

**AC 2008-1591: A SET OF COMPUTER-CONTROLLED EXPERIMENTS IN
INTRODUCTORY ELECTRIC CIRCUIT LABORATORIES FOR ELECTRICAL
ENGINEERING (EE) AND NON-EE MAJORS**

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A Set of Computer-Controlled Experiments in Introductory Electric Circuits Laboratories for EE and non-EE Majors

Abstract

This report is focused on development and implementation of a set of Virtual Instruments (VIs) for all lab projects of introductory courses in electric circuits for EE and non-EE majors. Due to using the Interchangeable Virtual Instruments (IVI) standard, these programs can be used with different lab equipment with very little software change.

The distinctive features of our lab projects include:

- (1) Combination of front-panel operation of instruments, which helps the student develop intuition, with the use of Virtual Instruments, which saves in-lab time;
- (2) A shift of the paradigm of learning in the lab from obtaining a few data points to comparison of several data plots and relating them to theory;
- (3) Requirement that each student prints out experimental plots before leaving the lab, which helps to authenticate the data and organize the lab reports.

In this report, the Virtual Instruments are described along with a discussion of their educational value, and the statistics is provided of student evaluation of the VIs as learning tools in the lab.

1. Introduction

To bring automatic, computer-controlled experiments into teaching laboratories, especially at the introductory level, where they must be accessible to every student, might be a dream of many lab instructors. There are several challenges on the road to its fulfillment, both on the technical and pedagogical sides. The technical ones include: (a) availability of proper test and measurement instruments along with computers, (b) successful choice of software, (c) its adaptation to the needs of Instructional Laboratories, and – nearly inevitable – (d) debugging. The main pedagogical challenge is to find the wise balance between traditional, front-panel operation of standalone instruments such as oscilloscopes and function generators, which help students develop their intuition, and automatic measurements which could save valuable in-lab time but, taken alone, might look like another video game.

Many instructors have reported computer-controlled measurements in teaching laboratories; their teaching strategies range from the creation of entirely virtual labs¹ to combinations of use of data acquisition boards plugged into the computer² to courses based on the NI ELVIS® prototyping platform³.

Our goal has been to develop a comprehensive set of computer-controlled experiments that would complement front-panel operation of real instruments, save valuable lab time, and foster the development of hands-on skills and intuition. The set of Virtual Instruments presented here embraces the contents of standard introductory courses – from DC measurements of volt-amp

curves to transient responses of circuits and their transfer functions. Noteworthy, it includes several unique tools for teaching the key concepts.

With minor adjustments of the software, these Virtual Instruments can be used at many other schools on various types of standard instruments, for which LabVIEW drivers are available.

In section 2, hardware and software are briefly discussed, along with the strategic plan for their development. Sections 3 – 6 are focused on the Virtual Instruments used in particular lab projects throughout the typical introductory courses; sections 4 and 5 specifically discuss the unique educational value of several Virtual Instruments. Section 7 outlines the significance of Virtual Instruments in organizing student lab reports. Section 8 shows the student perception of the Virtual Instruments in the lab, which was assessed using a specially designed questionnaire. Section 9 presents the conclusion; section 10 lists the references. The numbering of Figures follows the section numbers.

2. Hardware and software

Our Instructional Laboratories are equipped with Agilent instruments: 3000-series oscilloscopes, 33220A function generators, 34405A digital multimeters (complementing 34401A in some labs), and E3631A power supplies, one for each workstation (serving a team of two students). All student workstations are also equipped with new Windows computers. Our choice of software for automated experiments was focused on its flexibility and the competitive advantage, which students familiar with such software would get in workplace. Due to its popularity in industry, LabVIEW¹ was chosen as the software for our Instructional Labs. Individual instrument drivers were of course available, but a comprehensive set of LabVIEW-controlled experiments designed for introductory Labs in Electrical Engineering was definitely lacking.

One of the authors of this report, then an undergraduate student, experienced with LabVIEW, was also teaching introductory circuits labs in the required course for EE majors that he had taken a few years earlier, which helped him see the lab instruction from both sides – the student and the teacher. The other authors supervised writing the LabVIEW Virtual Instruments (VIs), focused on maintaining the proper balance between fostering student intuition and taking advantage of speedy data acquisition. Thus the challenge of writing necessary software was successfully overcome.

From the very start, the strategic plan was focused on building the foundation – a set of VIs that would employ all the instruments listed above and could be used in many projects in various Instructional Laboratories. As the result of our efforts, several VIs have been included in the new editions of Lab books for introductory courses in circuits and electronics for both EE and non-EE majors. These Lab books address the pedagogical challenge of combining front-panel operations with automated measurements.

3. Where the lab courses begin: Experiments in the DC Lab

The introductory lab courses in electric circuits begin with DC measurements of voltages and currents. To complement front-panel operation with computer-assisted data collection, several VIs were written, all of them based on the same block diagram shown in Figure 3.1.

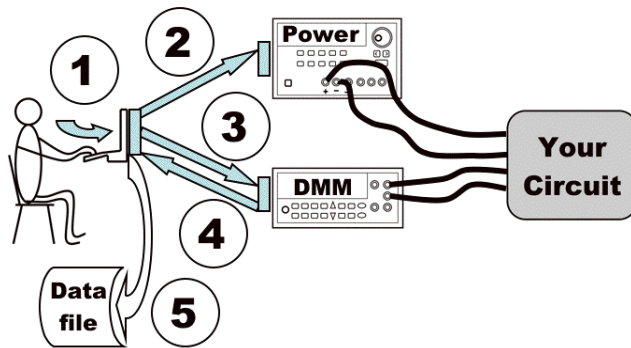


Figure 3.1.

The generic block diagram for computer-assisted control and measurement of voltages.

Before doing the lab, students should read the introduction and do the pre-lab assignment. The introduction explains step-by-step the logistics of front-panel measurements of volt-amp characteristics of a light-emitting diode (LED) and explains the block diagram of the VI, shown in Figure 3.2, which follows the same steps, collects more data points, and stores the data.

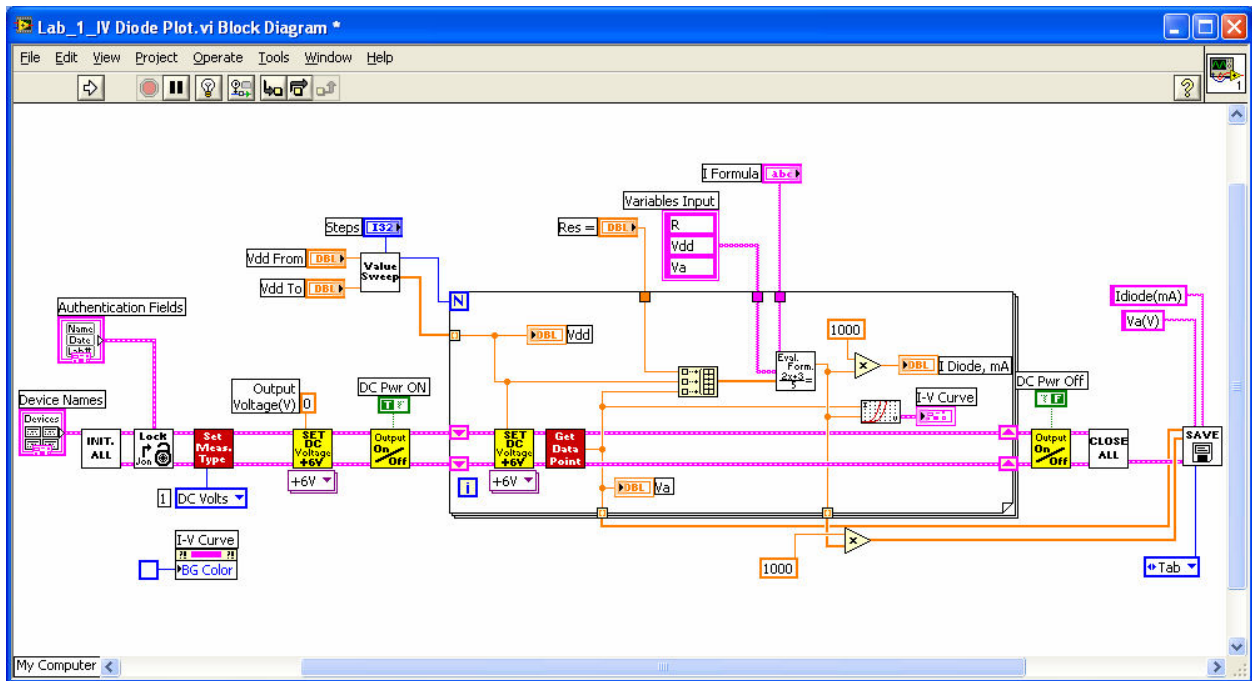


Figure 3.2.

The block diagram of the VI for measurements of volt-amp characteristics of an LED.

The logistics of front-panel operations is straightforward: the student varies the voltage on the power supply, measures the signal with the multimeter and records the data; the VI follows the same steps thus it is easy to introduce and explain its block diagram. As part of their pre-lab assignment, students have to explain which blocks on the LabVIEW diagram (Figure 3.2) correspond to each of the numbers on the generic diagram (Figure 3.1). Although this learning experience does not make students LabVIEW designers, it certainly helps them understand the logic of programming and become good users of the software.

