

A Cost-Effective and Simplified Integration of Simulations and Hands-on Experiments in the Teaching of Electronic Instrumentation and Measurement Laboratory Course

Ikechi A. Ukaegbu
Nazarbayev University

Elochukwu Onyejebu
Nazarbayev University

Francis Mokogwu
Boise State University

Refik Caglar Kizilirmak
Nazarbayev University

To develop students into effective engineers upon graduation, it is important to bridge the gap between theory and practice. This is achieved through hands-on laboratory experiments, which form an important part of engineering education especially electronic circuits-related courses within the undergraduate level of education. Hence, it is important to develop well-outlined laboratory experiments that reflect the theoretical part of a course. Equally important is comparing simulation and measurement data, to better appreciate the theory. This work presents integrated simulation and hands-on experiments in teaching electronic instrumentation and measurement laboratory course, using low-cost off-the-shelf components. A no-cost circuit simulator software (LTspice) and low-cost breadboard with readily available off-the-shelf circuit components can be used both at home (self-paced) and in the laboratory to motivate students and align results for an improved learning approach. The advantage of this integrated laboratory is that no specialized or expensive teaching kit is required, which improves accessibility and course delivery. In addition, based on the feedback received, students are satisfied with this simplified and low-cost integrated laboratory.

Keywords: integrated laboratory, low-cost teaching, electronic instrumentation and measurement, DIY

INTRODUCTION

There is a growing shift from the conventional offline mode of education to online education, which can be attributed to the advancements in Information and Communication Technology (ICT) (Gravier, 2008) (Cooper, 2009). While ICT has contributed greatly to improved distance education delivery, remote laboratories are still struggling to catch up. As a result, one of the hottest research topics in recent times

within the electrical and computer engineering community is the development, integration and implementation of remote laboratories (Garcia-Zubia, 2009) (Tawfik, 2012). In general, laboratory sessions are considered the heart of engineering education and distinguishes it from degrees in other fields such as applied mathematics (Wankat, 1993). Remote laboratories in these engineering fields offer several advantages such as improved access to education, and making it possible to conduct laboratory sessions from “home” without being physically present in the lab at a specified time either through remote access to lab equipment, automated laboratory procedures or conducting the laboratory sessions at “home” using specially tailored laboratory kits. However, remote laboratories are expensive to deploy most of the time due to the high cost of development, integration and implementation, as well as the high cost of custom-made laboratory kits. In addition, the remote laboratory session can be interrupted if someone touches or removes any part of the set-up at the remote site, especially for electronic circuits/hardware-based laboratories.

In this paper, we present a simplified and inexpensive (low-cost) integrated simulation and hands-on experiments approach in teaching and learning for the Electronic Instrumentation and Measurement Laboratory course for third year undergraduate students. The laboratory methodology incorporates a combination of self-paced simulation of laboratory content (pre-labs), using free circuit simulator, LTSPICE, and actual hands-on experiments on the same topics using easily available and low-cost breadboard and off-the-shelf components. Recorded laboratory session tutorials are provided to the students to review before coming for the hands-on experimental (practical) session. The results/data from the simulation and experimental parts are compared, to enhance understanding on the topics, demystify scientific theories and tutorials, and positively stimulate students’ interests in learning. The rest of the paper is organized as follows: first, we briefly describe the required tools and components in Section II, followed by a comparative cost analysis in Section III. In Section IV, we present a case study of two sample laboratory experiments from the course, followed by the evaluation methodology in Section V. Finally, Section VI shows the accomplished learning objectives as well as some concluding remarks.

DESCRIPTION OF REQUIRED TOOLS AND COMPONENTS

No-Cost Circuit Simulator

There are numerous circuit simulation software tools available today, and they provide reliable results, comparable to real-life component/circuit behavior. However, getting access to some of these software might not be possible for students experimenting on their own or for schools, without a paid software license. Cadence, Advanced Design System (ADS), NI Multisim, Eagle and Proteus Professional are some of the well-known licensed circuit simulators. When funding is an issue, free EDA tools like LTspice, QUCS and MultiSim can be chosen. Of the circuit simulators in the latter category, LTspice is adopted for the course reported in this work because of its flexibility, ease of use and third-party component customization.

Function Generator

This equipment generates different kinds of functions for exciting the circuits. The functions could be typical, like sine, cosine and saw tooth waveforms, or customized non-conventional waveforms. Several high-end function generators are available in the laboratory equipment market but these are usually costly. The experiments reported in this paper can be performed with more affordable Metrix GX 310 or Rigol DG821 (up to 10 MHz). Similar equipment can be obtained for a brand new or second-hand value from sales representative of the manufacturers. Alternatively, for home settings, USB based function generators can be used and can be obtained from e-commerce sites like amazon and aliexpress.

Dual-Trace Oscilloscope

The oscilloscope helps designers in evaluating the performance of a circuit, upon excitation. The term dual-trace refers to the technique used in obtaining the display and the number of channels it is capable of displaying. The more advanced the oscilloscope, the more expensive. The Tektronix TDS 2002x is one of

the more affordable oscilloscopes available in the market with manufacturer support. There are also USB-based oscilloscopes, more suited to a work from home set up. Some of them come with function generator features.

