

# An educational virtual tool for teaching electric circuits to undergraduate students



## Colaboración

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**RESUMEN:** En este artículo se presenta una herramienta educacional para la enseñanza de circuitos eléctricos enfocada a estudiantes de nivel licenciatura. La herramienta fue desarrollada en el lenguaje de programación de LABVIEW el cual ayuda a construir interfaces de usuario amigables llamadas instrumentos virtuales (VI's). Esta herramienta es un complemento en la enseñanza de la teoría de circuitos eléctricos y se compone por algunos experimentos útiles los cuales refuerzan el conocimiento adquirido durante los cursos teóricos. Entre las prácticas propuestas se encuentran: Análisis de CA en estado estable, redes de dos puertos, circuitos eléctricos acoplados, transformación delta-Y, medición de potencia eléctrica y respuesta a la frecuencia. Los experimentos de laboratorio son parte de un programa de educación a nivel licenciatura los cuales son supervisados por un instructor y llevados a cabo por los estudiantes. La herramienta educativa incluye ejercicios de laboratorio intuitivos e interactivos los cuales evitan el empleo de equipo costoso. Además, esta herramienta es de ayuda cuando no se tiene a la mano dicho equipo para prácticas.

**PALABRAS CLAVE:** Virtual instrument; educational tool; electric circuits

**ABSTRACT:** In this paper, the development of an educational tool for teaching electrical circuits to electrical engineering undergraduate students is presented. The tool is developed in the LabVIEW programming language which helps to build up useful and friendly user interfaces called virtual instruments (VI's). This tool is a complement for the teaching of electric circuit theory and it is composed by some useful lab experiments which reinforce the acquired knowledge during the theoretical courses. Among the proposed practices are found: Alternating Current (AC) analysis on steady-state, two-port networks, electric coupled circuits, delta-wye transformation, electric power measurement and frequency response. The laboratory experiments are part of a university undergraduate program and they were supervised by an instructor and carry out by undergraduate students. The educational tool includes intuitive and interactive lab exercises which avoid the use of expensive equipment. Also, this tool is helpful when the equipment it is not available.

**KEYWORDS:** Instrumento Virtual; Herramienta Educativa; Circuitos Eléctricos.

## INTRODUCCIÓN

In recent years the developments of computer and communication technologies have given many advances to educational matters. Computer-aided educational tools have become popular nowadays because they help to visualize theoretical concepts [1]. The use of simulation software has helped to teach several topics of a wide range of knowledge areas with the purpose of complement the theory taught in classrooms. Tools like virtual learning environments have features such as interactive virtual panels or friendly user interfaces which avoid the traditional way of teaching any subject in the engineering area [2].

There are many examples on the use of virtual panels or user interfaces that helps to a better understanding of a specific issue. In a recent study an integrated virtual learning system for the development of digital signals processors (DSP)-based control schemes for motor drives applications was programmed, this tool has an integrated based C++ graphical user interface (GUI) [3]. Virtual environments have demonstrated that enhance the acquired knowledge and to motivate the students in a positive way. Moreover, these virtual environments have been employed successfully in order to provide a realistic pre-laboratory experience, and they are helpful on distance learning courses for students with mobility disabilities [4]. In some cases the environments consists on the simulation of laboratory experiments which avoid the use of expensive equipment and its possible damage [5]. For this reason several commercial software as PSpice, Workbench, Multisim have been commercially launched. The measurement area generally involves the use of expensive measurement devices and sensors that are present in most of the industries; this has led to the implementation of learning management systems programmed in LabVIEW with remote access to real instrumentation [6].

Electric circuits and electromagnetic theory are the basis for the understanding of many areas of knowledge in electrical engineering, i.e. electrical machines, power, control, electronics, instrumentation and communication. The understanding of electric engineering issues is challenging. This is the main motivation of the development of virtual tools for the comprehension of every of its branches [7-12]. In this sense, electrical and electronic circuit topics represent one of the most challenging subjects inside the study of electrical engineering area [13]. In a recent study a generalized negative feedback model for teaching feedback amplifiers in engineering schools was proposed [14]. The reinforcement of the lectures given in power electronic courses is a matter of interest. Power electronic represents a difficult subject, for this reason a web-based la-

batory exercise with remote access have been developed in MATLAB and PSpice [15]. Meanwhile, researchers have developed computer-based tools for DC-DC converter circuits using MATLAB/Simulink toolbox [16].

