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Measuring impedance using an open-source instrumentation platform

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Abstract

The article presents development and design of a precision LCR meter based on an affordable open-source instrumentation platform. The design of the instrument has been performed by an interdisciplinary group of students. A project-based approach has been used in order to make a practical use of engineering knowledge within the group of participants. The results cover all the necessary project results achieved by the participants from the state-of-the art analysis in the domain of LCR meters to dissemination of project results. These may serve as a guide for similar project specifications. Alternatively, the presented results may be used in preparing student assignments in electrical impedance measurements based on affordable hardware.

Keywords

LCR, impedance, measurement, education, industrial project

Introduction

Electrical impedance is an important parameter used to characterize the behavior of a two-terminal (one-port) electrical circuit. It demonstrates to what extent the circuit opposes the alternating current flow. Impedance is a complex quantity

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defined as a ratio of voltage to current phasors resulting in two parameters, the impedance modulus (absolute value of impedance) determined as a ratio of voltage to current amplitudes and a phase, determined as a difference between the phases of the voltage and current signals. As a fundamental quantity expressing linear relation between current and voltage it is often named as Ohms law for AC signals. It should, however, be noted that Ohms law in its original form is used only to relate voltage and current at DC biasing.

As being a fundamental quantity in circuits theory it is presented to the students of electrical engineering already in the introductory courses. The students should be familiarized with basic elements of electrical circuits such as resistors, capacitors, and inductances and their role in the circuits. They should also be aware of their nonidealities, in particular, in their frequency dependence that is most clearly explained through the concept of impedance.

Using a commonly available digital multimeter, a student can easily estimate the principal electrical parameter of a given component such as resistance, capacitance, or in some cases inductance, but may remain unaware of its behavior over a wider frequency range. For such a purpose, a dedicated professional-grade laboratory equipment, typically an LCR meter (also called impedance meter) is commonly used. Such instrument is not widely available for hands-on experiments within larger student groups or in DIY home laboratories. Recently, however, several programmable data acquisition and processing kits are becoming available to the students, makers, and engineering professionals. Throughout the paper, we demonstrate how a readily available and affordable open-source instrumentation platform, capable of precision multichannel signal generation and data acquisition may be used on a student laboratory workbench as a good alternative to dedicated professional instruments. Moreover, we will demonstrate how we challenged an interdisciplinary group of students to design and implement their own design of an LCR meter.

The presented design has been supported through an application to a national tender supporting partnership between university (students) and the industry. Throughout the presented project, students utilized a commercially available instrument development platform produced by the industrial partner and developed the necessary hardware and software extensions, designing an instrument which can accurately measure impedance properties of a physical electrical element. The project results were made available as an open-source extension to the platform user community and have served as a foundation for a further commercial LCR meter platform extension. The presented method can be easily deployed as a laboratory experiment utilizing various core programmable instrumentation platforms. The results may also serve as a guide for supervisors who consider to include LCR meter or similar instrument student design project in their curriculum.

Materials and methods

The students obtain a solid theoretical knowledge on resistance, capacitance, and inductance and their behavior in electric circuits during fundamental courses in electrical engineering. Starting to design electrical circuits and devices, young engineers often realize that a physical electrical component may not match the expectations based on its ideal model. We used a project-based learning approach,[1,2] to improve the understanding of the physical components' behavior. We decided to propose a project activity that would give the participating students a first-hand experience with the caveats of impedance measurements.

Project-based learning tender

The proposed idea has been evaluated and supported by a tender application to a national program called "Creative path to practical knowledge" funded by the Slovene human resource and management fund.[3] The program targets students who wish to participate in small research projects in addition to their studies. It was established to stimulate students' activities on practical engineering assignments in a partnership with the industry and to help in transitioning from the school environment into the working one. After its initial success in 2013, the program is gaining on popularity and is currently reaching the end of its third call. Under first two calls, it included more than 3400 students and 500 organizations.

Goals and activities

The project goal was to design an instrument that measures impedance of physical electrical components. The instrument should exploit capabilities of signal generation, capturing and processing, as offered by a commercially available instrumentation and control platform. Resourcing only to harmonic signal generators and voltage measurements in time, we were expecting of the students to get a deep insight in how complex measurements of impedance should be performed, what are the real characteristics of physical electrical elements and what are the caveats of precise measurements of electrical values.

We founded the project on the following activities that should take place throughout the project duration.

- Evaluation of commercially available LCR meters.
- Theoretical overview of LCR measurement methods.
- Performance evaluation of a given open-source instrumentation platform.
- Development framework configuration and setup.
- Design and implementation of an LCR meter.
- Validation and performance evaluation of results against a reference impedance instrument.
- Dissemination of project results.

We have defined the scope of the project in the initial project proposal. Based upon the desired outcomes, the students were allowed to plan the project activities autonomously. Among the participants, a senior student member volunteered as a project leader who managed the assignments for project rollout and execution and supervised the project activities. At the end of the project, the objectives of the project have been verified and the results disseminated in selected public events. We have prepared a final project report containing main project results and project evaluation by participating teaching and industrial personnel as required by the tender. In addition, a self-assessment has been performed among the student participants to identify the overall level of satisfaction and perceived benefits of project participation.