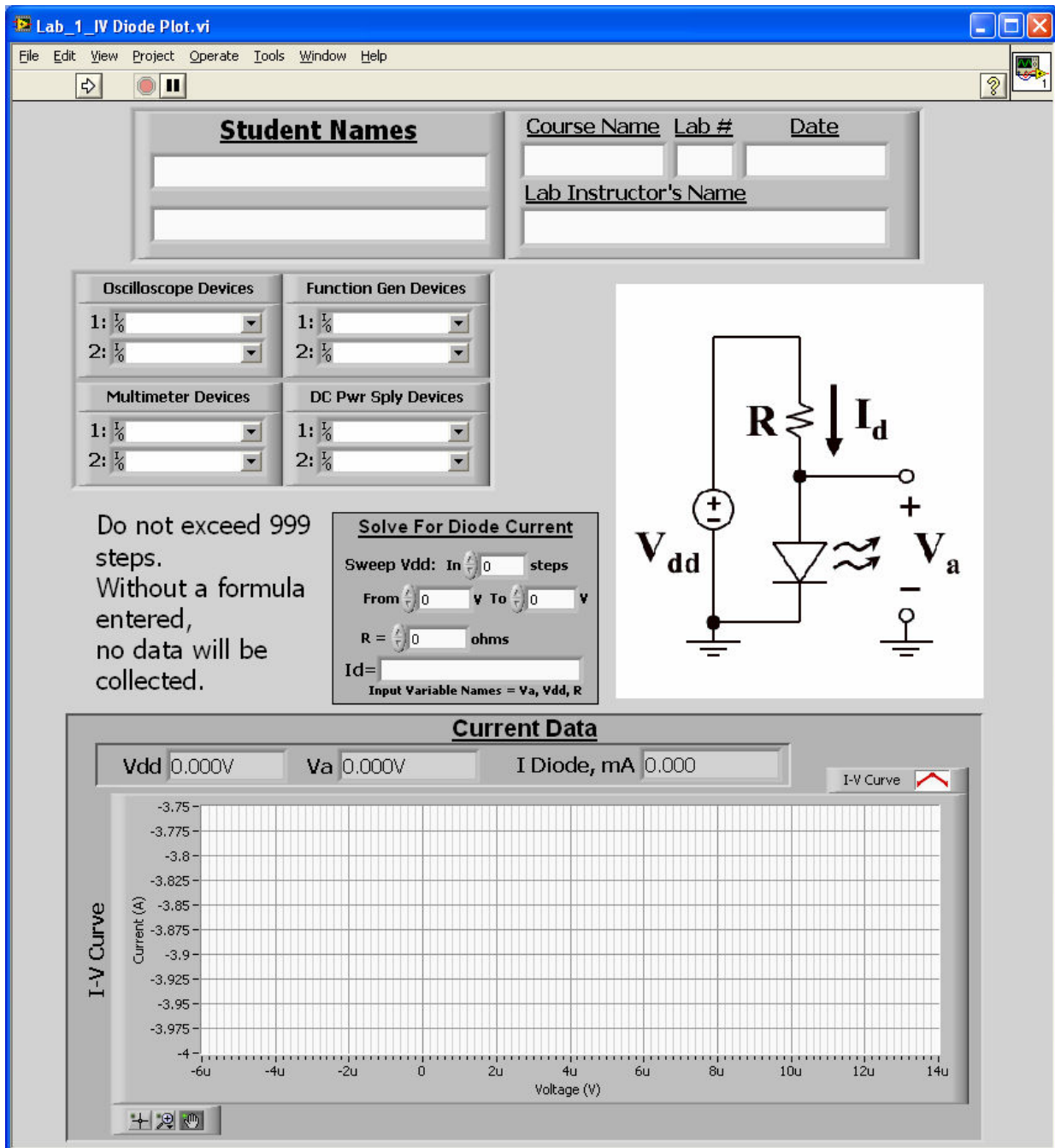


Figure 3.3. The front panel of the VI for measurements of volt-amp characteristics of an LED.

The front panel of the VI, shown in Figure 3.3, is also explained in the introduction thus students see a familiar display when they start the lab experiment.

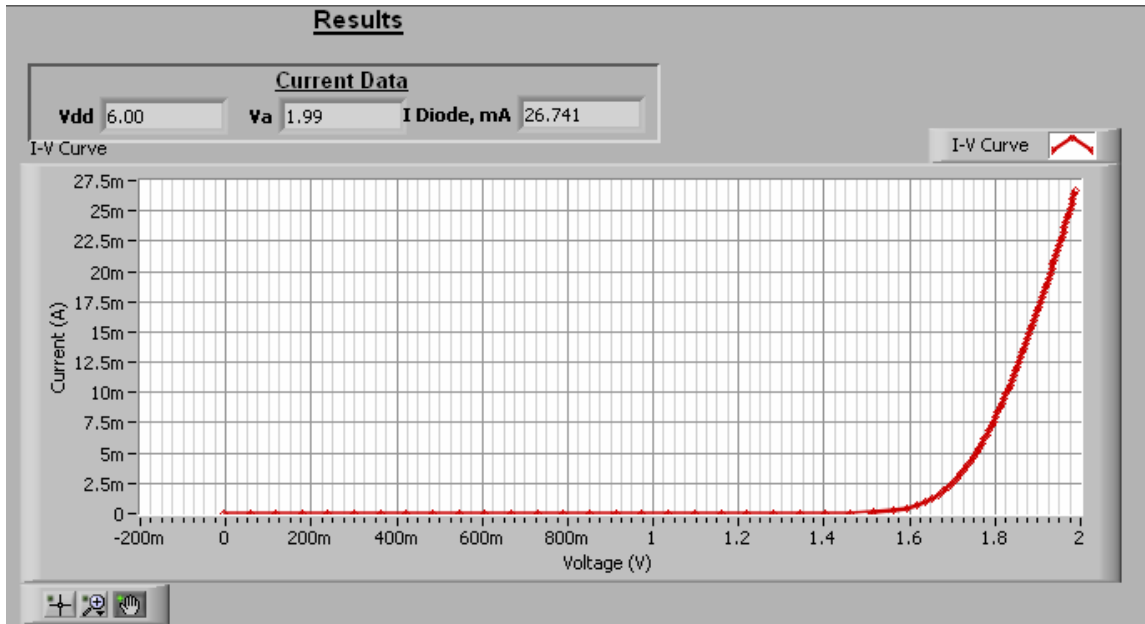


Figure 3.4.

A typical plot of lab data obtained in measurements of volt-amp characteristics of an LED.

The lab book provides an example of the data plot such as students should obtain in the lab: see Figure 3.4. This is valuable guidance: significant deviations from this shape clearly show the students that something is wrong with their circuit. Thus the VI becomes an important troubleshooting tool. Noteworthy, the students strongly agree with the statement in the questionnaire “When I see my own data plotted by the VI, and it looks as expected, I know that I built my circuit correctly”, as discussed in Section 8.

In real time, the VI displays data point-by-point, first greatly zoomed-in, then gradually zooming out in order to fit the entire plot in the window on the computer screen. If the range of voltages or currents is very narrow, the contribution of electronic noise into the measured values becomes quite noticeable. For example, Figures 3.5 and 3.6 show typical records of LED volt-amp characteristics at very low currents: evidently, due to the noise, the data sets are distinct, although they were obtained in the same circuit, with the same instruments, and under the same experimental conditions.

“It is extremely easy to copy computer files and share them with friends. Nevertheless, submitting someone else’s data is plagiarism, to be handled with all consequences.” This warning to students is reinforced with the following example.

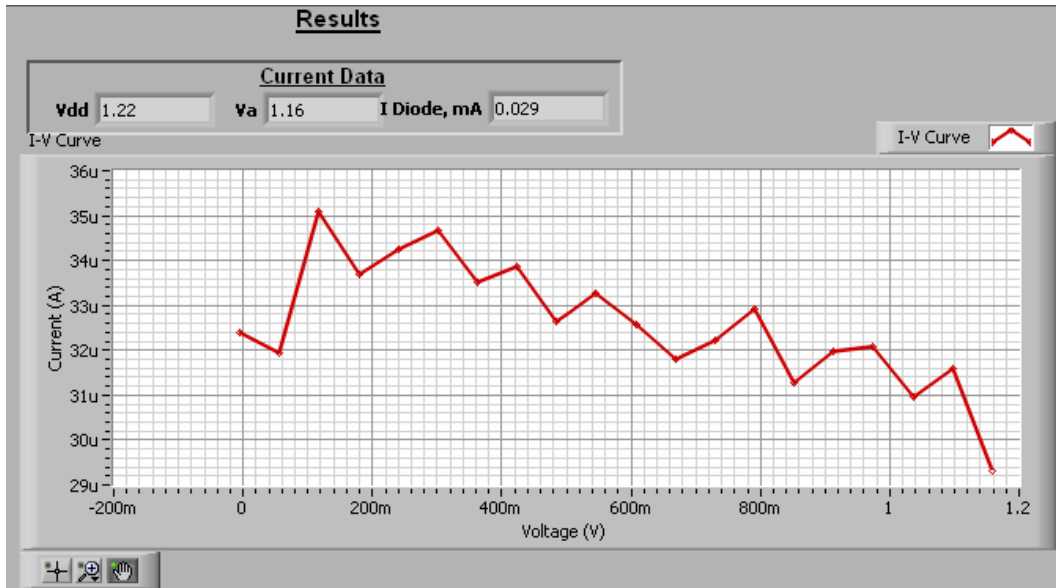


Figure 3.5
Sample volt-amp data points at very low currents.