In order to teach circuit theory, tools as NI ELVIS have been commercialized. This tool has the functionality of combine virtual measurement instruments and a connecting board. However, for some applications this tool has limitations in the usage of physical input/output acquisition channels, and the frequency response analysis cannot be performed accurately in a range of frequencies less than 5 Hz [17]. As it was said, the topic of electric circuits is a subject whose learning is complemented with lab practices and simulations which reinforce the studied theory in the classroom.

In this paper an educational tool focused on electric circuits teaching is presented. The tool is based on the LabVIEW programming language and consists of five interactive practices among them are found: two-port networks, electric coupled circuits, delta-wye-delta transformation, electric power measurement, and finally frequency response. These topics are included in the undergraduate electrical engineering program of electric circuits which is given twice in a scholar year, and it comprises 4 theory-hours and 2 practice-hours per week. It is worth to mention there are no virtual tools that include five different practices of this sort in one learning tool whose design is based in a university undergraduate official program. The proposed practices are integrated into a single virtual interactive panel which guides students throughout them; at the same time the most important theoretical concepts taught in the classroom are complemented with the lab practices. Among the benefits are found a fast learning of the studied topics in the program, reduced time on the understanding of the concepts seen in classes. The tool was evaluated in one hundred students along a scholar year which is normally divided into two semesters.

## THE EDUCATIONAL TOOL FOR TEACHING ELECTRIC CIRCUITS

As it was mentioned above, this educational tool was developed in order to cover an undergraduate program of electric circuits II whose contents is shown in Table I. This program is divided into six units which are: AC network analysis on stationary state, two port networks, magnetically coupled circuits, three-phase circuits, electric power and frequency domain analysis.

This educational tool is formed by a front panel and a block diagram. The front panel of this tool is shown in Fig. 1.

Table I. Undergraduate study program for the electric circuits II subject.

Unit	Topics
1. AC network analysis on steady-state	Sine signal characteristics: period, frequency, maximum and <i>rms</i> values, instantaneously and <i>rms</i> power, complex numbers operations, impedance and admittance concepts.
2. Two-port networks	Two-port network parameters, <i>z</i> , <i>y</i> , <i>h</i> , <i>T</i> and $\Pi$ parameters
3. Magnetically coupled circuits	Self-induction, mutual induction, magnetic coupling, equivalent circuits, polarity.
4. Three-phase circuits	AC generation, three-phase delta and wye circuits with balanced and unbalanced loads
5. Electric power	Real, reactive and apparent powers, power factor, three-phase power measurement
6. Frequency domain analysis	Introduction to the frequency response problems, frequency response in RL, RC and RLC circuits, resonant circuits, filters.

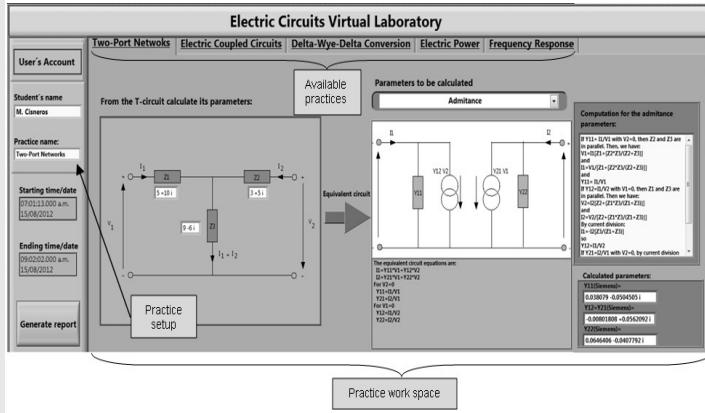


Fig. 1. Virtual tool for the two-port networks parameters.