Results

LCR measurement instruments

The project participants have analyzed typical commercially available LCR meters for their measurement method, technical characteristics, and price–performance ratio. The analysis should help to determine a list of goals the designed instrument should achieve. They have identified a variety of commercial LCR meters in the following main categories:

Handheld digital multimeters can measure resistance and capacitance, some even inductance of a passive electrical component. The measurement is usually based on time constant method. The meters in this class are affordable and have a typical accuracy of $\pm 1\%$. These instruments measure only a dominant electrical value and cannot provide complex measurement results. These instruments are affordable and their price starts at 15 USD.

Handheld LCR meters are portable, lightweight, and operate on batteries. Most models can operate at multiple test frequencies and provide an interface to an external PC, usually via USB port. They are intended for general use and are practical for field maintenance and repair applications. These meters utilize AC measurement methods and can typically provide resistive and reactive readouts. The expected accuracy of measurement is within 0.2–0.1%. The price range is moderate, within 200–1,000 USD.

Benchtop LCR meters, in general, offer more features compared to handheld instruments which include programmable frequencies, computer control and data collection for automated applications, DC bias voltage, DC bias current, and sweep capabilities. They offer a better measurement accuracy of up to 0.01%. They are used for laboratory tasks like AC calibration of inductance, capacitance and resistance standards, measurements of dielectric constant, and testing of components and sensors in production. The price range is high, in range from 2000 to 20,000 USD.

LCR measurement methods

Several measurement methods can be used to measure electrical properties of passive electrical components such as resistors, capacitors, and inductors. Commonly, we associate an electrical component with its principal electrical parameter that can be easily estimated using a digital multimeter or even an oscilloscope. For a precise analysis of parasitic values we may use a dedicated impedance (LCR) meter or similar precision instrument based on complex impedance analysis over a wide frequency range. We discuss some typical LCR measurement principles below. The methods discussed are shown in Figure 1, where the measured component is referenced as "device under test" (DUT).

Time constant measurement method. A simple and efficient reactance measurement method utilizes a time constant of a resistive and reactive electrical component connected in series. The measurement circuits are represented in Figure 1, left. When a capacitor is connected to a constant voltage source $V_{\max}$, the capacitor voltage increases exponentially as $V_C(t) = V_{\max}(1 - e^{-\frac{t}{\tau}}), \tau = RC$. It is easy to see that $V_C(T) = V_{max}(1 - e^{-1}) \approx 63\% V_{\max}$, so the capacitance can be directly calculated from measured τ as $C = \tau/R$.

Adequately, if voltage source is connected to an inductor, the voltage on an inductor decreases as $V_L(t) = V_{\max}(e^{-\frac{t}{\tau}}), \tau = L/R$ and inductance is obtained from measured τ of an LR circuit $V_L(T) = V_{\max}(e^{-1}) \approx 37\% V_{\max}$ and equals to $C = R\tau$.

The time constant measurement method is commonly used in digital multimeters to measure capacitance.[4] It has low accuracy and is not suitable for extreme capacitance values and cannot determine a complete readout of parasitic values. The method can also be utilized using a signal generator and an oscilloscope.

Bridge network method. Most accurate impedance measurement methods utilize an alternating current bridge network in order to measure both the resistive and reactive component of the DUT. A bridge typically consists of four arms, a source of excitation and a balance detector,[5] as shown in Figure 1, center. In "balance," there is no potential difference over a detector, and the value of the unknown impedance Z_x is obtained using the expression

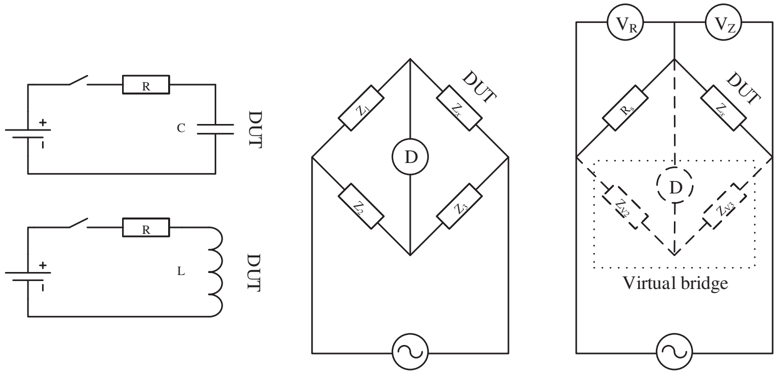

Figure 1. Typical circuits for impedance measurements. DUT: device under test.

$$Z_x = \frac{Z_1}{Z_2} Z_3$$

With a bridge circuit we can measure impedance using relatively simple indicator instruments. No complex measurement instruments are required, which was of a particular importance in time of analog instruments. The method is, however, cumbersome as not only modulus but also the phase of the impedances should be "balanced" in order to get zero reading of the detector (D).

