

2006-2191: A VIRTUAL INTRODUCTORY ELECTRICAL ENGINEERING LABORATORY FOR TAKE-HOME EXPERIMENTS

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A VIRTUAL INTRODUCTORY ELECTRICAL ENGINEERING LABORATORY FOR TAKE-HOME EXPERIMENTS

INTRODUCTION

A virtual laboratory in the form Java Applets was created for Electrical and Computer Engineering (ECE) sophomores at North Carolina State University to support an introductory course on signals, circuits and systems. This is the first required ECE course our students take after they complete the core courses common to all engineering students during the freshman year. The new course was offered for the first time in the Fall 2000 semester and since then, it has been offered to more than 2000 students. The course includes a novel laboratory utilizing custom hardware enabling experiments on various systems level concepts such as amplification, analog filtering and modulation. Detailed information about the course and the hardware laboratory can be found in the proceedings of this conference in another paper by the first author of this paper.

To assess our success in several key areas, carefully planned student surveys were conducted and specific assessment questions were included in the exams. First and foremost, these studies indicated that spending three hours in the laboratory every week is not sufficient for the beginning students to master the modern bench-top measurement instruments. We saw that students' struggles with the instruments (especially during the first half of the semester) could result in frustration in the laboratory creating an artificial barrier in performing the experiments and learning the fundamental concepts. Extra time on the equipment could certainly help; however, limited resources available for laboratory instructors did not allow us to keep the laboratory open outside the regularly scheduled laboratory sessions. The problem became worse when one of the students in a laboratory group assumed the primary operator role, while the others remained relatively passive. A passive student could still record all the measurement results in his/her laboratory book to include them later in the report for that experiments and receive a good grade in spite of his/her lack of active involvement in the laboratory. Finally, a student did not get the full benefit of running an experiment when he/she came to the laboratory without reviewing the background material properly. Assigning a few homework problems related to the next experiment helped but it often did not guarantee satisfactory preparation for the experiment. We believe that similar concerns are also shared by other institutions offering introductory laboratories and they are expected to be amplified even further when large enrollment numbers, limited laboratory facilities and long list of subjects to cover during a four year ECE curriculum force the institutions to reduce the hours dedicated to traditional hardware laboratories. The virtual laboratory concept presented in this paper emerged as a potential solution to address the above challenges. The original idea was simple: create a software tool that simulates the operation of standard bench-top equipment and use the homework assignments to revisit and reinforce some of the key experimental concepts from previous week's experiment.

A primary objective of the virtual laboratory is to help the students learn the standard measurement tools including the function generator, oscilloscope and spectrum analyzer. The virtual instruments are hard wired to a system under test (SUT), which can be a simple circuit intended for beginning students just learning the circuit laws or a two-port circuit such as an amplifier or filter. The virtual laboratory allows the user to apply a periodic signal to the SUT and observe its response in both time and frequency domains. Therefore, the virtual laboratory

can be effectively used to reinforce theoretical concepts introduced in an introductory class on signals, circuits and systems. We believe that even though the virtual lab was never intended as a replacement for a hardware laboratory, it can be used as an independent tool provided the students had some experience with the measurement tools in a previous course.

The screenshot shows a Mozilla Firefox browser window titled "NCSU - Intro. to ECE - Virtual Lab - Mozilla Firefox". The address bar shows the URL "http://www.ece.ncsu.edu/virtu". The page content includes the NC State University logo, the title "Virtual Laboratory", and several paragraphs of text describing the lab's purpose and requirements. A central circular menu lists various simulation tools: Amplification, Spectrum Analyzer, Basic Op-Amp Stages, Simple Diode Circuits, Summing & Subtracting Amplifiers, Circuits with Resistors & AC/DC Sources, Low-Pass Filter, Oscilloscope & Function Generator, and Equalizer. A ShinyStat widget in the bottom left corner displays "Today visits: 1" and "Tot. visits: 1541". The browser status bar at the bottom shows "Done".

NC STATE UNIVERSITY **Virtual Laboratory**

Virtual laboratory is a collection of applets on introductory topics in Electrical and Computer Engineering. The laboratory provides a user friendly simulation environment which allows the students to experiment with simple circuits and systems connected to standard test instruments including the function generator, oscilloscope and spectrum analyzer.

The applets were originally created to support an introductory course (ECE 200: Introduction to Electrical and Computer Engineering Laboratory) at North Carolina State University, however, they are suitable for other courses, which emphasize analysis of signals in time and frequency domains.

To run the applets, you need a computer capable of running [JAVA](#) applets, an internet browser software, which supports frames and has the [Macromedia Flash plug-in](#) installed. You can start the individual applets by clicking on the buttons provided below.

Amplification

Spectrum Analyzer **Basic Op-Amp Stages**

Simple Diode Circuits **Summing & Subtracting Amplifiers**

Circuits with Resistors & AC/DC Sources **Low-Pass Filter**

Oscilloscope & Function Generator **Equalizer**

ShinyStat™
Today visits: 1
Tot. visits: 1541

[Free hit counters](#)

Done

Figure 1: Virtual laboratory home page.

One can find a large variety of applets on the internet intended to teach such concepts. The main difference between the virtual lab suite and other simulations is that the same user interface is used for all the simulations and the user interface closely resembles the front panels of the real test instruments.

The students can access the virtual laboratory through the course web site¹ and run the applets on a computer with Java capability. Figure 1 shows the home page of the virtual laboratory suite. Java applets included in the suite can be started by clicking on the buttons located around the circle. A collection of experimental problems (virtual experiments) were created by the author to help the future instructors of the course. One or two of these virtual experiments are given to the students as part of their weekly homework assignments throughout the course.

A detailed description of the software design methodology including signal generation and communication between different virtual instruments can be found in a previous publication by the author². In this paper, all of the applets included in the suite are reviewed with examples of virtual experiments included in the homework assignments.

VIRTUAL LABORATORY APPLETS:

The virtual laboratory suite consists of the nine applets as shown in Figure 1. Two of these applets are just intended to teach the measurement instruments, hence, they do not have an SUT.