Power Supply Unit (PSU)

This equipment typically supplies non-alternating voltage and current. For example, the EL302RT, which was used in the capacitor charging and discharging experiment can supply up to 2A of DC current and 30V of direct voltage. Some function generators like the Metrix GX 310 are also able to supply DC.

Breadboard and Off-the-Shelf Components

Our experiments include components like resistors, capacitors, inductors, diodes, transistors, transformers, and a breadboard for rapid prototyping. These components are very cheap and can be obtained in bulk for a very small amount of money. After testing the circuit with a breadboard, the veroboard can be used to produce a semi-permanent circuit through soldering. The prototyping board (EV_MCMBB board) used for the reported experiment uses co-joined breadboards with stepped power supply. Fig. 1 shows a sample of some of the laboratory equipment and breadboard used.

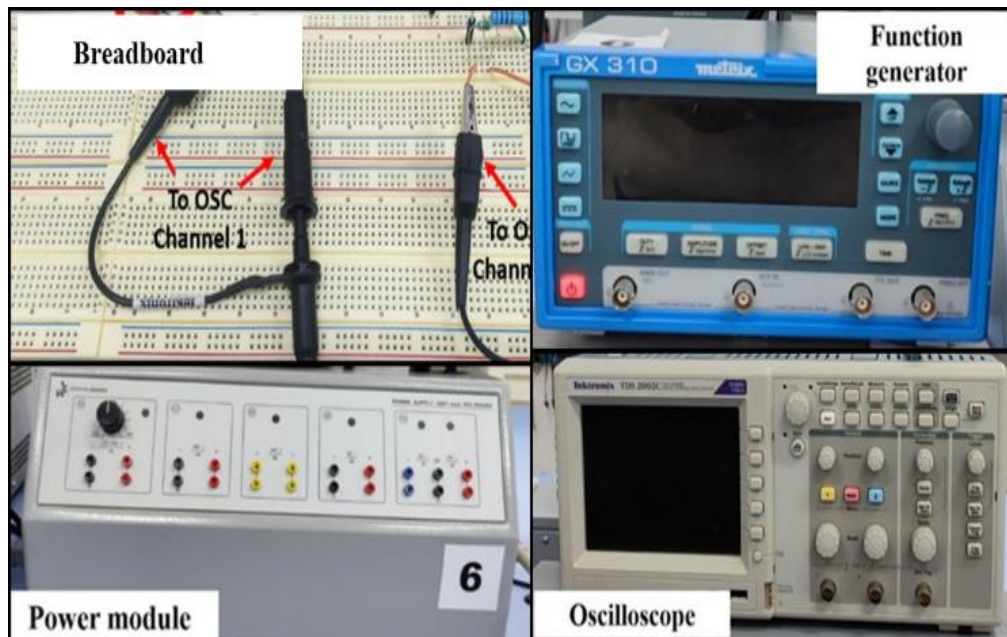
LCR Meter and Digital Multimeter

The LCR meter is capable of measuring the resistance, inductance and capacitance of resistors, inductors and capacitors respectively. Since the impedance of inductors and capacitors are frequency-dependent, the LCR meter is especially suited to measure the value of these components. There are different makers of the DMM and LCR meters. They are also relatively inexpensive. Fluke is a popular maker of these types of meters.

Connectors / Cables

Each of the aforementioned equipment requires cabling and relevant connectors. The function generator, dual-trace oscilloscope and power supply unit require a BNC cable. The terminations of the cable do differ. It could be a crocodile clip termination or a banana-type termination.

FIGURE 1
SAMPLE LABORATORY EQUIPMENT AND BREADBOARD



COMPARATIVE COST ANALYSIS

In this section, we make a comparison of the equipment cost for running the experiments described in Section IV, for a state-of-the-art laboratory, a typical university as well as an individual confronted with budgetary constraints. The second column in Table I shows the cost of acquiring the best available equipment, while columns three and four shows the price estimates for a school or an individual respectively, to acquire good enough equipment for the same experiments. It is worth mentioning that for very sensitive experiments, it is best not to prioritize cost-savings in equipment purchase over accuracy of results. The estimates in Table I show that for the same experiment a university can conduct for its students with about \$2,550, and individual can purchase all the equipment to conduct same experiment for about \$419. However, with state-of-the-art equipment and tools, a huge sum of \$20,036 is required.

