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Impedance Measuring System based on a dsPIC

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Abstract **-** This paper describes a device based on a dsPIC (Digital Signal Peripheral Interface Controller) as a processing unit, capable of making impedance measurements at multiple frequencies. A DDS (Direct Digital Synthesizer) stimulates the measurement circuit composed by the reference impedance and the unknown impedance. The voltages across the impedances are amplified by programmable gain instrumentation amplifiers and then digitized by analog to digital converters. To measure the impedance, a seven-parameter sine-fitting algorithm is used to estimate the sine signals parameters. The dsPIC is connected through RS-232 or USB to a computer where the user can view the measurement results. The device also contains an LCD.

Keywords**:** Impedance measurement, dsPIC, ADC, Sine-fitting.

I. Introduction

Typical measuring techniques/instruments are either too costly, or don't have enough accuracy and have a reduced frequency range. Agilent Technologies is one of the reference companies for impedance measurement systems. Its flagship impedance measuring system [1] covers frequencies from 40 Hz up to 110 MHz with a basic accuracy of 0.08 %. However, its price of nearly 30.000€ makes the system well beyond the budget capabilities of many companies and research institutes.
Therefore there has been an increasing demand for low-cost impedance measuring systems capable of performing measurements at a broad range of frequencies but still with comparable accuracy to that of sophisticated impedance measurement equipment.
This work describes a developed low-cost device capable of measuring impedances at a wide range of frequencies by using ADCs (Analog to Digital Converters) and a dsPIC (Digital Signal Peripheral Interface Controller) as a central processing unit to both control all the necessary hardware of the measuring circuit and implement the sine fitting algorithm necessary to the proper measurement of the impedance. A personal computer is also used, which acts as an interface between the user and the device, allowing the user to choose the measurement frequency and to monitor the acquired samples.
The device is able to measure impedances in the amplitude range from 100 Ω to 10 kΩ at frequencies between 500 Hz and 200 kHz.

II. System's Architecture

A. Measurement Circuit and Method

Several impedance measurement methods exist. Traditional methods include: bridge, resonant, I-V or volt-ampere, RF I-V, network analysis and auto balancing bridge [2].
The measurement method used in this work is based in the volt-ampere method [2] and it is similar to that in [3], but in this case a dsPIC is used as a processing unit and a DDS (Direct Digital Synthesizer) is used to inject current in the circuit.
The impedance measurement circuit used to estimate the unknown impedance is presented in Figure 1.
The measurement procedure is done according to the following steps:

(i) The dsPIC controls the DDS in order to generate a sine wave with the user-defined impedance measurement frequency.
(ii) The dsPIC selects the proper reference impedance and the gains of the programmable gain instrumentation amplifiers (PGIAs) according to the magnitudes of the signals across the reference impedance and the impedance under measurement.

(iii) The dsPIC controls the ADCs to acquire simultaneously the samples (in this case 1024 per channel) of the output voltage of the PGIAs, which amplify the signals across the reference impedance (PGIA 1) and the unknown impedance (PGIA 2). The gains of both amplifiers are set by the dsPIC to maximize the amplitudes of the signals, but with care to avoid saturation of the digitizing channels.

(iv) A seven parameter sine-fitting algorithm is applied in order to determine the amplitudes $|U_x|$ and phases ϕ_{U_x} of the sine waves that best fit the acquired samples of both channels ($x = Z, R$).

(v) The amplitude and phase angle of the impedance under measurement are calculated by

$$|Z| = |Z_R| \times \frac{|U_Z|}{|U_R|} \tag{1}$$

$$\phi_Z = \phi_{Z_R} + (\phi_{U_Z} - \phi_{U_R}) \tag{2}$$

Once all the calculations are done, the experimental results of the measurement are transmitted to the computer using an RS-232 or USB connection, and displayed on the LCD.

