3.04.02 - Engenharia Elétrica / Medidas Elétricas, Magnéticas e Eletrônicas, Instrumentação

# An impedance-meter for physics laboratories

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**Abstract:**
Electrical impedance measurements are very common jobs in physics laboratories. Commercial impedance meters are very expensive and the conventional techniques based on manual adjust of the function generator and oscilloscope are inaccurate and boring. Nowadays, the electronic technology is being inserted in the learning process so, we have proposed an automatic system for the measurement of electrical impedances that can be used in laboratories activities. This system adds low cost and simple understanding of the concepts by students from introductory classes in Physics and Engineering courses. The system is set by a digital module that acquires voltages from a test circuit, and a computer that runs the digital processing of the signals using LabView. Experiments were performed in several devices, and the results were compared with measurements done by a commercial impedance analyzer. The results obtained with our system and the commercial reference impedance-meter are well adjusted. The major deviations were detected when the impedances are superior to 100 kΩ and operation frequency is larger than 300 kHz.

**Keywords:** Digital Module, Automatization, Electrical Impedance, Impedance Spectroscopy

**Financial suport:** Authors thank to FAPESP (2012/07639-4), FAEPEX / UNICAMP (825/2014) and Faculty of Technology Unicamp

**Work selected for the JNIC by the institution:** University of Campinas UNICAMP

**Introduction:**

Physics III and Physics IV are classes usually inserted in Physics and Engineering courses programs. Usually, in these classes are taught basic concepts of electrical impedances on alternating current circuits [1-3]. Of course, the impedance measurements represent an important piece in the learning process of this subject. Impedance measurements are not only important for the better understanding of alternating current circuit concepts but in several other jobs associated with electronic instrumentation in physics, as an example the characterization of sensors.

Equipments for measuring electrical impedances are found in the market. In general, measurements performed with RLC bridges are restricted to few frequencies and not allow us to know, in a simple and quick way, a precise impedance curve. The impedance analyzers, as, for example, HP4294A, made by Agilent, measures in a broad frequency ranges (between Hz and hundreds of MHz), but they have a high cost.

A typical, simple and didactical procedure to determine electrical impedance consists in to use a function generator to supply with a sinusoidal voltage to a serial circuit composed of the device whose impedance is to be determined and of a shunt resistor. Figure 1 shows this arrangement. Voltages and phase differences in the components of the circuit are measured with an oscilloscope and, applying the circuits theory, the impedance (magnitude and phase) are calculated [4]. Tough, when the impedance has to be determined in a large range of frequencies or from devices with large Q factor, this procedure is slow and inaccurate. The reason for these difficulties can be the simplicity of equipment used in laboratories. As examples, in many situations the control of function generator is manual and the reading of oscilloscope depends on the visual perception of the operator.

Nowadays, a tendency of introducing technology and boost the teaching process points to the employment of automatic systems to perform experiments aiming to get results with more agility. Typically, technological innovations are concentrated in data acquisition techniques including apparatus that combine sensors [5,6], software [7] and computers [8-10], and simulations [11].

In this paper, we introduce a digital module in the experimental set to obtain, quickly, results in a classical experiment for determining curves of electrical impedance with a larger number of points, a broad frequency range, and inferior reading errors caused by human factor.

There are some methodologies that are used to measure impedance based on voltage dividers [12]. The range of impedance magnitude values is one of the bottlenecks for the development of measurements systems. In the literature are found some sophisticated procedures to the determination of impedance of the testing device.

Doerner et al [13] have developed a system based on digital signal processing techniques that work on broadband, with nice frequency resolution and low level of noises. The results obtained from this system

show that the assumptions for the project were fully assisted. However, taking into account a didactical application, the complexity of the system embarrass the comprehension of the procedures by students of introductory physics classes.
Magnetic sensors can be used to measure current [14], however, depending on the operation frequency the inductive feature of these sensor can yield interference in the results.
Other methods are detailed in [15].In physics learning laboratories intended to perform of experiments to the determination of impedance in conventional circuits with resistors, capacitors and inductors and other devices, as piezoelectric transducers, it would be recommended that the system puts together the following characteristics:low cost, simple operation concepts, more accurate control of frequencies and larger range of readings of the impedance magnitudes. Thus, the goal of this work is to present an automatic system which combines all these features and assist didactic and research objectives in the impedance measurements.

