Applying IT Tools to a Laboratory Course for Measurement, Analysis, and Design of Electric and Electronic Circuits

Shuhui Li, *Member, IEEE,* and Abrar A. Khan

Abstract—The paper presents the application of information technology (IT) tools to a laboratory course for measurement, analysis, design, and simulation of typical electric and electronic circuits. It shows modern computer data acquisition systems used for measurement of real circuits, mathematical software IT tools used for theoretical analysis and design, and circuit simulation software IT tools used for the development of a virtual laboratory. It illustrates how spreadsheets and other IT tools are used for data recording and/or result comparisons among measurement, theoretical calculation, and simulation. The paper shows the mechanisms and approaches developed for strong correlation between theories and hands-on experimentation using modern computer tools for the purpose of quality education of the laboratory course in electric and electronic circuits.

Index Terms—Circuit simulation, computer data acquisition, education, electric and electronic circuits, laboratory, mathematical IT software, spreadsheets.

I. INTRODUCTION

COMPUTERS and microprocessors have changed much of traditional electrical engineering (EE). They are also changing the traditional teaching styles in higher education. When digital computers and various software and hardware IT tools are used in laboratories and classrooms, they can provide much more effective and efficient environments in teaching and learning and make many mathematical-related engineering problems easy to understand.

The Circuits and Electronics Laboratory, a first-semester junior EE laboratory course at Texas A&M University—Kingsville (TAMUK), is designed and intended to draw on and correlate with the knowledge obtained by students in the sophomore- and early junior-level EE courses, such as Electric Circuits and Electronics. Previously, all the laboratory experiments of the course were based on traditional equipments, devices, methods, and techniques for measurements, data recording, and result analysis. This base made experiments time consuming and inefficient and, therefore, greatly limited students' effective understanding of fundamental concepts and theories from the hands-on experimentation. This paper gives methodologies for significant improvements of the course by developing a completely computer-assisted measurement, analysis, and design environment that incorporates modern computer data acquisition systems, mathematical software IT tools, circuit simulation IT tools, and spreadsheets.

The paper first gives a brief description about the curriculum structure and objectives of the laboratory course in Section II. Section III presents the development of a computer measurement and data acquisition system for the course. Section IV shows methodologies and approaches used to teach fundamental concepts of computer data acquisition and graphical programming. Section V illustrates how mathematical IT tools are used to let students more effectively understand theoretical, analytical, and design aspects of experiments. Section VI gives circuit simulation IT tools used for circuit simulation, analysis, and design in a virtual laboratory environment. Section VII shows the methodologies for result comparisons among theoretical calculation, circuit simulation, and computer measurement by using spreadsheets and mathematical IT tools for the purpose of strong correlation between theories and hands-on experimentation. Section VIII assesses the educational effectiveness of IT tools applied to the laboratory. Section IX concludes the paper.

II. THE CIRCUITS AND ELECTRONICS LABORATORY AT TAMUK

The Circuits and Electronics Lavoratory was Electrical Engineering Laboratory I and II, a two-semester junior EE laboratory course at TAMUK. At the time when the course was changed to the Circuits and Electronics Laboratory, a one-semester laboratory course, modern computer measurement and data acquisition systems, and several other software IT tools were introduced. Currently, the course has 14 laboratory experiments with one for each week, except for the last one as shown in Table I [1].

The course consists of time spent in both the classroom (one hour) and the laboratory (three hours). The classroom time is used to present and develop specific topics that support the corresponding laboratory work. Students are expected to spend time in the classroom reviewing/learning the theoretical background, objectives, and purposes of the experimental work to be performed in the laboratory. In the interval between the classroom period and the actual laboratory period, students are expected to have completed all required preparations necessary for the corresponding laboratory work. These include circuit simulation in a virtual laboratory environment, determination

TABLE I
LABORATORY EXPERIMENTS FOR CIRCUITS AND ELECTRONICS LABORATORY AT TAMUK

No.	Topics
Lab 1	Verification of Basic Circuit Laws for Resistive Circuits
Lab 2	Network Analysis Techniques
Lab 3	Using the Oscilloscope
Lab 4	Introduction to LabView in Three Hours
Lab 5	Introduction to LabView Data Acquisition
Lab 6	Transients in RL, RC, and RLC Circuits
Lab 7	Two Port Networks and Equivalent Circuits
Lab 8	Design and Evaluation of First-order RC Low-pass and High-Pass Filters
Lab 9	Design and Evaluation of Second-order RLC Band-pass and Notch Filters
Lab 10	V-I Characteristics of Simple Electrical and Electronic Elements
Lab 11	Operational Amplifiers
Lab 12	Common-Emitter Small Signal Amplifiers
Lab 13	Design and Implementation of Digital to Analog Conversion
Lab 14	Design and Implementation of Analog to Digital Converter

of the required empirical data to be obtained, choice of acceptable measurement techniques, determination of appropriate instrument signal levels and sensitivities, establishment of appropriate ranges over which data is to be acquired, and any other preparation that may be required. The time spent in the laboratory should be used just to build circuits, make measurements, and acquire data that allow students to evaluate the characteristics of the associated networks and/or devices.

The course has four primary objectives, and upon successful completion of the course students should have demonstrated an acceptable level of proficiency in all. These objectives are as follows:

1) the ability to use and exploit the capabilities of both computer data acquisition systems and analog electronic instruments in the acquisition of engineering and scientific data;
2) the ability to design data acquisition and measurement strategies to obtain empirically the necessary and required information;
3) the ability for data interpretation and presentation using different IT tools leading to a meaningful written report;
4) demonstration and support for some of the fundamental concepts in electrical and electronic networks and device behavior developed in the previous course works, such as Circuits and Electronics.

