Modular FFT Impedance Spectroscope for Measuring Passive Circuits Dynamically

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Abstract* – This work presents the design and implementation of a Fast Fourier Transform (FFT) electrical impedance spectroscope using low-cost function generator, oscilloscope, personal computer and operational amplifiers. The electrical impedance measurement is carried out by sending several probe voltage signals with different frequencies, modulated in a single-one, by means of a function generator. The response is monitored using an oscilloscope and analyzed in a PC. The amplitude and phase of the electrical impedance at low frequencies (Hz to kHz) are obtained using the FFT. This is a quick method to obtain real-time measurements, useful to measure impedance of dynamical systems. To validate the system, it tested to measure an RC circuit and a thermistor-capacitor cell; the results were compared with theoretical calculations and measurements made by a commercial potentiostat. The system exhibited the ability to measure impedance spectra of circuits whose response evolve in time, sampling every 600 ms.

***Keywords:* FFT Impedance spectroscopy; off-the-shelf devices; Impedance spectroscope; dynamical systems.**

I. INTRODUCTION

One of the most powerful techniques for determining the electrical properties of materials and devices is the electrical impedance spectroscopy (EIS) [1]. Electrical impedance Z is the opposition to the electrical current flow when an electrical potential is applied. $Z(j\omega)$ is a complex quantity that depends on frequency ω [2]. With EIS, it is possible to determine the electrical impedance of a material at different frequencies. There are several electrical impedance spectroscopy meters, which provide information on an electrical impedance value at each of the frequencies they measure. This technique is widely used in electrochemistry and biomedical applications, with a wide range of literature in this respect [3-5].

One of the main problems when measuring electrical impedance and obtaining spectra is that when the analyzed system changes its characteristics over time, the measurement is not reliable. As the impedance measuring system measures with a frequency at the time, the system could have already changed by the time when the second or the third voltage signal is applied, so it cannot be ensured that the entire impedance spectrum corresponds to the response under same condition or state. This is the case for energy storage systems when charging or discharging, or a biological system that changes its properties over time due to proliferation or aging, which causes its electrical properties to change [2]. In these cases, it is necessary to use a real-time measurement technique, such as a fast impedance spectroscopy technique.

A typical impedance spectroscopy equipment is an electronic system that injects multiple signals of different frequencies using electronic frequency generators or digital signal synthesizers, and then measures the amplitude of electrical potential and the amplitude of electrical current to determine the amplitude and phase of the impedance at each frequency. This process is commonly done one frequency at a time, leading to obtain a spectrum of impedances [6].

On the other hand, impedance spectroscopy with Fast Fourier Transformation (FFT-IS) is a relatively recent technique (for the last 15 years) to obtain electrical impedance spectra of materials and devices in real time. This technique uses a test signal containing a finite number of known frequency components (usually 30 to 50) that is injected into the material (or system that is required to be measured). The response is monitored and separated into components of different frequencies by the FFT. Then the amplitude and phase of each component are obtained, with which the electrical impedance spectrum can be plotted [7]. Nevertheless, the use of this technique has been scarce; only some reports of a limited number of research groups can be found, who have applied the technique to the study of sensors, solar cells, electrochemical etching processes and batteries [8-10].