Oscilloscope and Function Generator

The first applet shown in Figure 2 introduces the function generator and the oscilloscope. The oscilloscope includes a digital meter, which measures the frequency, DC value and RMS value of the periodic signal displayed. It also has a sound engine allowing the user to listen to the signal. Typically, the instructor demonstrates the applet during a lecture period and the students are encouraged to use it prior to the hardware laboratory dedicated to teaching these instruments.

The function generator produces five different signals including sinusoid, square wave, triangular wave, random wave and noise. The random wave consists of ten harmonics with decreasing amplitudes and random phase. The noise signal is generated by adding sinusoids of equal amplitude up to a maximum frequency of 20 kHz. As such, this is not a true noise signal, however, it can be used to demonstrate the white noise concept and its features in both time and frequency domains. The user can set the frequency, magnitude (amplitude or peak-to-peak value) and the DC off-set using knobs provided on the front panel of the function generator.

The oscilloscope is a two-channel oscilloscope closely resembling the real instrument. Except triggering controls, it includes all of the basic controls available on a typical bench-top oscilloscope. The user can set the vertical and horizontal scales, choose between AC and DC coupling and change the position of the zero-volt reference.

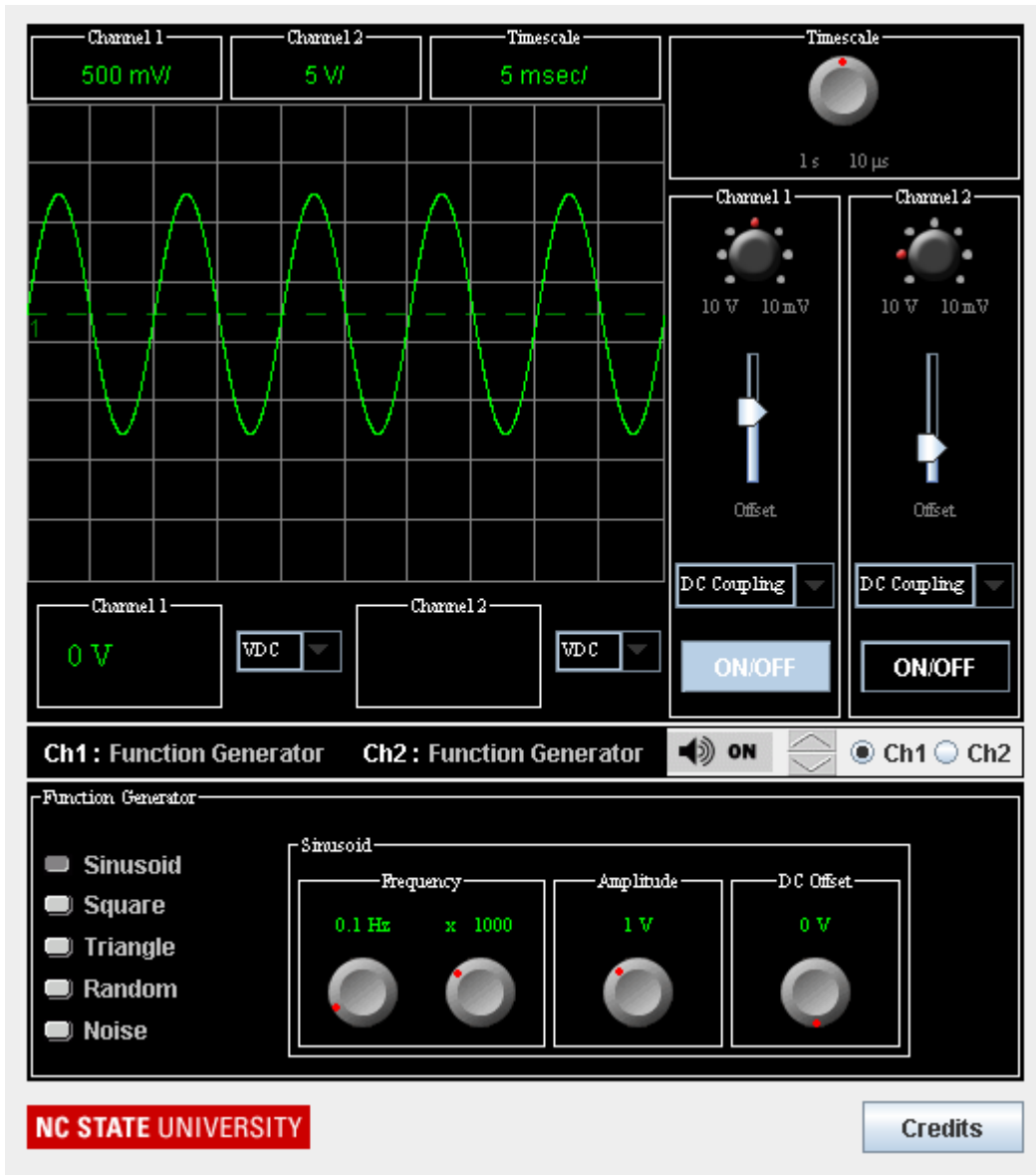


Figure 2: Function generator and oscilloscope used in the virtual laboratory suite.

A typical take-home experiment with this applet is given in Example I. The objective of this experiment is to demonstrate the relationship between the DC and RMS values of a sinusoid with a non-zero DC off-set. Prior to similar homework assignments, students perform the first experiment in the hardware laboratory using these tools. In the real experiment, in addition to the function generator, students are given microphones to generate speech signals to display on the oscilloscope screen. In addition, music files stored at the course web site are used to analyze the periodic waveforms generated by different musical instruments.

Example I

Set Up:

- Start the Oscilloscope & Function Generator applet of the Virtual Lab.
- Generate a 100 Hz, sine wave with amplitude of 2V and a DC offset of 0V.