The laboratory room is equipped with ten stations, each of which include a computer data acquisition and measurement system, a dual-trace cathode ray oscilloscope, a digital multimeter, a universal digital counter, a function generator, a dual dc power supply, and a computer equipped with various IT software packages intended for the acquisition, reduction, analysis, and presentation of experimental data. For many experiments, both computer and traditional measuring systems/equipments are used to develop students' capability for using modern and traditional equipment for measurements, showing students that data displayed by a computer or data applied to a circuit from a computer is real rather than simulated.
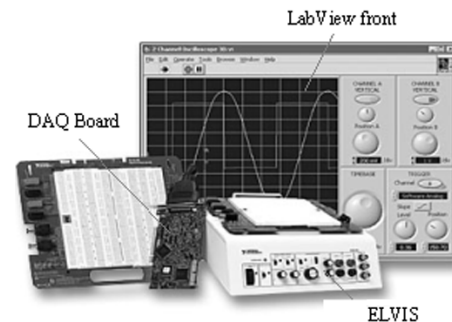

Fig. 1. NI Educational Laboratory Virtual Instrumentation Suite (ELVIS).

III. COMPUTER MEASUREMENT AND DATA ACQUISITION

A computer measurement system usually consists of a digital computer, a data acquisition (DAQ) hardware device, and a software package to support obtaining, displaying, and analyzing data from the DAQ device, and has been used as a valuable tool for modern engineering education [2]–[5]. LabVIEW, developed by National Instruments (NI), is one such software package that has a graphical development environment with built-in functionality for simulation, data acquisition, instrument control, measurement analysis, and data presentation [6], [7]. A graphical development environment normally does not require any lines of traditional text-based code to create applications. A user interface for an application can be created quickly and simply by dragging and dropping prebuilt objects, and then system functionality can be specified by assembling block diagrams—a natural design notation for electrical and computer engineering students.

Since the introduction of computer data acquisition and measurement systems in the Circuits and Electronics Laboratory at TAMUK, the ways of teaching and learning have greatly improved. Rather than focusing on tedious and/or time-consuming methods of gathering data, students can now obtain measured results much faster and more efficiently. Results can be obtained by capturing the screen and/or by saving to data files for future analysis. This procedure not only makes possible having
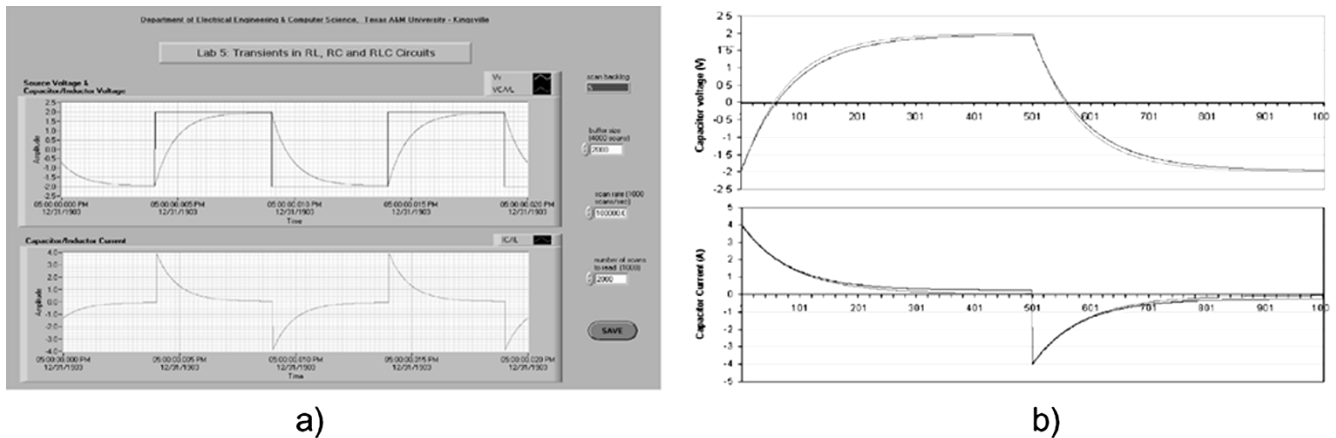
Fig. 2. Measured and calculated results for transient of an *RC* circuit: (a) Measured results by screen capture and (b) comparison of measured/calculated results.
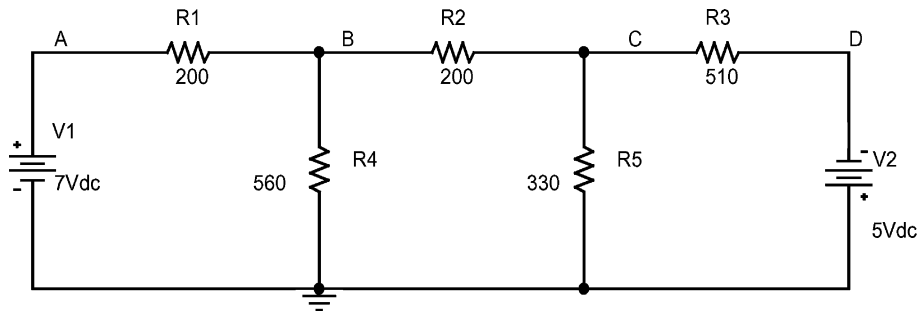

Fig. 3. Circuit for experiment of network analysis techniques.

more coverage in an experiment but also makes students more focused on results, concepts, relations to theories, and/or design aspects of the experiment, providing an improved and favorable methodology for quality education.

The course has been more improved since 2003, when the NI Educational Laboratory Virtual Instrumentation Suite (ELVIS), a suite of more professional LabVIEW-based virtual instruments, was introduced. The NI ELVIS uses LabVIEW-based software, a multifunction DAQ board, and a custom-designed workstation (Fig. 1) to provide functionality for a suite of instruments. This specially designed suite of virtual instruments provides functionality of common laboratory instruments, such as an oscilloscope, a function generator, a digital multimeter (DMM), a variable power supply, a Bode analyzer, a dynamic signal analyzer, an impedance analyzer, and current–voltage analyzers. Those virtual instruments have been used in the 14 laboratory experiments of the course for measurement, analysis, and design of typical electric and electronic circuits, filters, operational amplifiers, and digital–analog (D/A) and analog–digital (A/D) converters [1].