This is the interface that the student uses freely for performing the practices, and it is divided into five main tabs. These tabs are named as the practice to be developed and the student can choose them manually. On the other hand, the block diagram contains the programming code, in this part; the student is not able to access. As it was mentioned before, five practices were programmed in this virtual instrument which includes laboratory experiments, theory and simulations. One of the proposed laboratory exercises consists on introducing the student on the use of data acquisition cards, sensors, and measurement instruments in an effective way. Moreover, a user's control

was programmed in order to have a register of the users in a text file. The file has the student's name, the starting/ending time, the practice's name, and finally, a report is generated with the evaluation results obtained by the student in the lab exercise.

## Analysis of Two-Ports Networks with the Virtual Tool

The study of two ports networks arises from the necessity of the understanding several electrical engineering areas such as control, power, communications, and electronics systems. Basic concepts of two port networks are useful on the modeling of transistors and operational amplifiers [14]. On theory, the independent and dependent variables in these systems are voltages and currents, respectively. These variables can be easily measured; however, there are parameters of interest inside these systems that cannot be measured. In most cases, two-port networks are seen as black-box models where a set of parameters are needed to identify or describe their dynamics [18].

These types of models are usually embedded in large networks that need to be simplified for their understanding. For the comprehension of the estimation of two-port network parameters, an interactive virtual tool was also developed. This virtual tool was designed to calculate impedance, admittance, hybrid and g-parameters of a simple T-circuit. Within it, complex number computations are involved, admittance and impedance concepts covering in this way some of the topics seen on unit 1 of the course. The front panel of this tool is shown in Fig. 1. One of the main advantages of this tool is its front panel that allows setting the circuit parameters given in complex form. On the other hand, the user is free to choose which kind of parameters will be calculated (impedance, admittance, hybrid and g-parameters). Moreover, equations, figures such as T-circuit and an equivalent circuit are automatically displayed in the front panel depending on the parameters to be calculated. After setting the complex quantities in the T-circuit and the parameters to be calculated the simulation is executed. The equivalent circuit, its parameters, and its equations are displayed after the simulation has finished.

On the other hand, the T-circuit shown in Fig. 1 is considered here to illustrate how to obtain its impedance, admittance, hybrid, and g-parameters, of each equivalent circuit. The admittance parameters of the equivalent circuit in an example practice are given in the calculated parameters box (see Fig. 1). These parameters are calculated using eqn (1)-(4):

$$V_1 = I_1 \left[ Z_1 + \left\{ \frac{Z_2 Z_3}{(Z_2 + Z_3)} \right\} \right] \quad \text{Ec. (1)}$$

$$I_1 = \frac{V_1}{Z_1 + \left\{ \frac{Z_2 Z_3}{Z_2 + Z_3} \right\}} \quad \text{Ec (2)}$$

And  $Y_{11} = \frac{I_1}{V_1}$ . If  $Y_{12} = \frac{I_1}{V_2}$  with  $V_1 = 0$ .

Impedances  $Z_1$  and  $Z_3$  are in parallel. Then we have:

$$V_2 = I_1 \left[ Z_2 + \left\{ \frac{Z_1 Z_3}{Z_1 + Z_3} \right\} \right] \quad \text{Ec. (3)}$$

$$I_2 = \frac{V_2}{Z_2 + \left\{ \frac{Z_1 Z_3}{Z_1 + Z_3} \right\}} \quad \text{Ec (4)}$$

the current  $I_1$  is given by  $I_1 = -I_2 \left[ \frac{Z_3}{(Z_1 + Z_3)} \right]$ , and  $Y_{11} = \frac{I_1}{V_1}$ . If  $Y_{12}$  with  $V_2 = 0$ , then  $I_2$  can be obtained as  $I_2 = -I_2 \left[ \frac{Z_3}{(Z_1 + Z_3)} \right]$ .