TABLE 1
COMPARATIVE COST ANALYSIS OF LABORATORY EQUIPMENT

Item	State-of-the-Art / Industry Standard	Estimates on a School / University Budget	Estimates on a Personal Budget
EDA Tool	Up to 55,000/year for Cadence	Zero cost for open-source, limited and student editions	Zero cost for open-source, limited and student editions
Function Generator	\$2,069 for Rigol DG4202	\$700 for Metrix GX310	\$109 for Koolertron Sig. Gen.
Dual-Trace Oscilloscope	\$6,184 for Siglent SDSS054X	\$625 for Tektronix TDS2002C	\$183 for Aiteme ADS1014D
Power Supply Unit	\$5,668 for Shicmi RS232	\$841 for EL302RT	\$70 for Ikococater B09WDDRJN9
Breadboard	Comes with expensive customized kits, the C20/EV Kit	Very cheap over-the-counter purchase in electronic components store	Very cheap over-the-counter purchase in electronic components Store
Electronic Components			
LCR Meter	\$370 for East Tester ET4410	\$149 for DE-5000 Handheld LCR Meter	\$38 for Proster LCR Meter
Digital Multimeter	\$745 for Siglent SDM3065X	\$235 for Fluke 117	\$19 for AstroAI ASIDM130B
TOTAL	\$20,036	\$2550	\$419

*These are price estimates obtained online. Actual prices from manufacturers may vary.

CASE STUDY: SAMPLE LABORATORY EXPERIMENTS

Two sample laboratory experiments are presented briefly in this work. In one laboratory, students have to design RL and RC circuits and in the other laboratory, students have to design circuits for analog signal conditioning (specifically, a Class A amplifier). LTSPICE is used for the simulation; breadboard with off-the-shelf electronic components is used for the experimental part; and then the results of both simulation and experimental parts are compared.

RL and RC Circuits Lab

In this experiment, the basic behavior of an RC and RL circuit was studied, with emphasis on the RC and RL integrating and derivative networks. The change of voltage across the plates of a capacitor with time is studied, as well as the behavior of the current through an inductor; first when the capacitor is being charged, and then when it is being discharged. Also, the time constant of this change was obtained. The

simulation and measurements results show very minimal deviations. Fig. 2 shows a sample derivative R-C network and Tables II & III below show side by side, the simulated and measured results for the RC circuit charging and discharging operations.

RC Charging and Discharging Cycles

In this section, the students learn how to use of time constants to determine the time it takes a capacitor or inductor for fully charge or be discharged. This is called the time constant. For an RC circuit, the time constant, τ_{RC} , is given by equation (1) while equation (2) shows the time constant τ_{RL} for an RL circuit.

$$\tau_{RC} = R * C \tag{1}$$

$$\tau_{RL} = L/R \tag{2}$$

where R, C and L stand for the resistance, capacitance and inductance of the resistor, capacitor and inductor respectively.

The experimental setup for charging and discharging a resistor is shown in Figure 2 while Figures 3(a) and 3(b) show the schematic of the respective circuits. First, the students have to simulate the circuits in Figure 3(a) and 3(b) and then during the laboratory practicum, build the circuit in Figure 2, energize it and take measurements using the oscilloscope. Owing to the tolerance of the components, losses and inherent errors in the equipment used, the simulation results and measurement result will be close but not exactly the same. The course content covers this and the student are required to account for the differences in their submitted reports at the end of the practicum. Figures 4(a) and 4(b) show the voltage and current behavior in a capacitor during charging and discharging respectively.