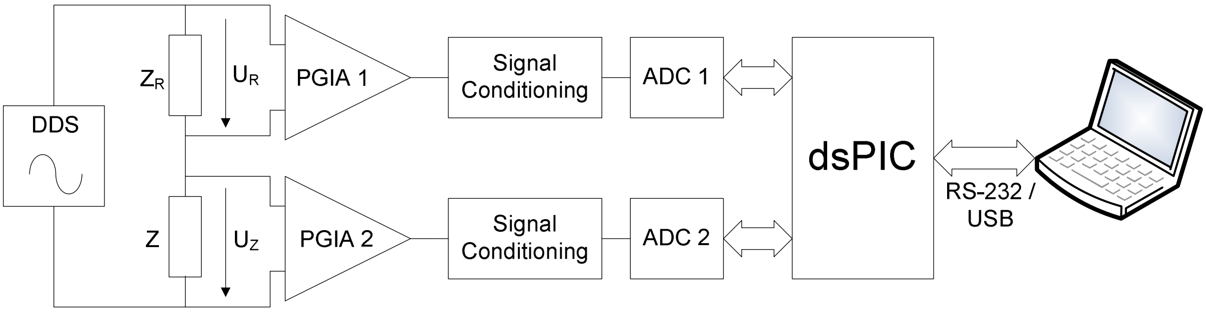

Figure 1. Measurement circuit. Z is the impedance under measurement and Z_R is the reference impedance.

B. Devices Used in the Circuit

The processing unit used is a 16-bit dsPIC33FJ256GP710 microcontroller from Microchip [4]. It has a throughput up to 40 MIPS, 256 kB of flash program memory and 30 kB of RAM (Random Access Memory).

To maximize the use of the ADC dynamic range, different reference impedances are used. The reference impedance is selected from a fixed set of six resistors using six relays controlled by the dsPIC. The relays used are the A5W-K from Takamisawa which have two poles and a nominal voltage of 5 V. The nominal values of the resistors are: 100 Ω, 200 Ω, 500 Ω, 1000 Ω, 2000 Ω and 5000 Ω. These resistors have a tolerance of ±5% and they were measured with a 3522-50 LCR HiTESTER from HIOKI to obtain their values with 0.08% accuracy.

In this work, the AD8250 PGIA from Analog Devices was used. It allows four programmable gains: 1, 2, 5 and 10. The gain is digitally set by the dsPIC in order to maximize the voltages at the ADCs inputs, while avoiding saturation of the digitizing channels. This is done in order to obtain a better resolution of the acquired signals.

The ADCs used were the AD7980 from Analog Devices. The AD7980 is a successive approximation converter (SAR) with a 16-bit resolution and conversion speeds up to 1 MS/s.

Although the ADCs can operate at 1 MS/s, due to limitations of the SPI (Serial Peripheral Interface) module of the dsPIC, which is used to control the ADCs, they can only operate up to 178 kS/s. This is because the SPI module can operate at a maximum frequency of 10 MHz, but it would have to operate at 32 MHz to read the samples of both ADCs (32 bits).

The DDS module used to stimulate the measurement circuit is the AD9833 from Analog Devices with a 28-bit resolution, which produces the sine signal with the desired measurement frequency. The DDS module is controlled by the dsPIC using the SPI protocol. An example of the DDS output sine signal with a frequency of 1 kHz and the correspondent FFT (Fast Fourier Transform) is presented in Figure 2.

The signal was measured with an Agilent 54622D Mixed Signal Oscilloscope from Agilent Technologies. Two million samples were acquired and transferred to a computer where they were processed in the MATLAB environment to obtain the sine signal and its correspondent FFT. The Total Harmonic Distortion (THD) of the signal was also estimated: 51 dB.

