Complex Impedance Measurement System for Environmental Sensors Characterization

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Abstract — **In this paper description of complex impedance measurement system for environmental sensors characterization is described. Device can be used as standalone device but it also can be connected to the PC through serial communication. Color display is used for local graphical presentation of measured values while for online PC analysis specialized application was developed. System verification was done in frequency range from 5 to 100 kHz for impedance range from 100 Ω to 100 kΩ. Verification of impedance magnitude and phase angle measurement results as done as proof that developed system can be used for characterization of sensors for air, soil and water pollution monitoring developed within SENSEIVER project.**

Keywords — **complex impedance measurement, material characterization, environmental sensors.**

I. Introduction

ENVIRONMENTAL monitoring is one of the most important sensor network application domains [1]. Sensor networks for air, water and soil quality monitoring have to collect data for chemical, biological and microbiological parameters. Various types of sensor principles can be used but most common characterization method is complex impedance measurement.

One realization of complex impedance measurement system based on integrated circuit AD5933 is described in [2]. In that system AD5933 was controlled by microcontroller ATmega128 and it was equipped with self-calibration system which ensured error lower than 5% in frequency range from 10 to 20 kHz. Created report of measured values of impedance magnitude and phase angle was stored on micro SD card in format which is compatible with MS Excel for off-line analysis on PC. Device also had alphanumeric LCD for displaying results.

All good features of system described in [2] were kept for implementation in new design presented in [3]. That system was also based on AD5933 and ATmega128 microcontroller but more resistors were placed in calibration and feedback resistor networks so higher accuracy was achieved. System was verified with various RC networks measurements; magnitude and phase angle measured values were compared with theoretical in wide frequency range (5 to 100 kHz) with system error lower than 2%.

Further upgrade of systems described in [2, 3] is presented in [4] where system was tested as RLC meter. Obtained results were verified with commercial impedance analyzer HP4194A. Developed device also performed calculation of additional parameters such as dissipation and quality factor which are very important in impedance spectroscopy.

Main contribution of work presented in this paper is making possible measurements under 1 kΩ with acceptable accuracy as well as adding color display for local online analysis of measured values and PC application developed in Microsoft Visual Studio. This system configuration eliminates need for offline processing and makes measurement procedure more comfort and user-friendly.

II. Device structure

Proposed structure of redesigned system for complex impedance measurement and material characterization is presented in Fig. 1. Main hardware improvement is replacement of LCD display that was used before [2]-[4] with TFT color display which allows realization of portable handheld device with online graphical analysis of obtained results. New system also can be USB powered and has smaller dimensions.

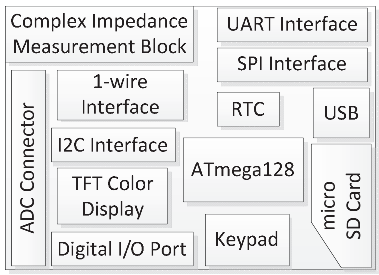

Fig. 1 Block-scheme of proposed device

Developed system has a lot of peripherals useful for many applications (UART, SPI, I2C, 1-wire, 8 ADC channels, 8 digital Input/Output interfaces are available) but “Complex Impedance Measurement Block” is the most important part for environmental sensors characterization. The main part of this block is the AD5933. Design details of measurement board are based on [5] where analog front end (AFE) for AD5933 is described. AFE has two main benefits: to reduce the output impedance of the signal source and to rebias the excitation voltage signal [3]. All used components are SMD type which ensured low dimensions of complete board. Small dimension of board

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made shorter path for AC signal and decreased level of noise. The block has 7 calibration and 8 feedback 0.1% tolerance resistors connected with two analog switches ADG706. Values for calibration/feedback resistors were chosen to accomplish aim which is impedance range from 100 Ω to 100 kΩ. Electric schematic of complex impedance measurement block is shown in Fig. 2.

