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VIRTUAL INSTRUMENT USING BILINEAR TRANSFORMATION FOR PARAMETERS IDENTIFICATION OF ANTICOROSSION COATINGS

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Abstract – The paper presents the method and the virtual instrument for monitoring of anticorrosion coatings performance. The developed method of component identification of the coating equivalent circuit is based on bilinear transformation. During the identification, the vector measurement of the object impedance is necessary at four selected frequencies. The analysis of optimal frequencies selection is presented assuring minimal identification error. The test results of implemented algorithm are shown. The results proved the possibility of shorten several times the testing time of anticorrosion coatings performance in relation to traditional impedance spectroscopy technique.

Keywords: virtual instrument, bilinear transformation, impedance measurement.

1. INTRODUCTION

The corrosion is destructive, so it's necessary to characterise the state of anticorrosion coating for estimation of the protection renewal time, due to economic and safety relation. The anticorrosion protection diagnostics using impedance spectroscopy is rather complicated, because of multi-element equivalent circuit of the anticorrosion coating. The element values estimation is possible on the basis of the impedance spectroscopy of the anticorrosion coating in a wide frequency range 10µHz÷1MHz [1]. The impedance spectroscopy for very low frequencies (<0,1mHz) is very onerous due to long measurement time. The measurements using Solartron instrumentation: frequency response analyser 1255A and high impedance interface 1294A, in frequency range 1mHz÷10kHz with 1, 2, 5 step, lasted 26 hours in the case of integration time set to 10 periods of measurement signal, which assured sufficient accuracy.

In order to shorten definitely time of anticorrosion coating performance estimation, the authors developed a virtual instrument measuring impedance components with the aid of DSP technique and performing the equivalent circuit component identification using bilinear transformation. The method allows component identification on the basis of the impedance measurements at 4 selected frequencies.

2. EQUIVALENT ELECTRICAL CIRCUIT OF ANTICORROSION COATING

Simplified model of the coating at the stage of electrolyte penetration and onset of undercoating rusting is shown in fig. 1 (the small electrolyte resistance was omitted) [2].

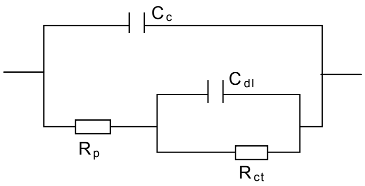

Fig. 1. Simplified equivalent circuit of the anticorrosion coating at the stage of electrolyte penetration and onset of corrosion , where: R_p – the resistance of the electrolyte in pores, C_c – the capacitance of coating, R_{ct} – the charge transfer resistance, C_{dl} – the double layer capacitance

Resistance R_p depends on electrolyte in pores of the coating, which create from microscopic defects, blisters, delaminations, etc. and are penetrated by water and electrolyte ions. It is known that polymers resistivity without electrolyte is in the order of 10^{12}-10^{16} Ωcm. So, when values of the resistance R_p obtained from measurement are much lower (of some orders), they usually represent resistance of electrolyte in the pores.

The coating dielectric property is represented by the capacity:

$$C_c = \frac{\varepsilon \cdot \varepsilon_0 \cdot S}{d} \tag{1}$$

where: S – the coating surface, d – the coating thickness, ε – the coating material dielectric constant, ε_0 – the vacuum dielectric constant.

Because polymers dielectric constant ε is on the level of 3-4, the coating capacitance (assuming that the coating is few mm thick) can be estimated as a few tens of pF/cm^2. During the exposition in the electrolyte, the penetration of the coating and water absorption begins. As result dielectric constant increases by few ten times, influencing meaningfully on the capacity of the coating C_c. Usage of this property allows monitoring of kinetics of water absorption of the coating during the exposition. This way obtained result characterises protective properties of the coating.

Appearance of the charge transfer resistance R_{ct} and the double layer capacitance C_{dl} means that undercoating rusting exists and characterises the rate of corrosion reaction. The value of capacity C_{dl} can be estimated on the basis of (1), because there is flat capacitor, which one electrode consist of electrolyte ions, and a second one of electrons (at the electrode). Assuming that ε=1 (there is no material) and d=1-3 10^{-10}m (the layer of ions) the value of C_{dl} is in range of 3-9 µF/cm^2.