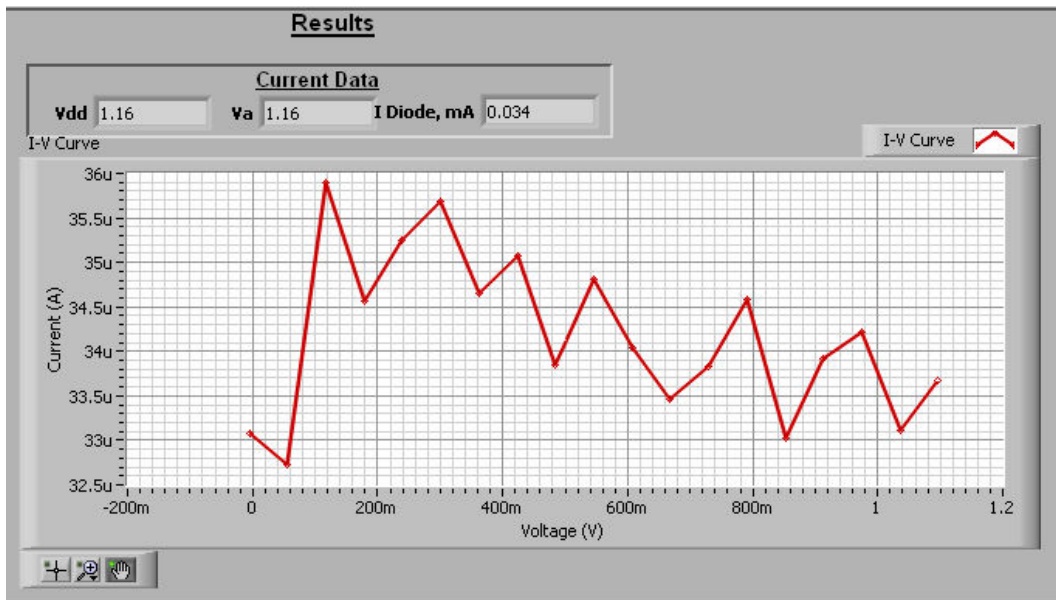


Figure 3.6
Another sample volt-amp data points at very low currents, obtained in the same circuit as the data shown in Figure 3.5.

The data plots in Figures 3.5 and 3.6 were obtained in consecutive runs of the same VI using the same circuit. Observe that individual data sets are distinct as fingerprints. Every student team is required to submit the computer files with original data and their analysis; all files are stored on the server and automatically compared for duplication.

From the instructor's viewpoint, the electronic noise recorded with Virtual Instruments is used to achieve two goals. The first goal is educational: introduce students to the concept of noise and let them observe its contribution in their own data. Also, since the noise is never exactly reproduced, individual data sets are authentic: digital records made by different student teams are distinct. Thus the second goal is achieved: storing data files on the server prevents plagiarism.

Additional educational value of Virtual Instruments

A similar VI is used for measurements of volt-volt characteristics of a metal-oxide-semiconductor field-effect transistor (MOSFET). The screen shot in Figure 3.7 shows the front panel of another VI, specially designed for EE students who should relate voltages across the load resistor to the voltage V_{DS} in the MOSFET in their post-lab calculations and plotting.

Several sets of data obtained with this VI at various values of the controlling voltage V_{GS} can be used in homework related to the transistor theory (most likely, in a more advanced course).

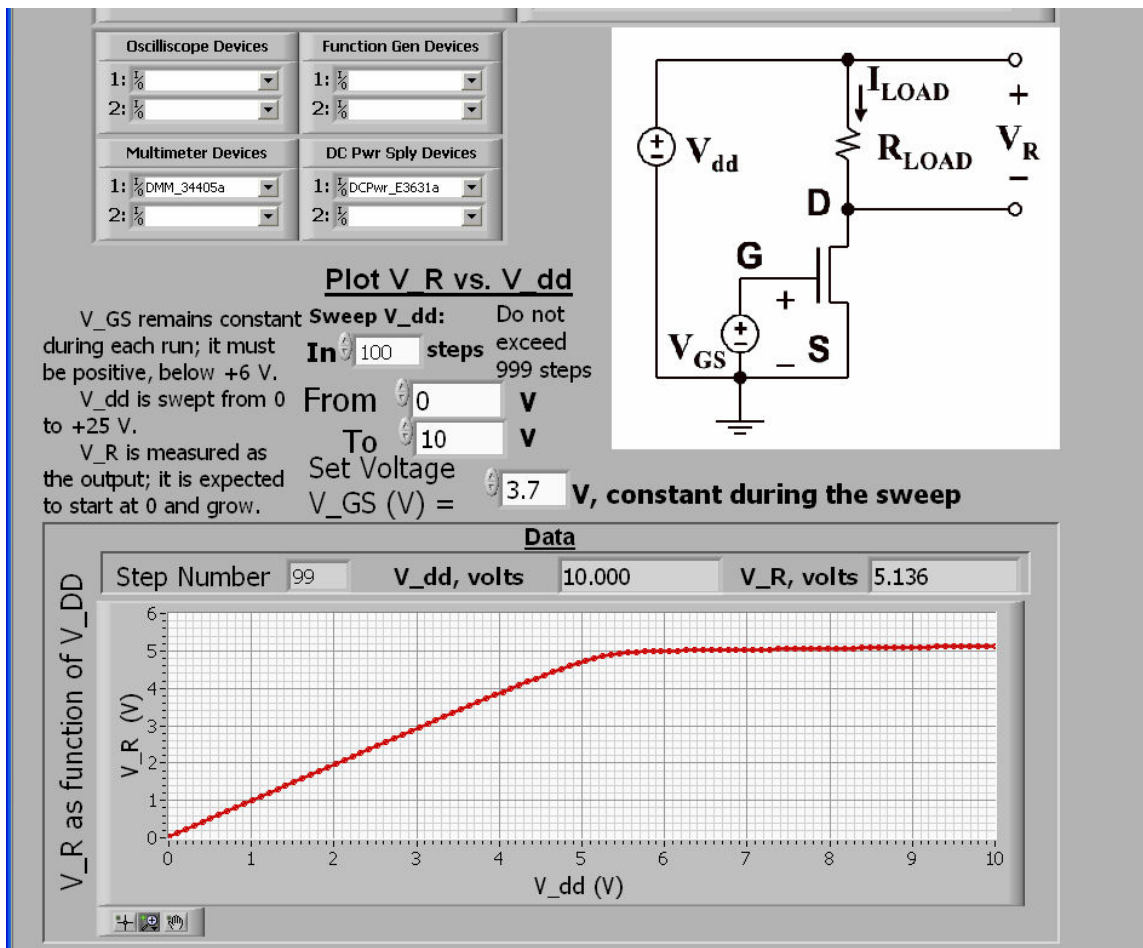


Figure 3.7
The front panel of the VI for measurements of volt-volt characteristics of a MOSFET.

Thus VIs in the lab yield additional educational value: students can use their own data to verify the theory, to extract parameters of particular electronic devices from their own data.

4. Virtual Instruments as unique tools for teaching the Fourier series

It is common knowledge that, for many students, Fourier series is not always an intuitive concept. To overcome this difficulty, a unique **Fourier Example.vi** was designed that builds standard waveforms step-by-step as a sum of their harmonic components, displays the results at every step, and illustrates several features of each result, as shown in Figure 4.1.

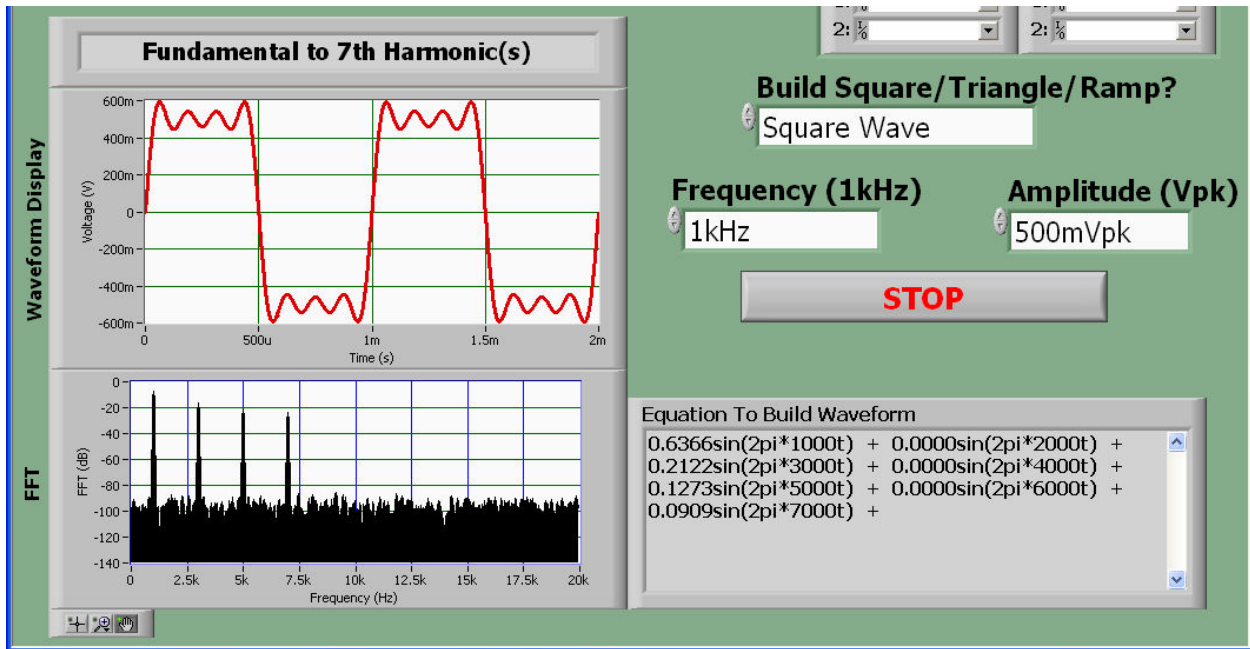


Figure 4.1.