, and  $Y_{21} = \frac{I_2}{V_1}$

### Electric Coupled Circuits Virtual Tool

Circuits can be broadly classified into two main groups: magnetically coupled and electrical coupled circuits. In the electrical engineering area, the study of rotating electrical machines and transformers is based on the understanding of magnetically coupled circuits. Some important introductory definitions as mutual inductance and dot marking convention are important for the understanding of the electric coupled circuits. These concepts are new for the students due to them are mainly acquainted with the analysis of conductively coupled circuits. For the understanding of the electric coupled circuits a virtual tool was programmed and its front panel is shown in Fig. 2. This virtual tool gives a first approach to the new concepts by solving simple electric coupled circuits. The tool allows changing manually some circuit parameters as for example the applied voltage to the primary. Additionally, after finishing the computation of stored energy in the coupled inductors, the coupling coefficients and currents in the magnetic circuit; the tool displays in two different plotting areas the behaviour of the applied voltage, output voltage and the currents that flows in the primary and secondary. The resulting waveforms can be saved in text files for being analysed further or corroborate the results by solving the equations given in the front panel.

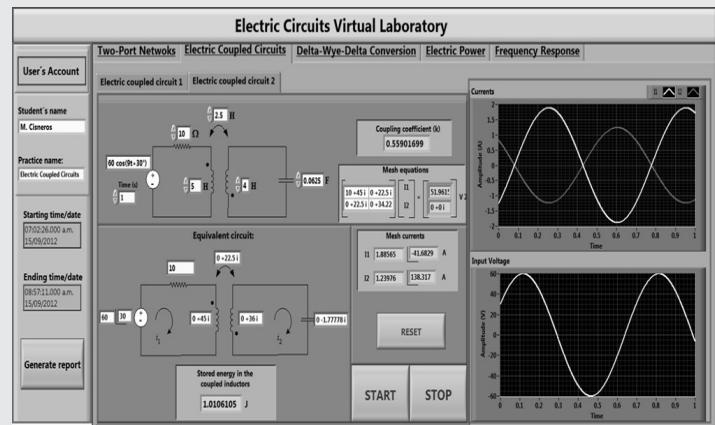


Fig. 2. Virtual tool for the electric coupled circuits.

Two additional practices can be developed with the virtual tool. These practices deal with the fundamentals of electric coupled circuits and their solution. In a practice simulated by the students, the primary and the secondary currents in a coupled circuit are calculated and plotted. The set of equations to be solved in this practice is given by eqn (5), it can be easily solved by the virtual tool using the inverse matrix method.

$$[\mathbf{I}] = [\mathbf{A}]^{-1} [\mathbf{V}] \quad \text{Ec (5)}$$

where  $\mathbf{I}$  is the current vector,  $\mathbf{A}$  is the coefficients matrix and  $\mathbf{V}$  is the voltage vector.

In this example practice, both circuits are fed by a voltage supply of  $60 \cos(9t+30^\circ)$  where  $t=1s$  and that can be modified by the student. Also, the circuit parameters can be changed in order to study the different responses given by the transformer equivalent circuit. Additionally, coupling coefficient, as well its stored energy in the coupled inductors, are calculated by the tool using eqn (6) and (7) respectively.

$$k = \frac{M}{\sqrt{L_1 L_2}} \quad \text{Ec (6)}$$

$$W = \frac{1}{2} L_1 i_1^2 + \frac{1}{2} L_2 i_2^2 + M i_1 i_2 \quad \text{Ec (7)}$$

where  $k$  is the coupling factor,  $M$  is the mutual inductance,  $L$  is the inductance,  $W$  is the stored energy in Joules,  $i$  is the time domain current and the subscripts 1 and 2 are for the primary and secondary quantities.

By solving eqn (5) it is possible to obtain the primary and the secondary currents in the circuit. The currents calculated in this laboratory practice are illustrated in Fig. 2. The model simulation gives currents of  $I_1=1.88565 \angle -41.6829^\circ$  A and  $I_2=1.23976 \angle 138.317^\circ$  A and their frequency is 1.4323 Hz. Meanwhile the coupling coefficient is 0.559017 and the stored energy in the coupled inductors is 1.01061 Joules.