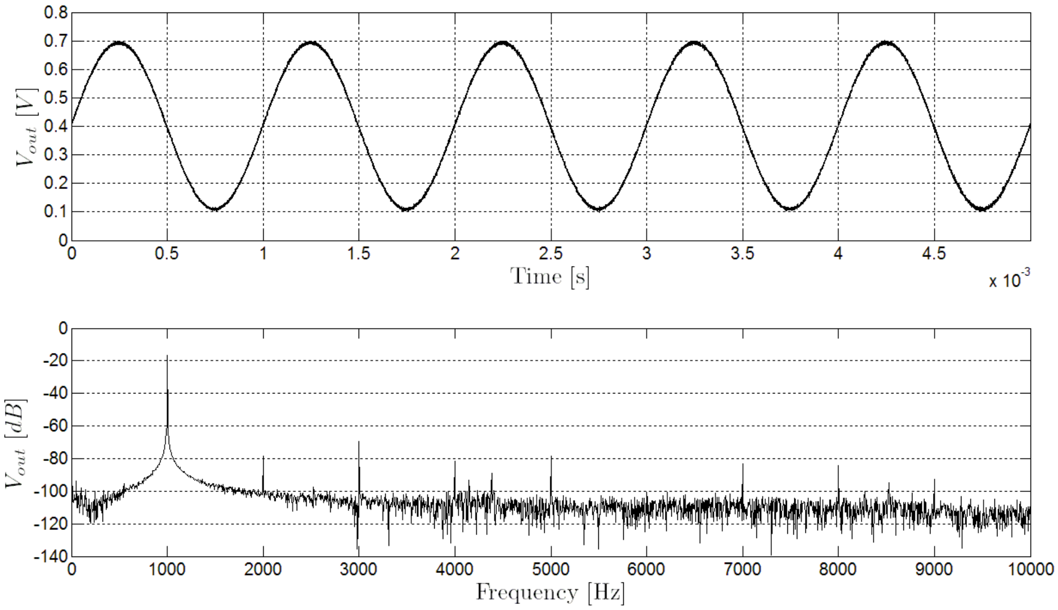

Figure 2. Output signal and corresponding FFT from the DDS at 1 kHz.

III. Algorithms

A. Selection of Sampling Frequency

The range of the measurement frequencies used in this work goes from 500 Hz to 200 kHz. Since the maximum sampling frequency (F_{Smax}) is 178 kS/s, two cases must be considered for the acquisition of the signals: the case with no under sampling and the case with under sampling.
In the case with no under sampling, the sampling frequency is chosen in a way that allows the acquisition of at least eight periods of the signals.
In the case with under sampling the sampling frequency is chosen according to

$$m_{real} = \left\lfloor \frac{f}{F_{S\max}/2} \right\rfloor \tag{3}$$

$$m_{ideal} = m_{real} + 0,5 \tag{4}$$

$$F_S = \frac{2 \times f}{m_{ideal}} \tag{5}$$

where f is the measurement frequency, F_S is the selected sampling frequency, m_{real} is the number of full folds of the signal spectrum and m_{ideal} is the desired number of folds of the signal spectrum. The m_{ideal} value is chosen in a way that the acquired signal's frequency (apparent) will be at the middle of the spectrum, which corresponds to the best case.

B. Three-Parameter Sine-Fitting

The three-parameter sine-fitting algorithm is a non-iterative algorithm that, with the knowledge of the frequency, estimates the amplitude, the phase and the DC component of the acquired sine signal [5].
The acquired sine signals can be represented by

$$u(t) = D\cos(2\pi ft + \phi) + C \iff u(t) = A\cos(2\pi ft) + B\sin(2\pi ft) + C \tag{6}$$

with

$$D = \sqrt{A^2 + B^2}\ ,\ \ \phi = \operatorname{atan2}(B, A) \tag{7}$$

where D is the amplitude, ϕ is the phase and C is the DC component of the signal.
The estimated parameter vector is

$$\hat{\boldsymbol{x}} = [A \quad B \quad C]^T = \boldsymbol{M}^\dagger \boldsymbol{y} \tag{8}$$

where $\boldsymbol{y}$ is the sample vector

$$\boldsymbol{y} = [u_1 \quad u_2 \quad \dots \quad u_N]^T \tag{9}$$

and

$$\boldsymbol{M} = \begin{bmatrix} \cos(2\pi f t_1) & \sin(2\pi f t_1) & 1 \\ \vdots & \vdots & \vdots \\ \cos(2\pi f t_N) & \sin(2\pi f t_N) & 1 \end{bmatrix} \tag{10}$$

N is the number of samples acquired, and $\boldsymbol{M}^\dagger$ is the pseudo inverse matrix of $\boldsymbol{M}$.
The frequency used in the three-parameter algorithm was estimated using the FFT and the IpDFT (Interpolated Discrete Fourier Transform) algorithms [6].