A screen shot of the front panel of the **Fourier Example.vi** that builds a standard waveform as a sum of sinusoids.

As seen from Figure 4.1, the **Fourier Example.vi** can build square, triangular, or ramp (saw-tooth) waveforms step-by-step. The student chooses the type of waveform, its frequency and amplitude. At each step, the VI displays: (1) the number of harmonics already summed (7, in Figure 4.1), (2) the waveform and the spectrum obtained for the particular sum of harmonics, and (3) the formula for summation, with numeric coefficients (zeros for the vanishing components). All calculations are done within the computer but the resulting signal is real: it can be fed to the function generator, downloaded to its memory, and played back into the speaker, which allows the student to hear the sounds and appreciate the effect of each additional harmonic on the sound quality.

From observation of student work in the lab and discussions with students, it becomes clear that integrated learning, which combines mathematical calculations with measurements in the time and frequency domains, along with listening to the sounds, is an effective teaching tool that helps students appreciate the concepts of Fourier series. Additionally, the sum of a few harmonics, which is stored in the memory of the function generator, can be fed as an input into real circuits, such as filters, built by students; the output of that circuit can be monitored with an oscilloscope (and also saved as a file). These simple measurements mimic what happens in real-world circuits where finite pass-band of a device truncates the spectra of signals.

Finite pass-band of real circuits limits the frequency at which the circuit could be used for digital (square wave) signals: if the pass-band is narrow, fewer harmonics get through, thus the rise time gets longer. A special **Fourier Rise-Fall Time.vi** was developed to emphasize this limitation. A fragment of its front panel is shown in Figure 4.2.

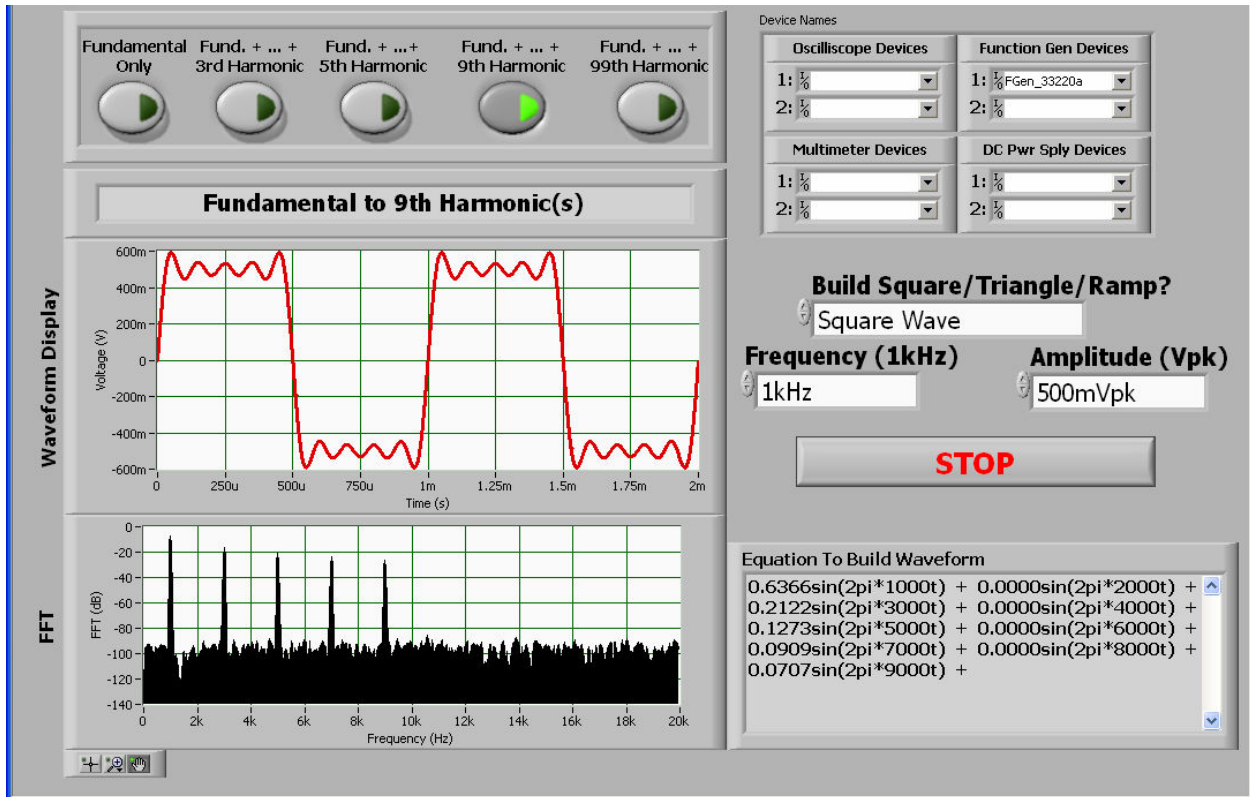


Figure 4.2
A screen shot of the front panel of the **Fourier Rise-Fall Time.vi** for rise time measurements.

The two VIs developed for studies of Fourier series are similar. Their main distinction is in the number of harmonic components summed into the waveform. Specifically, the **Fourier Example.vi** (Figure 4.1) illustrated the process of building a waveform as a sum of ever-increasing number of harmonics: it keeps adding the Fourier components until the student stops it; its purpose is to make the Fourier theorem more intuitive. On the contrary, the **Fourier Rise-Fall Time.vi** (Figure 4.2) produces the sum of a preset number of harmonics (3, 5, 9, or 99); its purpose is to allow the student to do measurements on each of the resulting waveforms. The waveform (such as the sum of 9 harmonics shown in Figure 4.2) is fed to the function generator, stored in its memory, and fed into the oscilloscope, which the student uses for measurements of the rise time. The following **OScope Plotter with zoom.vi**, whose screen shots are shown in Figures 4.3 and 4.4 is used to record the signals measured with the oscilloscope.

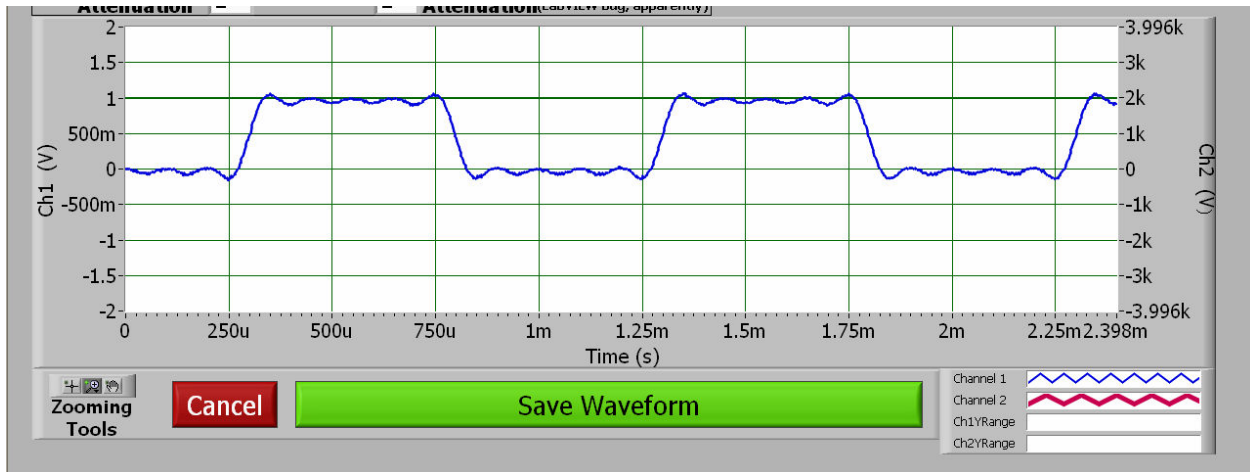


Figure 4.3.
A screen shot of the front panel of the **OScope Plotter with zoom.vi**, which shows the waveform (a sum of 9 harmonic components of a square wave) produced by the **Fourier Rise-Fall Time.vi**