During the stage before the undercoating rusting onset and in its early stage (on small surface), the values of C_{dl} and R_{ct} are on the level of some nF and GΩ, respectively.

When coating is new and there is no electrolyte penetration, resistance R_p is of an order of several GΩ and capacity C_c values are from a few tens to a few hundreds of pF, so they determine resultant impedance of the equivalent circuit. During the exploitation of the coating, the barrier protection decreases and the electrolyte begins to penetrate the coating. This causes that the R_p resistance decreases and the dielectric constant increases, so as a result the capacity C_c increases. Longer exploitation breaks continuity of the coating and undercoating rusting appears.

To avoid undercoating rusting, it is necessary to identify all components in specified time periods to monitor their values changes. Till now methods of equivalent circuit components identification has been based on computer programs [3], which find components values on the basis of impedance measurement performed on some (few tens) of measurement frequencies. In order to shorten measurements, the authors proposed use of bilinear transformation to identify components of the equivalent circuit of the anticorrosion coating.

3. DESCRIPTION OF THE METHOD

As we know [4], two-terminal multi-element network impedance for specified frequency can be expressed as a bilinear function of single element value p_i:

$$Z(j\omega, p_i) = \frac{A_i(j\omega)p_i + B_i(j\omega)}{C_i(j\omega)p_i + D_i(j\omega)} \tag{2}$$

where: A_i, B_i, C_i, D_i – complex coefficients meeting the condition: $A_iD_i - B_i C_i \neq 0$,
i=1, 2, 3, 4 – i-element of the equivalent circuit.
p_i=[C_c, R_p, R_{ct}, C_{dl}]

Presented function for all elements can be drawn on a complex plane (ReZ, ImZ) as curves crossing at point, in which all elements have nominal value. Assumed nominal values (C_c=330pF, R_p=10GΩ, R_{ct}=5GΩ, C_{dl}=20nF) describe real anticorrosion coating in a middle of a lifetime. The family of p_i-loci for two-terminal network impedance at frequencies 1mHz and 100mHz are shown in fig. 2 and 3. As one can see, curves image really depends on frequency. At 100mHz C_c curve is dominating and at 1mHz R_p curve is the longest. For presented method, measurement frequency has to be selected to assure that the curves have meaningfully different length – one of them is dominating, other as short as possible. The measurement at selected optimal frequency (ω_i) enables identification of *i-th* element value on the basis of inverse bilinear transformation of function (2) from (3):

$$p_i = \frac{D_i(j\omega_i)Z_i - B_i(j\omega_i)}{A_i(j\omega_i) - C_i(j\omega_i)Z_i} \tag{3}$$

where: Z_i – measured value of impedance (ReZ_i, ImZ_i).