C. Selection of Reference Impedance and PGIAs Gains

The algorithm selects the reference impedance that best matches the amplitude of the impedance under measurement. To do so, an initial acquisition is performed to estimate the amplitude of the unknown impedance by resorting to the three-parameter sine-fitting algorithm.
This algorithm also digitally controls the gains of the PGIAs. Given the amplitude of the signals, obtained with the three-parameter sine-fitting algorithm, the algorithm determines whether it is possible or not to increase the gains of the amplifiers and if so how much.

D. Seven-Parameter Sine-Fitting

The seven-parameter sine-fitting algorithm is an iterative algorithm which uses the acquired data from two channels with the same frequency to estimate the amplitude, phase and DC component of both signals, plus their common frequency [7].
Just like in the case of the three-parameter algorithm, the sine signals of each channel can be represented by (6) considering the relations in (7). Since the initial estimates of the parameters are crucial for the algorithm to converge, these values were obtained through the three-parameter sine-fitting.
The iterative process of the algorithm ends when the relative frequency adjustment $\Delta f^{(i)} / f^{(i)}$ is below a preset threshold, which is set to 5×10^{-7} in the case of this work. $\Delta f^{(i)}$ is the frequency correction that updates the estimated common frequency.
With the estimated sine signal parameters of this algorithm it is possible to determine the unknown impedance using (1) and (2).

IV. System's control software

The system's control software acts as an interface between the user and the device. This software allows the user to choose the frequency at which to perform the measurement of the unknown impedance, and to view and interpret the acquired samples of the measurements done. The user can also decide whether he wants to save the data of the measurements done for further analysis.
The software was developed in the LabVIEW environment, which has simple and intuitive programming tools.

V. Experimental results

Seven impedances with different amplitudes in the range from 100 Ω to 10 kΩ, and phases in the range from -90º to 90º were tested at 1 kHz and the results are compared to those obtained with the 3522-50 LCR HiTESTER from HIOKI. The measurement results are presented in Table 1.
As shown in Table 1, the experimental results obtained with the implemented system are quite close to those obtained with the HIOKI, demonstrating that it is possible to implement a low-cost impedance measurement device with comparable accuracy of that of sophisticated impedance measurement equipment.

Table 1. Measurement results obtained with the HIOKI and the implemented system.

Impedance		C	L	Series RC	Series RL	R	R	R
HIOKI	$\lvert Z \rvert$ (Ω)	4979.4	105.9	6527.7	184.61	1782.6	8957.1	9866.8
	ϕ_Z (°)	-89.74	69.18	-31.08	32.07	0	0	0
Implemented System	$\lvert Z \rvert$ (Ω)	4989.23	105.39	6546.40	183.95	1790.8	9005.64	9923.33
	ϕ_Z (°)	-89.72	68.95	-31.13	31.83	0.0012	-0.056	-0.027

A resistor with the nominal value of 7.5 kΩ was tested at 1 kHz. Five hundred measurements were taken in order to obtain the histograms of the measurement frequency, impedance amplitude and impedance phase (Figure 3). The impedance amplitude presents a mean of 7455.68 Ω, a standard deviation of 1.29 Ω and a relative standard deviation of 0.017 %. The impedance phase presents a mean of -0.0399 ° and a standard deviation of 0.0999 °. The measurement frequency presents a mean of 1000.03005 Hz, a standard deviation of 0.00664 Hz and a relative standard deviation of 0.00069 %.
The implemented impedance measurement system is presented in Figure 4.