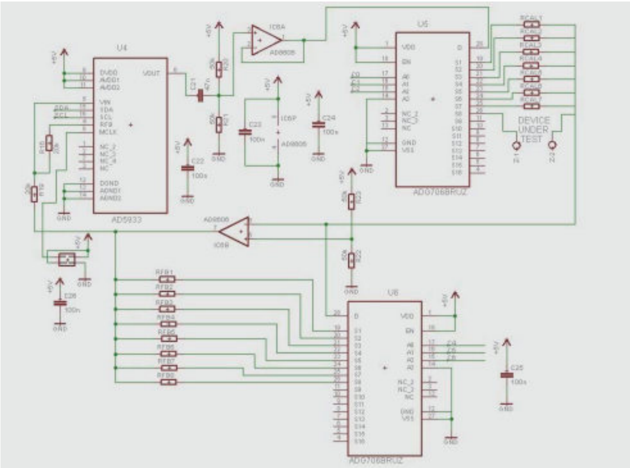


Fig. 2 Electric schematic of complex impedance measurement block

A hardware outcome of Control board with connected sample under test is presented in the Fig. 3.

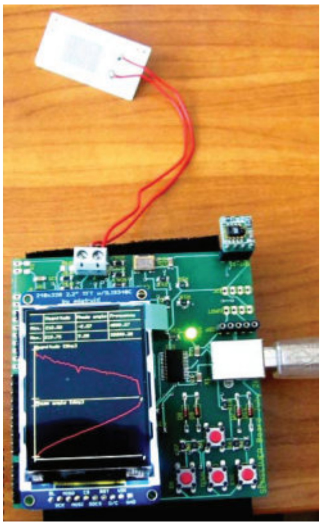


Fig. 3 A hardware outcome of Control board with connected sample under test

Main purpose of developed system presented in the Fig. 2 and 3 is to be used as portable standalone device for complex impedance measurement and material characterization in the field. But USB power supply option also can be used to provide real time connection of the board with PC and more detailed analysis of obtained results. That was accomplished with PC application developed in Microsoft Visual Studio 2013 that provides a user-friendly interface to capture and display the obtained data received from the board though the serial port. The application's main feature is a graphical plot of the received data and the ability to export the data to a CSV (comma separated value) file. The graphical area allows overseeing the data after the measurement process is completed. The option of exporting the data collected to a file allows processing the data with third party tools. In Fig. 4 main screen of PC application for complex impedance measurement is presented.

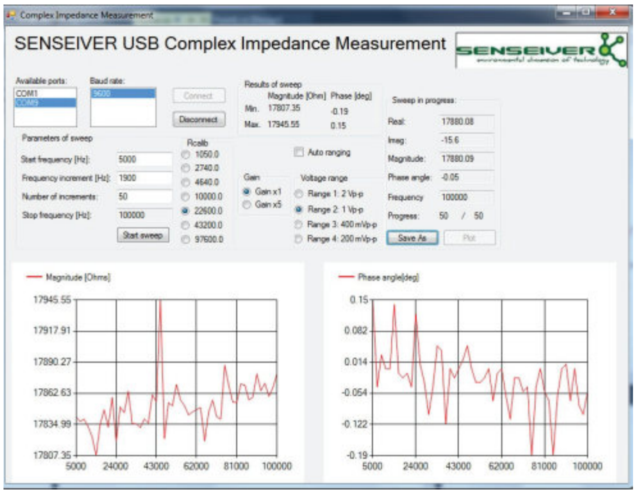


Fig. 4 Main screen of the PC application

As may be seen from Fig. 4, main blocks of developed PC application are:

- Communication
- Parameters of sweep
- Auto ranging
- Results of sweep
- Graphs
- Export results to file

Communication. User can choose communication PC port which is connected with the Control board. Baud rate is fixed and can not be changed because it was set to 9600 bps in the microcontroller program.

Parameters of sweep. After the Control board is connected with PC, user has to define parameters of sweep. Start frequency, frequency increment and number of increments are parameters required for stop frequency calculation. Each field has implemented input value check so invalid configuration is not possible.