Experiment:

- Measure, record and tabulate the DC and RMS values of the signal as you increase the DC offset on the Function Generator. Five to six measurements spanning the full range of the DC offset knob are sufficient.
- Plot the DC and RMS values of the signal as a function of the DC offset.
- Derive an equation for the RMS value of a sinusoid with a DC off-set. Compare your resulting equation with the plot generated for part (e).

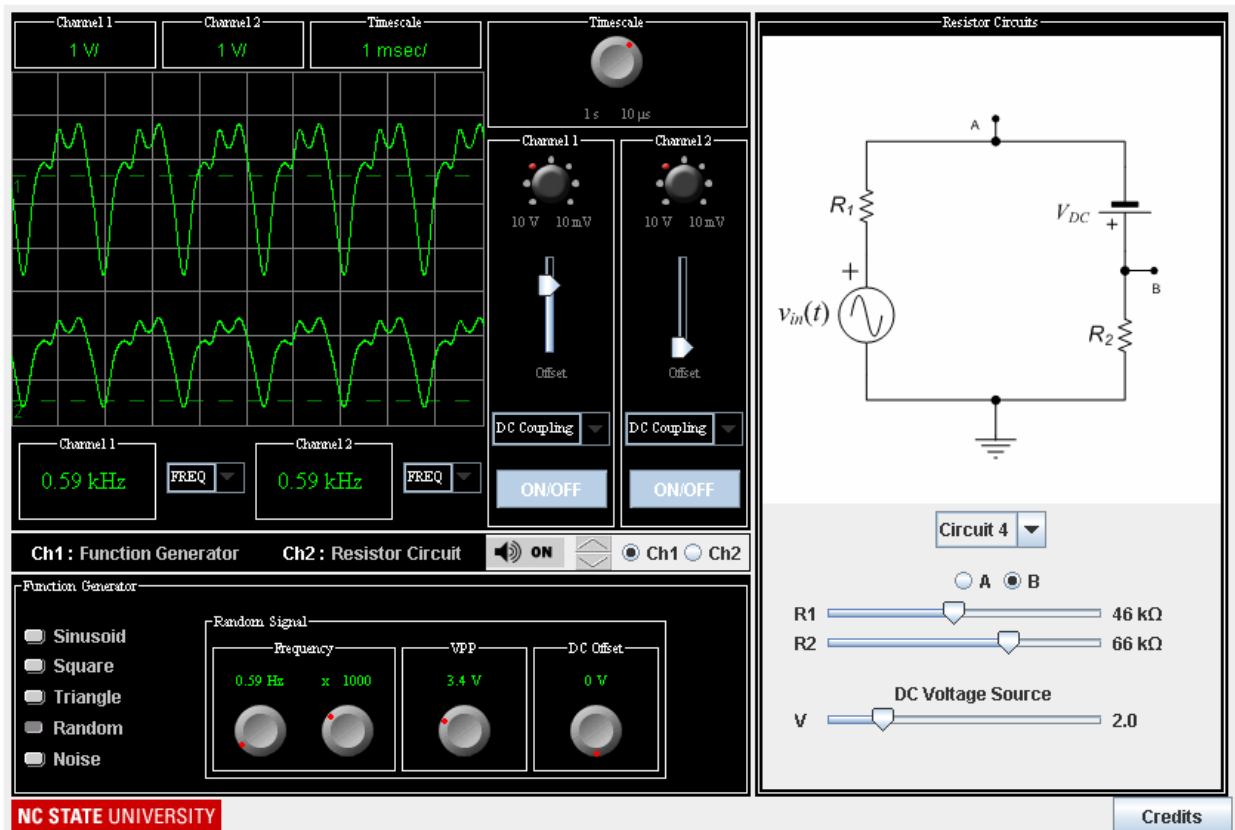


Figure 3: Java applet on simple circuits with resistors and AC/DC voltage sources.

Resistive Circuits with AC/DC voltage sources

This applet uses the function generator and the oscilloscope to display the voltage waveforms at different nodes of simple circuits featuring resistors and AC/DC voltage sources. As shown in Figure 3, the user can choose a circuit from a pull-down menu and the applet provides the controls to change the resistance values and the voltage of the DC battery. The AC source in the circuit represents the function generator. The main purpose of this circuit is to teach basic circuit