## Delta-Wye-Delta Transformation Using the Virtual Tool

The goal of this transformation is simplify the analysis of some delta or wye circuits without changing its behaviour. The delta-wye-delta transformation applied to resistive circuits it is also suitable for the study of circuits based on impedances. In order to analyse the behaviour of voltages and currents waveforms a virtual tool which handles a set of three-phase balanced voltages was programmed. The virtual tool shown in Fig. 3 allows the student to set two main features: one is the load given in complex form, and the second one, is the level and frequency of the applied three-phase voltage. Through a simulation the student is able to visualize the generated set of three-phase voltages that are displayed in graph indicators; also a graph indicator displays a set of three-phase currents which is given depending on the programmed load. To facilitate the understanding of this kind of transformation, equations that describe the transformation were embedded. The simulation runs continuously so, changes can be made online.

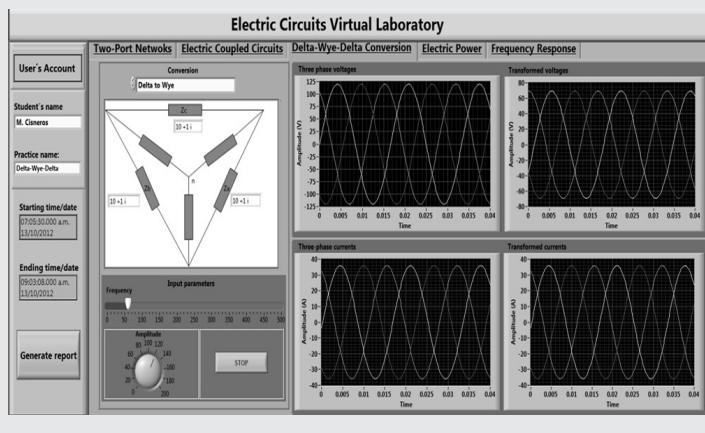


Fig. 3. Virtual tool for the delta-wye-delta conversion.

Measurements of current and voltage are taken from simulations of delta-wye-delta conversion are made. These simulations help to the understanding of this useful transformation. In a wye-delta conversion the impedances are given by eqn (8)-(10):

$$Z_a = \frac{Z_1 Z_2 + Z_2 Z_3 + Z_3 Z_1}{Z_1} \quad \text{Ec. (8)}$$

$$Z_b = \frac{Z_1 Z_2 + Z_2 Z_3 + Z_3 Z_1}{Z_2} \quad \text{Ec. (9)}$$

$$Z_c = \frac{Z_1 Z_2 + Z_2 Z_3 + Z_3 Z_1}{Z_3} \quad \text{Ec. (10)}$$

Meanwhile in a delta-wye conversion the impedances are given by eqn (11)-(13)

$$Z_1 = \frac{Z_b Z_c}{Z_a + Z_b + Z_c} \quad \text{Ec. (11)}$$

$$Z_2 = \frac{Z_c Z_a}{Z_a + Z_b + Z_c} \quad \text{Ec. (12)}$$

$$Z_3 = \frac{Z_a Z_b}{Z_a + Z_b + Z_c} \quad \text{Ec. (13)}$$

Simulations of delta-wye conversion can be carried out under balanced conditions with impedance values of  $Z_a = Z_b = Z_c = 10+i1$ , a balanced three-phase voltage set of 120 V and 60 Hz. The values obtained from simulations are shown on the plotting areas (see Fig. 3). It is worth to mention that simulations can be made under unbalanced resistive, inductive and capacitive loads at different levels of voltage and frequency.

In the interface, parameters as impedances, frequency and amplitude can be easily changed by the student at the same time the program is running. This fact allows visualizing any changes on the behavior of the studied circuit.

## Electric Power Virtual Tool

Power represents one of the most important quantities in electric utilities because such systems involve transmission of power from a node to another one [19]. For this reason, several commercial instruments have been developed with the main objective of measuring power and its components. However, those instruments usually work within a specified bandwidth. In this work, a virtual instrument that works in a wide range of frequencies was programmed with the purpose of teaching how to measure electric power and its components. The interface used for this practice is shown in Fig. 4. Here an experiment is simulated by selecting two types of three-phase topologies. One consists on measuring power under balanced conditions in a wye-wye circuit and the other type consists on measuring power in a delta-delta three-phase circuit. Through the user interface, the student is able to select the circuit diagram using a tab control. In the circuit, parameters as voltage, line impedance and load impedances can be modified in order to obtain a set of three-phase readings of voltage, frequency, currents, and a phasor diagram that are displayed in plotting areas. Electric power components are displayed in numeric indicators. After the practice has finished, the readings of electric power and power usage are saved in text files to allow its analysis afterwards.