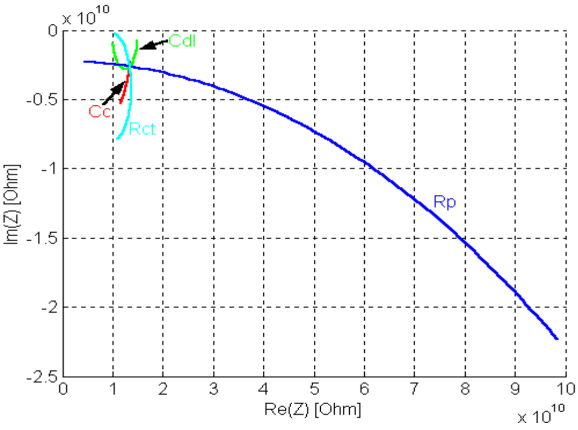

Fig. 2. P_i-loci for two-terminal network impedance at 1mHz

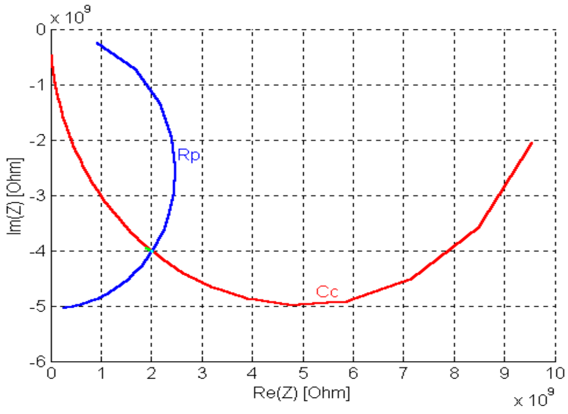

Fig. 3. P_i-loci for two-terminal network impedance at 100mHz

For precise analysis of phenomena of curves (in this case arcs) length change for all elements as a frequency function the measure of arcs length has been defined. The measure is calculated as a sum of distances from nominal point and the ends of *i-th* curve drawn for element value changing from 0,1 to 10 times nominal value. The absolute arc length can't be compared directly due to impedance modulus change by some orders (for frequency changing in wide range). The arc length has been normalised to impedance modulus value at element nominal value. Relative length of arcs for all elements as a frequency function is shown in fig. 4.

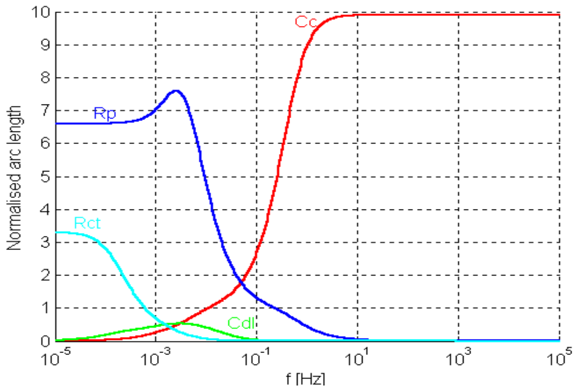

Fig. 4. Normalised arc length for two-terminal network impedance

The maximum values of arc length and related frequencies has been put together in Table 1.

TABLE 1. Maximal values of relative arc length

Element	Maximum of arc relative length	At frequency
C_c	9.8958	>16.65Hz
R_p	7.5898	<2.8mHz
R_{ct}	3.1859	<44.38uHz
C_{dl}	0.3616	12.9mHz

When analysing fig. 4 and Table 1, one can state that different measurement frequencies exist for each component of two-terminal network under test. Because in case of the tested coating all elements can change simultaneously, the relative error of specified component identification has been examined as a result of other component changes and as a frequency function. The measurement frequency for each element is selected assuring not only maximum sensitivity of analysed element, but also minimal influence of other elements. The sequence of element identification (C_c, R_p, R_{ct}, C_{dl}) has been chosen depending on element localisation in structure of the coating equivalent circuit.

In first step, the identification of C_c is performed. In fig. 5-7 relative error of C_c identification (absolute error is defined as difference between value from calculation based on (3) and nominal value) is shown as relation of measurement frequency and values of till unknown elements R_p, R_{ct}, C_{dl}. The range of element value change has been chosen due to permissible element fluctuation in real object. Measurement frequencies are marked in figures assuming error of C_c identification below 1%.