Fig. 2 presents an example of using computer data acquisition hardware and a specially designed LabView program to measure the transients of a series resistance–capacitance (*RC*) circuit under a square-wave input voltage. After the measuring circuit is set up and is provided with necessary connections to DAQ analog input channels, measuring results can be displayed in the front panel of the program by clicking the running icon. Any result in the front panel can be screen-captured, as shown in Fig. 2(a), or saved to a file by clicking the Save button in the

figure. This strategy greatly reduces the time needed to get the results. On the other hand, a large amount of data saved in a file can be analyzed and compared with calculation and simulation results generated by other IT software packages [Fig. 2(b)] to re-emphasize most effectively students' understanding of theories.

## IV. Understanding Computer DAQ and Graphical Programming

It is important to note that students must understand the significance of digital computer virtual instruments as replacements of traditional instruments and understand the basic graphical programming concepts. This understanding could motivate students' interests and confidence to use modern digital computer data acquisition and measurement systems for diverse problems in measurement, analysis, and design of various electric and electronic circuits, and more advanced design projects.

A. Comparing Virtual Instruments With Traditional Instruments

Result comparisons between traditional and virtual instruments usually give students better understanding and stronger confidence on digital computer virtual instruments for experimentation. Fig. 3 shows a circuit of an experiment related to network analysis techniques, such as node voltage, mesh current, superposition, and Thevenin equivalent methods. It is one

TABLE II
COMPARISON OF MEASUREMENT BY NI ELVIS DMM AND FLUKE 45 DMM

Measurement	Mesh Current			Node Voltage		
	Calculated	Measured		Calculated	Measured	
		DMM	NI ELVIS		DMM	NI ELVIS
I_{R1} (mA)	18.79	18.49	18.38	18.79	18.71	18.7
I_{R2} (mA)	13	12.85	12.4	13.005	13.0015	13.01
I_{R3} (mA)	11.06	10.92	10.42	11.060784	11.0935294	11.094118
I_{R4} (mA)	5.79	5.64	5.98	5.7892857	5.81785714	5.8214286
I_{R5} (mA)	1.94	1.93	1.98	1.9424242	1.9930303	1.9939394
V_A (V)	7	7	7	7	7	7
V_B (V)	3.2424	3.1584	3.3488	3.242	3.258	3.26
V_C (V)	0.6402	0.6369	0.6534	0.641	0.6577	0.658
V_D (V)	-5	-5	-5	-5	-5	-5
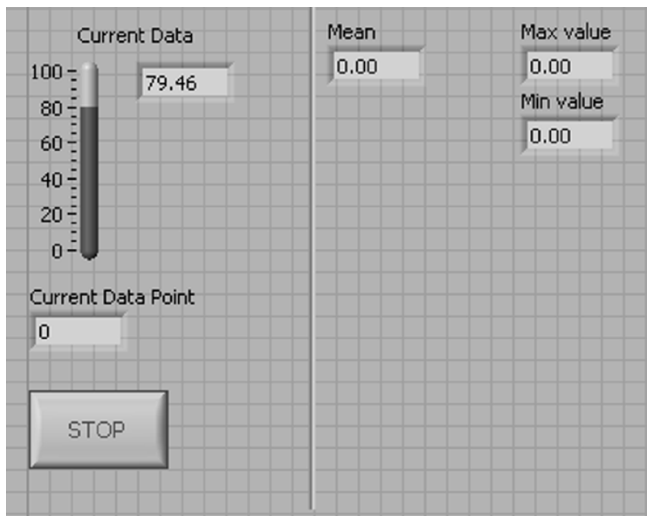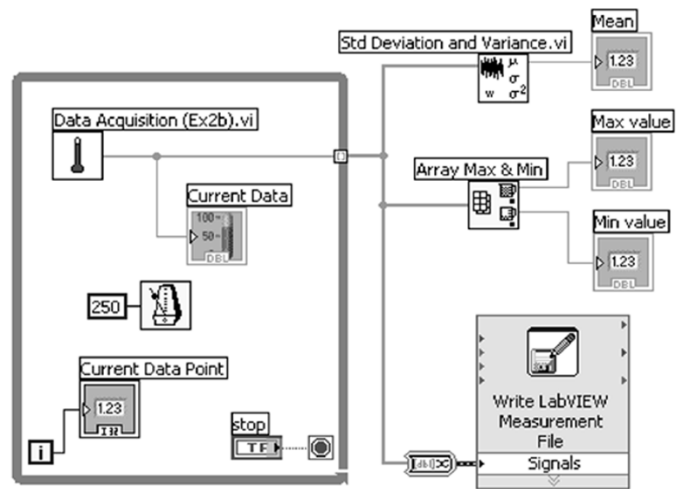
Fig. 4.   LabView front panel and block diagram of a temperature monitoring system: (a) temperature-monitoring front panel and (b) temperature-monitoring block diagram.

of the experiments for this comparison purpose. Specially designed spreadsheet tables have been used for data recording. Normally, the comparisons show a very small difference among results from traditional instruments, the virtual instruments, and theoretical calculations, as shown by Table II. Those comparisons could strongly motivate students' interests to learn and use digital computer DAQ for more extensive measurement, analysis, and design of various electric and electronic circuits.

B. Introduction of Graphical Programming and Computer DAQ

Introducing basic concepts of graphical programming and computer DAQ is important to let students understand the fundamentals of both hardware and software aspects of a typical modern computer measurement system. However, unlike text-based programming languages, one can teach the graphical programming fundamentals in one or two laboratory experiments in an environment that has computer facilities for students

to use while the instructor is teaching. A typical example for this introduction is to develop a simple temperature monitoring and recording system as shown in Fig. 4 [8]. The temperature sensor can also be replaced by a voltage source for simplicity or convenience. This example can be subdivided into four or five exercises that could help in developing students' ability and understanding step by step from basic graphical programming concepts and skills to the final implementation of the simple temperature data acquisition and recording system in both hardware and software. All those exercises will give students opportunities to learn and practice general graphical programming fundamentals, such as subVIs, loops, arrays, charts and graphs, DAQ and waveforms, and file input–output (I/O).