**FIGURE 2
EXPERIMENTAL SETUP FOR CHARGING AND DISCHARGING A CAPACITOR**

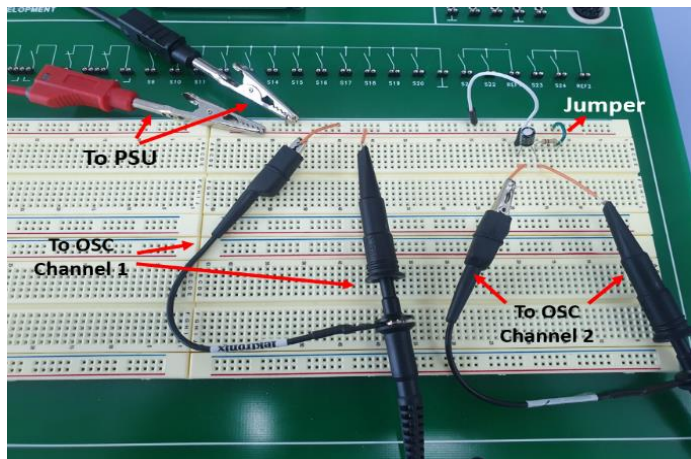


FIGURE 3
(A) CAPACITOR CHARGING SCHEMATIC AND (B) CAPACITOR
(B) DISCHARGING SCHEMATIC

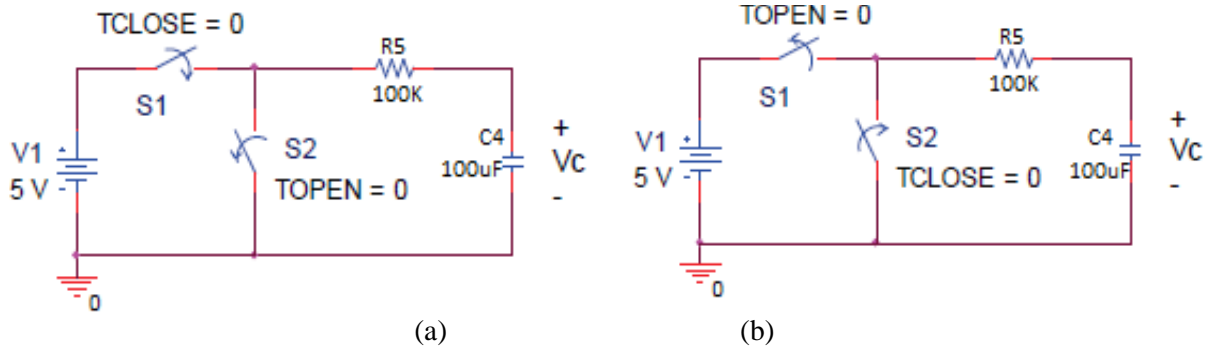
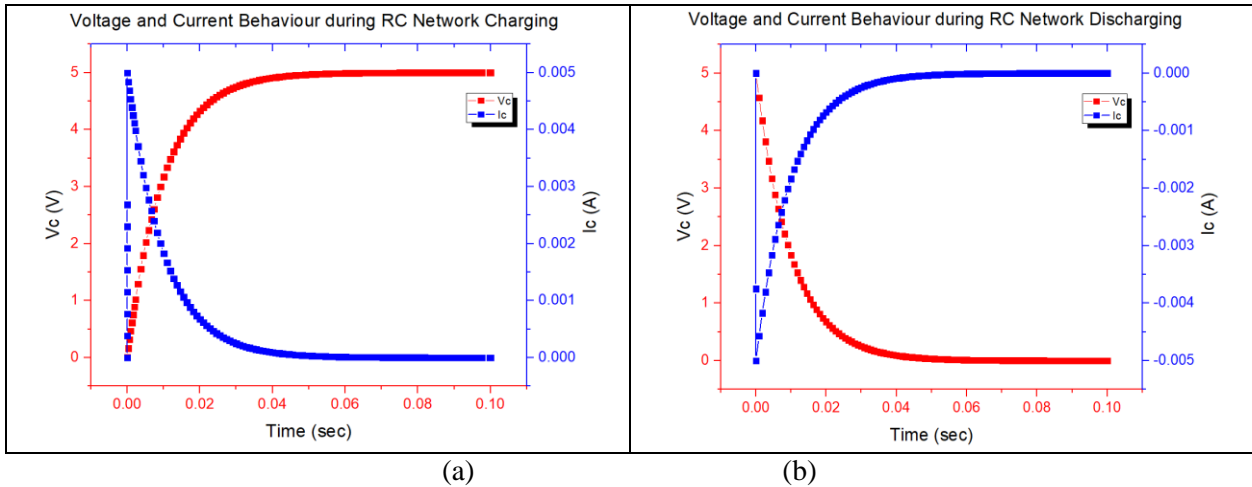


FIGURE 4
(A) I-V BEHAVIOUR IN THE CAPACITOR CHARGING CYCLE AND (B): I-V BEHAVIOR IN
THE CAPACITOR DISCHARGING CYCLE



Tables II and III show a comparison of the simulation and measurement results for the capacitor charging and discharging experiments respectively. The experiments are allowed to run until 5τ . Additionally, the meanings of $V_c(0-)$, $V_c(0+)$, and $V_c(\infty)$ are expressly defined for uniformity.

RC Integrating Network

With the theoretical background for this circuit already covered in classes and tutorial videos, the students were given the circuit of Figure 5 to simulate, then build during the practicum. Fig. 5(a) shows how to connect the circuits during the practicum while Fig. 5(b) shows the schematic for simulation using the adopted EDA tool.