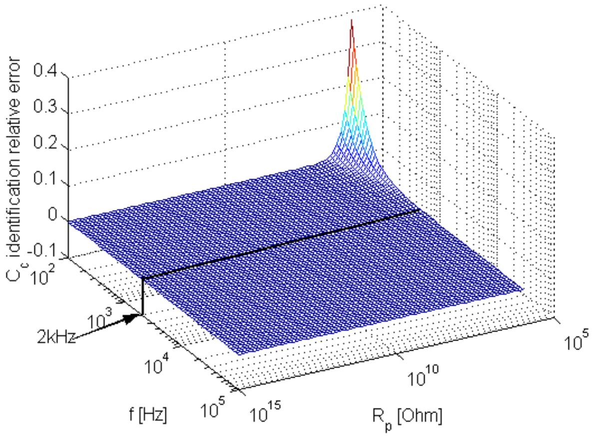

Fig. 5. C_c identification relative error due to R_p changes

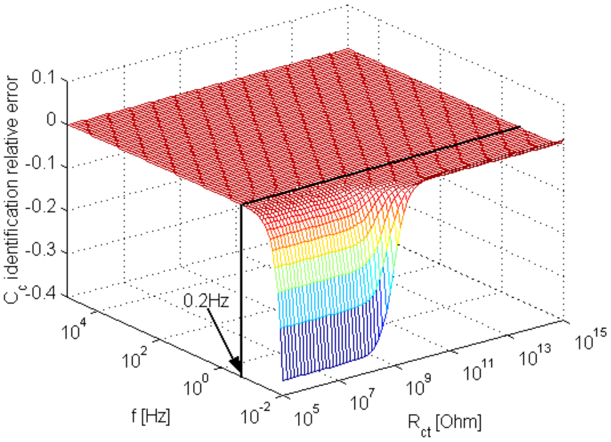

Fig. 6. C_c identification relative error due to R_{ct} changes

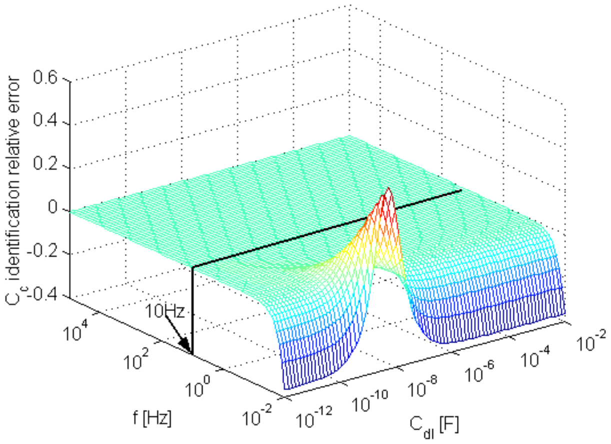

Fig. 7. C_c identification relative error due to C_{dl} changes

The element R_p extorts the highest measurement frequency (2-3kHz). Elements R_{ct} and C_{dl}: require 0,2Hz and 10Hz, respectively. Due to analysis of sensitivity (fig. 4) the measurement frequency f_{Cc} was set to 10kHz assuring C_c identification with error below 0,1%.

In the second step, for selection of optimal measurement frequency, the relative error of R_p identification has been analysed assuming R_{ct} and C_{dl} values change (fig. 8 and 9) and C_c identification error in the first step (fig. 10).

