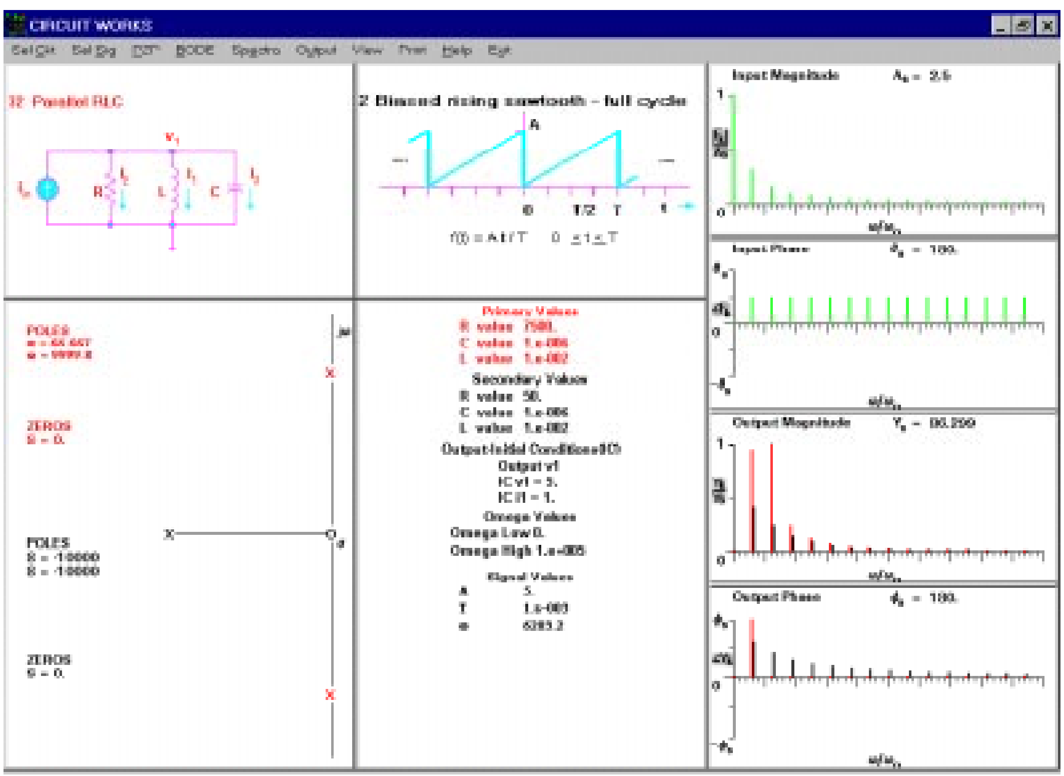

Figure 16. Input-output spectral relationships.