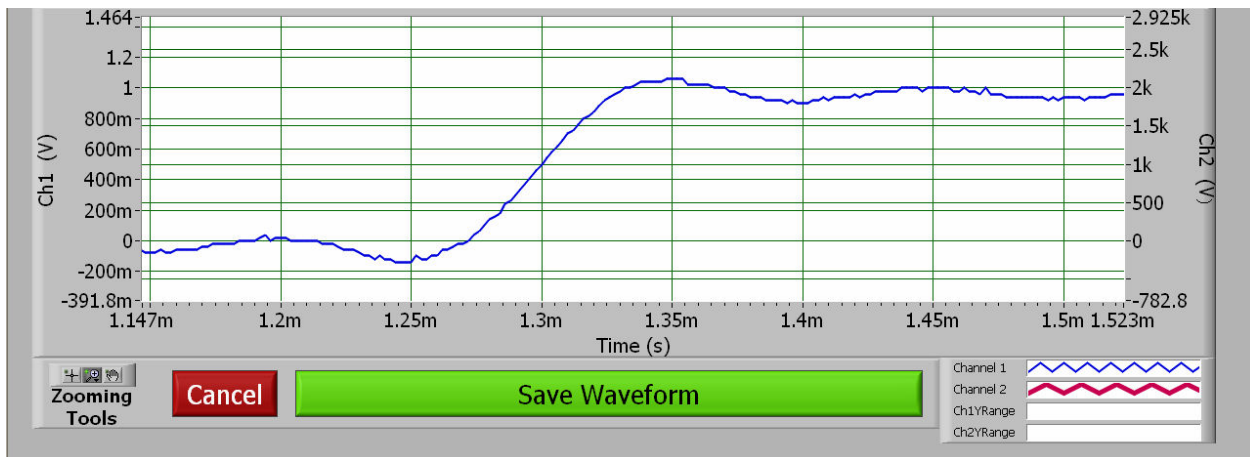


Figure 4.4.
A screen shot of the front panel of the **OScope Plotter with zoom.vi**, which shows the waveform produced by the **Fourier Rise-Fall Time.vi**

Students print out the screen shots similar to those in Figures 4.3 and 4.4 before they leave the lab. They are useful for several purposes. First of all, the screen shot proves that the students did the measurement themselves: the authentication fields include student names, date of work, etc.; the lab instructor signs each screen shot before the students leave the lab. Secondly, the screen shot becomes a permanent part of each student's lab report, making it look more professional and easier to grade. Finally, they can be used to measure the signal parameters (period, amplitude, rise time, etc.) to ensure that the experimental conditions were as required, and compare with the results of automatic measurement with the oscilloscope. Also, detailed screen shots, such as Figure 4.4, show more details about the rising edge of the signal (overshoot, etc.) and reveal the digital noise.

The results obtained with Virtual Instruments can convey more subtle messages about the Fourier series, which can be equally useful in both lecture and lab assignments. The following examples illustrate the role of phase (Figures 4.5 and 4.6) and compare the convergence of Fourier series for different waveforms (Figures 4.2, 4.5, 4.6, and 4.7).

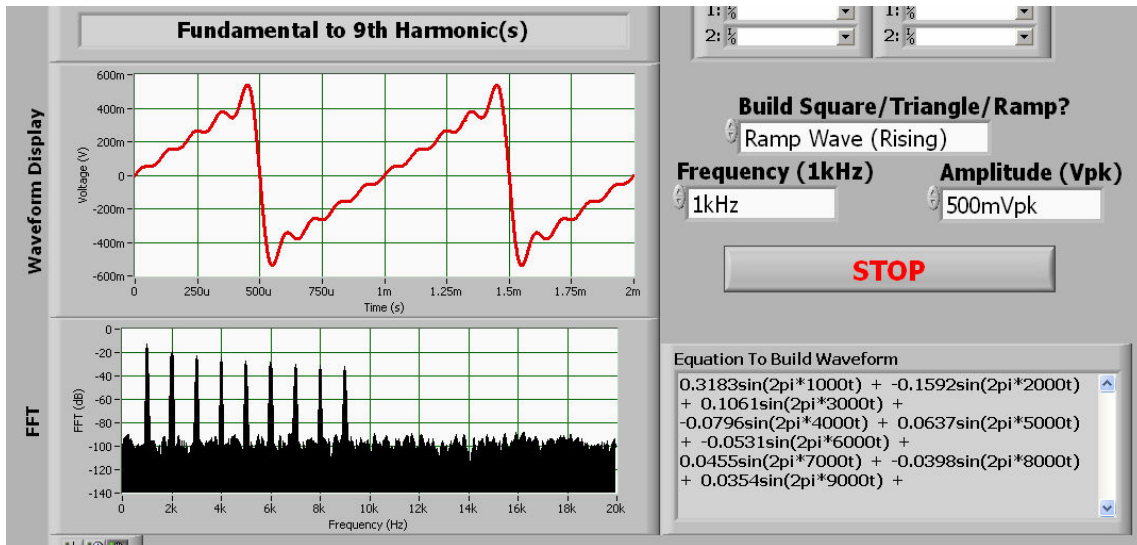


Figure 4.5
The screen shot of the rising ramp (saw-tooth) waveform obtained with the **Fourier Example.vi**

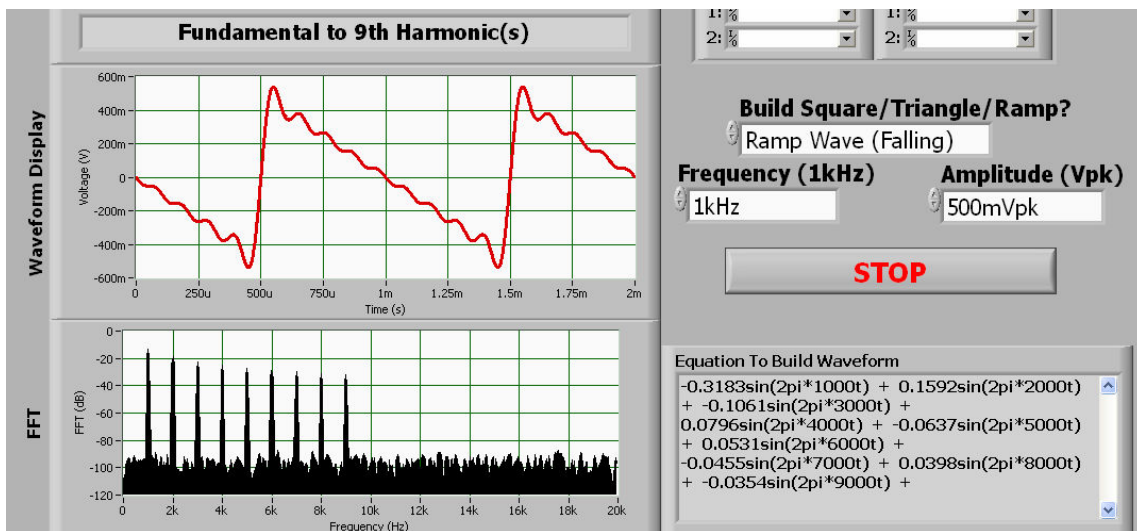


Figure 4.6
The screen shot of the falling ramp (saw-tooth) waveform obtained with the **Fourier Example.vi**

Mathematically, the only difference between the two waveforms shown in Figures 4.5 and 4.6 is in the signs of even-numbered harmonic components (since peak amplitudes are positive by definition, the negative signs are due to 180 degree phase shifts). These phase shifts affect the

overall slope of the waveform. Note that the FFT spectra show only the RMS amplitudes (expressed in dBV), which are the same for these two signals. Interestingly, one can find how many harmonics were added to produce any of the ramp waveforms in Figures 4.5 and 4.6 simply by counting the bumps on their slowly rising/falling edges.

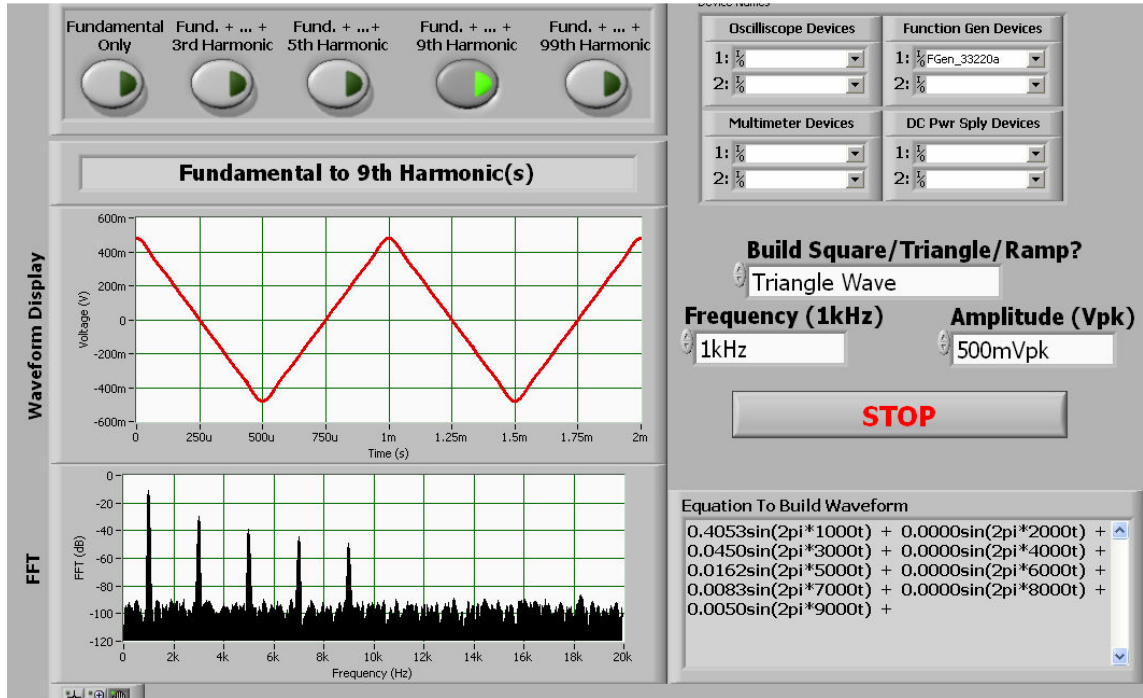


Figure 4.7
The screen shot of the triangular waveform obtained with the **Fourier Rise-Fall Time.vi**

The mathematical concept of convergence of the Fourier series for various waveforms can be illustrated through comparison of screen shots. Specifically, Figure 4.7 illustrates the fast convergence of the Fourier series of a triangular wave (the only waveform of the standard set whose first time derivatives are finite). In contrast with the square wave (Figure 4.2), the rising and falling ramp, or saw-tooth waves (Figures 4.5 and 4.6), the triangular waveform (Figure 4.7) is much smoother: only for the triangular wave, the sum of 9 harmonics does not reveal any bumps to a naked eye.