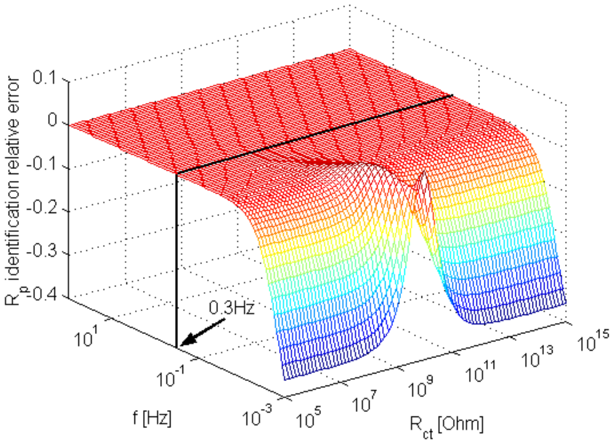

Fig. 8. R_p identification relative error due to R_{ct} changes

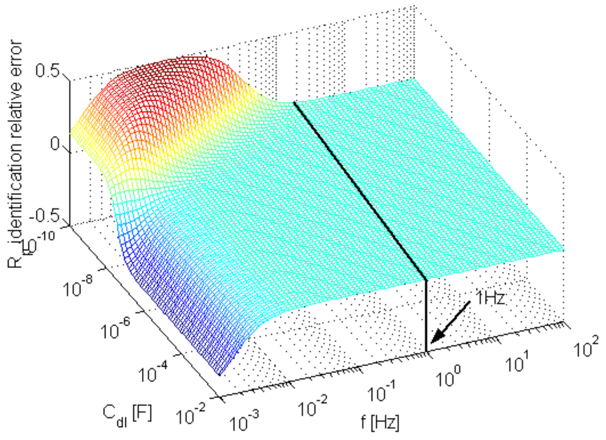

Fig. 9. R_p identification relative error due to C_{dl} changes

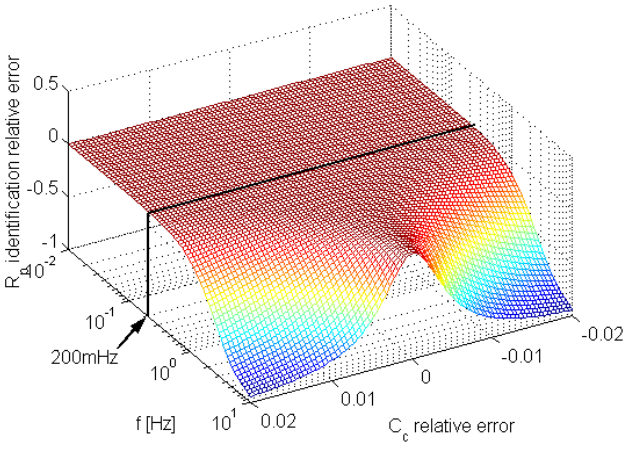

Fig. 10. R_p identification relative error due to C_c identification error

Analysing fig. 8 and 9 one can state that measurement frequency for R_p identification should be greater than 0,3Hz and 1Hz, respectively, and lower than 0,2Hz (fig. 10). These values are far from frequency of R_p maximum sensitivity (<2,8mHz due to fig. 4), but they should determine measurement frequency. The conditions from fig. 8 and 9 are conflicting with condition from fig. 10, so, as a compromise, frequency f_{Rp}=0,5Hz has been set up.

In the third step, the optimal measurement frequency for R_{ct} identification is determined. To do this, the relative error of R_{ct} identification has been analysed as a function of an unknown value of C_{dl} capacitor (fig. 11) and as a function of the error of previous determination of C_c (fig. 12) and R_p (fig. 13). Fig. 11 shows great influence of large capacitance C_{dl} (>1μF) on R_{ct} identification error. Assuming C_{dl} greater than 1μF, the measurement frequency has to be as low as 10μHz. At the early stage of undercoating corrosion, the values of C_{dl} are much lower (tens of nF), so it's possible to increase measurement frequency to 100μHz. Analysis of fig. 12 and 13 allows determining measurement frequency for R_{ct} identification to minimise influence of C_c and R_p identification errors in first two steps. The influence of C_c error will be negligible for frequencies lower than 1mHz but for R_p the limit is 100μHz. Taking into a consideration results of R_{ct} sensitivity analysis (fig. 4) and above discussion, the measurement frequency f_{Rct}=100μHz was set.