Auto ranging. Before starting of sweep user has to select mode of operation: manual or auto ranging. In auto ranging mode, which is default, device executes algorithm for estimation of unknown impedance value. In manual mode, user can select value for calibration resistor as well as magnitude of output voltage. Depending of magnitude of voltage across the unknown impedance, internal gain can be increased to 5 (default 1). This can be done only when it will not cause saturation of internal AD converter of AD5933. In some application as characterization of environmental sensors is, limitation of output voltage magnitude is very important because sample under test can has very small resistivity so maximum current through sensing material has to be limited in aim to avoid possible electrochemical reactions in materials.

In wide impedance range it was very hard to develop algorithm for high accuracy with relatively small number of calibration/feedback resistors so it is strongly recommended that after auto ranging more accurate measurement established with manual settings be performed.

Results of sweep. After sweep operation is completed, user can see minimum and maximum measured values for impedance magnitude and phase angle of device under test.

Graphs. After sweep operation is completed, user can plot measured values for magnitude and phase angle of device under test. Frequency values are shown on x-axis. Example of generated graphs is shown in Fig. 5.

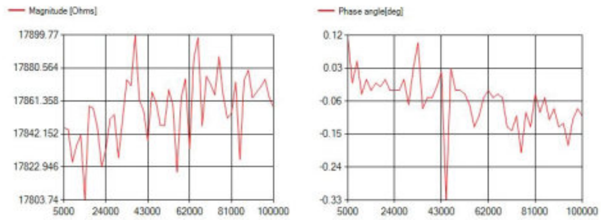
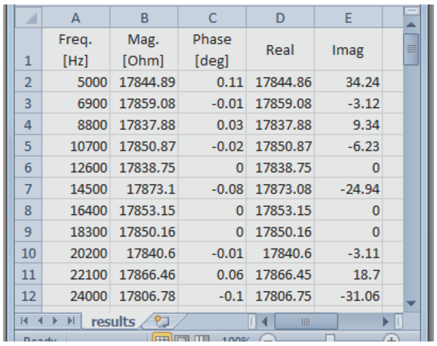


Fig. 5 Example of generated plots

Logging to file. Even the Control board performs local storing of measurement results on the micro SD card, as noted before, option for logging on PC hard drive is implemented. Example of created report is presented in the Fig. 6.



	A	B	C	D	E
1	Freq. [Hz]	Mag. [Ohm]	Phase [deg]	Real	Imag
2	5000	17844.89	0.11	17844.86	34.24
3	6900	17859.08	-0.01	17859.08	-3.12
4	8800	17837.88	0.03	17837.88	9.34
5	10700	17850.87	-0.02	17850.87	-6.23
6	12600	17838.75	0	17838.75	0
7	14500	17873.1	-0.08	17873.08	-24.94
8	16400	17853.15	0	17853.15	0
9	18300	17850.16	0	17850.16	0
10	20200	17840.6	-0.01	17840.6	-3.11
11	22100	17866.46	0.06	17866.45	18.7
12	24000	17806.78	-0.1	17806.75	-31.06

Fig. 6 Example of created report

A hardware outcome of complete system is shown in Fig. 7.

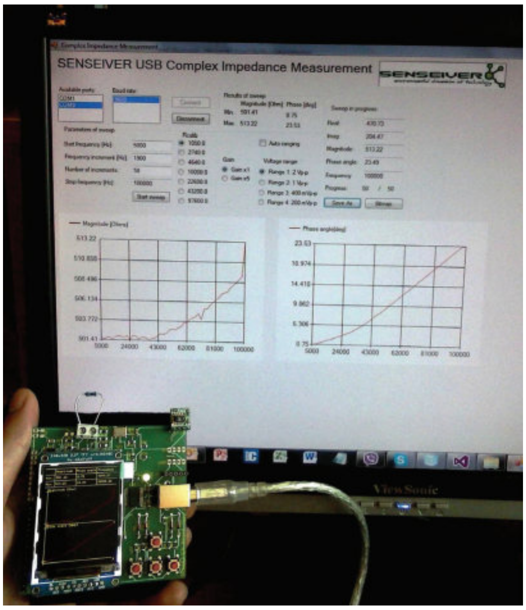


Fig. 7 Hardware outcome of device for complex impedance measurement

III. Experimental verification

Verification of proposed system was done with large number of measurements with resistors and capacitors as device under test. Obtained results for resistors in range (100 Ω to 100 kΩ) are given in Table 1. Verification tool was digital multimeter PC5000a from Sanwa.