Another Virtual Instrument developed for the studies of waveforms and spectra is called the **Phone Lab.vi** (Figure 4.8). Its front panel is similar to the keypad of a telephone: when the user clicks any key with the mouse, the waveform is calculated and sent to the 33220A function generator whose signal can be measured with the oscilloscope. The 3000-series oscilloscope can measure both the waveform and FFT spectrum of the signal. However, in its today's form, 3000-series oscilloscope can transfer only the waveform to the computer: currently, thus, there is no way to store the FFT spectra measured by the oscilloscope as a computer file. Students perform FFT measurements using the front panel of their oscilloscope and write down the results for post-lab analysis. In addition to producing signals that correspond to the familiar keys available

on any telephone, the **Phone Lab.vi** also produces signals corresponding the special keys A-D, which are absent on consumer phones but are used by the military, etc. A possibility to use these special keys in the lab provides an additional motivation to students.

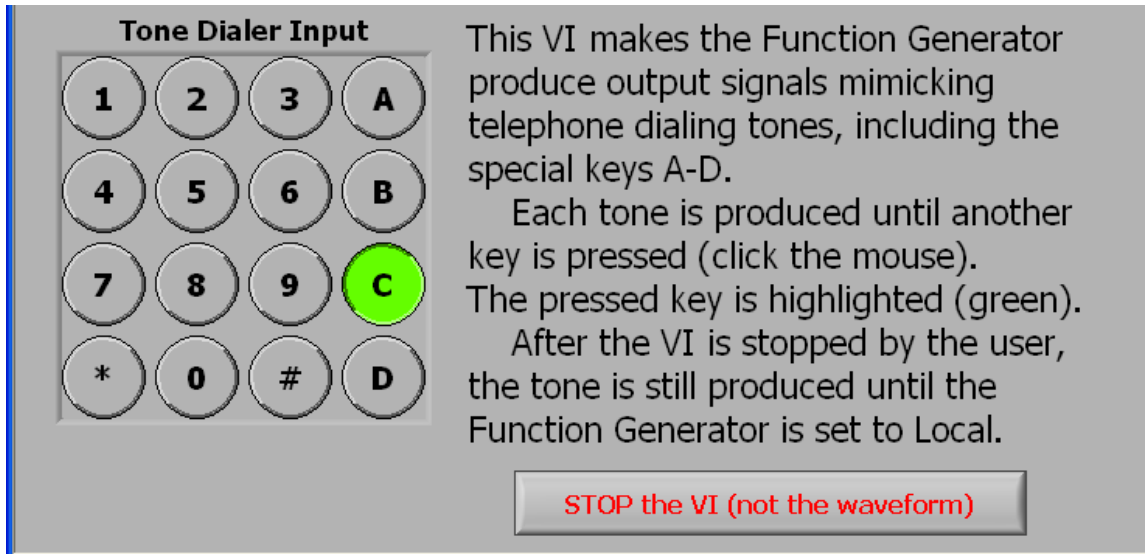


Figure 4. 8
A screen shot of the **Phone Lab.vi**

The function generator endlessly plays back the waveform produced by this VI, which allows the user to measure the output with the oscilloscope and record it as a data file. Some of the waveforms are quite peculiar, as Figure 4.9 illustrates.

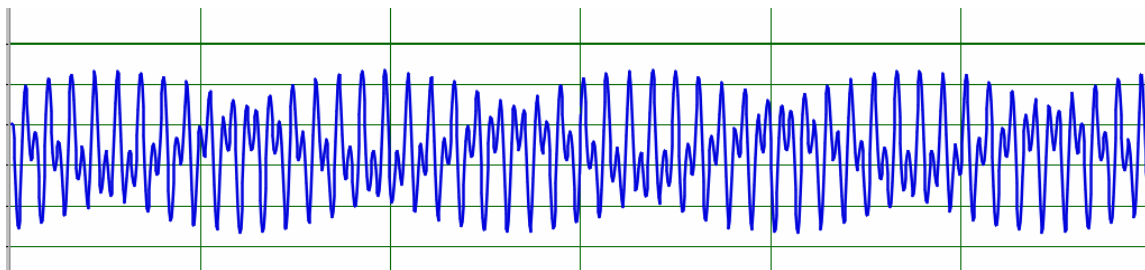


Figure 4. 9
A screen shot of the **OScope Plotter with zoom.vi**, which shows the waveform produced by the **Phone Lab.vi** (the C key).

5. PULSE.vi: A unique tool for teaching “digital” aspects of “analog” circuits

A typical shortcoming in student learning is the gap between of analog and digital circuits. In particular, transient events are studied in the context of analog circuits described with differential equations, while operation of digital circuits could be understood as entirely governed by Boolean algebra. In order to bridge the gap and highlight the “digital” aspects of “analog” circuits, a special **PULSE.vi** was developed (Figure 5.1).

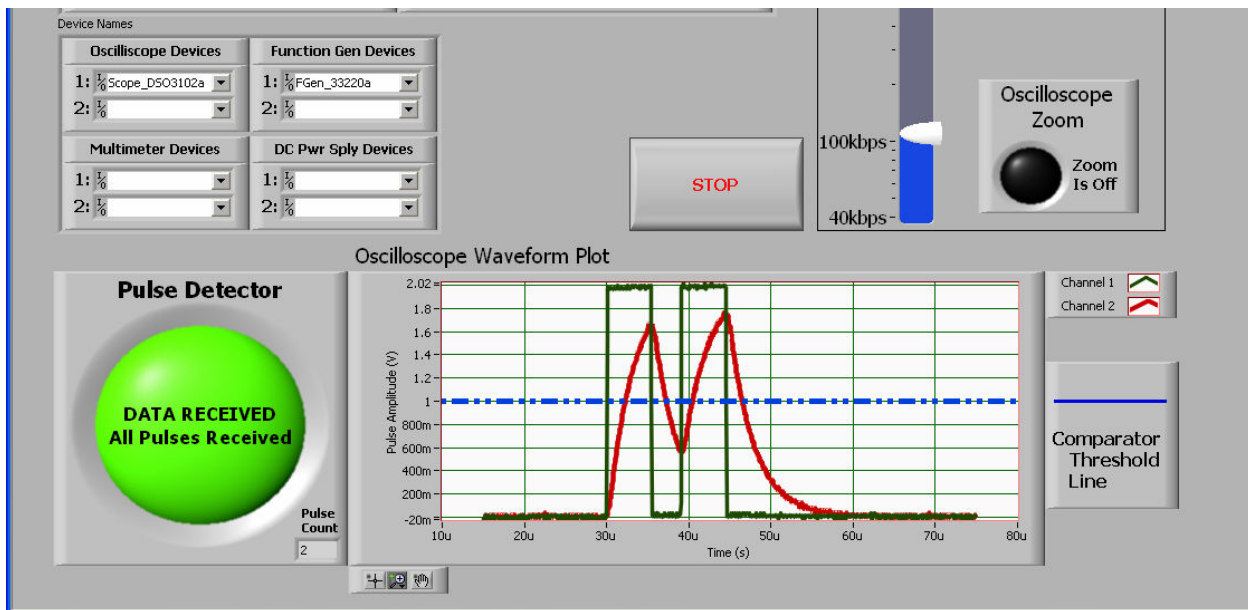


Figure 5.1

A screen shot of the **PULSE.vi** that shows both pulses detected.

The operation of the **PULSE.vi** is similar to a pulse counter: two pulses are sent to the input of a real circuit – but how many pulses are detected by the counter connected at the circuit’s output? The **PULSE.vi** repeatedly generates pairs of rectangular pulses; the student varies their duration or data transfer rate in bits/sec with a scroll bar on the front panel (upper right corner of Figure 5.1). The signal generated by the **PULSE.vi** is fed into the function generator and stored in its memory; from the function generator, the signal is fed as the input into the circuit built by the student: in a typical experiment, it is a series RLC circuit with a potentiometer connected as a variable resistor. The circuit’s output signal is measured with an oscilloscope and transferred to the computer into **PULSE.vi**, which “detects” the pulse if its amplitude exceeds the preset threshold (dashed-dotted line in the middle of the window in Figure 5.1) and counts how many pulses exceed the threshold. The big round indicator changes color depending on how many pulses were received. The example of Figure 5.1 shows both pulses received: in this case the indicator is green.