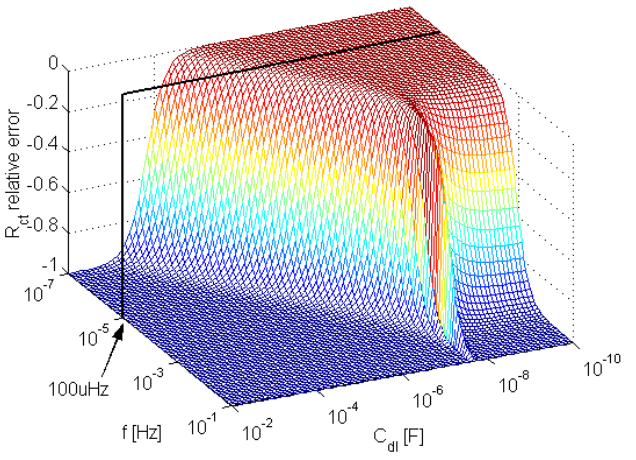

Fig. 11. R_{ct} identification relative error due to C_{dl} changes

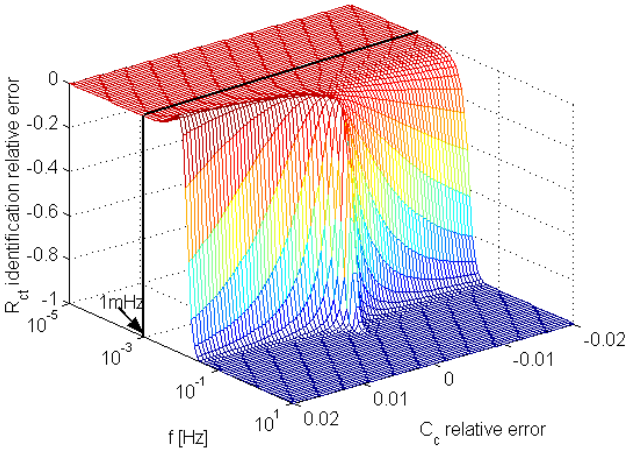

Fig. 12. R_{ct} identification relative error due to C_c identification error

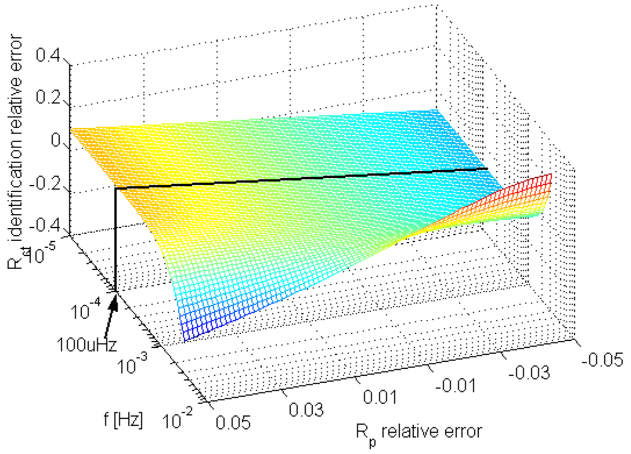

Fig. 13. R_{ct} identification relative error due to R_p identification error

The identification of the last element C_{dl} was performed at the measurement frequency f_{Cdl}=2mHz chosen on the basis of plots presented in fig. 14 and 15. There is no dependence on R_{ct} element. The obtained value of f_{Cdl} agrees with the frequency assuring maximal sensitivity of C_{dl} element (as shown in fig. 4).

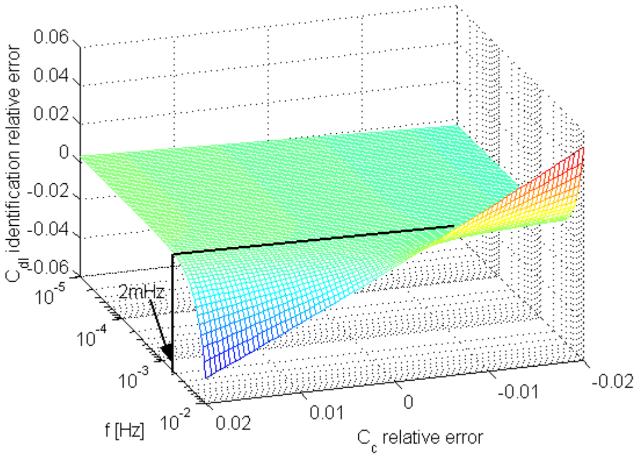

Fig. 14. C_{dl} identification relative error due to C_c identification error

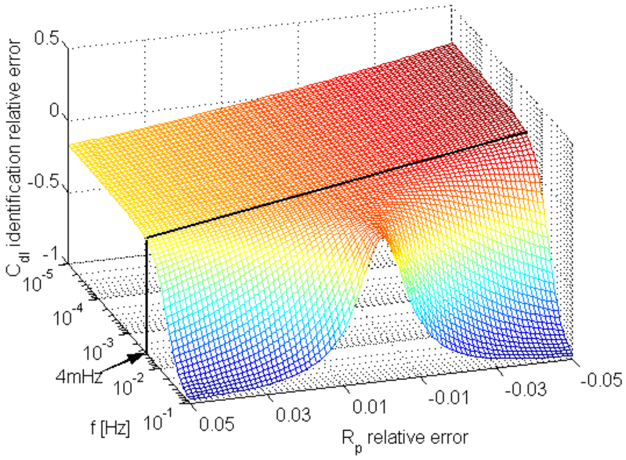

Fig. 15. C_{dl} identification relative error due to error of R_p identification

4. VIRTUAL INSTRUMENT FOR ANTICORROSION COATINGS MONITORING

The above method for identification of anticorrosion coatings parameters was implemented in the high impedance measurement microsystem. The microsystem was realised by authors of the paper as the virtual instrument consisting of the measurement module connected via RS-232 interface to portable PC (fig. 16). The instrument allows measuring of real and imaginary parts of two-terminal networks impedance of an order $100\Omega \leq |Z| \leq 10G\Omega$ in frequency range of 100μHz÷1MHz with basic error not exceeding 1%. The following solutions for the instrument have been chosen [5]:

