

# LOW COST IMPEDANCE ANALYSER FOR DIAGNOSTICS OF NON-ELECTRICAL OBJECTS

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**Abstract** – *The paper presents an impedance analyser designed for impedance spectroscopy of non-electrical objects described by multi-element electrical circuits. The analyser measures a modulus and a phase or a real and a imaginary part of impedance in a wide frequency range 100μHz-100kHz. The special feature of the analyser is ability of measuring very high impedance ( $|Z_x| \leq 10G\Omega$ ). The method based on discrete Fourier transformation has been used to determine the orthogonal components of measuring signals. The analyser has been built as virtual instrument using DSP processor. This assures high flexibility and low price, because adaptation of the analyser to selected object requires only modification of PC software.*

**Keywords** - impedance measurement, technical diagnostic, virtual instrument.

## 1. INTRODUCTION

There are many technical objects, which can be modelled by electrical equivalent circuit. To this group one can include, described by multi-element two-terminal networks, biomedical objects (like skin, biological liquids), physico-chemical objects (e.g. electrolytes, anti-corrosion coatings), electromechanical objects (like electrical motors). Such kind objects diagnosis requires multi-frequency impedance measurements known as impedance spectroscopy. The main objective of the coating measurements is analysis of very high impedance (of an order of  $G\Omega$ ) in a wide frequency range ( $10^{-5}$ – $10^6$ Hz) assuming the measuring signal amplitude on level of 10mV-100mV due to nonlinearity of the object under test. Nowadays, main disadvantages of the currently in use impedance spectroscopy instrumentation are a high complexity of the equipment to be used, as a rule, for laboratory experiments and a high price (Solartron impedance analyser 1260 and high impedance interface 1294 costs ca. 25.000£ [1]).

In view of the presented facts the authors on the base of previous experiences [2, 3] and new literature concepts [4 - 6] have developed a new field-worthy low-cost analyser for measuring impedance parameters of two terminal networks described above (e.g. intended for continuous monitoring of the very high impedance anti-corrosion protection performance).

## 2. THE CONSTRUCTION OF THE ANALYSER

The presented measurement requirements (a high impedance  $|Z_x| \leq 10G\Omega$ , a wide frequency range 100μHz-100kHz) extort use of following solutions:

- ◆ Input circuitry allowing to measure impedance in range of  $100\Omega \leq |Z_x| \leq 10G\Omega$  with simultaneous elimination of parasitic capacitance of cables connecting object under test  $Z_x$  and input capacitance of operational amplifiers (5-wire connections: 2 current terminals, 2 voltage terminals and a guard terminal),
- ◆ Phase sensitive detector utilising discrete Fourier transformation (DFT), which allows to determine orthogonal parts (Re, Im) of measuring signals for very low frequencies (two A/D converters AD9225),
- ◆ DSP processor taking two main tasks: the preparing of measuring signal – a sine wave or a different shape evaluation and the calculating of DFT transformation of sampled signals  $u_U$  and  $u_I$  proportional to current and voltage on object under test extracted in input circuitry.
- ◆ Sinusoidal waveform measuring generator utilising direct digital synthesis (DDS) synchronised with sampling of voltages  $u_U$  and  $u_I$  (D/A converter AD9765),
- ◆ The form of virtual instrument allowing to identify parameters of multi-element two-terminal networks in PC on the base of algorithms developed individually for each kind of the object under test.

After pre-set delay time (in which transient state on the object under test is vanishing) acquisition of two sets of  $N$  samples of voltages  $u_U$  and  $u_I$  starts. It is synchronised with clock signal of a DDS generator with sampling frequency  $f_s$  and utilises two 12-bit A/D converters. As a result of this operation we obtain discrete representation of both voltages, according to (1), stored in two independent memory blocks (RAM0 and RAM1).

$$u_U^m = u_U(m \cdot \Delta t), \quad u_I^m = u_I(m \cdot \Delta t) \quad (1)$$

where:  $m = 0, 1, \dots, N - 1$ ,  $\Delta t = \frac{1}{f_s}$

Utilising DFT, on the base of collected samples, the representation of signals  $u_U$  and  $u_I$  in frequency domain  $U_U$