**Theory:**
A basic circuit to be used to determine the impedance, $Z_t$, of any electrical device is shown in Figure 1

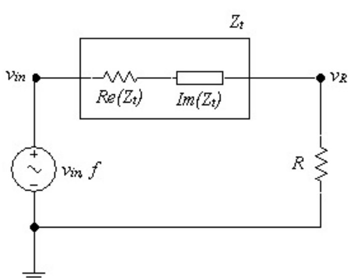


Figura 1 Schematic diagram of the circuit used to detemine the impedance of a device $Z_t$.

Equation 1 shows the impedance $Z_t$

$$Z_t = Re(Z_t) + jIm(Z_t) = R_t + jX_t \quad (1)$$

where $R_t$ and $X_t$ are the real and imaginary components of the impedance of the device under test, respectively, and $j = (-1)^{1/2}$ is the complex number.
$Z_t$ e R are connected in serial circuit (a voltage divider).According to the circuits theory, the voltage magnitude in the shunt, $v_R$, is:

$$v_R = v_{in} \frac{R}{\sqrt{(R_t+R)^2 + X_t^2}} \quad (2)$$

The phase difference between the supplying voltage, $v_{in}$,and the current that flows in this circuit is the same that between $v_{in}$ and $v_R$. Thus, the difference of phase is :

$$\tan\theta = \frac{X_t}{R_t + R} \quad (3)$$

After making some algebraic handling of Equations 2 and 3, we obtain the components $X_t$ and $R_t$ given by Equations 4 and 5, respectively

$$X_t = \frac{v_{in}}{v_R} R \, sen\, \theta \quad (4)$$

$$R_t = \sqrt{Z^2 - X_t^2} - R \quad (5)$$

$Z = R\frac{v_{in}}{v_R}$ is the impedance "seen" by voltage source, i.e., Zt and R in serial association. Using the measured values of θ, $v_{in}$ and $v_R$, and Equations (4) and (5) we can determine the impedance magnitude ($Z_t$) and phase ($\theta_t$) through of Equations (6) and (7), respectively. We must point out that this last procedure is fundamental to correct the phase difference due to the resistive effect introduced by R.

$$Z_t = \sqrt{R_t^2 + X_t^2} \quad (6)$$

$$\theta_t = \tan^{-1}\left(\frac{X_t}{R_t}\right) \quad (7)$$

**Metodologia:**
To accomplish the experiment, we have used a function generator Tektronix AFG3021C, a digital module NI USB51-32 from National Instruments, a computer and the test circuit shown in Figure 1. Both, function generator and digital module, are controlled by software developed in LabView (National Instruments). A block diagram of the experimental set is shown in Figure 2. LabView controls the function generator putting forward the frequencies sweep in the range and resolution defined by a system operator. Also, Labview controls the full communication with the digital module. The voltages, $v_{in}$ and $v_R$, are collected by digital module through of CH0 and CH1 channels, respectively, and read by the software written in LabView. In addition, this software, through of internal routines, determines the phase difference between these voltages, and run an algorithm of the operations defined by Equations 4 to 7. Each measurement is repeated 10 times for each frequency aiming to get the average in the calculus to be performed by LabView and, thus, to reduce the errors caused by random external interferences. The function generator is controlled by LabView and supplies the voltage with amplitude of 5,0V to the circuit of Figure 1. The shunt used in the test circuit has a resistance of 100Ω. The measurements are made at a rate of 1000 samples/sec.
The superior limit of reading of the digital module is 20V. The measurements can be performed with tenth of μV, however, we choose to consider precision up to 1,0mV. The sweeping has 200 points/decade.
For the validation of the system, we have made comparative tests determining impedance curves with

our system and a commercial impedance analyzer (HP4294A, Agilent). The tests were performed with devices with different impedance characteristics. The devices have been tested along of frequency ranges so that extreme operation conditions could be evaluated, such as the magnitude order, and phase interval between -90º e 90º. To meet these needs, four devices have been tested:

a) a RLC serial circuit composed of R = 100Ω, L = 1mH e C = 100 nF.

b) a piezoelectric transducer with a resonance frequency of 38kHz, made by Beijing Cheng-cheng Weiye Ultrasonic Science and Technology Co. Ltda.