- 5-terminal input circuitry based on I/U converter extracting two signals proportional to current and voltage on the object under test (5-wire connections: 2 current terminals, 2 voltage terminals and a guard terminal),
- Phase sensitive detector utilising discrete Fourier transformation (DFT), which allows determining orthogonal parts (Re, Im) of measuring signals u_I and u_U for very low frequencies,
- Digital signal processor (DSP) calculating DFT of sampled signals u_U and u_I ,
- Sinusoidal signal generator utilising direct digital synthesis (DDS) synchronised with sampling of voltages u_U and u_I,
- The form of virtual instrument allowing parameters identification of multi-element two-terminal networks on the basis of algorithms developed individually for each kind of the object under test.

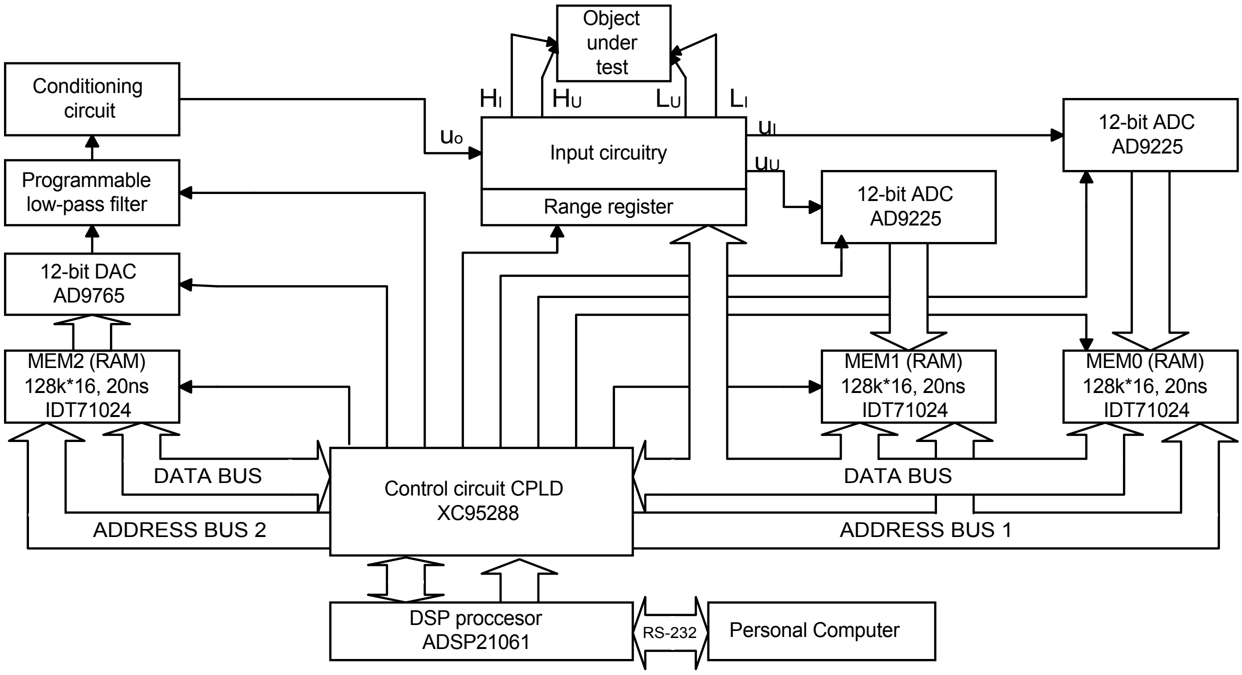

Fig. 16. Block diagram of the virtual instrument.

The identification of anticorrosion coating parameters is performed in the way of algorithm presented in fig. 17. The following steps can be pointed out:

1° At the before-test stage, on the basis of analysis presented in third section, four measurement frequencies (f_1=10kHz, f_2=0,5Hz, f_3=100μHz, f_4=2mHz) have been selected assuring optimal identification of all elements.