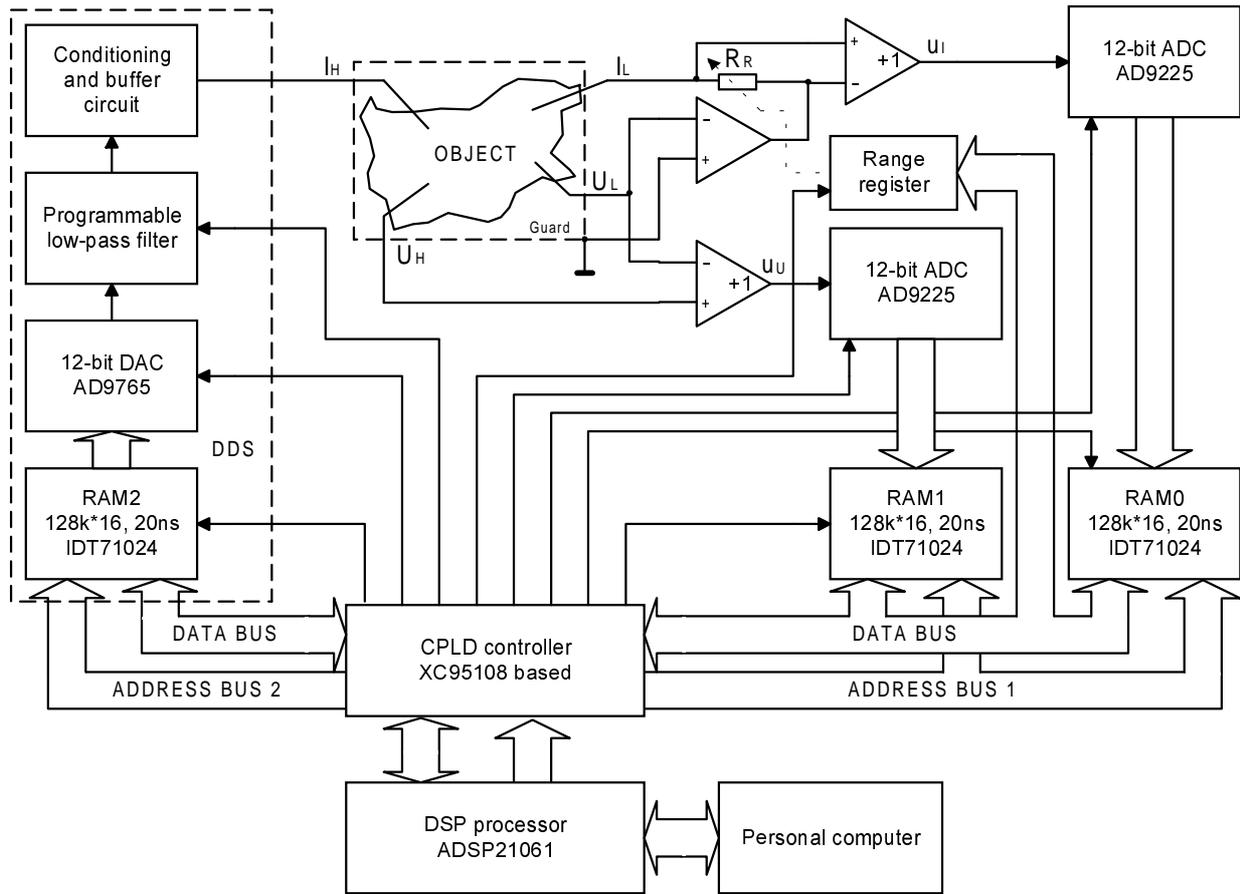


Fig.1 – Impedance analyser for diagnostics of non-electrical objects.

and  $U_I$  is evaluated, which  $k$  line  $U_U^k$  i  $U_I^k$  can be defined:

$$U_U^k = U_U(k \cdot \Delta f) = \sum_{m=0}^{N-1} u_U^m \cdot e^{-j \cdot \frac{2\pi \cdot m \cdot k}{N}}, \quad (2)$$

$$U_I^k = U_I(k \cdot \Delta f) = \sum_{m=0}^{N-1} u_I^m \cdot e^{-j \cdot \frac{2\pi \cdot m \cdot k}{N}},$$

$$\text{where: } k = 0, 1, \dots, L, \dots, N-1, \Delta f = \frac{f_s}{N} = \frac{1}{N \cdot \Delta t}.$$