V. UNDERSTANDING THEORETICAL BACKGROUND OF AN EXPERIMENT

One of the important purposes of the experimentation is to reemphasize students' understanding of theories. In order to

Lab Experiment 2: Network Analysis Techniques

Resistors of the circuit:

$R1 := 200\Omega$ $R2 := 200\Omega$ $R3 := 510\Omega$ $R4 := 560\Omega$ $R5 := 330\Omega$

Voltage sources:

$V1 := 7V$ $V2 := 5V$

1. Mesh current method:

$IR1 := 0A$ $IR2 := 0A$ $IR3 := 0A$

Given

$$\begin{pmatrix} R1 + R4 & -R4 & 0 \\ -R4 & R2 + R5 + R4 & -R5 \\ 0 & -R5 & R3 + R5 \end{pmatrix} \cdot \begin{pmatrix} IR1 \\ IR2 \\ IR3 \end{pmatrix} = \begin{pmatrix} V1 \\ 0 \\ V2 \end{pmatrix}$$

$$\begin{pmatrix} IR1 \\ IR2 \\ IR3 \end{pmatrix} := Find(IR1, IR2, IR3) \qquad \begin{pmatrix} IR1 \\ IR2 \\ IR3 \end{pmatrix} = \begin{pmatrix} 18.792 \\ 13.003 \\ 11.061 \end{pmatrix} mA$$

Fig. 5.   Calculating mesh currents using MathCAD.

better correlate the laboratory experiments with theories, mathematical IT tools are used for theoretical analysis and/or design of most laboratory experiments [9]. One of the typical mathematical IT tools is MathCAD [10], which is suitable for all the mathematical computations needed by the course. This mathematical IT tool can effectively show the relationship between mathematical equations and electrical variables represented in data, curves, and plots. Its animation features can provide a dynamic environment for students to see both theories/equations and what may happen in a circuit under the theories/equations [10]–[14].

Fig. 5 shows the MathCAD worksheet used to calculate the mesh currents of the circuit given in Fig. 3. In the MathCAD worksheet, a student types equations based on learned theories [15], and then the mathematical IT tool does all the calculations automatically. This technique not only provides faster results but also makes the theoretical background of an experiment easy to see and understand. For any condition change of the same circuit, the mathematical IT tool can quickly get new results. For example, when changing $V1 = 0$ V or $V2 = 0$ V, respectively in Fig. 3, a student can get calculated results for the superposition method of the circuit [15].

The mathematical IT tool is also used to draw plots for given theoretical equations of an experiment. Fig. 6 shows an example of using the mathematical tool to calculate and draw the Bode plot of a series *RC* low-pass filter [15], again demonstrating an easy way for students to understand the theoretical background of an experiment represented in both equations and plots. For any design specification change in the cutoff frequency, the MathCAD IT tool can automatically recalculate to obtain new data and then redraw the Bode plot, allowing students not only to find an appropriate design quickly for their need but also to see the design performance in Bode plot.

One may conveniently export mathematically calculated data, such as the Bode plots of Fig. 6, to a data file. Data saved in a file can be reloaded in a computer and then compared with measured results to reemphasize students' understanding of theories through the comparison (see Section VII).

VI. VIRTUAL LABORATORY USING CIRCUIT SIMULATION TOOLS

Many circuit simulation tools can simulate electric and electronic circuits and also perform various circuit analyzes for simulation data. PSpice and Electronics Workbench are two typical circuit simulation tools among them [16]–[18]. Although incorporating measurements with theoretical calculations for quality education is significant, the valuable role of simulation cannot be ignored [19]. First, the circuit simulation can provide a strong virtual laboratory environment for a practical experiment. Second, building or modifying an electric circuit or system in simulation is much faster than in hardware. Third, with most circuit simulation IT tools, analysis and design of an electric/electronic circuit is very easy to perform in a software simulation environment [20], [21].

A virtual laboratory using a circuit simulation tool such as PSpice has been shown successful for quality education in the Circuits and Electronics Laboratory at TAMUK. For each experiment, one hour for lecture and three hours for experimentation are required. Circuit simulation is required for each experiment before building actual measuring circuits. Through the simulation, students have virtual understanding of an experiment, preparing them for more productive measurements. Fig. 7 shows the circuit schematic of the experiment for designing and implementing digital–analog converter (DAC) [1]. Students start their designs of the DAC in simulation. In a software simulation environment, they can quickly set up the DAC circuit, check possible design errors, and simulate the circuit to see transients of any node voltage or branch current, such as the four-bit digital input voltages and the triangle analog output voltage presented in Fig. 8. Through the simulation, students can understand more clearly the basic DAC concepts, such as the gain, range, and resolution, and how those parameters can affect the DAC or can be modified [22]. After the analysis and design in simulation, students can quickly build a practical DAC circuit, preventing possible errors or mistakes that could damage any electric and electronic component or device and obtain meaningful experimental results.

The circuit simulation IT tool is also used during a laboratory experiment to assist students debugging a laboratory circuit or understanding the reasons for any inconsistency between measurement and pretheoretical calculation. For example, after setting up a DAC circuit of Fig. 7, students usually have difficulties getting the DAC circuit working properly. However, in a software simulation environment, they can easily simulate voltages of various nodes for a digital bit combination, as shown in Fig. 9(a). Then, they can use the computer measurement program specifically designed for the experiment [Fig. 9(b)] to generate this bit combination, measure node voltages of the practical DAC circuit, and compare measured and simulated results. In this way, problems of the DAC circuit can be quickly identified. In some situations where measured and simulated results do not match because of factors, such as internal impedance in a source and/or in electric/electronic components, students can easily modify the corresponding circuit schematic, resimulate the circuit, and then compare new simulated results with measured results. In this way, not only can theories be clarified but

Lab 8: Design and Evaluation of First-order RC Low and High Pass Filters

Design specification of cut-off frequency: $\quad f_{co} := 1000 Hz \quad \omega_{co} := 2\pi \cdot f_{co}$

- **Low pass filter design and evaluation:**

    1. Choose a capacitor: $\quad C := 1\mu F$

    2. Design a resistor for cut-off frequency requirement: $\quad R := \dfrac{1}{C \cdot \omega_{co}} \quad R = 159.155\, ohm$