Table 1: Obtained results for measurements with resistors.

R_actual [Ohm]	R_measured [Ohm]		θ_measured [°]		delta_R [Ohm]	delta_θ [°]	delta_R [%]
	Min	Max	Min	Max			
100	105.02	107.98	0.53	9.88	2.96	9.35	2.96
366.22	367.54	369.75	0.07	1.48	2.21	1.41	0.6034624
985.1	984.63	986.93	-0.05	0.09	2.3	0.14	0.2334788
2387.7	2383.13	2390.49	0	0.09	7.36	0.09	0.3082464
4650	4644.75	4661.03	0	-0.33	16.28	-0.33	0.3501075
8202	8193.7	8219.57	-0.01	0.14	25.87	0.15	0.3154109
12923	12886.33	12946.95	-0.08	-1.45	60.62	-1.37	0.4690861
17840	17813.38	17895.53	-0.11	0.06	82.15	0.17	0.4604821
26597	26398.59	26614.33	-2.67	-0.16	215.74	2.51	0.8111441
38764	38750.26	38892.71	-0.74	0.01	142.45	0.75	0.3674801
46950	46393.14	46980.78	-3.06	-0.18	587.64	2.88	1.2516294
100000	94754.32	99947.33	-5.84	-0.35	5193.01	5.49	5.19301

As may be seen from Table 1. the biggest errors have been generated at the borders of proposed impedance range (100 Ω and 100 kΩ). In the Fig. 8 impedance magnitude changes for 100 kΩ resistor are shown and it is obviously that in low frequency range (lower than 60 kHz) error is lower than 2 % but after it is increasing. This can be due the noise in high frequency band and/or appeared nonlinearity in amplifier loop.

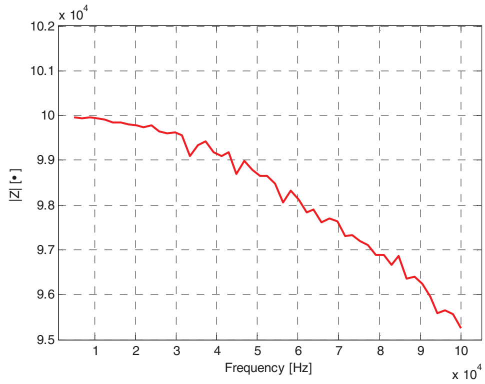


Fig. 8 Plot of measured impedance magnitude values for resistor 100 kΩ

Auto-ranging function was also tested with 1 nF capacitor. Verification tool was Impedance/Gain-Phase Analyzer 4194A from Hewlett Packard. Comparison of obtained results for impedance magnitude and phase angle are presented in Fig. 9 and Fig. 10, respectively.