The extracted in input circuitry voltages  $u_U$  and  $u_I$  are sinusoidal and  $N$  collected samples contain exactly  $L$  periods  $T_{I_H}$  of perturbing signal  $I_H$ , what can be written:

$$N \cdot \Delta t = L \cdot T_{I_H}. \quad (3)$$

Due to this fact obtained spectrum contains only one ( $L$ ) non-zero line. The analyser satisfies above condition because of utilised method of generation of perturbing signal. The clock signal of DDS generator (13.1072MHz, 1.31072MHz, 131.072kHz,...) was selected to be multiplication of constant number of samples (131072). This way, during generation and acquisition, the collected number of samples ( $N$ ) contains an integer number of periods ( $L$ ) of measuring signal.

Realised analyser uses classical DFT algorithm, because only one spectral line ( $L$ ) is evaluated and a sine-cosine table

resides in memory block RAM2 of DDS generator. Depending on this, the evaluation of real or imaginary part of both voltages brings to multiplication of appropriate sample set with cosine or sine sample set according to (4):

$$\begin{aligned} \text{Re}(U_U^L) &= \sum_{m=0}^{N-1} u_U^m \cdot \cos\left(\frac{2\pi \cdot m \cdot L}{N}\right), \\ \text{Im}(U_U^L) &= \sum_{m=0}^{N-1} u_U^m \cdot \sin\left(\frac{2\pi \cdot m \cdot L}{N}\right), \\ \text{Re}(U_I^L) &= \sum_{m=0}^{N-1} u_I^m \cdot \cos\left(\frac{2\pi \cdot m \cdot L}{N}\right), \\ \text{Im}(U_I^L) &= \sum_{m=0}^{N-1} u_I^m \cdot \sin\left(\frac{2\pi \cdot m \cdot L}{N}\right). \end{aligned} \quad (4)$$

The impedance modulus and phase can be calculated on the base of (5):

$$\begin{aligned} \phi &= \text{arctg} \frac{\text{Im}(U_U^L)}{\text{Re}(U_U^L)} - \text{arctg} \frac{\text{Im}(U_I^L)}{\text{Re}(U_I^L)}, \\ |Z_x| &= \frac{\sqrt{(\text{Re}(U_U^L))^2 + (\text{Im}(U_U^L))^2}}{\sqrt{(\text{Re}(U_I^L))^2 + (\text{Im}(U_I^L))^2}} \cdot R_R. \end{aligned} \quad (5)$$