    3. Frequency response plots: $\quad \omega := 0, 0.1..6 \quad \omega 1(\omega) := 2\pi\, 10^{\omega} \cdot s^{-1} \quad H(\omega) := \dfrac{1}{1 + \dfrac{j \cdot \omega 1(\omega)}{\omega_{co}}}$
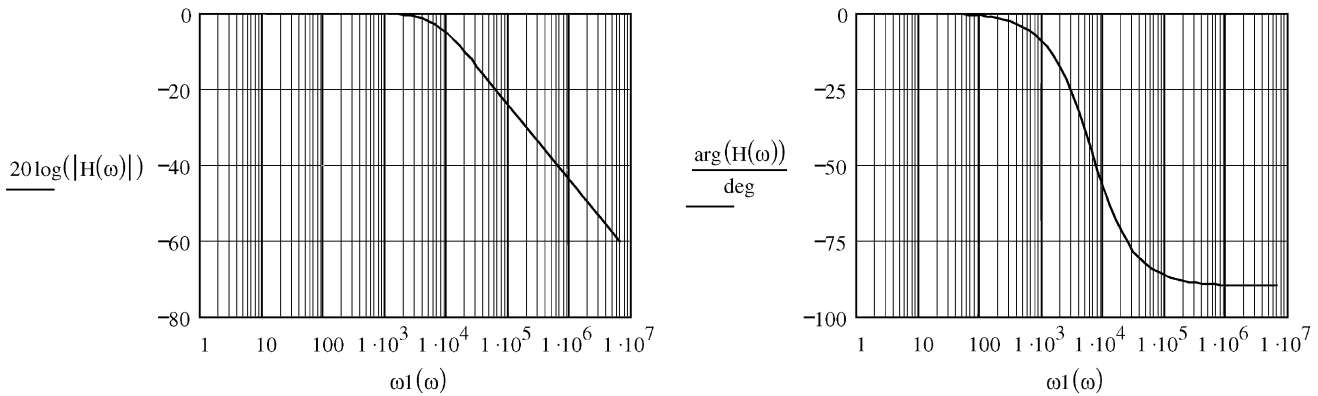

Fig. 6. MathCAD worksheet used for designing and evaluating a first-order *RC* low-pass filter.
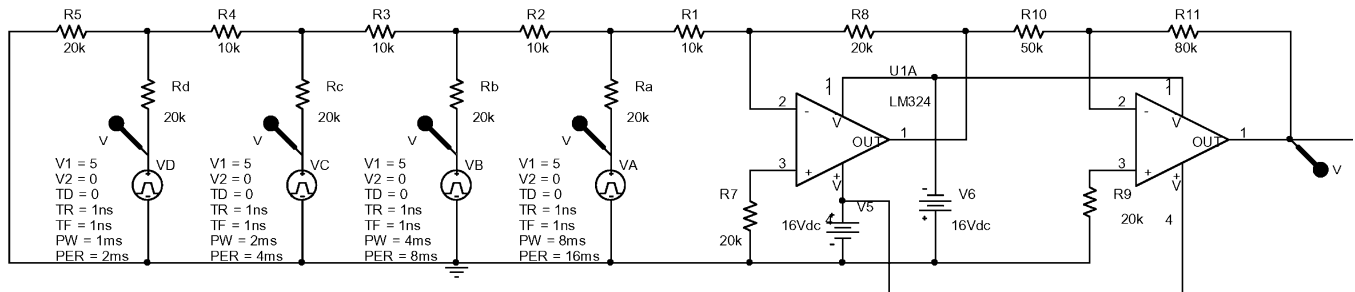

Fig. 7. Simulation circuit schematic of DAC in PSpice.

also the deviation of the measured results caused by such factors can be understood.

Simulation results can be easily exported to a file for most circuit simulation IT tools. This exportation is not only true for a small amount of data obtained from bias point simulation but also true for a large amount of data obtained through general dc sweep, ac sweep, and transient simulations, giving students an appropriate way to compare results obtained from measurement, simulation, and calculation by using different engineering and mathematical IT tools.

VII. COMPARING MEASURED, SIMULATED, AND THEORETICALLY CALCULATED RESULTS

Comparisons among measured, simulated, and theoretically calculated results are important for effectively reemphasizing students' understanding of theories. The result comparisons use

modern IT tools, such as spreadsheets and mathematical software packages. For each laboratory experiment, spreadsheet tables [23] are designed. In addition for the comparison purpose, the spreadsheet tables are also used for data recording and some automatic theoretical calculations to save time in an experiment and make students more focused on other aspects of measurement and analysis.

Fig. 10 shows a circuit for measurement of Z parameters of a two-port network [1], [15], and Fig. 11 gives corresponding spreadsheet tables designed for data recording and partial theoretical calculations. The Z parameters of the two-port network can be calculated automatically in the spreadsheet table when a student types in measured or simulated data in relevant cells for the open circuit tests at input and output ports. For example, the Z parameters of Z_{11} and Z_{21} are calculated automatically when data in cells B6, B7, and B8, or C6, C7, and C8 are provided with measured or simulated results of the output port open
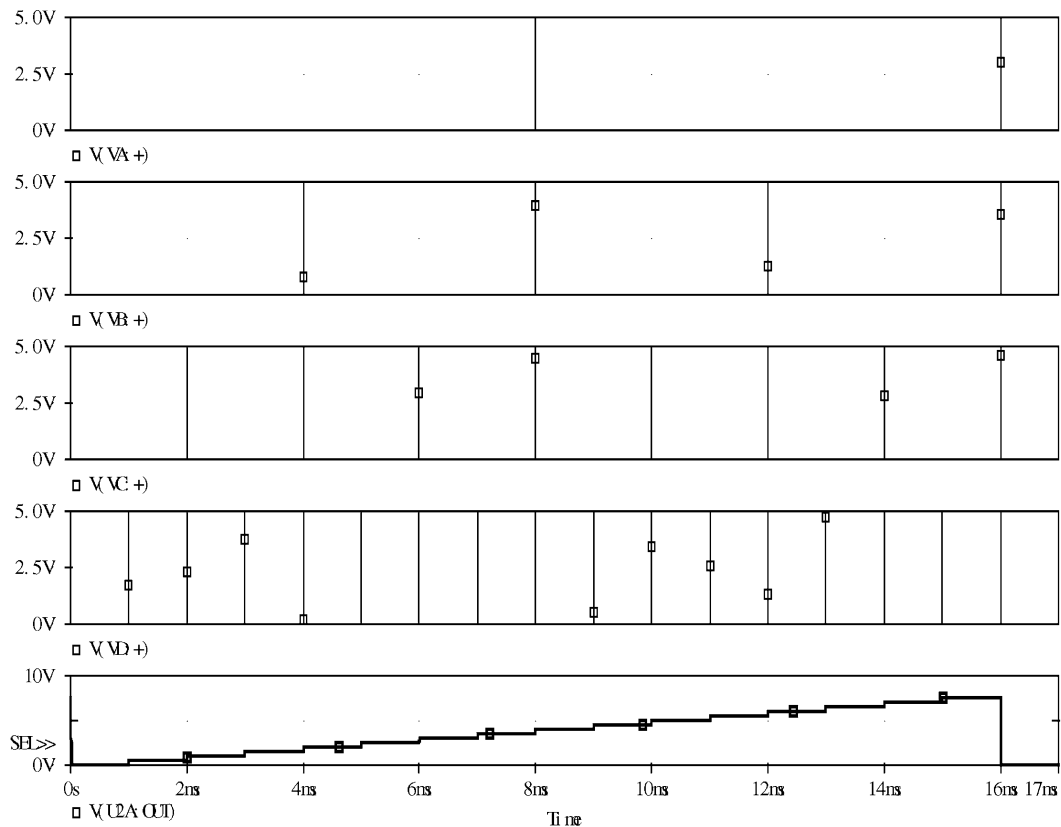
Fig. 8.   Simulation results of the digital inputs and analog output of the DAC.