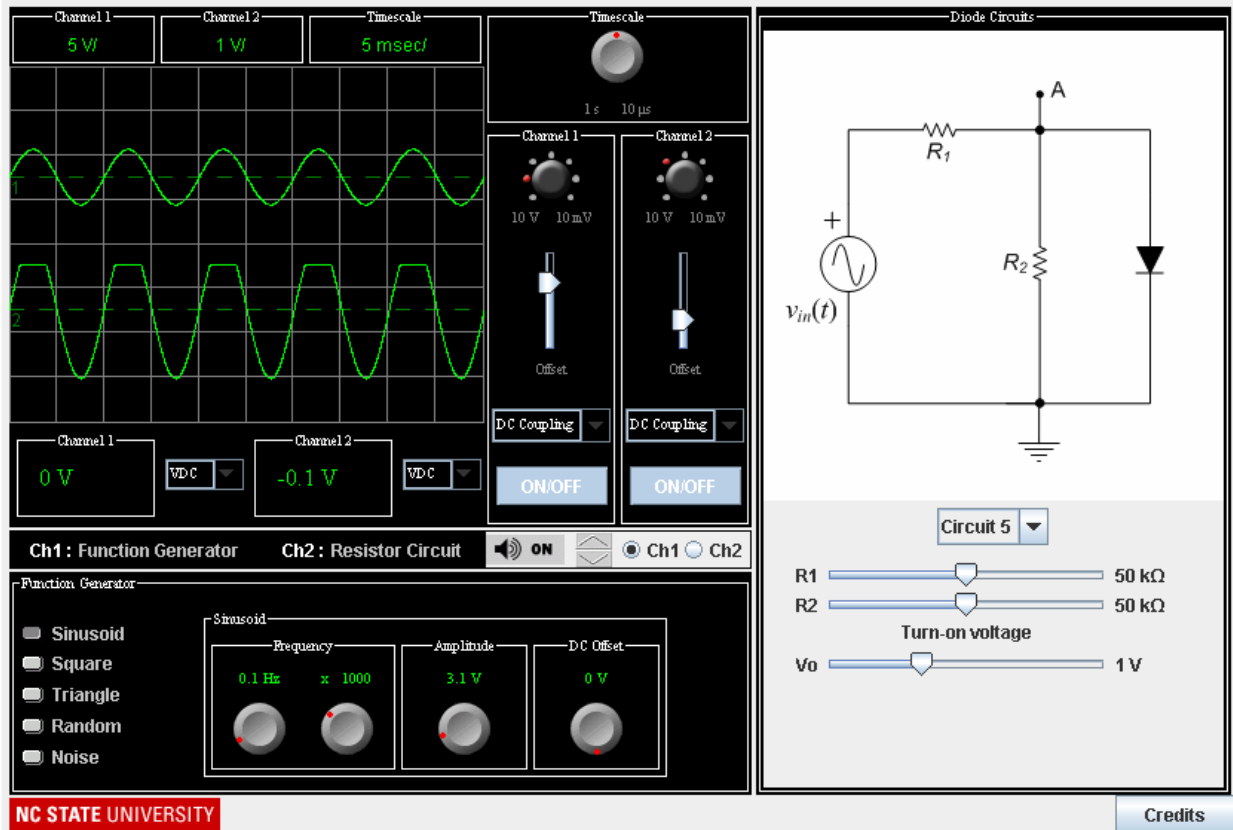


Figure 4: Java applet on circuits with AC/DC voltage sources and diodes.

concepts while providing the opportunity to practice using the function generator and the oscilloscope.

Simple Diode Circuits

The objective of this applet shown in Figure 4 is to teach analysis of simple circuits with AC/DC voltage sources and diodes. By selecting different diode circuits from a pull-down menu, the user can observe the voltage waveform across a resistor or a diode. The user can change the resistor values, the DC voltage source in the circuit and the turn-on voltage of the diode.

One of the key objectives of this applet is to teach the half-wave rectifier. Students also study the characteristics of this circuit in the hardware laboratory and use this knowledge in the mandatory hardware project involving construction of a variable power supply featuring a full-wave rectifier circuit. Details of the hardware project can be found in another publication included in the proceedings of this conference by the author of this paper³.

A typical take-home experiment using this applet is given below in Example 2. The experiment employs the circuit shown in Figure 4. The concepts emphasized in this experiment include a) finding the region of operation for the diode in a resistive circuit and b) analysis of the circuit for 'on' and 'off' states of the diode.

Experiment II

Set-up:

- a) Start the virtual lab “Simple Circuits with Diodes”
- b) Select Circuit 5 from the pull-down menu. Note that the oscilloscope will display the output signal between the point A and the ground.
- c) Set $R_1 = 50\text{ k}\Omega$, $R_2 = 10\text{ k}\Omega$ and $V_\gamma = 1\text{V}$.
- d) Generate a 100 Hz sinusoid with an amplitude of 3 V.
- e) Adjust the vertical and horizontal scales of your oscilloscope to display input and output signals simultaneously.

Experiment:

- a) Observe the output waveform. Do you see any clipping or distortion? Do you think the diode is on or off?
- b) Measure the DC value and the peak-to-peak value of the input/output signals.
- c) Increase R_2 and repeat steps (a) and (b) for several resistance values. Plot the peak-to-peak value of the output signal as a function R_2 .
- d) Analyze the circuit to determine the range of R_2 values for which the diode will be off. Derive an equation for the output voltage when the diode is off and compare with your result obtained for part (c)
- e) At some resistance value you should observe clipping of the output signal. What is this resistance value? Is the diode on or off when the signal is clipped? Derive an equation for the output voltage when the diode is ‘on’. Compare with your measurement result.
- f) How does the DC value of the signal change when the signal is clipped?
- g) Set $R_2 = 70\text{ k}\Omega$. You should observe clipping. Increase the turn-on voltage of the diode. Does the clipping disappear at a certain value of this voltage? Why?

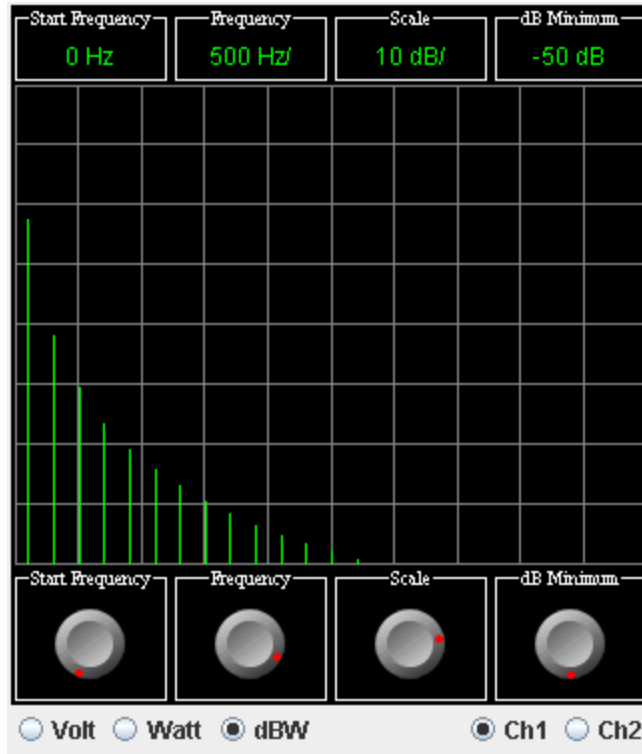


Figure 5: The spectrum analyzer can display the amplitude and power spectra of periodic signals.

Periodic Signals in Time and Frequency Domain

The main purpose of this Java applet is to introduce the spectrum analyzer. The applet also includes the oscilloscope allowing the users to observe signals in both time and frequency domains. The spectrum analyzer includes all basic controls available on bench-top instruments. The virtual spectrum analyzer can display the amplitude spectra of signals as well as the power spectra using both Watt and dBW scales. Figure 5 shows a triangular waveform displayed by the spectrum analyzer.