The present work deals with the development of an FFT electrical impedance spectroscopy system integrating off-the-shelf devices such as oscilloscope, function generator, voltage source and computer, which can be easily obtained in any electronic laboratory worldwide. The potentiostats, which commonly include this characterization technique, are highly specialized and therefore expensive. For example, a basic measurement set composed of oscilloscope plus a signal generator and circuits could cost less than 1/3 of the price of the cheapest potentiostat. The spectroscope system developed in this work has the advantage of being modular, and can be constructed with equipment from different brands, which can be cost-effective. It also has the possibility of measuring systems that evolve over time, due to the speed and precision provided by each of the modules (each equipment separately). In recent years, an impedance spectroscopy system using off-the-shelf devices was developed as a first approach to study topics like state-of-charge and state of health in batteries [11], while in some other works, the authors only deal with the connectivity between measurement instruments [12]. However, the possibility of measuring systems that change in time (a significant advantage of FFT impedance spectroscopes), has not been exploited. The present work highlights the functionality of a new system that has been built with instrumentation equipment available in any basic electronics laboratory, to perform impedance spectroscopy measurements of dynamical systems in the range of 10 Hz to 100 kHz (and 1 Hz to 100 kHz for static measurements). It is important to mention that measurements with frequencies slower than 10 Hz make no sense in dynamical systems, since these systems may evolve faster than 1 s, and it is important that the measured systems looks like stationary (quasi-stationary) while it is measured with all the test frequencies (the test frequencies must be at least 1 order of magnitude faster); thus the bandwidth of the present impedance spectroscope is the appropriate for such applications. At this stage the spectroscope has been used to measure passive systems, statically and dynamically.

II. METHODOLOGY

An FFT electrical impedance spectroscope was designed following the model presented in Figure 1. The input is a signal produced by a signal generator, which contains several frequencies. For this work, the input signal is a sum of several sinusoidal signals; however other waveforms could also be used. Rp is a test resistor of arbitrary value. Z is the impedance to be measured. The voltages Vv and Vi are the ones indicating voltage and current in Z respectively; these voltages are acquired by an oscilloscope and stored in its internal memory to be sent to a Windows PC where the FFT is computed by software.

The construction of the spectroscope was carried out with off-the-shelf components of two brands: A Tektronix AFG1022 signal generator, a Tektronix TBS1102B Oscilloscope and a PC with Windows 7; it was also constructed with an SDS1104X-E oscilloscope and an SDG1032X signal generator, both of the Siglent brand, and a computer with Windows 11. Additionally, for interfacing the measured signals, a 1 kΩ Rp test resistor, a INA114 op-amp (U1) and a TL071 op-amp (U2) were used.

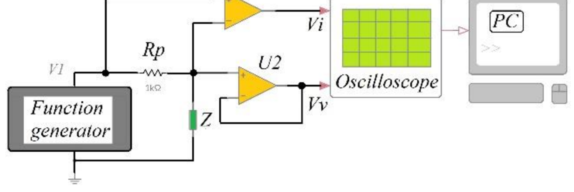

Fig. 1. Module diagram of an FFT electrical impedance spectroscope using off-the-shelf equipment.

The signal generator is used to modulate a signal that contains all the frequencies at which it is desired to measure; this signal is the one that is injected to the test object whose impedance Z is required to be known. At least one output channel is necessary. The equipment must be compatible for programming and/or storage of arbitrary signals in memory. The function generator must be compatible for programming with the Standard Commands for Programmable Instruments (SCPI) instructions; in this case, and for simplicity, a SCPI-compliant USB function generator is used. The voltage range at the signal output ranges from 1 mV to 10 V p-p. It must be considered that the programmed signal, being a sum of signals of various frequencies, can saturate the maximum output of the generator and may cause inaccurate measurements.

The resistor Rp is used to measure the electric current indirectly, through the voltage drop between its terminals. The current is determined by the equation Ohm's law: i=Vi/Rp; where Vi is the potential difference across Rp and it is measured with an oscilloscope channel through the operational amplifier INA114. A 1 kΩ resistor Rp has been placed; nevertheless, it is possible to exchange it for another with a more convenient value if the voltage signal is too small (there is a saturation of the voltage signal) or too large (the measured signal has an amplitude in the noise amplitude range).