In this example lab practice, it is simulated a wye-wye three phase circuit with load of  $Z=15+j6$  in balanced conditions as it is shown in Fig. 4. The computation of active power ( $P$ ), apparent power ( $S$ ); reactive power ( $Q$ ) and power factor ( $PF$ ) are made by using eqn (14)-(17), respectively.

$$P = \frac{1}{N} \sum_{k=1}^N v_k i_k \quad \text{Ec. (14)}$$

$$S = VI \quad \text{Ec (15)}$$

$$Q = \sqrt{S^2 - P^2} \quad \text{Ec (16)}$$

$$PF = \frac{P}{S} \quad \text{Ec (17)}$$

where  $v_k$  and  $i_k$  are the  $k$ -th samples of the instantaneous voltage and current values, respectively. Measurements are depicted on the power measurements and power usage boxes of Fig. 4.

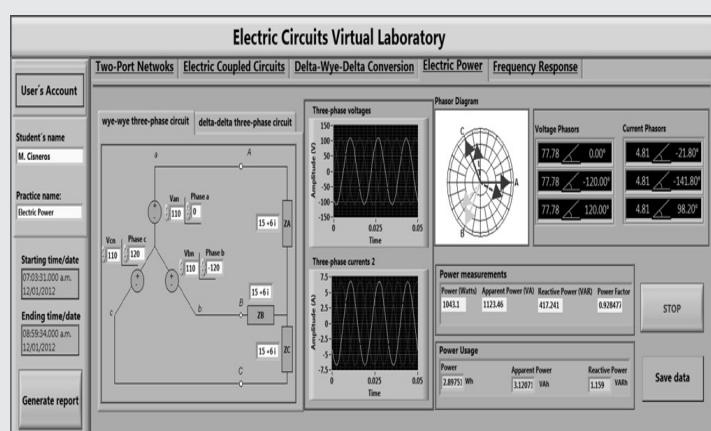


Fig. 4. Virtual tool for the measurement of electric power and its components.

### Frequency Response Virtual Tool

Once the student has been introduced and familiarized with some of the features that the LabVIEW software has, it is time to teach the basic theory of the frequency response besides data acquisition concepts. In order to develop the frequency response practice, a virtual interface was programmed. With the guidance of an instructor the student is able to set up a straightforward laboratory experiment which can be performed on simple RC or RL circuits. This experiment is complemented by the use of a signal generator HP-3120A handled via serial port and a linear power amplifier for supplying enough power to the loads. The virtual interface of the frequency response experiment is shown in the Fig.

5. The front panel allows the user to write a list the frequencies which the practice will be performed. Additionally the student is able to choose the testing time in seconds for every frequency written in the list and, a control let choosing the input voltage for the circuit to be studied. Plotting areas help to visualize the acquired responses, impedance and phase angle obtained in the practice.

A menu option was included and it is located on the upper right corner of the front panel shown in Fig. 5. Its purpose is helping to develop the practice in a correct way. The first option called "experiment setup" which guides through the configuration of the test, this option displays an emergent window where is shown the way the experiment should be connected. Save data option allows to save voltage and current data in text files in order to post process the results for obtaining impedance and phase angle by means of the Fast Fourier Transform. On the other hand, an option denominated validation helps to corroborate the results using an analytical solution. This option employs a routine programmed in a math script node where parameters of range of frequencies, resistance, inductance or capacitance are supplied by the student. After the student has fed the required values, two windows are displayed; in them are shown the comparisons of experimental and analytical results of impedance and phase, and they are shown in Figs. 6 and 7 respectively. It is worth to mention, this practice was inspired in the frequency response test that is commonly developed in synchronous machines. This testing procedure is fully described in [20]. With some modifications in the program as well in the suitable instrumentation it is possible to develop this test in a synchronous machine.