circuit test. Cells B9 and C9 are prespecified constants of 0 mA and are password protected. The formula used for B10, for instance, is

$$= \mathrm{IF}(\mathrm{OR}(\mathrm{B6} = "\ ",\ \mathrm{B7} = "\ "), "\ ", \mathrm{B6}/\mathrm{B7}*1000). \quad (1)$$

According to (1), the calculated Z parameters are shown only after measured results in cells B6 and B7 are provided. The parameters for equivalent T network of the measured circuit are also automatically calculated when results in cells B10 and B11 and E10 and E11 are available. The formula used for calculation of Z_a in cell D15 is

$$= \mathrm{IF}(\mathrm{OR}(\mathrm{B10} = "\ ", \mathrm{B11} = "\ "), "\ ", \mathrm{B10} - \mathrm{B11}). \quad (2)$$

Besides the example presented in Figs. 10 and 11, spreadsheets are also used significantly to draw graphs for comparisons. Normally, data for the comparisons are generated/obtained and then exported to files by using mathematical calculation, circuit simulation, and LabView measurement IT tools. Those data can then be loaded into a spreadsheet, and comparison plots can be drawn easily [24].

However, for comparison in spreadsheets, data need to be collected consistently, such as having the same starting and ending times and time interval or having the same starting and ending frequencies and frequency interval. These conditions may not always be true for measurement, calculation, and simulation obtained in different environments of the IT tools. MATLAB is one of the mathematical IT tools able to handle the comparison under these inconsistent conditions and has also been one of the most important engineering education tools today [25],

[26]. Fig. 12 gives the main MATLAB code lines for comparison of results saved in three files. The program loads data on line 6 and draws mathematical calculation, circuit simulation, and actual measurement results on lines 10, 14, and 18, respectively. The MATLAB "hold on" command on lines 11 and 15 allows one to draw results obtained in different software environments in the same plot without the requirement for all the curves to have the same starting and ending values and the same intervals on the horizontal axis. The basic structure of the program is suitable for comparison purposes with all the other experiments of the course. Fig. 13 shows an example of the comparison of Bode plots generated/obtained through different IT tools of MathCAD, PSpice, and NI ELVIS for an *RC* high-pass filter. It demonstrates that the comparison in MATLAB gives more flexible and easier ways for students to evaluate measured, simulated, and calculated results generated/obtained in different IT hardware and/or software environments to more effectively reemphasize students' understanding of theories.

VIII. ASSESSMENT OF THE APPLICATION OF IT TOOLS

The laboratory course has been improved greatly after the introduction of the IT tools. Traditionally, this course was a two-semester course with each laboratory topic covering a period of two weeks. However, students spent most of their time gathering data, and the approaches they used to analyze and organize data were inefficient, greatly reducing the effectiveness of reemphasizing students' understanding of fundamental concepts and theories in the previous EE course works through the experimentation.
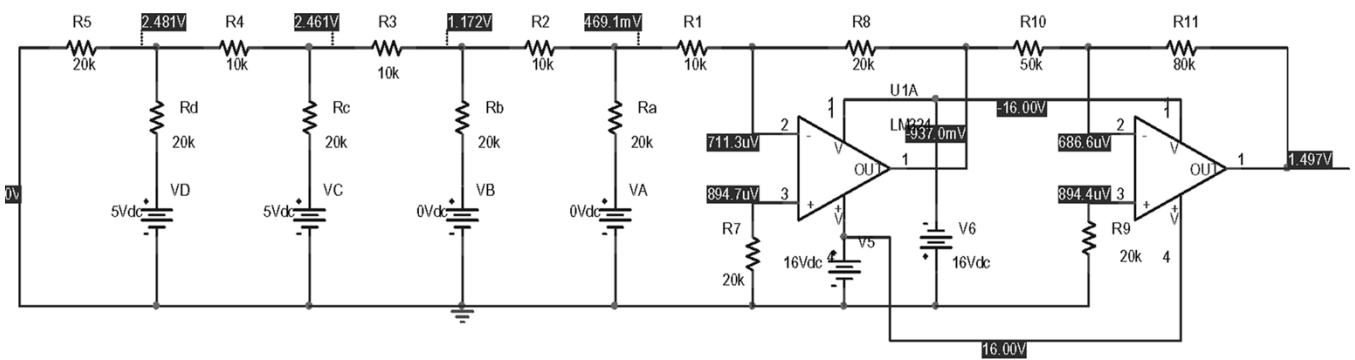
a)
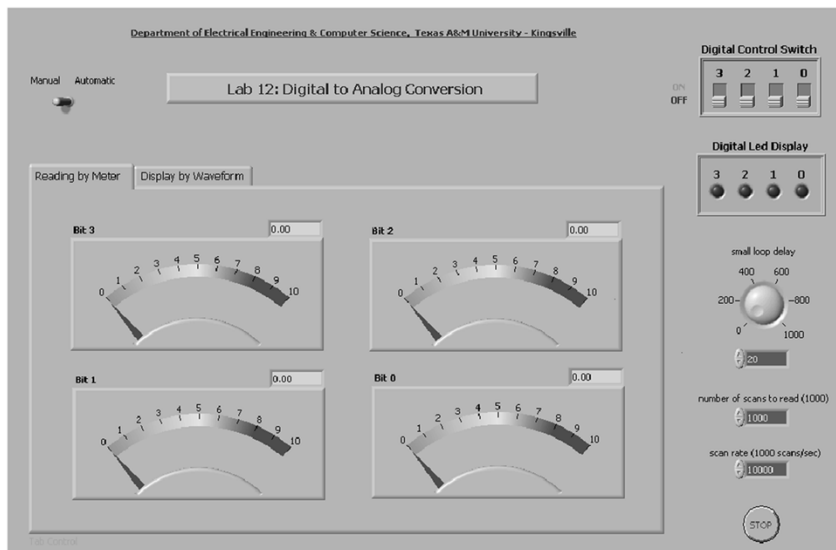
b)