The operational amplifier INA114 was employed to measure the potential difference Vi at the Rp terminals; it is a precision instrumentation Op-amp. In this work, an INA114 instrumentation Op-amp, with 1 MHz bandwidth and high common-mode rejection (with Gain G = 1) was used, but if it is desired, another instrumentation amplifier as INA818 (or better) with higher bandwidth may be used. The TL071 low-noise Op-amp was connected in a voltage follower configuration. This Op-amp is necessary for the signal coupling between the measured impedance and the measurement instrument because a direct connection through an attenuated tip can unbalance the circuit and give incorrect results. The oscilloscope must have at least two measurement channels, one to measure current indirectly and the other to measure voltage. It must be programmable with SCPI and be compatible with the VISA virtual instrumentation standard; it must also have a USB communication interface and a bandwidth that allows the highest frequency signal to be used as a component of the applied signal to be measured. It is important to note that if the test leads included with oscilloscope are used, it should be considered to add the attenuation parameter of the leads to the oscilloscope settings, typically 10X as in some brands.

The PC must have the following minimum requirements: a 32 bits operating system (e.g., Windows, Ubuntu, macOs) that supports MATLAB software (minimum version 2014), with a USB interface and with a minimum RAM of 2 GB. The PC must have installed the oscilloscope communication driver and the function generator driver to use SCPI communication (commonly provided by the manufacturer, or a generic driver) for virtual instruments such as VISA (Virtual Instrument

Standard Architecture). Each block of the FFT electrical impedance spectroscope is described in detail below.

A. *Signal generation*

An FFT impedance spectroscopy measurement requires to measure simultaneously voltage and current; the voltage is injected from the function generator block (see Figure 1), and the current is measured through the Rp resistor. In this example, a test voltage signal was injected into an RC system in parallel. The voltage signal contained 46 frequencies ranging from 1 Hz to 100 kHz (This is only an example using a desired frequency separation between decades but it may be different if desired). In order to inject the signal with the 46 frequency components into the test system, a Tektronix AFG1022 function generator was programmed with the following output: $v_o = \sum_{n=1}^{9}[\sin(2\pi nt) + \sin(2\pi 10nt)]$, where n is an integer from 1 to 9. This output was programmed in a window of 2 decades, and then $v_0 = \sum_{n=1}^{9}[\sin(2\pi 10^2 nt) + \sin(2\pi 10^3 nt)]$, in another window of 2 decades, with n from 0 to 9, and at the end, $v_0 = \sum_{n=1}^{9}\sin(2\pi 10^4 nt) + \sin(2\pi 10^5 t)$ in the last window of 2 decades, with n as an integer from 0 to 9 and an additional term for the frequency of 100 kHz. Stepping was performed in this way because the oscilloscope is not able to acquire samples in more than two decades at the same time.

The AFG1022 generator accepts up to 1000 samples to be programmed in its internal memory and is compatible with signals in .tfw file extension. One can use MATLAB's createTFW() function to generate the signal or ArbExpress Application software to do so. It is also possible to program the desired signal point by point directly on the device. For this work, the software Matlab was used. An example of injected signal is shown in Figure 2.

Figure 2 shows a voltage signal that is composed of 18 sinusoidal signals of same amplitude and different frequencies. Note that the amplitude of the composed signal grows above 6 V, a case that can be attenuated directly in the function generator or through the generation program, to prevent the function generator from saturating. For this work a signal with amplitude 1 Vpp was injected. Just sinusoidal signals were programmed as inputs, but other inputs could be programed directly in the signal generator using MATLAB functions.

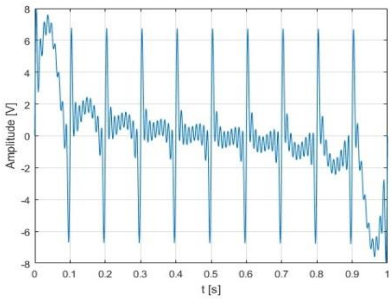

Fig. 2. Signal stored in a signal generator to be injected into the measured system.