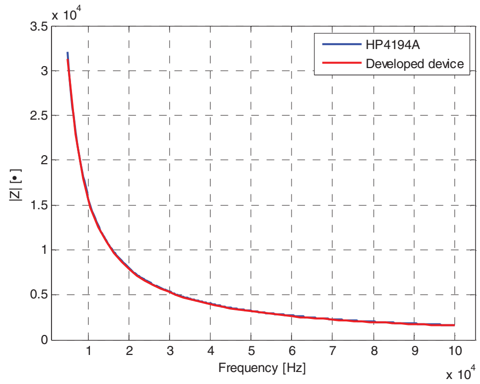


Fig. 9 Plot of measured impedance magnitude values

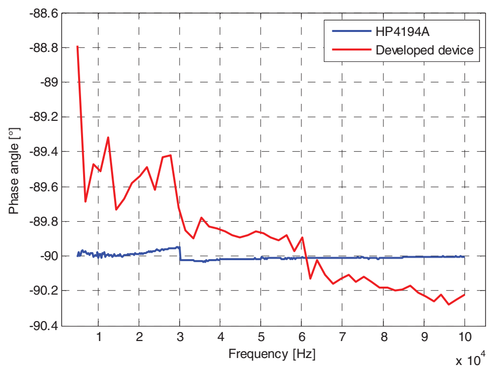


Fig. 10 Plot of measured impedance phase angle values

Based on theoretical calculations (Eq. 1 and 2) for impedance magnitude and phase angle of capacitor with capacitance C:

$$|Z|_{\text{theoretical}} = \frac{1}{\omega C} \; [\Omega], \; \omega = 2\pi f \quad (1)$$

$$\theta_{\text{theoretical}} = -\pi/2 \; rad \quad (2)$$

relative errors can be estimated as well. This values can be easily calculated with equations 3 and 4:

$$|Z|_{error} = 100 \cdot \left(|Z|_{measured} - |Z|_{\text{theoretical}} \right) / |Z|_{\text{theoretical}} \; [\%]$$

$$\theta_{error} = 100 \cdot \left(\theta_{measured} - \theta_{\text{theoretical}} \right) / \theta_{\text{theoretical}} \; [\%]. \; (3, 4)$$

In this equations, $|Z|_{\text{measured}}$ and θ_{measured} present values obtained with developed complex impedance measurement system. Curves presented in Fig. 11 and Fig. 12 are estimated errors for impedance magnitude and phase angle measurements for 1 nF capacitor.

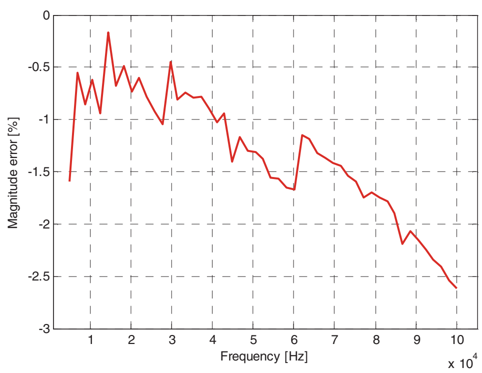


Fig. 11 Plot of impedance magnitude measurement error

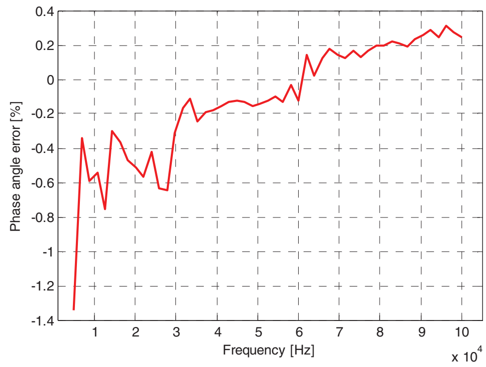


Fig. 12 Plot of impedance phase angle measurement error

As may be seen from Fig. 11 and 12, the maximum obtained error for impedance magnitude is -2.5 % while for phase angle is -1.4 %.

IV. Conclusion

The main task in this study was to provide online analysis tool for environmental sensors characterization by complex impedance measurement method. System presents complete solution from measurement to presentation of final results.

Device can be used as standalone or with PC connection. In both modes of operation, user has information about current step in sweep and obtained values. After sweep is completed, local presentation of results is performed on color display with graphs of impedance magnitude and phase angle values and tabulated information about minimum and maximum measured values. If device is connected to the PC, more detailed analysis is possible with PC application.

Possible further upgrades such as measurement of low impedance (<100 Ω) in low frequency range (< 1kHz) are marked as very important because some sensors with very low impedance should be characterized in low frequency band.

Main application of developed system is to be used for characterization of environmental sensors developed within SENSEIVER project

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