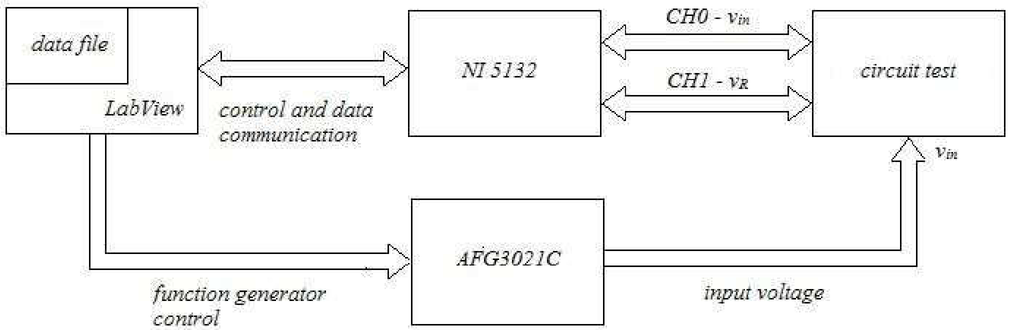


**Figura 2 Block diagram of the automatic system to the determination of impedances**

## Resultados e Discussão:

Figures 3 and 4 show the results of magnitude and phase, respectively, of the impedance of RLC serial circuit, the maximum of impedances is around 15 kΩ in 100 Hz. We can note that the deviation, in this case, occurs only in high frequencies.

The circuits used in the experiments have a shunt resistor of 100Ω. The voltage in this resistor is very small when the impedance of the device to be tested is very larger than the shunt resistance. The digital module has a lower limit for the voltage measurement (under 40 mV, readings are not recommended) and the insertion of noise due to a low current in the circuit are important sources of errors for the measurements Under this voltage level, the reading is not precise and the algorithms that process the phase difference can not work rightly. Surely, this is the source of the large errors shown in results from Figures 3 and 4 on low frequencies. A change in the resistance shunt can help to overcome this restriction.

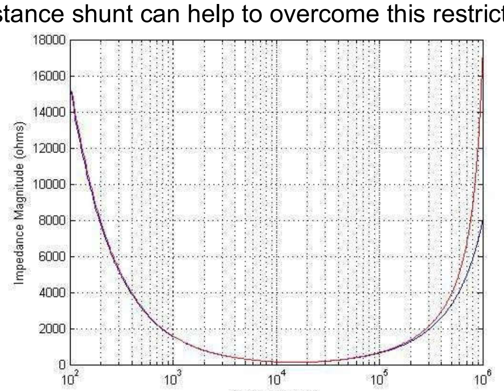


Figura 3 Impedance versus frequency of a RLC serial circuit composed of a capacitance of 100 nF, an inductance of 1 mH and a resistor of 100Ω between 100 Hz and 1 kHz (HP4294A – blue line; our system - red line).

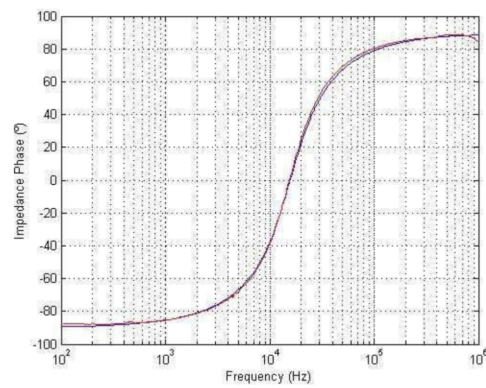


Figura 4 Phase versus frequency of a RLC serial circuit composed of a capacitance of 100 nF, an inductance of 1 mH and a resistor of 100Ω between 100 Hz and 1 kHz (HP4294A – blue line; our system - red line).