FIGURE 5
SCHEMATICS OF AN RC INTEGRATING NETWORK FOR (A) LAB PRACTICUM
(B) SIMULATION

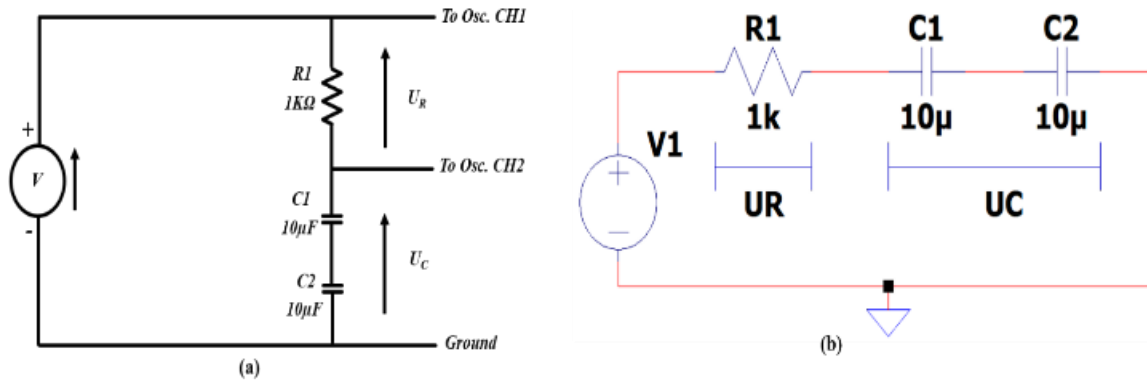


TABLE 2
COMPARISON OF SIMULATION AND MEASUREMENT VALUES FOR THE RC CHARGING CYCLE

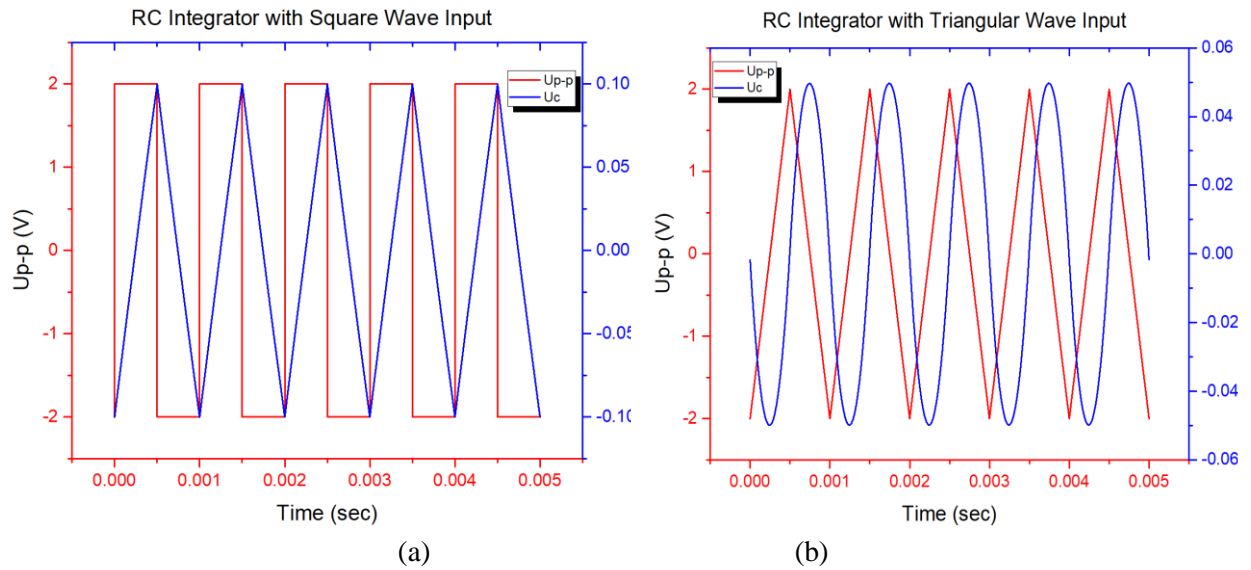
Parameter	Simulation	Measurement
$V_c(0-)$	0V	0V
$V_c(0+)$ at 10secs	3.1614477V	2.96V
$V_c(\infty)$ at 100secs	4.9997730V	5.04V
Time Constant	10secs	10secs
Capacitor voltage at 5τ	4.9662948V	4.88V
$V_c(t)$ for $t > 0$	$V_0(1 - e^{-\frac{t}{RC}})$	$V_0(1 - e^{-\frac{t}{RC}})$

TABLE 3
COMPARISON OF SIMULATION AND MEASUREMENT VALUES FOR THE RC DISCHARGING CYCLE

Parameter	Simulation	Measurement
$V_c(0-)$ at 100secs	4.9997V	5.04V
$V_c(0+)$ at 110secs	1.8299851V	2.32V
$V_c(\infty)$ at 200secs	226.9816μV	80mV
Time Constant	10secs	10secs
Capacitor voltage at 5τ	33.45246mV	160mV
$V_c(t)$ for $t > 0$	$V_0 e^{-\frac{t}{RC}}$	$V_0 e^{-\frac{t}{RC}}$

Figures 6(a) and 6(b) show the output of the RC integrator with a square wave input and triangular wave input respectively. The output of the RC integrator is measured across the capacitors C_1 and C_2 as shown in Figure 5(a). U_{p-p} is the input peak-to-peak voltage.

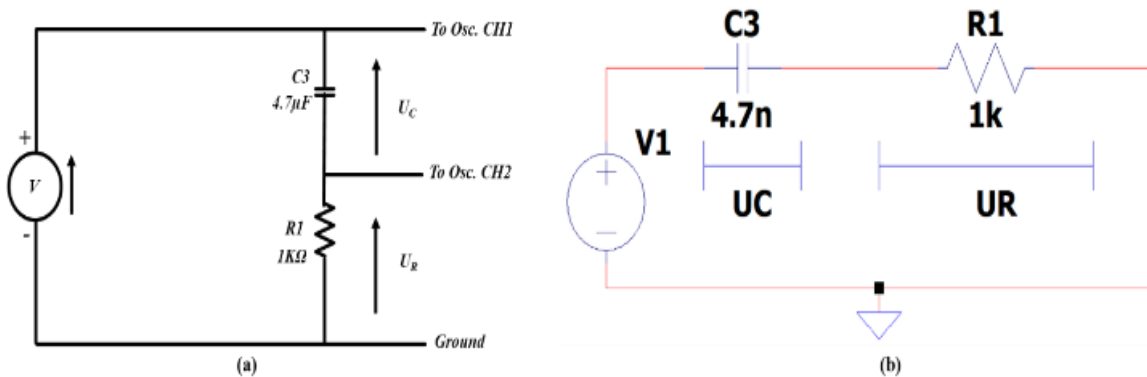
FIGURE 6
(A) OUTPUT OF AN RC INTEGRATOR WITH SQUARE WAVE INPUT AND (B) OUTPUT OF AN RC INTEGRATOR WITH TRIANGULAR WAVE INPUT