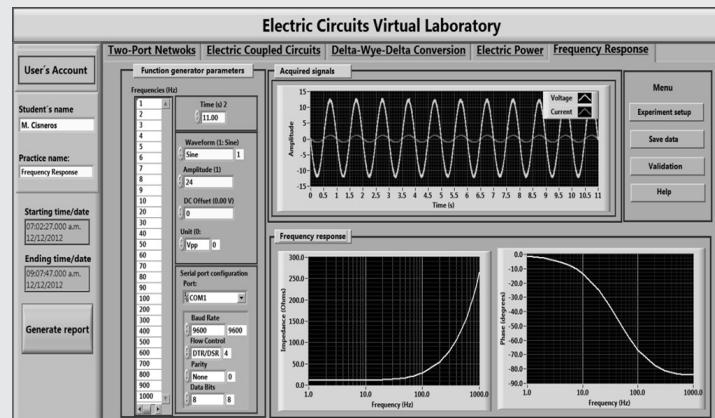


Fig 5. Front panel of the virtual instrument for the frequency response test in RL and RC circuits.

To validate the virtual instrument a set of experiments were developed by the students. The first experiment of the proposed virtual tool is carrying out a frequency domain test in an inductive circuit. In this case, an experiment is setup as it is shown

in Fig. 8; also a validation test was made using the analytical solution to verify the results.

The function generator HP 33120A is driven by serial communication and it is used to supply a sine signal which is fed to the power amplifier in order to supply enough power to the load. A PCI 6221 data acquisition card is used to acquire the test responses vs and is. These measurements are used to compute impedance and phase angle by using the Fast Fourier Transform. An air-core solenoid of 42 mH and  $11.6 \Omega$  was employed on the experiment. The schematic of the frequency response experiment is shown in Fig 8. The computations of impedance and phase made by the frequency response tool are shown in the plotting areas of Fig. 5.

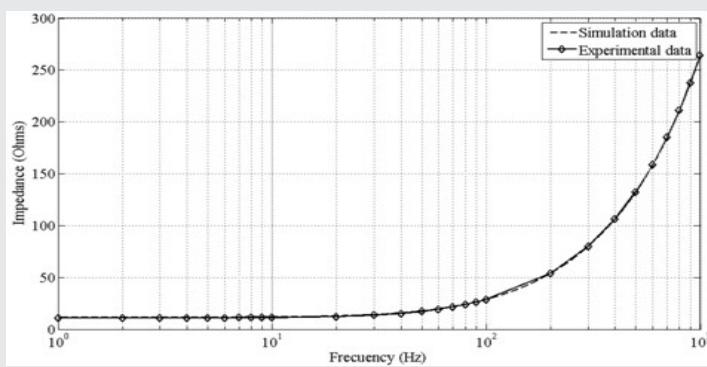


Fig. 6. Comparison of the analytical and experimental impedance data from the frequency response test in an air core solenoid.

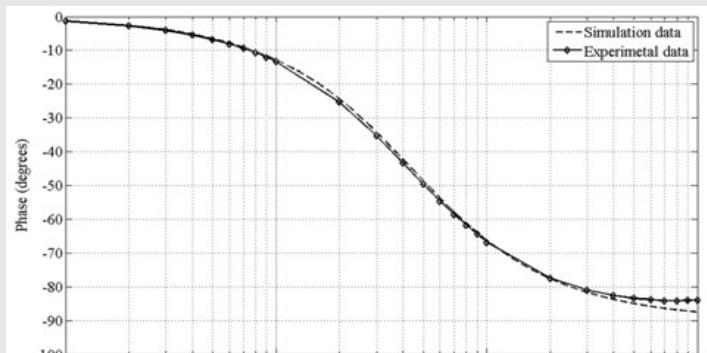


Fig. 7. Comparison of the analytical and experimental phase data from the frequency response test in an air core solenoid.

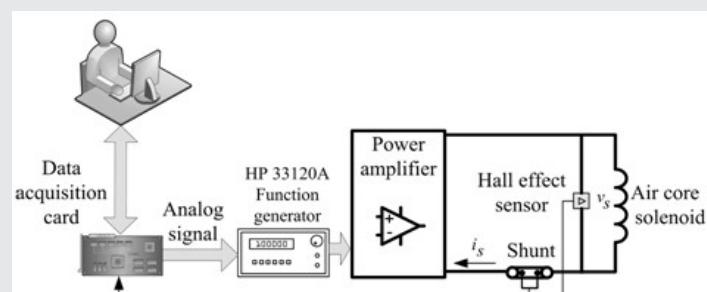


Fig. 8. Schematic of the frequency response experiment in a solenoid.