Depending on the circuit parameters of (such as resistance in an RC or RLC circuit) and on the frequency, at which the function generator sends pulses, several scenarios are possible. Of course, the screen shot in Figure 5.1 shows the best-case scenario from the standpoint of digital communication, observed at low frequencies, when the capacitor in the circuit has enough time

to get charged. As the frequency increases, each pulse gets shorter, providing the capacitor less time to charge. Above a certain frequency, which depends on the circuit parameters, the capacitor fails to charge above the threshold voltage in response to the first pulse: only the second pulse is registered. Then the VI reports a bit error, as shown in Figure 5.2. The big round indicator on the front panel is “lighted” yellow (also note the digital Pulse Count window below the indicator).

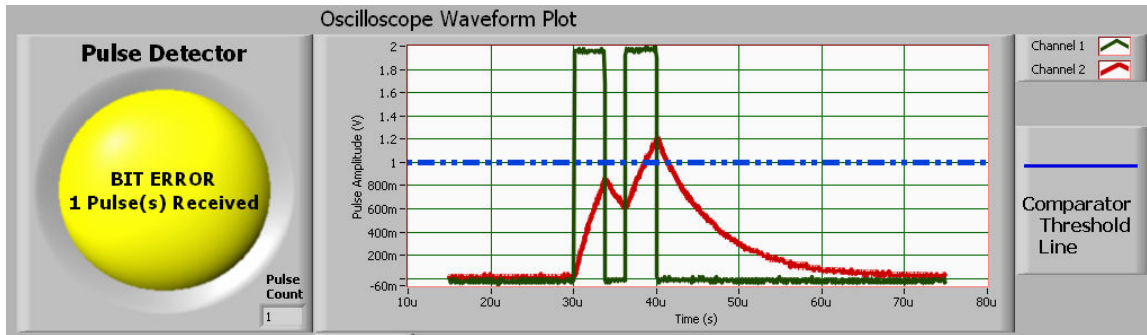


Figure 5.2
A screen shot of the **PULSE.vi** that shows only the second pulse detected.

If the frequency grows further, the capacitor voltage fails to reach the threshold at all, as shown on the screen shot below. Then the VI reports “no data”, as shown in Figure 5.3. The big round indicator on the front panel is “lighted” red.

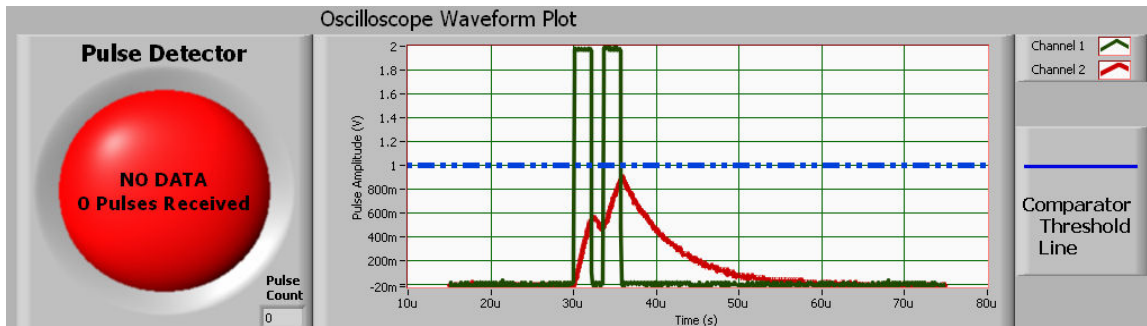


Figure 5.3
A screen shot of the **PULSE.vi** that shows no pulses detected.

The examples of Figures 5.2 and 5.3 illustrate the typical failure of digital circuits at very high clock frequencies, which may be caused by parasitic capacitances, etc. This Virtual Instrument helps students relate their learning about the First-Order and Second-Order Circuits to the operation of digital devices.

Another type of response can be observed in circuits prone to oscillations, such as RLC circuits or any other Second-Order Circuit whose capacitances and/or inductances may be parasitic,

unexpected by the user. If the amplitude of oscillations is not too big, the pulse count might still be correct, as seen on the screen shot in Figure 5.4.

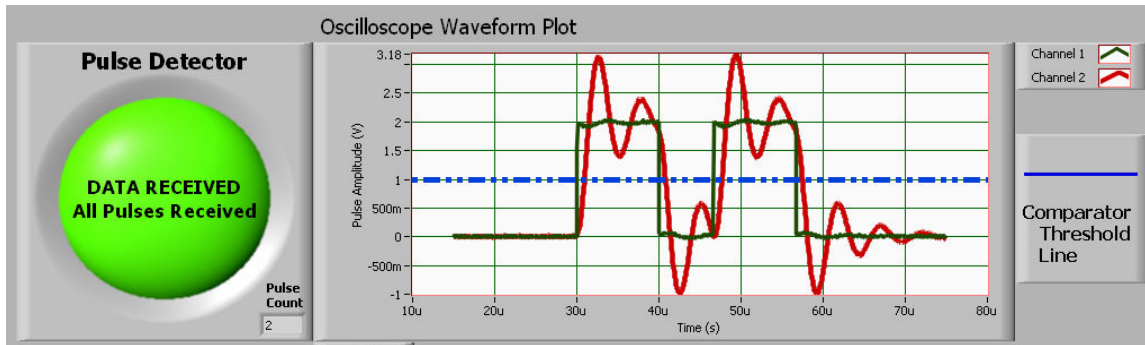


Figure 5.4
A screen shot of the **PULSE.vi** that shows oscillations, which do not fail the pulse detector.

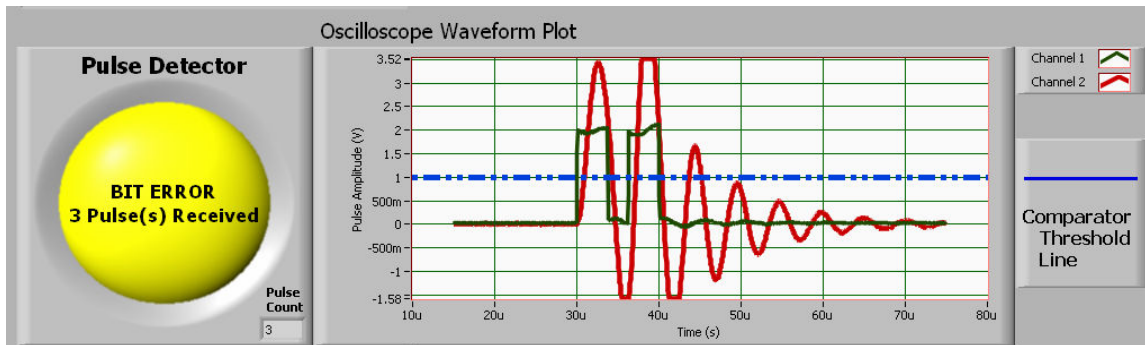


Figure 5.5
A screen shot of the **PULSE.vi** that shows oscillations leading to erroneous detection.

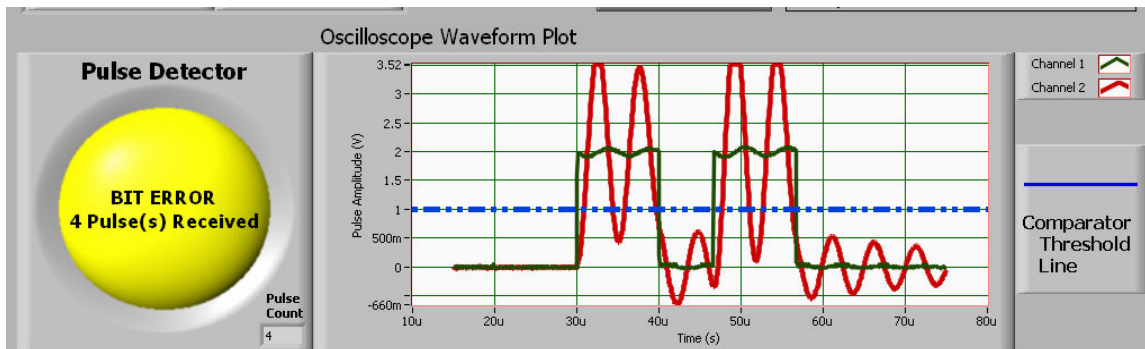


Figure 5.6
A screen shot of the **PULSE.vi** with extremely strong oscillations, failing the pulse detector.

Students should learn that oscillations in digital circuits are undesirable: they lead to bit errors as shown on the two screen shots below, with 3 and 4 pulses “received” when only 2 were sent. Such examples are shown in Figures 5.5 and 5.6. This Virtual Instrument helps students learn that, in order understand a real world circuit, they should keep in mind both analog and digital aspects of its operation.

6. Transfer function measurements

The set of Virtual Instruments for electric circuit laboratories must include a tool for measurements of frequency responses, or transfer functions: it is one of the general-purpose tools useful for studies of filters, amplifiers, and many other circuits. The **Bode Plot.vi** is the most elaborate Virtual Instrument of the entire set created for these lab courses. Students use it several labs, including the Op Amp Lab, Filter Lab, and Audio Lab.