Complex current and voltage measurement method. By definition, the impedance of a DUT may be calculated directly from measurements of current I_Z and voltage V_Z as shown in Figure 1, right. Digital instruments may provide fast and accurate acquisition of samples in time domain enabling determination of amplitude, frequency, and phase shift of an alternate voltage or current with ease. Normally, we would use a reference resistor to measure the current $I_Z = V_R/R_S$ and use the current signal amplitude to calculate the absolute value of the impedance through a definition of impedance as $Z_x = V_Z/I_Z = R_S V_Z/V_R$ where V_Z is the amplitude of the DUT voltage signal. Preferably, the reference resistor should not differ much from the impedance of the DUT to produce most accurate results. For direct readout of amplitude and phase difference between the voltage and current signal we would require an accurate quantizer and a high oversampling rate. Accuracy and noise resiliency can be improved using integrative (averaging) DSP algorithms. Using these techniques, the amplitudes and phases of the voltage and current signals can be obtained by comparing them with a reference sine signal over the entire period under observation. We could interpret the synthesized reference sine signal as voltage at a bottom-arm node of a virtual bridge as shown in Figure 1, right.

Complex current and voltage measurement method is a preferred impedance measurement method in digital LCR meters where digital signal processors provide accurate measurement of AC voltage signals and integrative methods can be used to improve the noise resiliency. This method has also been used in the presented project and is in more detail explained in the following chapters.

Open-source instrument hardware platform

As an instrumentation platform we have selected a ready-made, general-purpose open-source DSP system. The system consists of a credit card sized system board, featuring an ARM Cortex microprocessor combined with a field programmable gate array (FPGA) on a single chip and a precision digital-to-analog and analog-to-digital interface. The design of the board is compact and is, unlike most development kits, suitable for final deployment of the developed solution. These features make the implemented device not only ideal in education but also attractive as a signal processing module in certain commercial solutions. It has been announced as an affordable alternative to a series of professional laboratory instruments, especially for students and enthusiasts.[6] A wide range of softwaredriven instruments are available by the provider, and custom solutions can be made by the user as the entire system software is open and well documented.

The system offers a pair of fast analog inputs and fast analog outputs, operating at 125 millions of samples per second (MS/s) with a precision of 14 bits. The inputs are DC coupled, with bandwidth of 50 MHz (−3 dB). Additionally, it provides 16 general purpose input/output, four low-speed analog signal inputs, and four low-speed analog signal outputs. Data access, configuration, and control of the system is enabled over a wired Gigabit Ethernet connection, or, alternatively, using a Wi-Fi module in the form of USB dongle. The Zynq, 7010 system-on-chip is powered by a Xilinx's build of Linux operating system. The SoC utilizes a dual-core Cortex A9 processor combined with a 28K logic cell FPGA for heavy real-time signal processing.[7] A web interface is commonly used as a user interface as there is no native display provided. The system architecture is presented in Figure 2 with technical specifications listed at the official RedPitaya documentation website.[8]

The deployed hardware platform boots from an SD card into a Linux-based Red Pitaya operating system running on an ARM Cortex processing core. The minimum SD card size is 4 GB. Red Pitaya is a networked device and the initial configuration should normally be provided through DHCP in a local network. An IP discovery service assists the user through first-time configuration operations.

Upon booting, the device is operated through a web browser using a STEMLab interface. This is an environment designed by the manufacturer of a device, from which the user can start one of the preinstalled instruments, initiate Standard Commands for Programmable Instrumentation (SCPI) server providing Matlab/Scilab/Python/LabView data connectivity or load additional instruments. Apart from a set of officially supported measurement solutions, a user can download applications that were developed by the Red Pitaya community or their own software solutions. The source code of the core system and of the existing instruments is available under GPLv2, representing a solid WebIF-based instrument opened for full customization. Basic use of provided instruments requires little technical knowledge from end product user. For mobile use, a Wi-Fi access is possible, even with stand-alone operation in AP mode. Apart from web interface, a console terminal is provided locally or via a secure shell socket connection for advanced manual configuration including application installation.

The normal operation of Red Pitaya instrument relies on three core elements: a web-based graphical input/output interface, a controller running as a native Linux application, and an FPGA for signal generation and acquisition, as shown in Figure 3. Figure 4 demonstrates an optional command line application mode without the web interface.

Development framework

With a project explicitly encouraging teamwork and collaborative development, a suitable framework for online exchange of project documentation as well as a set of programming tools was required.