RC Derivative Network

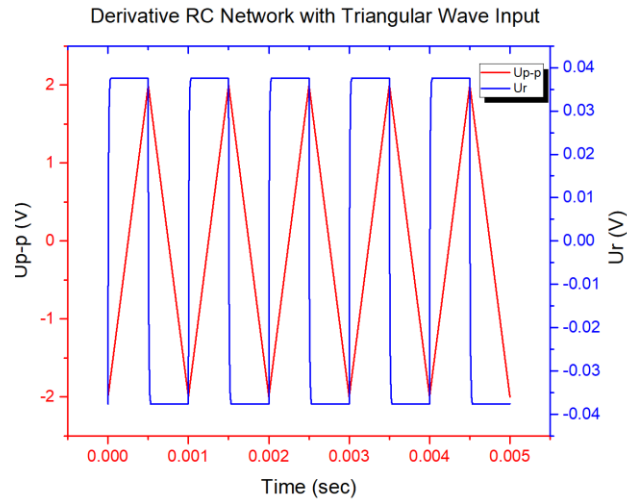
For the derivative RC network, a circuit akin to that of Fig. 5 is provided in Fig. 7, for practicum and simulation. Only one input wave type is used in this case.

FIGURE 7
SCHEMATICS OF AN RC DERIVATIVE NETWORK FOR (A) LAB PRACTICUM (B) SIMULATION



The nature of the input and output waveforms is shown in Fig. 8. The Mathematical basis for the observed results was covered during classes and in tutorial videos.

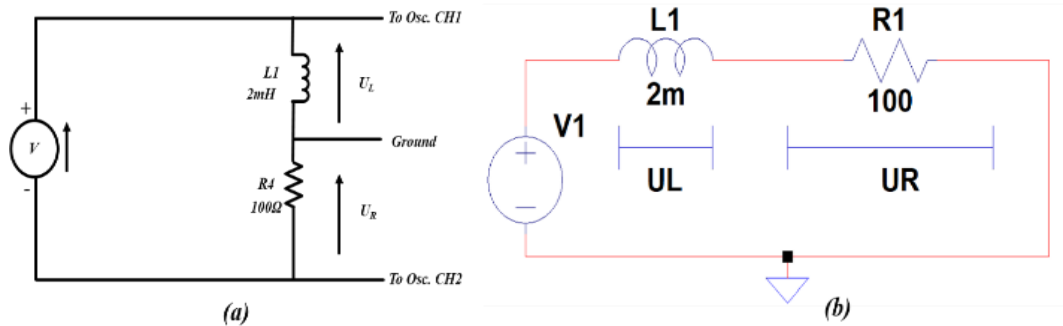
FIGURE 8
OUTPUT OF AN RC DIFFERENTIATOR WITH TRIANGULAR WAVE INPUT



RL Integrator Network

The setup for this experiment as well as the nature of the input and output waveforms of this circuit are shown in Figures 9 and 10 respectively. The values of the circuit components are as indicated.

FIGURE 9
SCHEMATICS OF AN RL INTEGRATING NETWORK FOR (A) LAB PRACTICUM
(B) SIMULATION



Analog Signal Conditioning Lab

Analog signal conditioning can be categorized into several general types, which include amplification, attenuation, filtering, isolation and linearization. In this lab series, emphasis is laid on amplification, specifically power amplifiers. As the name suggests, the power amplifier is mostly used to deliver more power to a load. The Class A amplifier is chosen due to the ease of analysis and implementation. The class A power amplifier conducts all through the complete cycle of the input signal. The maximum theoretical efficiency of class the A power amplifiers is 50% (with inductive coupling) and 25% (with capacitive coupling). LTSPICE is used for the simulation of this circuit. Fig. 11 shows the schematics of this inverting amplifier for both simulation and measurement. The results exhibited minimal deviation from the laboratory implementation. The recorded voltage gains are 8.5 and 12.3 during simulation and experimentation respectively. Same type of BJT was utilized in both situations. The same schematic is provided for both the simulation and practicum. V_i and V_o indicate where the input voltage is applied and output voltage taken

from, respectively. The C20/EV board is used for building the circuit during the practicum. It can be noticed in Fig. 12 that the output is 180 degrees out of phase with the input, which is typical of the Class A amplifier.