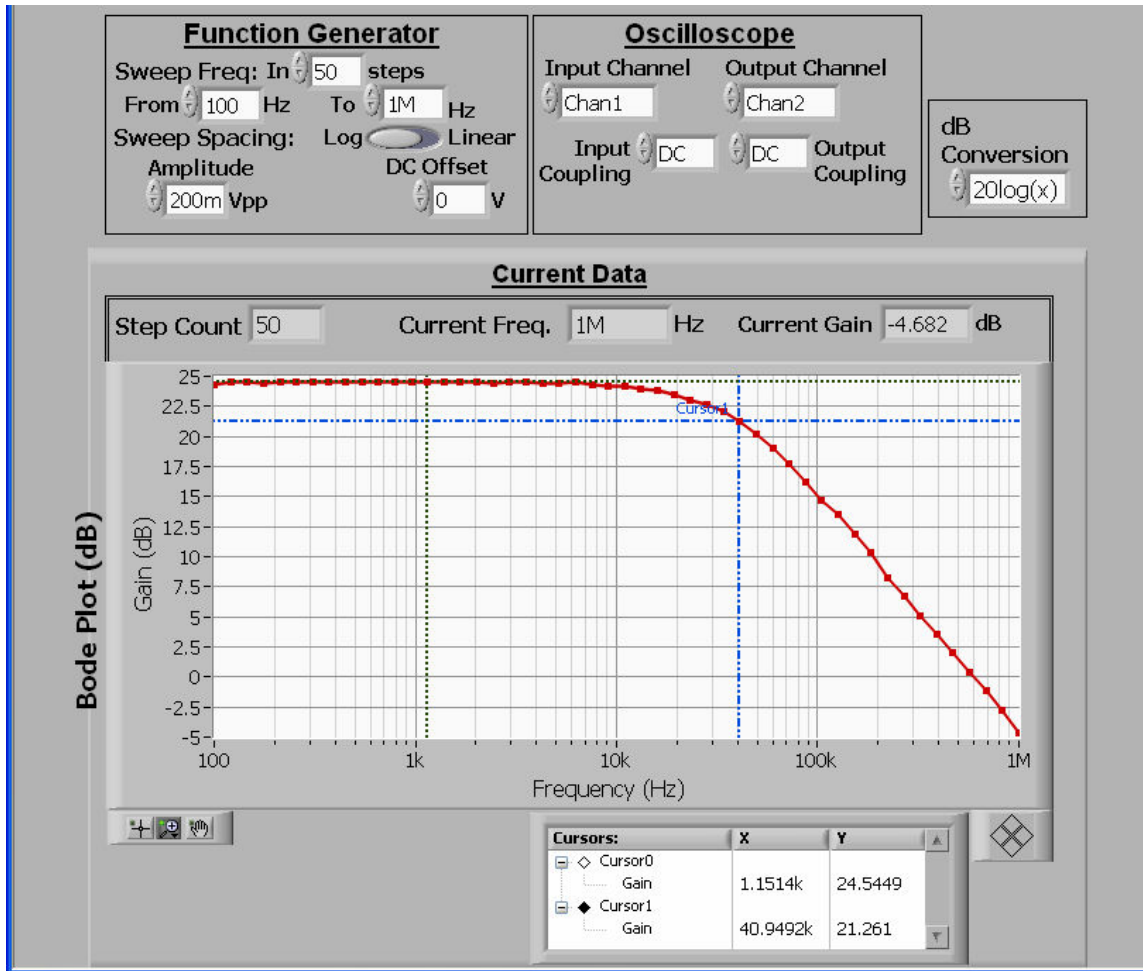


Figure 6.1

A screen shot of the **Bode Plot.vi** that shows the transfer function of a Low-Pass filter.

Figure 6.1 shows a screen shot of the **Bode Plot.vi**, which illustrates its flexibility. From the front panel, students control the number of data points, the frequency span and the type of sweep (logarithmic or linear) as well as the vertical scale for the voltage gain (linear or logarithmic); they also set the amplitude of signals that the function generator feeds to their circuit, the coupling of both oscilloscope channels, etc. The two cursors on the screen shot measure the mid-band gain in dB and the high-frequency -3 dB point, which in this circuit is about 40 kHz. This flexible and powerful teaching tool helps students obtain several sets of data within the lab time, to compare responses of several circuits and relate the lab data to theory.

7. Significance of the Virtual Instruments in organizing student lab reports

The use of Virtual Instruments helps students write better lab reports, in several ways. First of all, the data plotted with the VIs are visually clear, easy to compare with the expected plots provided in the lab book and found in texts; they help students build confidence that their data are good and results meet the expectations. Secondly, for the instructor, reports with data in unified form are much easier to grade. Another important advantage is proof of authenticity: since every student team prints out their data before they leave the lab, and the Lab instructor signs each printout, which has student names and the date of work, it becomes self-evident that every team completed the required lab work. Eventually, uploaded data files, also authenticated and automatically checked for duplication, can be used in post-lab data analysis, comparison with theory, etc. Noteworthy, students emphasized the value of printouts for organization of their lab reports (see Section 8).

8. Student perception of the VIs in the lab

To assess the student perception of the Virtual Instruments used in the lab, a special questionnaire was designed and administered to the students in the lab course for non-EE majors; responses of 93 students were collected and summarized.

The students were asked to express their opinion about the VIs in the lab based on the scale from 5 (strongly agree) to 1 (strongly disagree), where 3 means no opinion.

The following table presents the most significant questions with statistics on the student responses (answers to the rest of the questions were too close to 3.0).

#		Average	Std. Dev.
1	VIs help me collect more data in the lab	4.43	0.68
2	VIs help me make sense of the concepts taught in the lab	3.90	0.74
4	When I see my own data plotted by the VI, and it looks as expected, I know that I built my circuit correctly	4.42	0.71
5	As the VI plots my data point-by-point in real time, I see how my circuit responds to the different voltages, etc.	4.12	0.70
6	By seeing the entire set of my data plotted on the computer screen in the lab, I better understand how the circuit works and can relate its operation to theory	3.88	0.90
7	From comparison between several data plots of my own, I learn more about different circuits	3.71	0.88
8	Printouts of lab data help me organize lab reports	3.80	1.05
16	I think I would have learned better <i>without</i> using VIs	2.19	1.02

In the perception of students, the highest value is placed in obtaining more data in the lab (question 1) and the proof that the students built the circuit correctly (question 4). This troubleshooting value of VIs is partly unexpected. Also, the students appreciate the VIs as tools that show how their circuit responds to different voltages, etc. (question 5). Very valuable for us is seeing the students' positive responses to question 2 "VIs help me make sense of the concepts taught in the lab".

Noteworthy are the students' positive responses to questions 6 and 7, which focus on comparison between experiments and theory as well as comparison between different circuits. Students also appreciate the Virtual Instruments as tools for organizing their lab reports (question 8). Finally, the students confirm overall value of Virtual Instruments for learning (see the lowest score in response to question 16, the only one phrased negatively).

9. Conclusion

After having taught the Labs with computer-controlled experiments in large classes for EE and non-EE majors, as standard part of curriculum, a substantial difference in the instruction process is seen. Obviously, automated experiments save time, but to reduce them to merely time-savers is as wrong as to claim that an automobile is simply a timesaving device. Everyone knows that having a reliable car for daily use affects all aspects of lifestyle; similarly, with the advent of computer-assisted measurements, the paradigm of learning in the lab is changing on the daily basis.

First of all, the focus of taking data in the lab is shifted from acquiring individual points to obtaining several plots – with inevitable comparison between functional dependences made "here and now" before students leave the lab, not a week later when they write lab reports. This is not merely an increase in the volume of data: with a proper focus, it is a powerful tool for relating theory to first-hand experience. For example, in their very first lab assignment, both EE and non-EE students obtain volt-amp characteristics of a light-emitting diode (LED) and volt-volt characteristics of a metal-oxide-semiconductor field-effect transistor (MOSFET). From their own data, students clearly see that both devices are non-ohmic, appreciate that a MOSFET can work as a switch, and get excited about having worked with some real-world stuff.

Moreover, when students acquire their data on an LED or a MOSFET, they clearly observe electronic noise – and intuitively compare the conditions under which this noise is important or negligible (this is a side-effect of auto-zooming feature of the standard software used here).

The functional dependences, easily plotted in computer-assisted measurements, can also serve as effective diagnostic tools of whether the student's circuit has been built correctly: for a human eye, it is much simpler to compare curves on two plots than to compare two tables of data.

In the lab, students make full-page printouts, which include plots of their lab data along with the authentication information (student names, date of work, etc.); the lab instructor signs each printout for every student before the student leaves the lab. These printouts let the student document key facts, such as "under these conditions, clipping of the output signals was observed" and help the lab instructor verify that every student team collected all necessary data.

The printouts are then included in the lab reports, making these reports more informative, looking more professional, and easier to grade. Students are required to upload some of their data files on the server to be used in post-lab analysis and homework assignments, linking lab experience to theoretical learning in the course.

Finally, the students obtain hands-on experience with the software, which is widely used in industry for control and data acquisition, thus they get a competitive edge in job hunting.

10. References

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