The identification of low voltage in the shunt and the switching of the resistor require new electronic implementation does not build in this work. Changing both, the configuration of the test-circuit and sensors based on other principles are also other resources to improve the system. In addition, the pedagogical practice proposed by Chinaglia et al [4], consisting of the determination of values of resistances and capacitances (or inductance) of components hidden in a black box, can be implemented using our system too. Figures 5 and 6 show the results of magnitude and phase, respectively, of the impedance of the piezoelectric transducer described in Theory section. In this case, the 200 frequency values are between 37 kHz and 45kHz.The results obtained for the piezoelectric transducer shows that our system embraces measures in a large range of impedances, between 100Ω and 100 kΩ and -90º and 90º approximately. This result shows that our system is useful as a tool for the characterization of piezoelectric transducer employed in high power ultrasonic generator. High Q factor components, as the piezoelectric transducers used in high power ultrasonics, need small frequency discretization to have a more precise characterization around resonance and anti-resonance. Our system includes this advantage through of the input parameters into LabView by the operator.

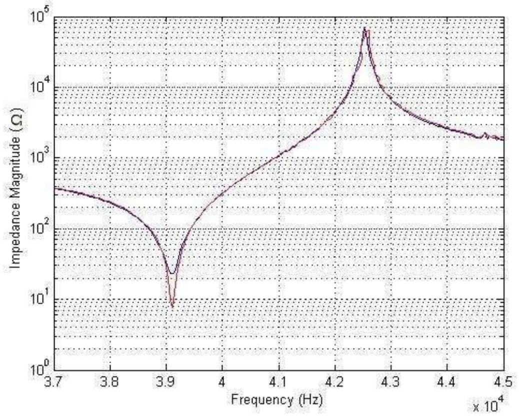


Figura 5 . Impedance versus frequency of the piezoelectric transducer between 37 kHz and 45 kHz (HP4294A - blue line; our system - red line).

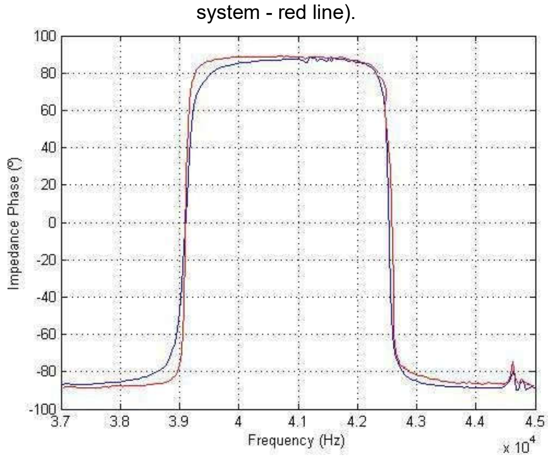


Figura 6 Phase versus frequency of the piezoelectric transducer between 37 kHz and 45 kHz (HP4294A - blue line; our system - red line).

## Conclusões:

An impedance-meter based on the digital capture of signals using a digital module and a computer routine written in LabView has been developed and tested.

The results show that this system can be useful as a cheap alternative to substitute more expensive impedance-meter in the laboratories. We can point out some positive characteristics of our system considering the didactical applications and similar equipments developed for the same objective: a) number of captured points and resolution are defined by the operator;b) range of impedance module between 100Ω and 100 kΩ ith excellent adjust compared to measures performed by a commercial impedance-meter; c) range of frequencies up to 300 kHz; d) use of digital module, computer and software which can be shared in other experiments, so that, reducing the investiment costs for the laboratory; e) the comprehension of the operation of the system is very simple and it can be absorbed by students from first semesters. The main limitation of this system consists in increasing of errors detected when the magnitude order is large. Our research group is working for the overcome this limitation considering a low-cost solution.

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