FIGURE 10
(A) OUTPUT OF AN RL INTEGRATOR WITH SQUARE WAVE INPUT AND (B) OUTPUT OF AN RL INTEGRATOR WITH TRIANGULAR WAVE INPUT

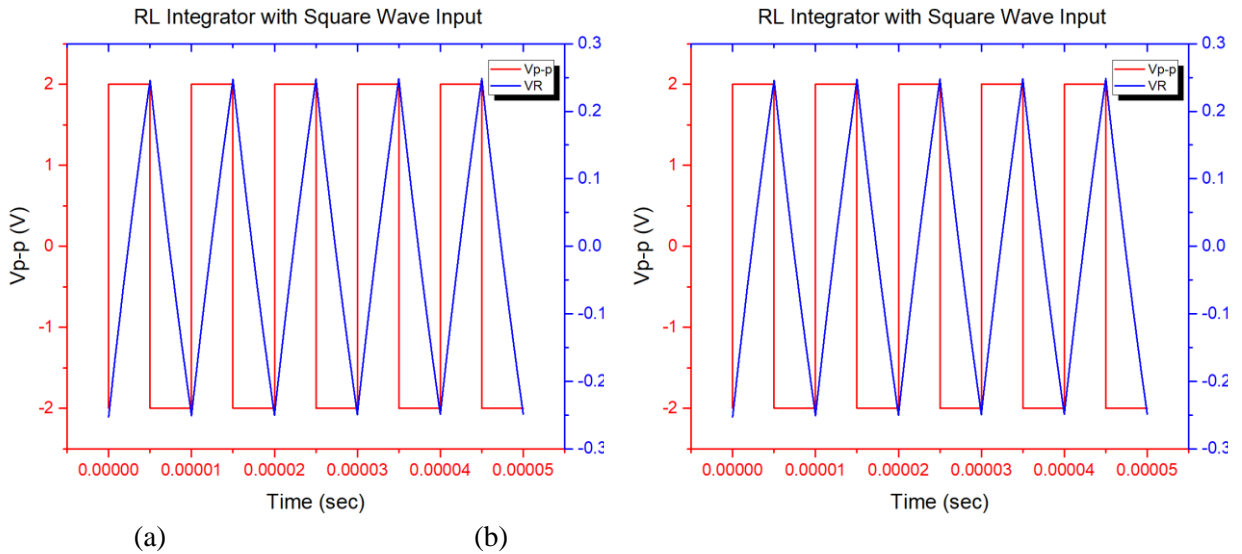


FIGURE 11
SCHEMATIC OF A CLASS A AMPLIFIER

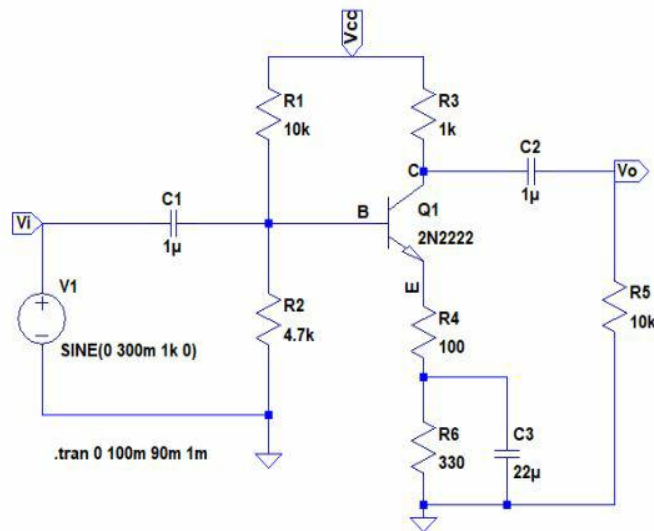
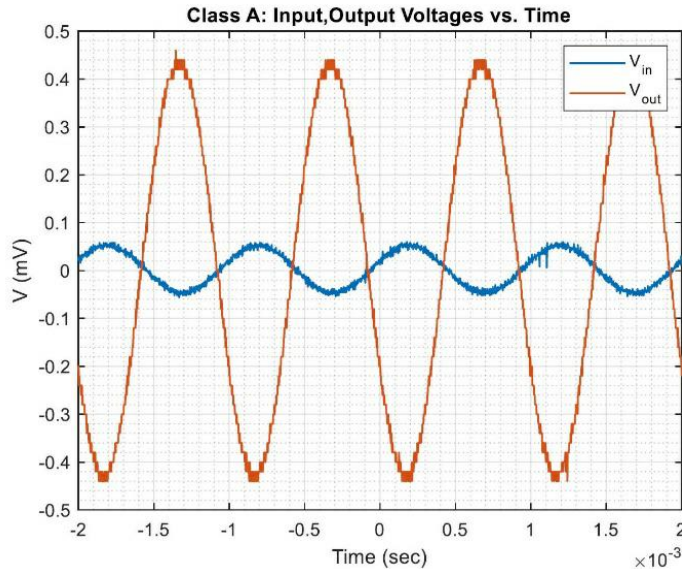


FIGURE 12
COMPARISON OF CLASS A AMPLIFIER INPUT AND OUTPUT WAVEFORMS



The deviation encountered in the results comparison between simulation and experimentation was due to the ideal conditions available in LTSPICE. Also, variations during fabrication/manufacturing of the components used in the experimental part contribute to the deviation between the simulation results and measured data. However, in general, there is agreement between simulation and measurement results, which provided more insights to the theoretical concepts and improved understanding of the course content.