The lectures cover basics of representing signals in frequency domain including a brief introduction to Fourier series, amplitude and power spectra, dB and dBW concepts. Students learn how to sketch the amplitude or power spectra of a time varying signal with a known equation. The fact that every periodic signal can be represented as an infinite sum of sinusoids (harmonics) is emphasized from a practical point of view. In other words, students understand that harmonics will exist at multiples of the fundamental frequency; however, they are not taught how to calculate the Fourier series coefficients. Obviously, if this applet is used to support a junior level signals & systems course, students may use this applet to verify their calculations.

In the hardware laboratory, students study test signals from the function generator and a microphone used to generate voice signals. In addition, the students test recorded signals generated by musical instruments available at the course web site and they are encouraged to bring their own musical instruments to the laboratory.

A typical virtual experiment is given in Example III. In this experiment, students study how the duty cycle of a square wave influences the amplitude spectrum of a square wave.

Example III

Set Up:

- a) Start the virtual lab “Periodic Signals in Time and Frequency Domains”
- b) Generate a 1 kHz square wave with a duty cycle of 50%, $V_{pp} = 4\text{ V}$ and $V_{offset} = 0\text{ V}$.

Experiment:

- a) Use the amplitude spectrum to measure the amplitudes of the harmonics under 10 kHz and generate a table listing the frequencies of the harmonics and their amplitudes.
- b) Sketch the amplitude spectrum using the measurement results obtained for part (c).
- c) Use the digital readout to measure the RMS value of the square wave and use this value to calculate the signal power.
- d) Change the duty cycle of the square wave to 20% and measure the amplitudes of the harmonics under 10 kHz and generate a table listing the frequencies of the harmonics and their amplitudes.
- e) Repeat parts (a), (b) and (c) for the new signal.
- f) Write a short paragraph explaining the impact of the duty cycle of the amplitude spectrum of the square wave.

Low-Pass Filter

The low-pass filter applet is used to demonstrate low-pass filtering of periodic signals. The applet simulates a Butterworth filter with variable cut-off frequency and filter order. The example power spectrum shown in Figure 6 was obtained by filtering the noise signal using a 4th order low-pass filter. Using the noise signal as the input signal provides a convenient method to display the frequency response of a filter.

The lectures begin with an overview of ideal low-pass, band-pass and high-pass filters. The concepts of voltage gain, power gain, frequency response and 3-dB cut-off frequency are introduced. Examples are given on finding the power spectrum of a filtered signal given the filter frequency response and the input spectrum.

Filtering is also used to reinforce students’ understanding of the Fourier series representation of periodic signals. An example is given in Figure 7 which demonstrates the impact of low-pass filtering on the time domain signal. The user can decrease the cut-off frequency of the filter eliminating the higher frequency harmonics of the filtered signal one by one. Then, the user can see how the sharp corners of the wave are lost as the harmonics are removed. The example shows that even three harmonics is enough to produce a signal, which at least looks like a triangular waveform.

Using the same example, the user can calculate the total power of the filtered signal by measuring and adding up the signal power of individual harmonics. This value can then be compared to the signal power calculated from the measured RMS value of the signal.

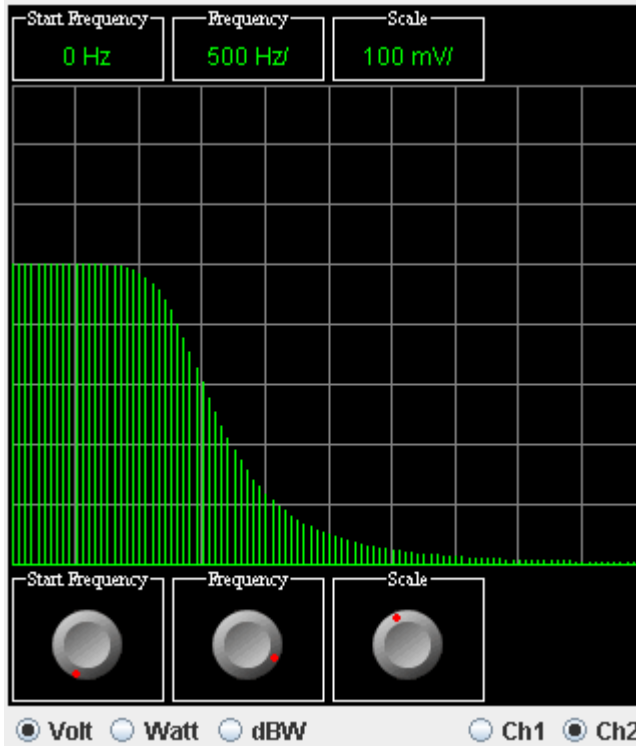


Figure 6: Power spectrum of a filtered noise signal. Filtering was done by a 4th order Butterworth low-pass filter.