B. *Current and potential measurements*

To measure current and voltage, two operational amplifiers were used as an interface with the measurement equipment (an oscilloscope). One in differential configuration (an INA114), was used to measure the potential difference between the terminals of the test resistor Rp and thus indirectly measure the current i = Vi/Rp. The other (a TL071) was connected in a voltage follower configuration, as shown in Figure 1, to measure the voltage dropped across the Vv terminals of the impedance Z. Both potentials were measured directly through a Tektronix TBS1102B oscilloscope, with two channels and 100 MHz bandwidth. Using the SCPI instructions, the voltage values read on the oscilloscope were communicated to the PC through the USB interface. It is important to mention that the communication could also be done by GPIB.

C. *Measurement algorithm*

Once the data for both potentials are available on the PC, the information is processed in MATLAB. The measurement algorithm is described below:

1. First, the voltage values Vv and Vi from the oscilloscope are stored into the oscilloscope.
2. The voltage data Vi is transformed into current data by dividing by Rp (Figure 3 shows Vv and the current I = Vi/Rp). Now the voltage and current of the impedance Z to be measured are obtained.
3. The FFT of the current and the voltage is obtained. At this point, the voltage and current in the frequency domain, as complex numbers are obtained.

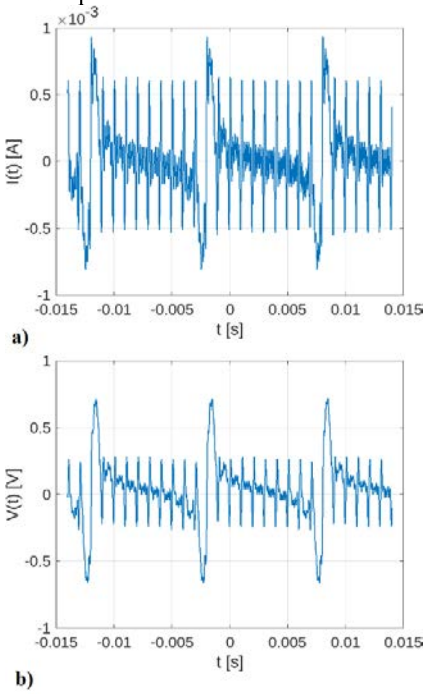

Fig. 3. Measured a) current and b) voltage, using an oscilloscope.

4. The magnitude of the impedance Z is obtained by dividing the amplitudes of V and I respectively, |Z| = abs(V)/abs(I). The magnitudes abs(V) y abs(I) are shown in Figure 4.
5. The phase θ is obtained from the difference of V and I phases, θ(V) and θ(I) respectively, using the arctan of each phase. With the amplitude and phase, it is straightforward to calculate the real and imaginary parts of the impedance Z = |Z|∠θ.

II. RESULTS

A. *Case study: Measurement of an RC circuit with time-invariant impedance (static system)*

One of the most used case studies to explain the operation of the impedance spectroscopy technique is a parallel RC circuit. The Nyquist diagram of the impedance spectrum of this circuit is a semicircle with a negative imaginary part. The diameter of the semicircle has a value of R. The phase of the impedance goes from 0° (at low frequencies) to -90° at high frequencies.
If the temperature is held constant, the system response is time-invariant. Thus, for this work, this circuit was used as the first case study.

For the calculation of the phase through the FFT, it must be considered that the calculated phase can have values from 0 to 360°, so conversions must be made to have final values from -90 to 90°. Another consideration is that the output amplitude of the function generator can saturate depending on the number of added frequencies, since the sum of the modulated signal is larger when more terms are added. This problem is solved by adding an amplification factor A < 1 to the form A*sin(ωt).

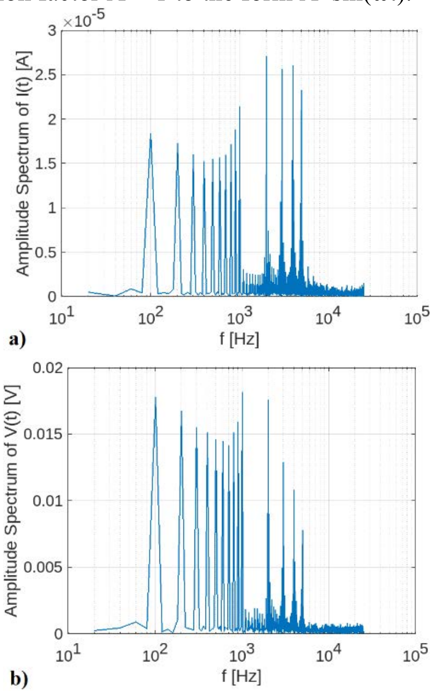

Fig. 4. Amplitude spectra of a) current and b) voltage, obtained with FFT.