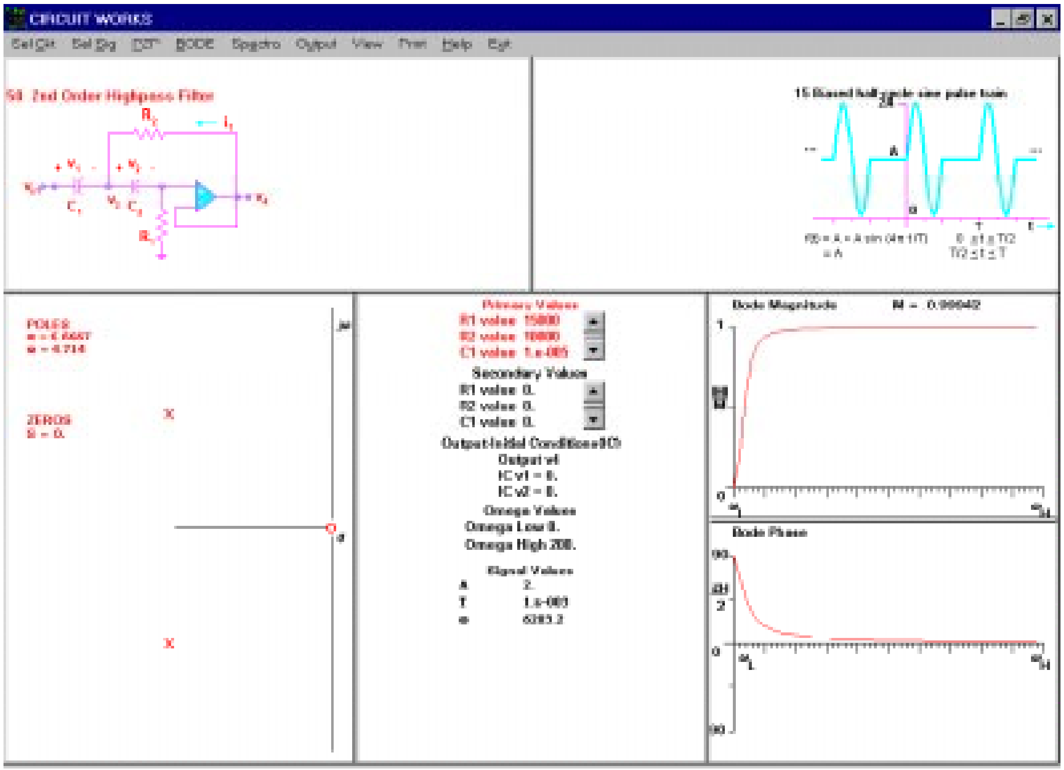

Figure 17. Frequency response of a second-order, active highpass filter.

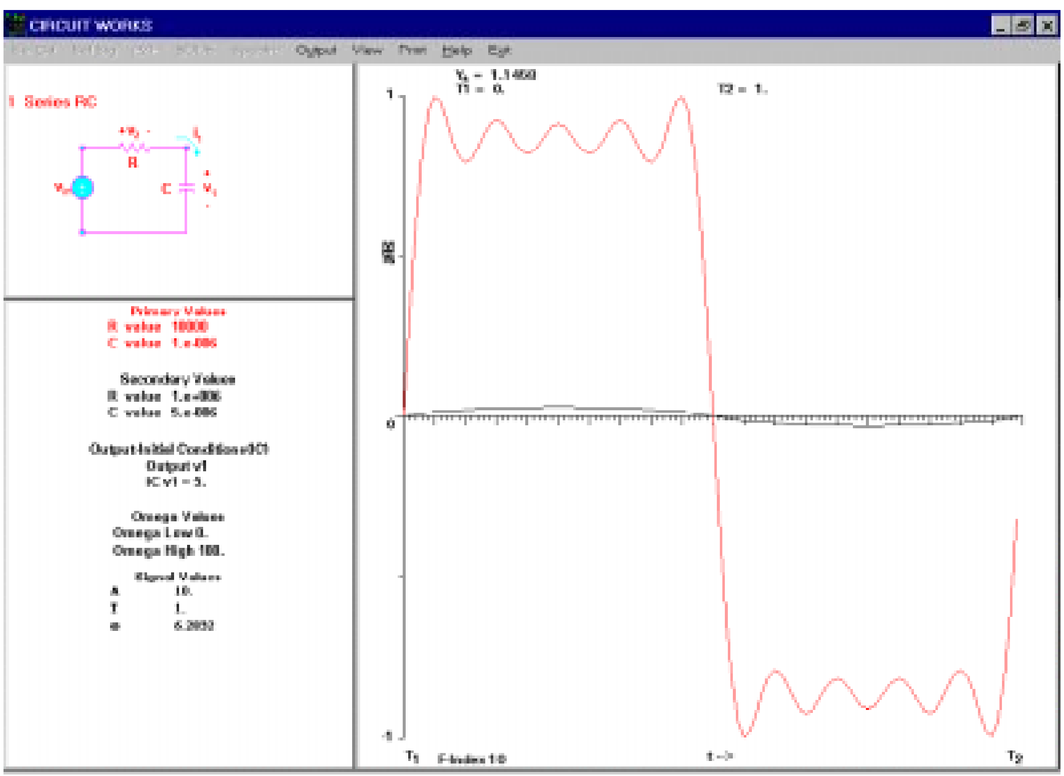

Figure 18 "Zoomed" display of the RC circuit's response to a square wave, approximated by 10 terms in the Fourier series (shown for primary and secondary component values).