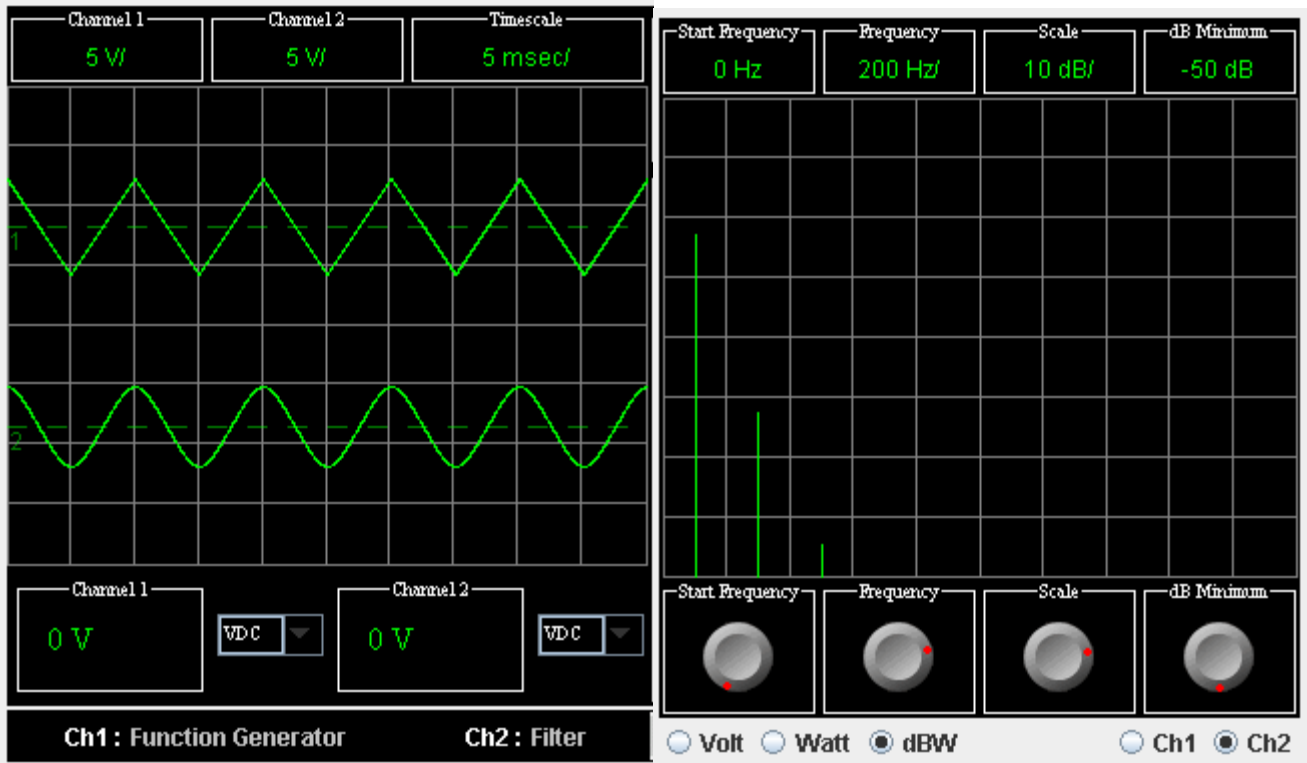


Figure 7: Low-pass filtering of a triangular wave in time and frequency domains.

Equalizer

This applet is an extension of the low-pass filter applet. The main difference is that the user can obtain the desired frequency response by setting the power gain in different frequency bands. Using this applet, the user can create different filter types (e.g. band-pass) and observe the effect of filtering in the time domain on the oscilloscope. The example in Figure 8 shows how an arbitrary frequency response can be created using the equalizer applet. The spectrum was obtained by filtering noise using the filter settings shown in Figure 8.

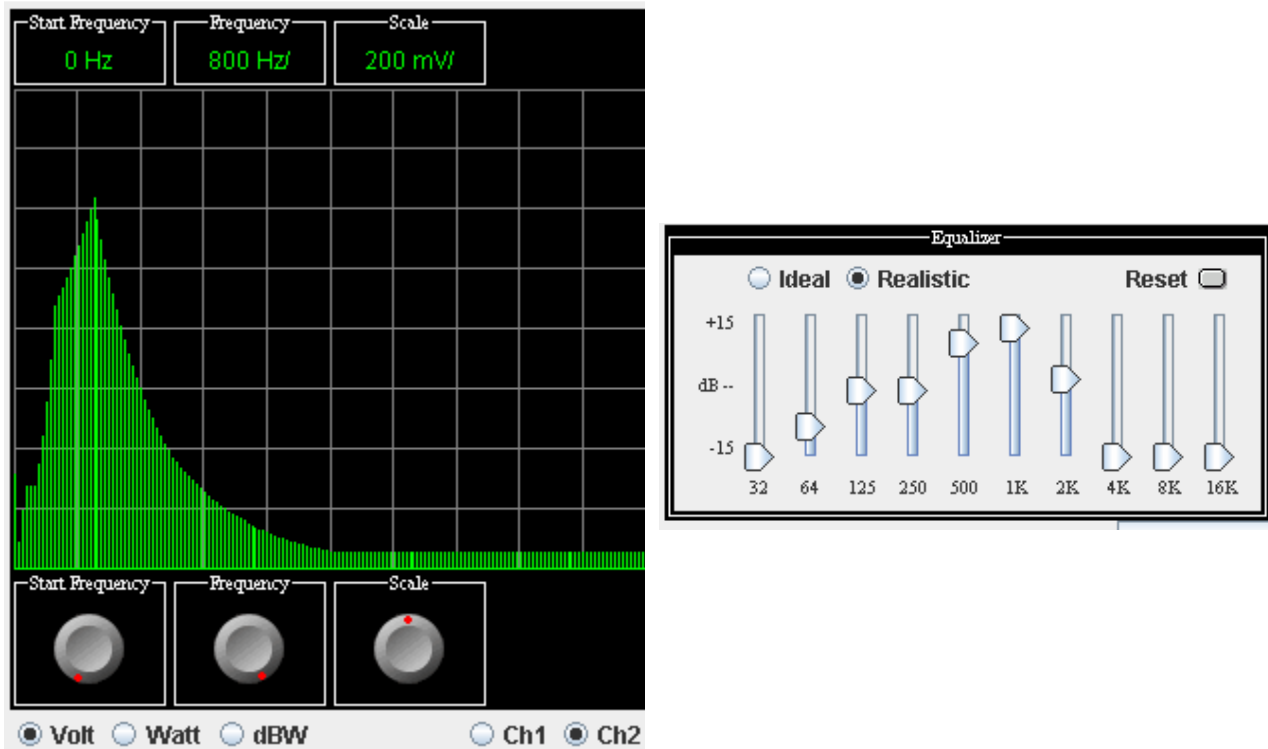


Figure 8: An arbitrary frequency response can be created using the equalizer applet.