EVALUATION METHODOLOGY

Each lab has assessment for simulation (pre-lab) report and experimental report. Also, during the experimental laboratory sessions, students were given oral evaluation (viva) as part of the experimental part evaluation. Students are organized in groups of two for each of the experimental (practical) laboratory sessions. During the oral evaluation/viva, each member of the group is asked questions from a section/part of the lab and is expected to provide explanations to the questions asked. The questions are asked at random to make sure that each student and each member of the group actively participates in conducting the lab, as well as ensuring active participation in the learning process. Also, for every completed task, each group member explains the tasks completed and its implications. This evaluation method improves learning experience and also allows instructors to detect any uneven distribution of work among the students within a group. The final grade is determined by the total grade obtained from pre-lab report (40%), hands-on experimental laboratory + viva (30%), and experimental laboratory report (30%).

ACCOMPLISHED LEARNING OUTCOMES

The four learning outcomes of the course are listed in Table IV. At the end of the course, students are expected to be able to design basic electronic systems, understand their basic operations, apply theoretical knowledge and conduct end-to-end measurements of designed systems. Based on our approach of integrated simulation and hands-on experimentation, the learning outcomes were achieved. Also, based on the feedback from students, the method used in this course received positive comments when compared to other related courses taken by the students. The students expressed satisfaction with the course methodology.

CONCLUSION

In this work, we have presented the delivery of a simplified and inexpensive integrated simulation and hands-on experiments in teaching Electronics Instrumentation and Measurement Laboratory course. We have listed the equipment used in our teaching laboratories; and further discussed more cost-effective alternatives. Based on the accomplished learning outcomes and student feedback, the integrated simulation and hands-on methodology and experience did not only stimulate learning and improve the understanding of course content, but were very successful with high acceptance and motivation among the students.

TABLE 4
SUMMARY OF PROPOSED PEDAGOGICAL METHODOLOGY

	Planned Learning Outcomes	Achievement Strategy	Outcome
LO1	Explain measurement principles	<ul style="list-style-type: none"> • Lectures • Tutorial videos • In-person instructions before and during labs • Email enquiry • Discussion forum hosted on Moodle 	<p>The students became familiar with measurement principle like:</p> <ul style="list-style-type: none"> • Accuracy • Precision • Component Tolerance • Systematic error • Offset and • Equipment resolution <p>Viva responses confirms this.</p>
LO2	Identify and operate basic measurement instrument such as: <ul style="list-style-type: none"> • Power supply • Function generator • Oscilloscope • Multimeter • Network and spectrum analysers 	<ul style="list-style-type: none"> • Lectures • Tutorial videos • In-person instructions before and during labs • Email enquiry • Discussion forum hosted on Moodle 	<ul style="list-style-type: none"> • The students can now use the measure instruments with ease. • Results of each task in the lab is first graded from the input on output configurations on the instruments prior to the lab reports. This is confirmatory.
LO3	Design basin electronic systems and understand their basic operation	<ul style="list-style-type: none"> • A refresher on the theoretical background provided in prerequisite courses • Underlying (relevant) circuit principles explained in the simulations and hands-on practicum manuals • Sample simulation and explanations with a similar circuit different from the assigned task 	<ul style="list-style-type: none"> • The students showed an understanding of the role of each component in the assigned circuit • Simulating the circuits in the pre-labs and assembling them on the breadboard came with ease.
LO4	Apply theoretical knowledge and conduct end-to-end measurements of designed circuits	<ul style="list-style-type: none"> • Tutorial videos • In-person instructions before and during labs 	<p>The student developed more confidence in handling all measurement instruments used in the course. In addition to those mention in LO2, they include:</p> <ul style="list-style-type: none"> • LCR Meter • Digital multimeter • Plotting software

ACKNOWLEDGEMENT

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REFERENCES

- Cooper, M., & Ferreira, J.M.M. (2009). Remote Laboratories Extending Access to Science and Engineering Curricula. *IEEE Transactions on Learning Technologies*, 2, 342–353.
- Garcia-Zubia, J., Orduna, P., Lopez-de-Ipina, D., & Alves, G. R. (2009). Addressing Software Impact in the Design of Remote Laboratories. *IEEE Transactions on Industrial Electronics*, 56, 4757–4767.
- Gravier, C., Fayolle, J., Bayard, B., Ates, M., & Lardon, J. (2008). State of the Art About Remote Laboratories Paradigms – Foundations of Ongoing Mutations. *International Journal of Online Engineering (iJOE)*, 4, 19–25.
- Tawfik, M., Sancristobal, E., Martin, S., Peire, J., & Castro, M. (2012). Trends in Remote Laboratories for Industrial Electronics Disciplines and Their Interoperable Implementation. *IEEE Industrial Electronics Magazine*.
- Wankat, P.C., & Oreovicz, F.S. (1993). *Teaching Engineering*. New York: McGraw-Hill.