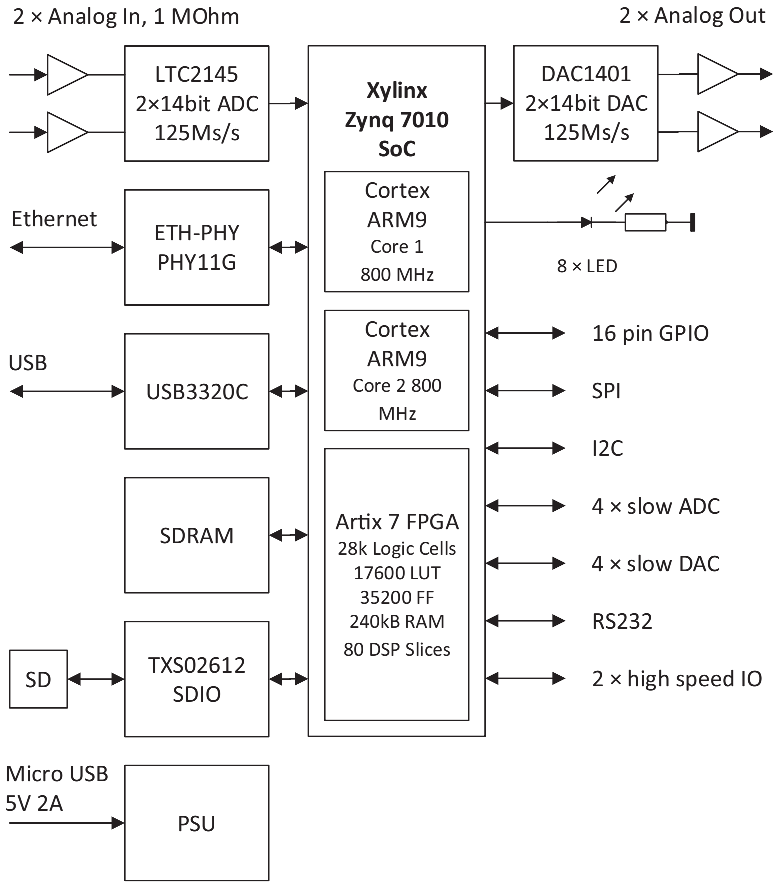

Figure 2. Red Pitaya architecture.

We decided to host the project-related documentation on a simple yet efficient internal Wiki page. Wiki servers are known for ease of management and universality for hosting project development and deployment documentation. In our case, the same infrastructure has been used to host participant profiles, a simple project workflow, administrative project document archive, hardware and software documentation, as well as meeting reports.

The software development environment was based on a GitHub repository. GitHub is a web-based, hosted Git repository service supporting distributed revision control and source code management. Its use has been encouraged by the Red Pitaya platform manufacturer, as it fits well for open-source-based project design and as it is available for free. GitHub provides fundamental tools for collaborative software development, which is beneficial in any team project design and specifically for open-source code development.

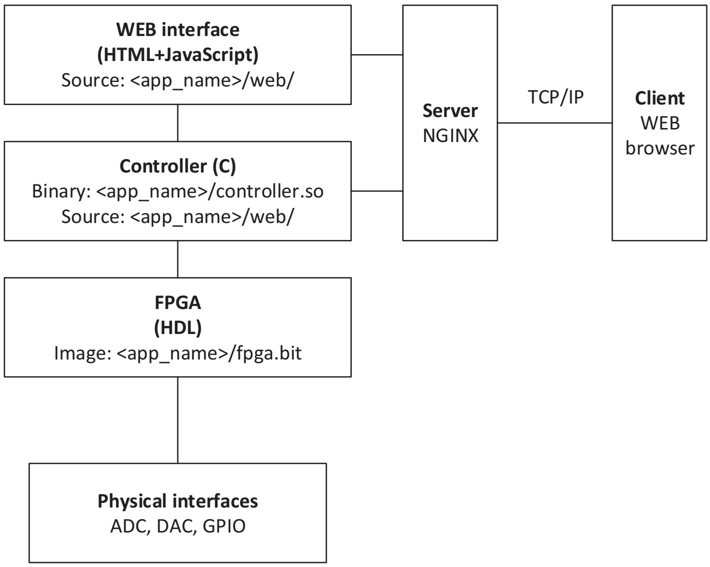

Figure 3. WEB application structure.

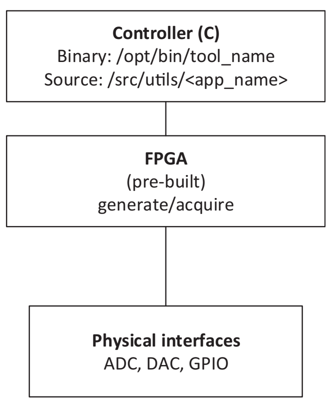

Figure 4. Command-line application structure.

Design and implementation of LCR meter

The student project participants have evaluated several LCR measurement methods for accuracy and completeness. Based on the results, they proposed a solution utilizing the selected instrumentation platform. We briefly describe the applied solution within this section.

The selected instrumentation platform offered the participants fully featured digital signal processing capabilities and an accurate analog and digital interface.

Therefore, they selected a method based on complex current and voltage measurements.