The best option to acquire the measurement is to take it when the oscilloscope has stopped (STOP button or instruction), since at free running configuration, the measurement may have a delay due to data acquisition. This step helps to obtain an optimal measurement, since the operating system jumps between processes and this presents acquisition problems on phase changes if only one acquisition card is used, for example.

After the modifications previously mentioned, the obtained results presented a measurement tendency like that of the theoretical behavior, and even quite similar to the measurements in a commercial potentiostat. Figure 5 shows electrical impedance data of the RC system measured with Tektronix instruments (Tektronix TBS1102 Oscilloscope and Tektronix AFG1022 Generator). The results were compared against the theoretical values and the values measured with a commercial Zennium potentiostat of the Zahner brand. The theoretical amplitude and phase were obtained from the transfer function of the parallel RC circuit, which is well known in the literature. The system was also implemented using a Siglent SDS1104X-E oscilloscope and a Siglent SDG2042X function generator (see Figure 6). Figure 6a shows the amplitude of the electrical impedance and Figure 6b shows the phase.

The results obtained with meter are suitable for determining the resistance and capacitance values. EC-Lab software was used to fit the measured spectrum using the equivalent circuit model R1+(C2/R2), which consists of a capacitor C2 in parallel with a resistor R2, in series with a resistor R1. For the fitting in the software, a series resistance R1 of 5 Ω was considered (cables).

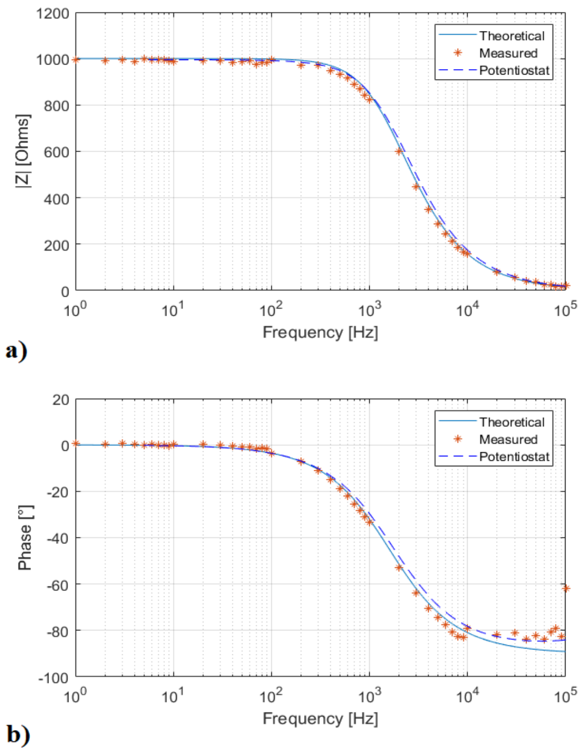

Fig. 5. Comparison of results (obtained with Tektronix devices: TBS1102 Oscilloscope and AFG1022 Generator) of a) amplitude and b) phase, with theoretical data and those measured with a potentiostat, as a function of frequency.