Amplifier

The objective of this applet is to come as close as possible to a real amplifier. The experiment begins by setting the amplifier parameters using the panel shown in Figure 9. The user can choose between a single or dual power supply, set the power supply voltage and the voltage gain of the amplifier. The panel displays the transfer characteristic of the amplifier, which is a concept covered in detail in the regular lectures.

By displaying the input and output signals on the oscilloscope screen, the user can measure the peak-to-peak values of the signals and determine the voltage gain of the amplifier. Clipping distortion is introduced as a practical problem and used as an opportunity to revisit Fourier series and calculating the signal power from the power spectrum. Using this applet, the user can observe clipping in both time and frequency domains as shown in Figure 10. It is emphasized that the clipped sinusoid is a periodic wave with harmonics occurring at multiples of the fundamental frequency. By computing the signal power of harmonics generated due to clipping, the user can determine the total harmonic distortion of the amplifier. The sound engine allows the user to hear the impact of clipping on the quality of the amplified sound.

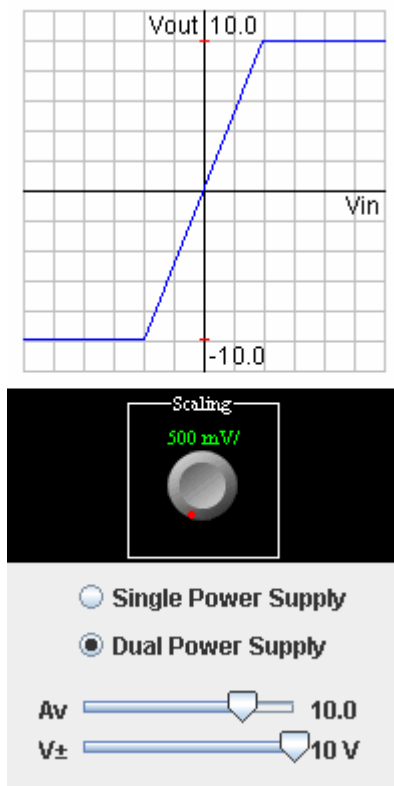


Figure 9: Amplifier controls

Example IV

Set Up:

- Start the amplifier applet.
- Generate a 300 Hz sinusoidal wave with an amplitude of 0.5 V.
- Use a +/- 5 V dual power supply
- Set the voltage gain to 12.

Experiment:

- Plot the power spectrum in dBW. Do you see any clipping in time domain? Do you see any harmonics due to clipping distortion?
- Make the necessary measurements and calculate the percent harmonic distortion. In calculating the harmonic distortion, assume majority of the signal power is contained in the first 5 harmonics including the fundamental.
- Repeat part (a) using a voltage gain of 15.

Operational Amplifier Circuits

This applet is very similar to the amplifier applet described above. Instead of setting the voltage gain of the amplifier, the user chooses an operational amplifier circuit from a pull-down menu. The user can set the power supply and the resistor values. The circuits included in the applet are variations of the simple inverting and non-inverting amplifier stages. Similar to the amplifier applet, signal clipping can be observed in both time and frequency domains.

In the lectures, students are given methods to analyze operational amplifier circuits including the virtual short concept. In the hardware laboratory, students construct a variety of amplifiers using operational amplifiers for applications including audio, ultrasound and infrared sensing.

Summing and Difference Amplifiers

This applet is an extension of the applet on simple operational amplifier circuits. Similar to the previous applet, the user chooses a circuit from a pull-down menu, which includes summing and difference amplifiers. The applet features two function generators to supply the two signals needed for the circuits. Again, the users can set the power supply and the resistor values used to construct the amplifiers.

This is a particularly interesting applet because it can perform a function the hardware can not in the hardware laboratory simply because we do not have two function generators available on the benches.