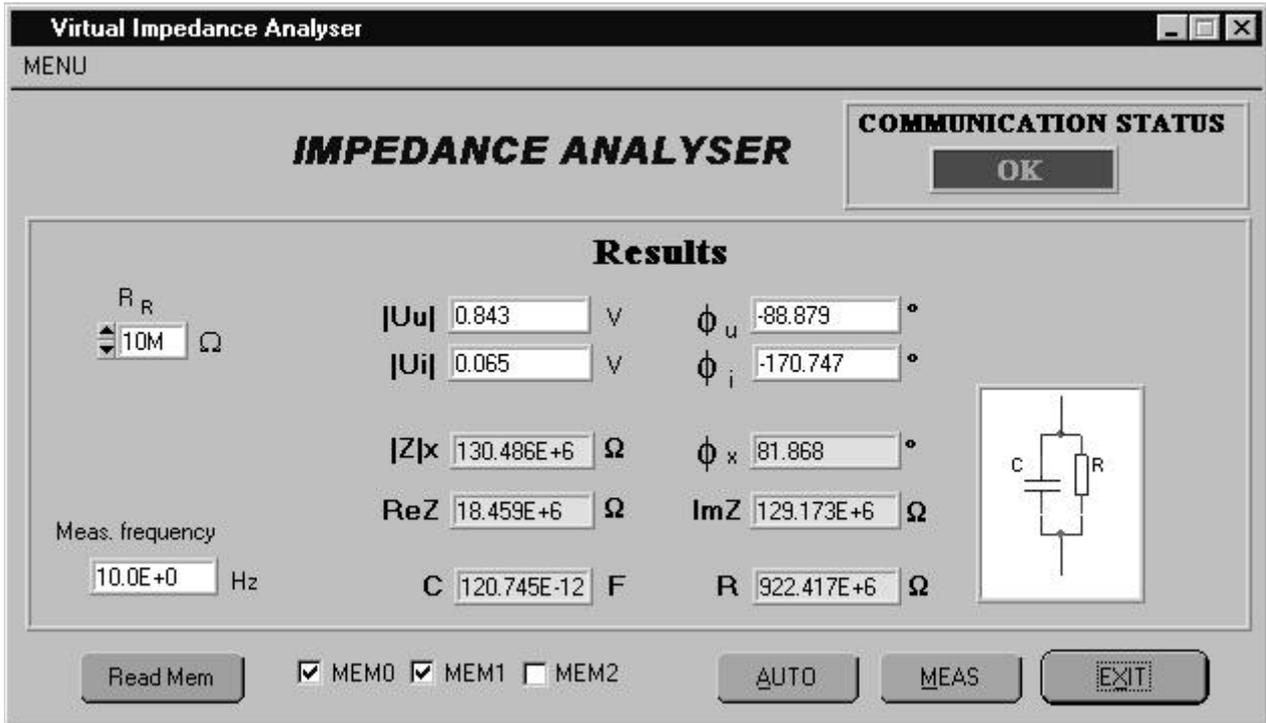


Fig.2 – Control panel for impedance analyser.

DSP processor makes the calculations after the end of each measurement cycle  $T_p$ . Duration of  $T_p$  depends on frequency range as shown in Table I.

Table I – DDS generator parameters.

$f_s$ [Hz]	$f_{meas}$ [Hz]	$T_p$	$\Delta f_{meas}$ [Hz]
13.1072M	100-100k	10ms	100
1.31072M	10-100	100ms	10
131.072k	1-10	1s	1
13.1072k	100m-1	10s	100m
1.31072k	10m-100m	100s	10m
131.072	1m-10m	$10^3$ s	1m
13.1072	$100\mu$ -1m	$10^4$ s	$100\mu$

### 3. TESTS OF REALISED ANALYSER

The analyser can be programmed via control panel created with LabWindows/CVI package (Fig. 2).

Measurements can be made in two modes: single measurements for selected measuring frequency (started with "MEAS" button) and performing of measurement series for specified frequency range (started with "AUTO" button). Selecting second mode opens new dialog window to allow setting a low and a high limit of frequency range and a frequency step.

It is possible to display the measurement results on a magnitude-phase impedance graph depending on frequency (Bode plot) or on a real-imaginary impedance graph with frequency as a parameter (Nyquist plot).

The control panel allows watching following signals: the perturbation (MEM2), the voltage response (MEM1) and the current response (MEM0) extracted in input circuitry (started with "READ MEM" button).

The measurements for two-terminal RC network has been performed in parallel equivalent circuit simulating the typical impedance of anti-corrosion coating ( $R=1G\Omega$ ,  $C=120pF$ ). The results of the measurement have been presented on Fig. 3 in a Bode plot.

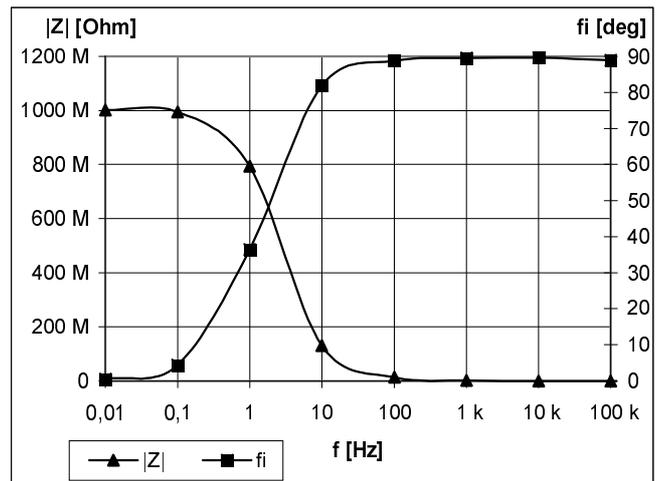


Fig.3 – Results of modulus-phase impedance measurement of two-terminal RC network .

Fig. 4 illustrates a relative error of impedance modulus and phase measurement of two-terminal network under test.