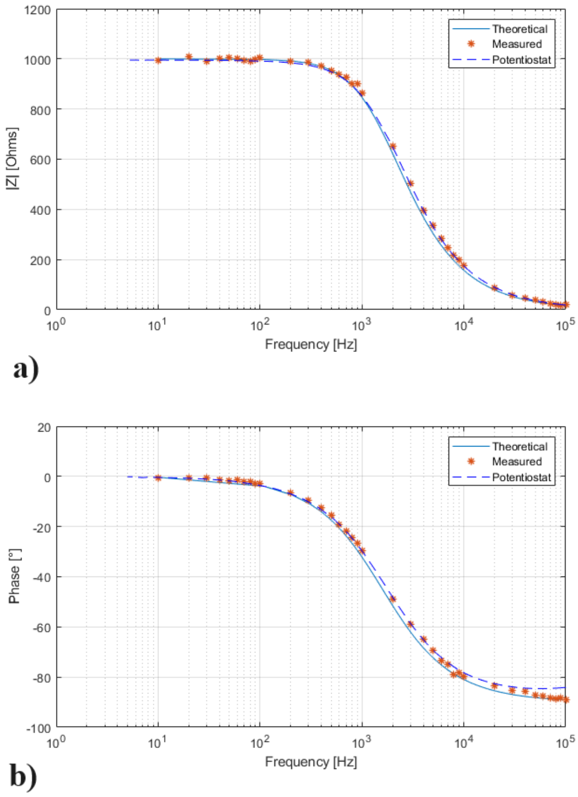

Fig. 6. Comparison of results (Siglent devices: Oscilloscope SDS1104X-E and Generator SDG1032X) of a) amplitude and b) phase, with theoretical data and those measured with a potentiostat, as a function of frequency.

Table 1 shows a comparison of the values by adjusting the obtained data using oscilloscopes and function generators of the two different brands considered in this work (Tektronix and Siglent). The nominal values of the electrical elements used for the analyzed RC circuit are also shown. The error amounts 3.1% for the resistor in both cases, and for the capacitor 2.06 % using Tektronix instrumentation versus 1.91 % using the Siglent brand.

TABLE 1. Comparison of R and C element values obtained by fitting measured data using two measurement systems.

Element	Nominal value	EcLab (Tekronix)	EcLab (Siglent)
R2	1000 Ω ±1%	969 Ω	969 Ω
C2	100 nF ±5%	97.94 nF	98.09 nF

The difference between the values in Table 1 is due to the quality in the measurement of the voltage signal of each oscilloscope; there is an intrinsic error that is different for each device of each brand. Also, the number of bits is important when making the measurement. For the present work, measurements have been made with 8-bit data acquisition regardless of the brand of the measurement equipment. In future work it is intended to make 16-bit measurements. At this stage of design and using different probe resistors (defined depending on the impedance to be measured), the system has these limits: resistor minimum value: 1 Ω; resistor maximum value: 10 MΩ; capacitor minimum value: 1 pF; capacitor maximum value: 100000 μF.

B. Case study: Impedance measurement of a time-variant impedance (dynamical system)

The developed impedance spectroscope can also be used for measurements of time-varying systems. For example, it could be applied to cases such as when semiconductor circuits are subjected to temperature variation. This is possible because the measurement takes a maximum of 2.3 s for a 14-frequency injection on a low-performance PC and using the Tektronix oscilloscope. In the case of the Siglent oscilloscope, the measurement takes an average time of 600 ms. The system implemented for these studies can be improved using a faster PC, a faster oscilloscope, and software that is programmed to run in real time.

For dynamic measurements, the spectroscopy system was implemented using a Siglent SDS1104X-E oscilloscope and a Siglent SDG2042X function generator. The electrical impedance of a circuit formed by a 0.1 μF capacitor with a NTC MF11-152 thermistor with a nominal value of 1500 Ω (at 25°C) in parallel was measured. Figure 7 shows Bode plots of the impedance amplitude of the analyzed thermistor circuit at different temperatures. The measurement was made dynamically, while the thermistor was cooled from 31 °C (room temperature at the laboratory) by immersing it in a cold-water solution at 13 °C.

A total of 8 measurements were made while the thermistor cooled from 31 to 13.5 °C. The measurements were performed with a 2 s pause between them.