A schematic measurement circuit is presented in Figure 5. A voltage output provided directly by the STEMLab platform (OUT0) has been utilized as an AC source and connected to a measured element (DUT) marked as Z_x and a reference resistor R_S connected in series. The applied voltage signal was measured by an input (INO) while the second input (IN1) was used to measure voltage on the reference resistor. Voltage over the measured element V_Z is thus obtained from the difference of voltages $V_Z(t) = V_{IN0} - V_{IN1}$ while the current through the DUT was determined from $I_Z(t) = \frac{V_{IN1}}{R_S}$.

A digital lock-in method has been used to determine the in-phase and quadrature components of voltage and current signals. For voltage over DUT we obtain

$$V_{ZI} = \langle V_Z(t), \sin(2\pi f_o t)\rangle = \int_t^{t+NT_0} V_Z(t)\sin(2\pi f_0 t)\mathrm{d}t \tag{1}$$

$$V_{ZQ} = \langle V_Z(t), \cos(2\pi f_o t)\rangle = \int_t^{t+NT_0} V_Z(t)\cos(2\pi f_0 t)\mathrm{d}t \tag{2}$$

$$T_0 = \frac{1}{f_0} \tag{3}$$

where f_0 is the excitation and reference signal frequency and N is the number of periods sampled. In a same way the in-phase I_{ZI} and quadrature I_{ZQ} current components are obtained. If we assume the voltage and current over

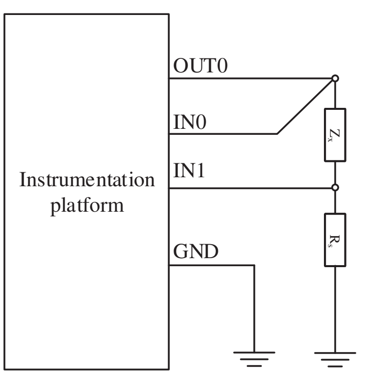

Figure 5. Measurement circuit.

DUT are $V_Z(t) = |V_Z|\sin(2\pi f_o t + \varphi_{V_Z})$ and $I_Z(t) = |I_Z|\sin(2\pi f_o t + \varphi_{I_Z})$ then the voltage and current amplitudes and phases are obtained from

$$|V_Z| = 2\sqrt{V_{ZI}^2 + V_{ZQ}^2} \qquad \varphi_{V_Z} = \arctan\frac{V_{ZQ}}{V_{ZI}} \tag{4}$$

$$|I_Z| = 2\sqrt{I_{ZI}^2 + I_{ZQ}^2} \qquad \varphi_{I_Z} = \arctan\frac{I_{ZQ}}{I_{ZI}} \tag{5}$$

and the impedance is

$$\mathbf{Z} = Ze^{j\varphi} = \frac{|V_Z|}{|I_Z|}e^{j(\varphi_{V_Z} - \varphi_{I_z})} \tag{6}$$

Measurements based on the proposed inner product demonstrate a high resistance to noise as, by definition, any signals orthogonal to excitation frequency does not contribute to the measurement.

The measurement method as we implemented provides the values of a complex impedance based on measured pair of amplitudes and a phase difference at a given frequency. The method can provide readouts at each frequency selected within the initialization of the measurement procedure.

For the initial algorithm design, we have relied on the SCPI platform interface which allowed us to directly operate the system from a high-level numerical computing environment Matlab. For those interested in similar laboratory setups, other environments like Python and LabView are also supported. A complete set of commands is available in the products' reference guide.[8]

After the measurement algorithm has been established and verified, we have implemented the one natively, resulting in a stand-alone LCR instrument utilizing the applied instrumentation platform. This step required an extended set of knowledge and skills, justifying the size and multidisciplinary nature of the team involved. There the necessary calculations were done in C language, with a dedicated user interface written in HTML and accessible via a generic browser. We have based the interface on the principles and technology of responsive web design, which allows the end users to utilize desktop web access as well as mobile browsers to perform and manage the measurements.

Validation and performance of the LCR meter

The physical setup of the experiment is shown in Figure 6. The STEMLab device is connected to a personal computer via Wi-Fi (not shown in the figure). A Matlab program using SCPI commands is used to run the experiments and plot the results presented in Figures 7 to 11.