Fig. 9.   Debug a DAC circuit with the assistance of PSpice simulation: (a) node voltage simulation for a digital bit combination and (b) LabView front panel for measurement and debugging of DACs.
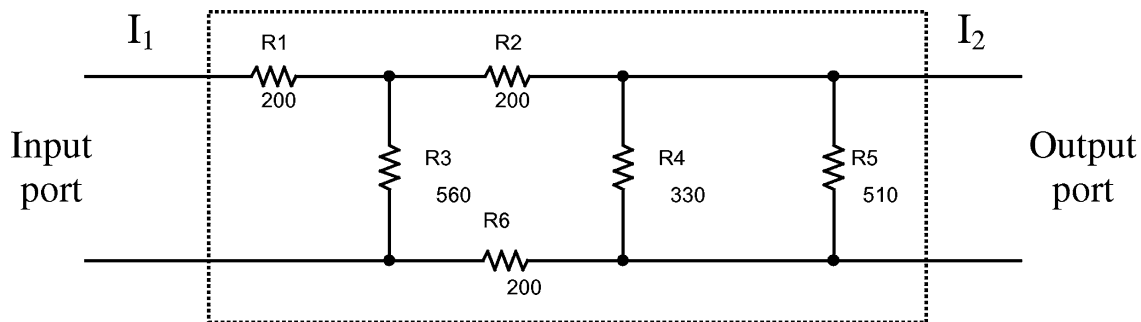

Fig. 10.   Circuit schematic for laboratory experiment of two-port networks and equivalent circuits.

The application of IT tools has made the laboratory course more efficient with each laboratory topic having more contents but covering only a period of one week. The time now needed for students to obtain, organize, and analyze data has been greatly reduced. Instead of using pen and paper, students now use disks [most use universal serial bus (USB) flash drives] to save data recorded in spreadsheet tables, specially designed for each laboratory experiment, such as Table II and Fig. 11. This electronic data recording is much faster, more convenient, and better or-

ganized. Students also use computer data acquisition hardware and software to obtain data and save measured results either as an image file for screen capturing or as a text file for general measured data. For many experiments, such as transients of *RC,* resistance–inductance (*RL*), and resistance–inductance–capacitance (*RLC*) circuits, students spent considerable time to get several dozen data points for measurement of one waveform, using the vertical and horizontal cursors of an oscilloscope. With a computer measurement system, however, a student can simul-

	B10	▼	=	=IF(OR(B6="",B7=""),"",B6/B7*1000)	
	A	B	C	D	E	F
1		Table 1: Z parameters of a two-port network				
2						
3	a) Measuring Z parameters					
4		Output port open circuit test			Input port open circuit test		
5	Variables	Measured	Simulated	Variables	Measured	Simulated
6	V_1 (V)	10.01	10	V_1 (V)	5.8	5.833
7	I_1 (mA)	20.37	20.42	I_1 (mA)	0	0
8	V_2 (V)	1.96	1.974	V_2 (V)	9.98	10
9	I_2 (mA)	0	0	I_2 (mA)	59.8	60.33
10	Z_{11}	491.4089347	489.7159647	Z_{12}	96.98996656	96.68489972
11	Z_{21}	96.21993127	96.66993144	Z_{22}	166.8896321	165.7550141
12						
13		b) Equivalent T network of measuring circuit				
14		Equivalent T network parameters				
15		Za (ohms)		395.1890034		
16		Zb (ohms)		69.89966555		
17		Zc (ohms)		96.21993127		
18						
19	c) Use of Z parameters - measured/simulated load voltage and current					
20		Method used			Load voltage	Load current
21					V_L (V)	I_L (mA)
22	Measurements from original network				1.71	1.72
23	Simulations from Z-parameter network				1.72	1.72
24	Measurements from equivalent T network				1.72	1.72

Fig. 11.   Spreadsheet table for the laboratory experiment of two-port networks and equivalent circuits.

```
1   %*********************************************************************%
2   %    Matlab Program for Comparing Mathcad, PSpice and NI ELVIS    %
3   %*********************************************************************%
4
5   % 1. Loading data
6   load Mathcad_hp.txt; load pspice_hp.txt; load ELVIS_hp.txt;
7   subplot(2,1,1);
8
9   % 2. Plot Mathcad results
10  x1=Mathcad_hp(:,1); y1=Mathcad_hp(:,2); semilogx(x1,y1);
11  hold on;
12
13  % 3. Plot PSpice results
14  x2=pspice_hp(:,1); y2=pspice_hp(:,2); semilogx(x2,y2,'go');
15  hold on;
16
17  % 4. Plot NI ELVIS measured results
18  x3=ELVIS_hp(:,1); y3=ELVIS_hp(:,2); semilogx(x3,y3,'r+'); grid;
19  grid on;
20
```

Fig. 12.   MATLAB program for comparing MathCAD, PSpice, and NI ELVIS results.

taneously get thousands of data points for several waveforms in seconds and then analyze the data by using other IT tools, making practical the production of valuable and high-quality laboratory reports.