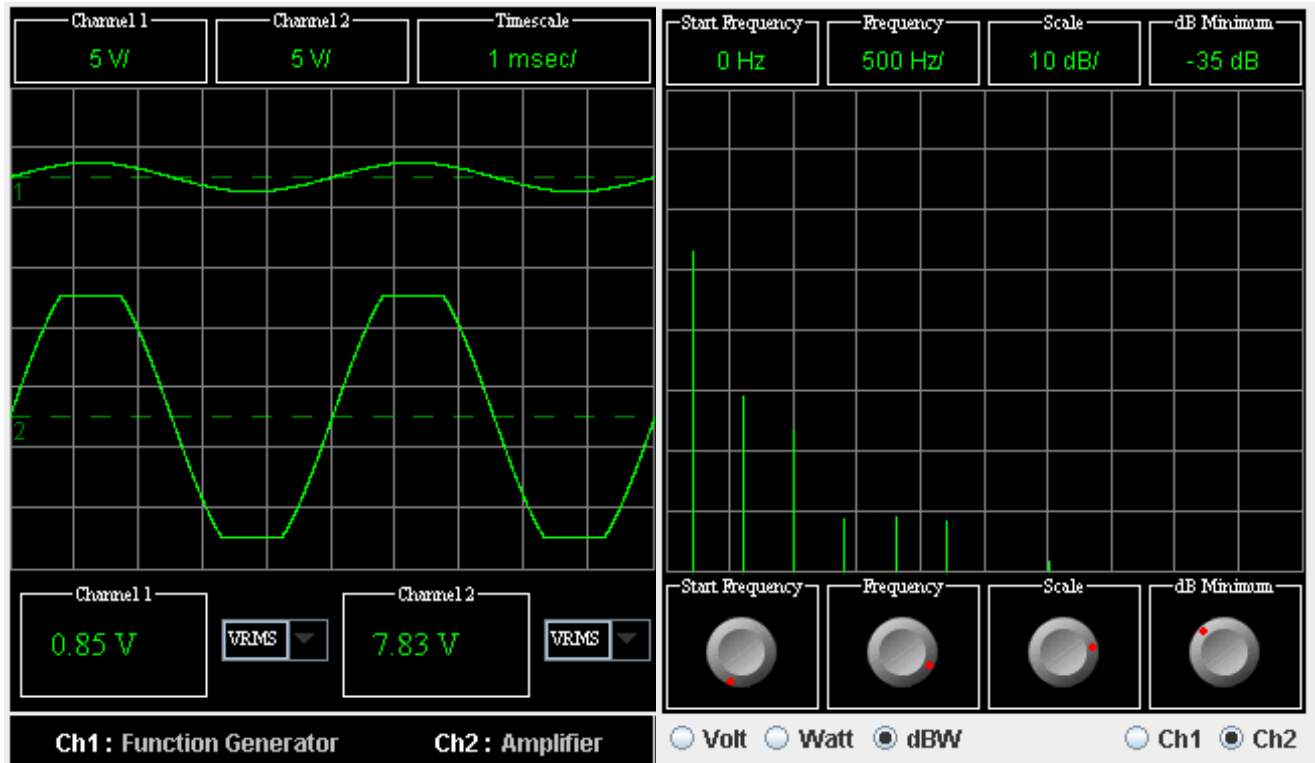


Figure 10: Amplifier applet demonstrating the impact of clipping in both time and frequency domains.

Using this applet, students can add/subtract all of the signals produced by the function generator including noise. Figure 11 shows the oscilloscope screenshot obtained by adding two sinusoids with different frequencies and amplitudes. The applet front panel resulting in this signal is also shown. The applet includes the spectrum analyzer continuing the trend of the former applets. The applet also has a time delay feature, which allows the user to observe the output waveform when one of the signals is shifted in time domain. Therefore, this feature can be used to demonstrate the role of the phase angle in determining the final shape of the time domain signal. At the same time, by observing the power spectrum of the signal on the spectrum analyzer, the users can see that the time delay has no effect on the amplitude or power spectra of the signal.

SUMMARY

Our preliminary assessment results based on student surveys and questions asked in the final exam indicate that the virtual laboratory has resulted in a measurable improvement in student learning of the basic concepts as well as using the laboratory equipment. Detailed assessment studies are underway to evaluate the impact of the virtual laboratory.

The virtual laboratory also proved to be a valuable tool for in-class demonstrations. Using a lap-top computer and a projector instructors can easily demonstrate practical concepts, which were previously limited to hardware laboratories.

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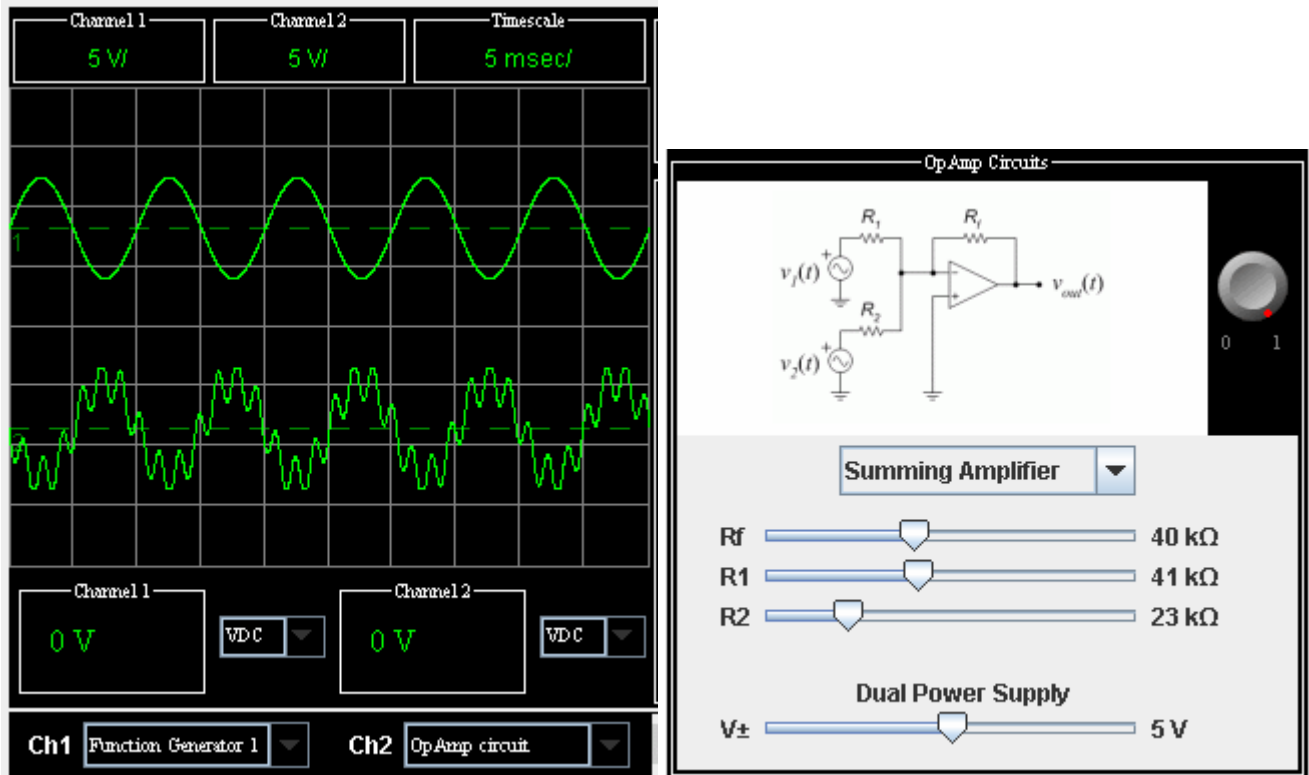


Figure 11: Two sinusoids of different frequencies and amplitudes added by the Summing and Difference Amplifier applet.

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¹ http://courses.ncsu.edu/ece200/common/Every_Semester/index.html

² E. d'Souza and M.C. Ozturk, "An Introductory Virtual Laboratory for Electrical Engineering", Proceedings of the ASEE Annual Conference and Exposition (2005).

³ M.C. Ozturk M.J. Escuti, "A New Introductory Course on Signals, Circuits and Systems", ASEE Annual Conference and Exposition (2006)