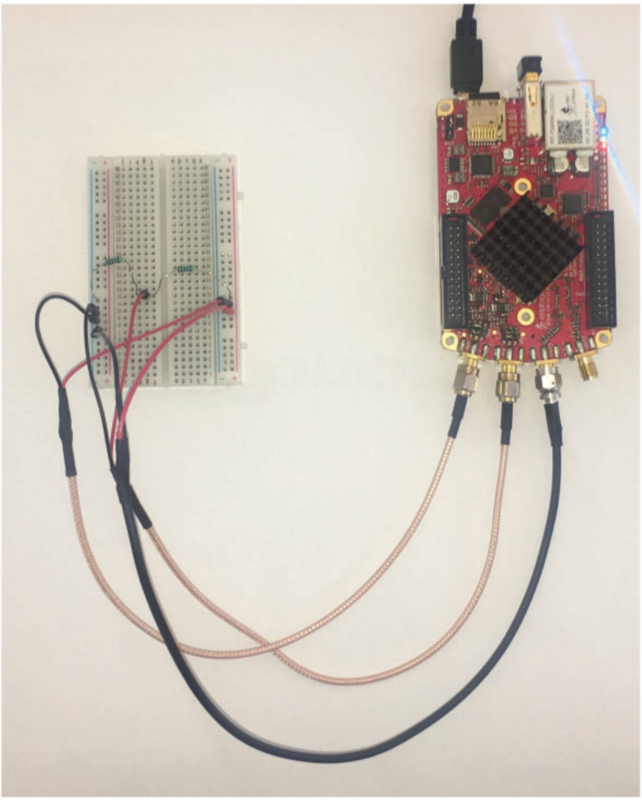

Figure 6. Photo of the actual measurement setup with a STEMLab connected to a protoboard containing the measured impedance (DUT) as well as a reference resistor. The black probe provides the output excitation signal while the two copper-colored probes are the input signals IN0 and IN1 used to measure the excitation voltage and the voltage over the reference resistor, respectively, as also sketched in Figure 5.

The first validation was done using a resistor of $R = 1785\ \Omega$ as a DUT and a reference resistor of $1\,\mathrm{k}\Omega$. The resulting current and voltage waveforms are presented in Figure 7 utilizing an excitation frequency of 10 kHz. As expected, the current and voltage waveforms are in phase which is well seen from the top graph showing development of current and voltage with time (samples) as well as from the bottom graph, presenting the current/voltage signals in an X/Y plane. The latter should look as a line for a resistor and as an ellipse for impedances possessing a nonzero phase value.

The second example utilizes a DUT consisting of a parallel connection of a capacitor and a coil as presented in Figure 8. The values of the capacitor and coil were determined with a professional LCR meter giving a capacitance of $C = 96$ nF and a resistance and inductance of $R = 7.88\ \Omega$ and $L = 6.256$ mH, respectively,

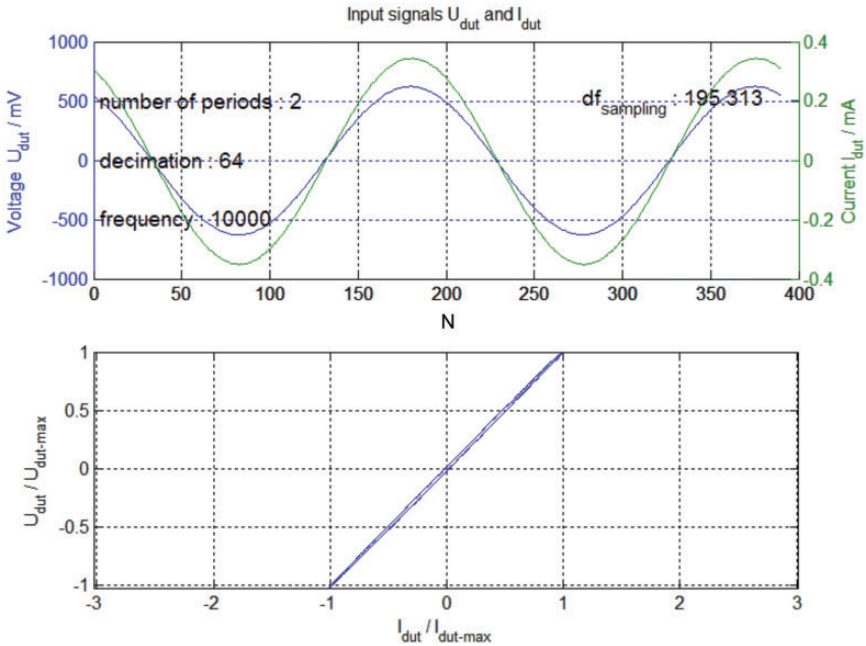

Figure 7. Voltage and current waveforms over a resistor of $R = 1785\ \Omega$.

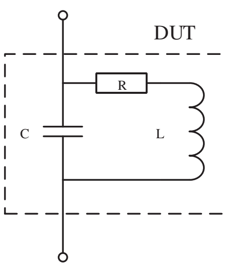

Figure 8. Real model of parallel connection of a capacitor and a coil, the coil is modeled as a connection of an ideal resistor and inductor in series. DUT: device under test.

for a coil by assuming it can be modeled as a series connection of an ideal resistor and inductor. The mathematical model of DUT impedance is thus given using an expression

$$\underline{Z} = \underline{Z}_C \| \underline{Z}_L = \frac{1}{j\omega C} \| (Rs + j\omega L_s) \tag{7}$$

where symbol $\|$ stands for a parallel connection of two impedances.