The application of mathematical IT tools makes understanding the theoretical backgrounds of an experiment more convenient and effective. Theoretical calculations of an exper-

iment were normally obtained by students using calculators. They spent considerable time on the calculation. For many experiments, large calculations, such as *RC*, *RL*, and *RLC* transients, became impractical or boring. Like many other mathematical IT tools, the advantages of MathCAD enable the integration of equations, variables, calculation results, and plots in one worksheet in which students can see both equations
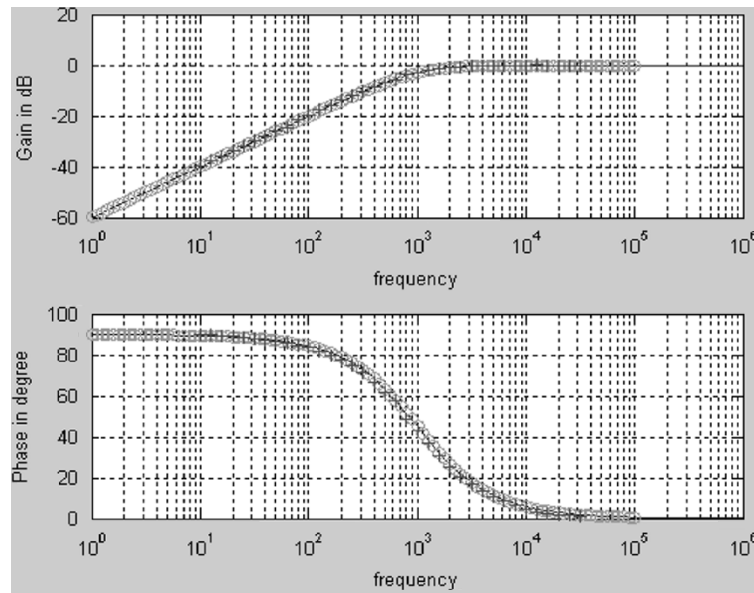
Fig. 13.   Result comparison among MathCAD calculation "−", Pspice simulation "-o-", and NI ELVIS measurement "-+-".

and results for any variable change. This integrated worksheet environment can not only motivate students' interests for theoretical calculations but also let them more clearly understand the theories. The mathematical IT tools also make practical significant repeated calculations under the same equations.

Circuit simulation tools were not required earlier by the laboratory course. Although each laboratory topic covered a period of two weeks and students had more time to prepare an experiment, most students were still not well prepared nor understood what they might get from the experiment. On the one hand, this situation usually resulted in longer time for an experiment. On the other hand, the chances for a student to get incorrect results increased. However, the situation has improved since the PSpice simulation IT tool was introduced into the laboratory course. The circuit simulation IT tool is actually working as a virtual laboratory for students. Using a circuit simulation tool, students can see both the circuit schematic of an experiment and the simulated characteristics of the circuit. Without damaging any circuit component, a student can learn what the performance or characteristic of a circuit will look like in a software simulation environment before measuring the circuit in the hardware laboratory. Now, the circuit simulation has become an important tool to assist students understanding a laboratory experiment. They bring simulation files to the laboratory, make a real circuit according to the simulation schematic of the circuit, and use the simulation tools to assist them in obtaining more productive experimentation results.

With the introduction of the IT tools in the laboratory, a great deal of positive feedback has been received from students. The application of the IT tools has not only helped them to understand theories more effectively through hands-on experimentation but also given them opportunities to learn modern computer software and hardware. The course has been recognized by students to be useful in reemphasizing their understanding of theories and in allowing them to become practical engineers.

IX. CONCLUSION

This paper gives the methodologies and approaches to develop a digital laboratory for analysis, design, simulation, and measurement of typical electric and electronic circuits using modern computer hardware and software. The use of computer data acquisition and measurement systems obtains experimental results more efficiently, provides more laboratory content, and keeps students more focused on results, concepts, relations to theories, and/or design aspects of an experiment. A mathematical IT tool, MathCAD, has been illustrated to show the relationship between mathematical equations and electrical variables represented in data, curves, and plots, making the theoretical background of an experiment easy to see and understand. Circuit simulation tools provide strong virtual laboratory environment, preparing students for more productive results from an actual experiment. The simulation also aids students in debugging a laboratory circuit or understanding the reasons for any inconsistency between measurement and pretheoretical calculation. The mechanisms and approaches designed for comparisons among measured, simulated, and theoretically calculated results are important for effectively reemphasizing students' understanding of theories for the purpose of quality education.

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Shuhui Li (S'99–M'99) received the B.S. and M.S. degrees in electrical engineering from Southwest Jiaotong University, Chengdu, China, in 1983 and 1988, respectively, and the Ph.D. degree in electrical engineering from Texas Tech University, Lubbock, 1999.

From 1988 to 1995, he was with the School of Electrical Engineering at Southwest Jiaotong University, where his research interests were in the areas of modeling and simulation of large dynamic systems, dynamic process simulation of electrified railways, power electronics, power systems, and power system harmonics. From 1995 to 1999, he evolved into the research areas of renewable energies, neural networks, and applications of massively parallel processing. He joined the Department of Electrical Engineering and Computer Science at Texas A&M University—Kingsville (TAMUK) in 1999, where he is currently an Associate Professor.

Dr. Li is a Member of the American Society of Engineering Education (ASEE).

Abrar A. Khan received the B.Eng. degree from Government College of Engineering, Amravati Maharastra, India, in 2000 and the Master's degree in electrical engineering from Texas A&M University—Kingsville in 2004.

He was the recipient of a Graduate Computer Science Scholarship for the 2002–2003 academic year. He is currently a Field Service Engineer with Positron Corporation, Houston, TX. His research topic was to develop a circuits and electronics laboratory using National Instruments software and hardware. His interests include automotive electronics, control systems, power systems, system design, and microprocessors.