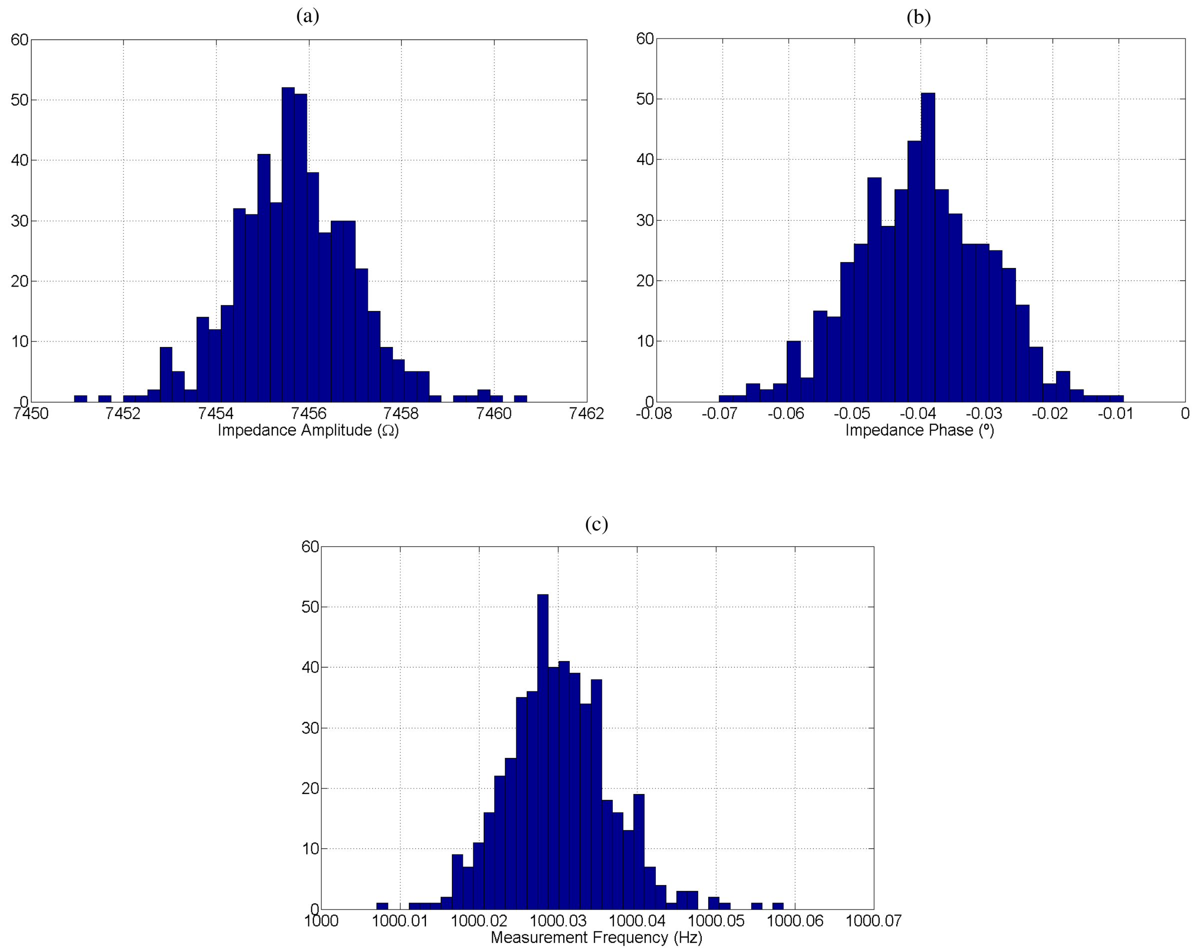

Figure 3. Histograms for a 7.5 kΩ resistor: (a) impedance amplitude; (b) impedance phase; (c) measurement frequency.