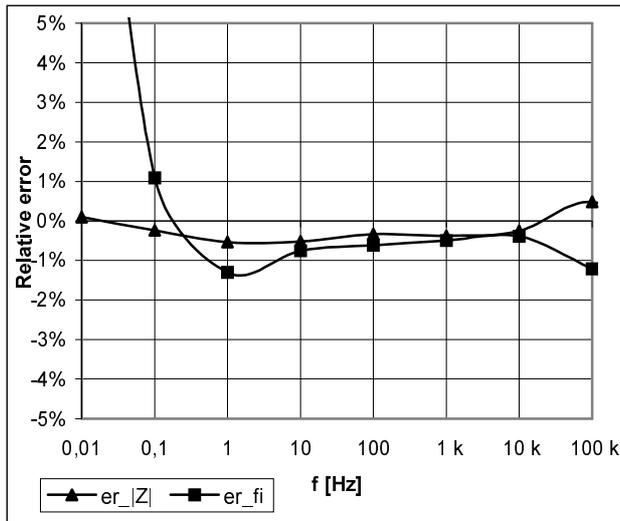


Fig.4 – Relative error of modulus-phase impedance measurement of two-terminal RC network.

Analysing errors' plot, one can differentiate 3 regions where analyser works. The middle region is appearing in frequency range of 10Hz÷20kHz, where errors doesn't exceed  $\pm 0.5\%$ . The range of high frequencies ( $>20\text{kHz}$ ), where op-amp bandwidth limit influence can be seen and the range of very low frequencies ( $<0.1\text{Hz}$ ), in which very high impedance is measured, assuming that no phase shift is entered ( $\varphi=0$ ), so relative error of phase measurement is increasing.

Using the realised analyser and an exemplary two-terminal RC network, the identification of R and C elements has been performed on the base of (6):

$$C = \frac{1}{|Z_x| \cdot \omega} \cdot \sin \phi, \quad R = \frac{|Z_x|}{\cos \phi}, \quad (6)$$

where:  $\omega = 2 \cdot \pi \cdot f_{meas}$ .

To estimate the identification accuracy, the relative errors of R and C values has been calculated and plotted (Fig. 5).

The graph analysis allows formulating the following conclusions:

- The error of the resistance R measurement is constant and doesn't exceed 0.5% in a low frequency range, but is increasing, when an impedance modulus of the shunting capacity C is an order lower than the measured resistance.
- The error of the capacity C measurement shows the smallest value ( $<0.5\%$ ), when ratio of reactive and resistive component is in range from 0.1 to 10 (e.g. in a frequency range from 1Hz to 100kHz).
- When the capacitor is strongly shunted by the resistor the error is rising to several percent ( $f_{meas} < 0.1\text{Hz}$ ).

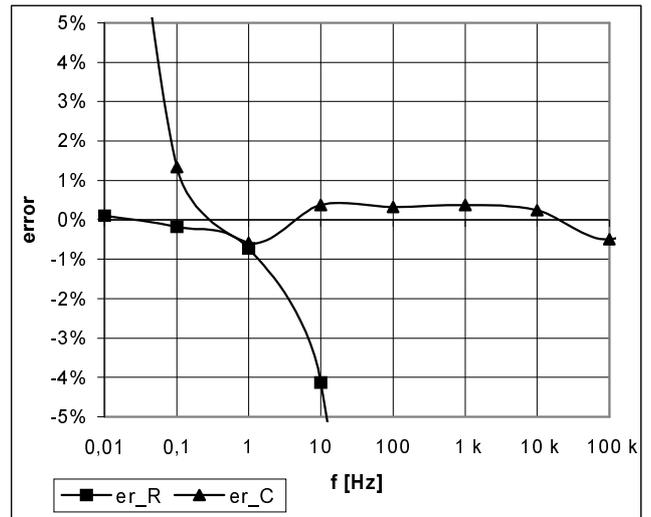


Fig.5 – Relative error of elements' identification of two-terminal RC network.

#### 4. CONCLUSIONS

The realised analyser is able to measure impedance parameters of two-terminal networks in a wide frequency range from 100 $\mu\text{Hz}$  to 100kHz. It was achieved by utilising DSP technique for determination of the orthogonal parts of the measurement signals. The resulted measurement accuracy and a relatively simple construction, assuring low price of the analyser (ca. 2000\$), allows to predict common usage of the presented solution. The form of a virtual instrument assures high flexibility, because an adaptation of the analyser to identification of parameters of multi-element equivalent circuit of different technical objects requires only PC software modification.

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