## CONCLUSIONS

A virtual tool that helps to the understanding some of the basic concepts of electric circuit theory was presented in this paper. The developed tool takes advantage of LabVIEW in the sense that this programming language allows to design real life environments. This tool is user friendly and avoids the use of expensive equipment, like three-phase power analysers, multimeters, oscilloscopes, variable high power supplies and electric devices. Moreover, this tool is useful when the laboratory equipment is not available.

Through a set of friendly laboratory practices focused for undergraduate student reinforces the theory taught in the classroom; this feature allows to experiment with several scenarios in every proposed practice. Additionally, these simulated practices avoid the risk to the student to be harmed by high currents which in real practices are common. It is worth to mention that this set of practices were programmed and designed according to a study program seen in an undergraduate course. In addition, LabVIEW has the characteristic of create executable applications; this is useful because it allows that practices can be performed without installing this program in each PC. This feature allows that most of the practices can be developed in the classroom as a complement of the theoretical classes. All the practices were supervised by an instructor.

On the other hand, positive feedback was obtained by part of the students. The educational tool raises their confidence about the learning of electric circuits which is due to the interaction between a simulation environment and theory taught in the classroom. This tool has given practical and theoretical support and it is helpful in their professional development. Finally, students showed good acceptance and interest in using the educational tool.

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#### APPENDIX

The flowchart shown in Fig A1 shows all the process followed by the user during the practice. In the start, the user introduces some important data as student's name and practice name. Starting time/date and ending time/date are given by the system. Those data are important because they give a record of assistance and progress. Once the student has selected the practice, the virtual tool develops the practice and the user is able to modify several fields in it. The practice finishes when the user generates a report with all the results obtained from the virtual tool.

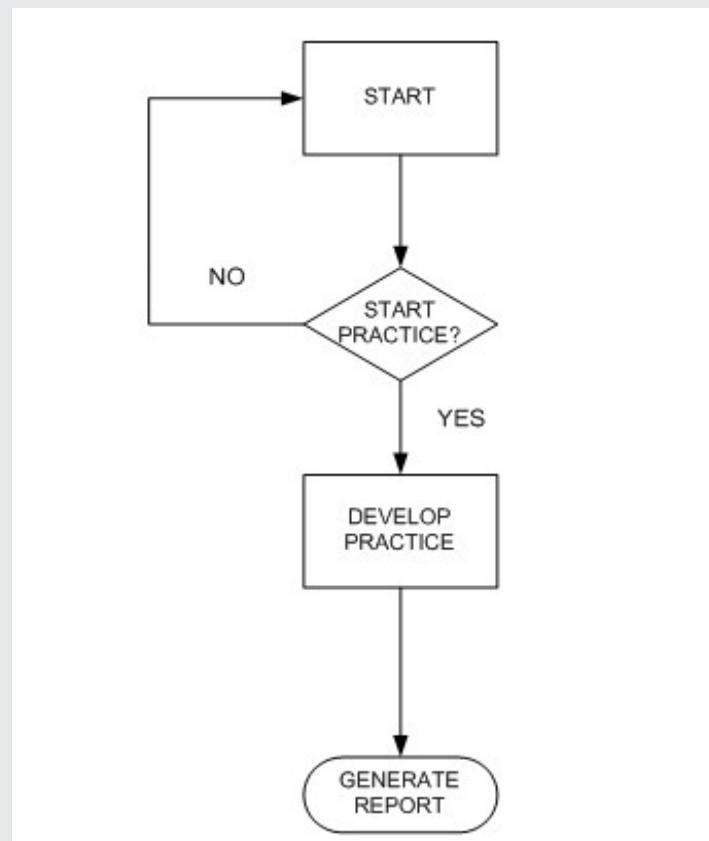


Fig A1. Flowchart of the educational virtual tool.

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