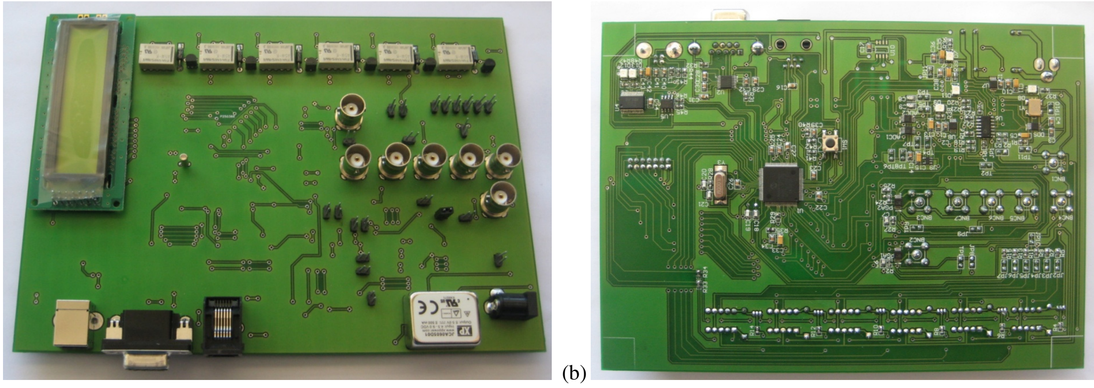
(a) (b)

Figure 4. Implemented impedance measurement system: (a) top view; (b) bottom view.

VI. Conclusions

The implemented system in this work is a low-cost device operating in a wide frequency range, 500 Hz to 200 kHz, and is capable of measuring impedances in the amplitude range from 100 Ω to 10 kΩ.
To operate in this frequency range it was necessary to apply under sampling techniques because of the constraints imposed by the dsPIC ADC communications that limit the maximum sampling frequency.
The system facilitates the interaction with its user, since it is possible to connect it to a computer, through a RS-232 or USB connection, allowing him to monitor the device and save the results of the measurements.
The experimental results obtained were compared with a commercially available device, the 3522-50 LCR HiTESTER from HIOKI. Given the experimental results presented, it was demonstrated that it is possible to implement a low-cost device operating at a wide frequency range, but still with measurement accuracy comparable to that of sophisticated impedance measurement systems. This is possible because of the great processing capability of the processing unit used, the dsPIC, combined with the signal processing techniques applied: the three-parameter sine-fitting algorithm and the seven-parameter sine-fitting algorithm.

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References

[1] Agilent 4294A Precision Impedance Analyzer, Data Sheet, available at www.agilent.com April 2008.
[2] *The Impedance Measurement Handbook – A Guide to Measurement Technologies and Techniques*, Agilent Technologies Co., 2000.
[3] Pedro M. Ramos, Fernando M. Janeiro, Mouhaydine Tlemçani and A. Cruz Serra, “Recent Developments on Impedance Measurements With DSP-Based Ellipse-Fitting Algorithms”, *IEEE Transactions on Instrumentation and Measurement*, vol. 58, no. 5, pp. 1680-1689, May 2009.
[4] Microchip dsPIC33FJXXXGPX06/X08/X10, Data Sheet, available at www.microchip.com October 2009.
[5] *IEEE Std. 1057-1994, Standard for Digitizing Waveform Records*, The Institute of Electrical and Electronics Engineers, New York, December 1994.
[6] H. Renders, J. Schoukens and G. Vilain, “High-accuracy spectrum analysis of sampled discrete frequency signals by analytical leakage compensation”, *IEEE Transactions on Instrumentation and Measurement*, vol. 33, pp. 287-292, Dec. 1984.
[7] Pedro M. Ramos, A. Cruz Serra, “A new sine-fitting algorithm for accurate amplitude and phase measurements in two channel acquisition systems”, *Measurement*, Elsevier, vol. 41, no. 2, pp. 135-143, February 2008.