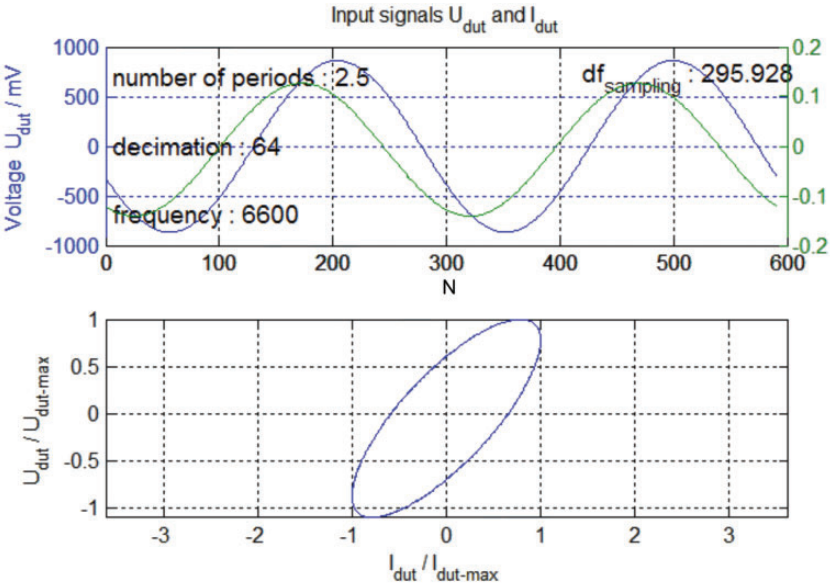

Figure 9. Matlab measurements: complex voltage/current readouts at a single frequency of a $L||C$ component.

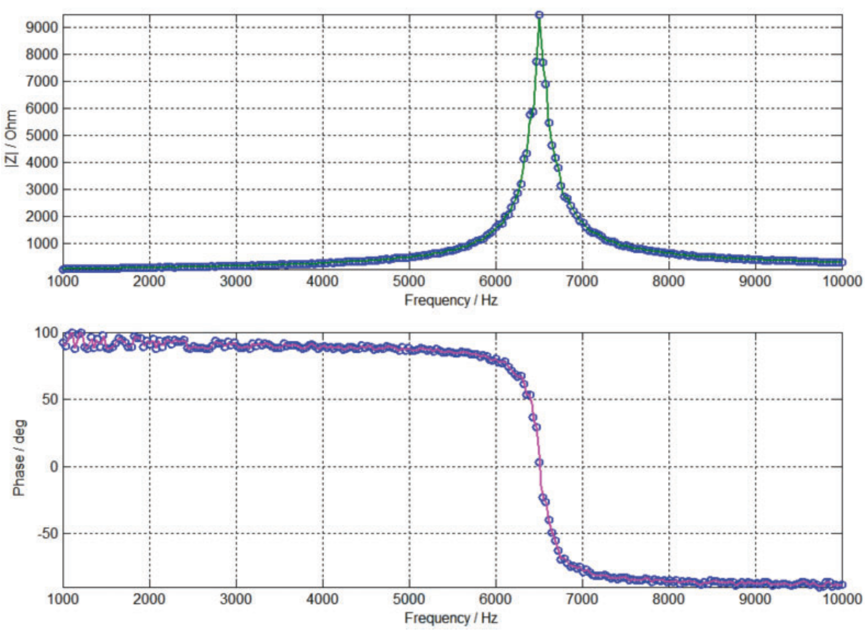

Figure 10. Measured impedance modulus and phase of a parallel connection of a capacitor and a coil as a function of frequency.

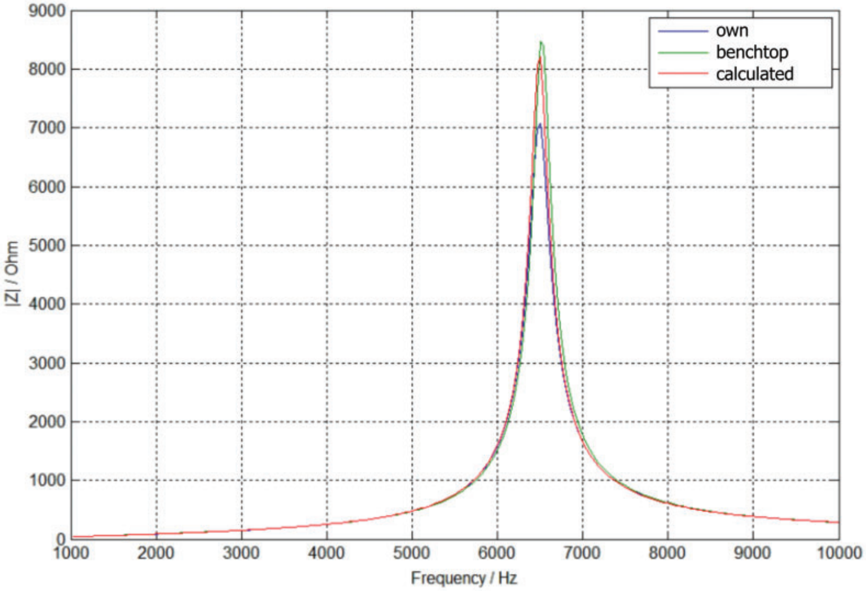

Figure 11. Impedance modulus obtained by the developed method (green), benchtop instrument (blue), and theoretically calculated values (red).