Figure 7a shows calculated curves, and Figure 7b shows the measured data. As can be seen in the theoretical and experimental curves, qualitatively the behavior is the same. Besides, figure 8 shows the Nyquist plot of the results shown in the Bode plot of Figure 7. As expected, the Nyquist plot looks like that of an RC circuit (a half circle), since the thermistor is a resistor, with temperature-dependent resistance. The diameter of the semicircle increases with increasing temperature, indicating that the resistance of the thermistor increases. The diameter is according to the resistance values of the thermistor at different temperatures, as in the datasheet.

With the test performed, it is possible to confirm that the developed impedance spectroscope enables to monitor the behavior of electrical impedance in real-time. For 8 measurements of electrical impedance with 46 frequencies, the system consumed a total of 20.8 s, enough to observe the electrical impedance while the thermistor goes to thermal equilibrium. Nevertheless, the temporal resolution of the system evolution could be improved by removing the 2 seconds pauses between measurements (that total time would be 600 ms).

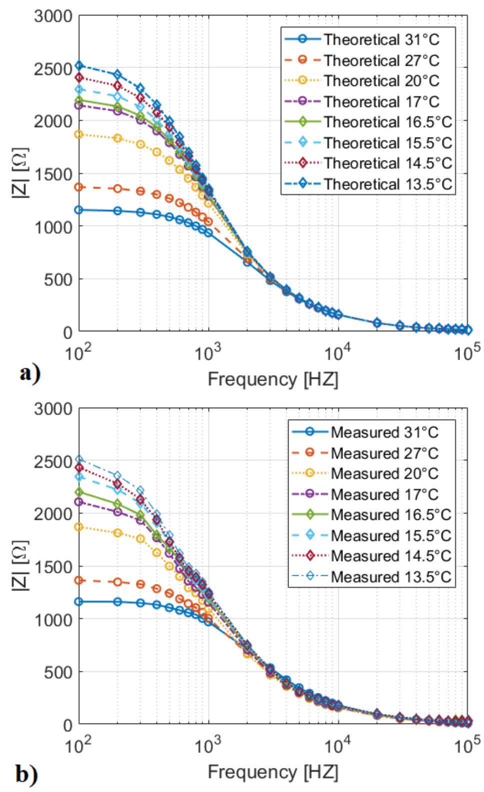

Fig. 7. Amplitude Bode plots of the impedance of a MF11-152 NTC thermistor with a capacitor in parallel. a) Calculated, b) measured.

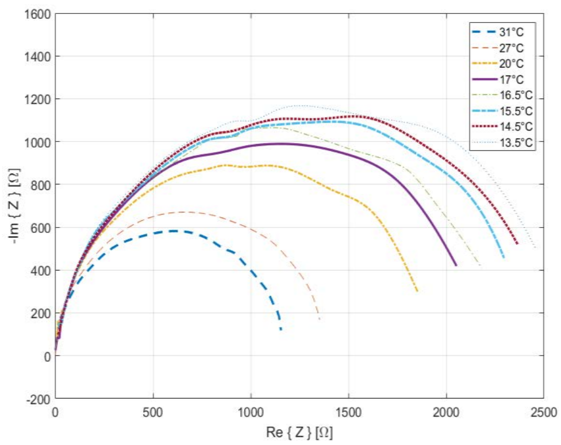

Fig. 8. Nyquist plots of the circuit of a thermistor with a capacitor in parallel at different temperatures, measured while the temperature varies with the time.

III. CONCLUSIONS

The FFT electrical impedance spectroscope built for this work has shown favorable characteristics for the measurement of both stationary and dynamic systems. The spectroscope has been built with commercial off-the-shelf, low-cost devices and can be integrated by modular equipment of different brands (only minimum requirements for reading and processing the measured signal must be met).

The main feature of the spectroscope developed in this work is that it allows impedance measurements by probing several frequencies at the same time in a short period compared to the time taken by a conventional spectroscope, which probes with one frequency at a time. It probed with 46 frequencies in 600 ms, representing a real option to measure impedance spectra in real-time.

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