The results acquired using STEMLab are shown in Figure 9 for an excitation frequency of 6600 Hz. The top as well as the bottom graph shows the expected phase shift of the voltage and current signals of about 60°.

Furthermore, a frequency sweep from a frequency of 1–10 kHz in 250 linear steps was performed. With this approach it is possible to show the resonant behavior of the circuit at a frequency of around 6500 Hz as shown in Figure 10. The top graph presents an impedance modulus (absolute value) while the bottom graph presents its phase response, both as a function of frequency. The complete measurement using STEMLab and Matlab took place for 950 s.

Once the algorithm for complex impedance measurement has been tested, a native measurement program in C language has been created. The measurement in the same frequency range took 38 s, which demonstrated a significantly more efficient realization.

Characteristics of the developed LCR meter were also compared to the measurements on a precision benchtop LCR meter. The frequency characteristics of amplitude and phase characteristics using the developed measurement method (own) and a benchtop meter are shown in Figures 11 and 12 together with theoretical values obtained through equation (7).

From the readouts one can identify some further calibration was required to improve the precision of the method.

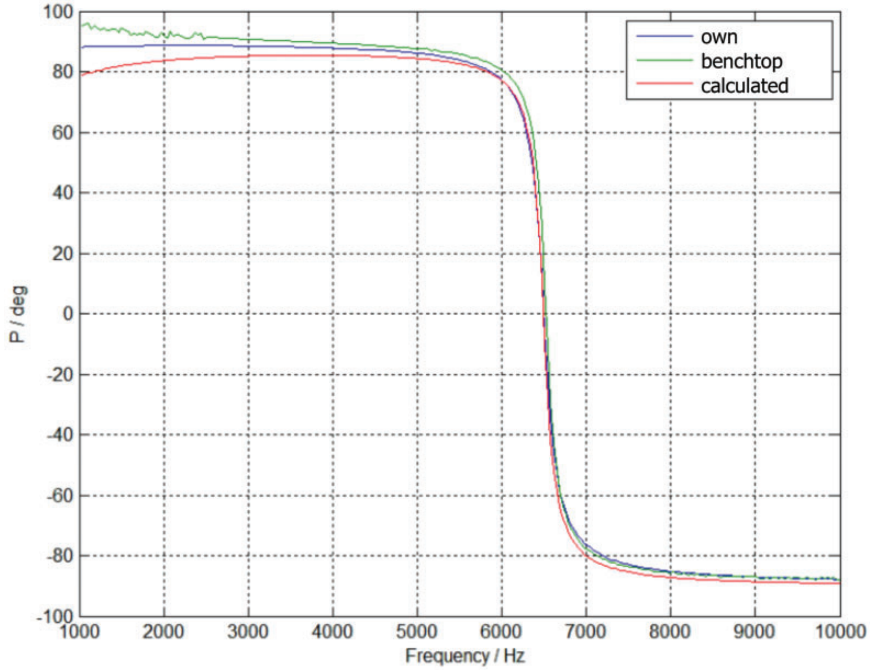

Figure 12. Phase impedance characteristics of own method (green), benchtop instrument (blue), and theoretically calculated values (red).

Dissemination of the results

First public presentation of the project results was made as a poster presentation at the International Electrotechnical and Computer Science Conference.[9] The LCR meter developed within our project was also presented in a special session at the Sixth European Conference of the International Federation for Medical and Biological Engineering in Dubrovnik. Selected results have been presented at a "MakerFaire" workshop in Rome; the presentation made by all student participants has been supported by the industrial partner and the company RS Components. The project has been selected as an exemplary project from University of Ljubljana within the first public tender "Creative path to practical knowledge" and was as an exemplary success story presented at the third national conference on career development in Laško. The company later developed a dedicated electronics add-on for STEMLab that improves the accuracy of the measurements by automatically selecting the optimal precision reference resistor depending on the value of the measured impedance.

Conclusion and discussion

Throughout the six-month project duration the participating students managed to perform all the necessary steps toward an autonomous development of an LCR measurement instrument. The students have demonstrated a high level of commitment as, despite technical challenges, they have managed to reach a complete set of objectives defined by the initial project assignment. In partnership with the manufacturer of the instrumentation platform they have severely improved their domain specific and soft skills and managed to deploy their theoretical knowledge obtained during studies to a practical engineering assignment.

This study can be used as an example in creating similar student projects to be deployed in a team or as a capstone or a final project. Alternatively, the study provides enough materials and references for the educators to serve as a guide for creating laboratory assignments in the area of measurement algorithm design, native algorithm implementation, and/or even FPGA programming using the described or similar instrumentation platforms.

Declaration of conflicting interests

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