2° Initial values of two-terminal network components modelling real, well condition (new), anticorrosion coating are given (C_c=10pF, $R_p=10^{11}\Omega$, $R_{ct}=10^{10}\Omega$, C_{dl}=1nF).

3° The real ReZ_i and imaginary ImZ_i parts of impedance Z_i of the coating is measured at frequency f_1 using the virtual instrument.

4° The coefficients A_i, B_i, C_i, D_i of bilinear transformation are calculated for the first identified element (C_c).

5° The component C_c value is estimated according to (3).

6° Step 3-5 are repeated for frequencies f_2, f_3, f_4, which allows identifying other elements R_p, R_{ct}, C_{dl}.

The monitoring of anticorrosion coating parameters requires continuous repetition of presented identification procedure. To do this, after programmed delay the identification algorithm is repeated from step 2°. The starting values are replaced with values obtained from the last identification procedure.

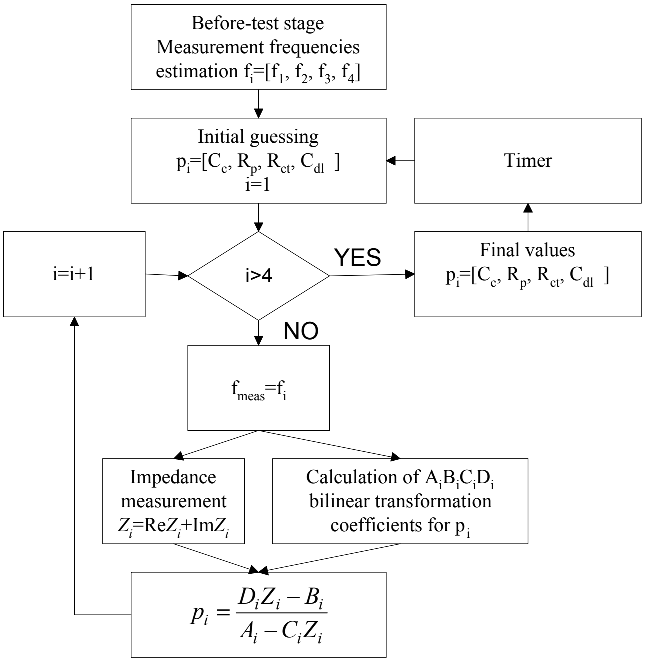

Fig. 17. The identification algorithm

The implemented algorithm has been tested. Table 2 presents results of component identification of equivalent circuit of the coating at 3 different stages of corrosion. The real values of objects 1-3 are modelling parameters of typical coating at the stage of excellent protection (object 1), at the stage of electrolyte penetration (object 2) and at the early stage of undercoating corrosion onset (object 3). Presented errors of component identification appear to grow up for elements laying deeper in network structure in relation to measurement terminals. The obtained error values are fully acceptable in case of anticorrosion coatings measurement. The identification procedure for selected frequencies takes less than 3 hours. But using traditional impedance spectroscopy technique, the measurement time for tested object is on the level of some tens of hours.

With aid of the proposed method, the testing time can be much shorter (a dozen or so of minutes) in case of replacing measurement frequency for element R_{ct} (100μHz) with frequency 1mHz not assuring minimal errors. Performed tests proved possibility of such solution. Obtained results in relation to presented in Table 2 differ only in case of element R_{ct} identification for object 1 – the error has increased to 5,2%.

TABLE 2. Tests results of the implemented method

p_i	Object 1		Object 2		Object 3	
	Real value	Relat. error	Real value	Relat. error	Real value	Relat. error
C_c	100pF	0,1%	330pF	0,1%	1nF	0,1%
R_p	10GΩ	1,1%	1GΩ	1,0%	100MΩ	1,2%
R_{ct}	5GΩ	1,1%	0,1GΩ	0,8%	10MΩ	2,7%
C_{dl}	10nF	1,3%	30nF	1,8%	100nF	5,2%

5. CONCLUSIONS

Performed tests of the developed virtual instrument using bilinear transformation for identification of 4-element two-terminal networks has proved the possibility of using the instrument for monitoring of anticorrosion protection performance. The proposed algorithm of identification allows shortening the measurement time to a dozen or so of minutes by using measurement at four frequencies. In comparison with traditional impedance spectroscopy (measurement time on a level of some tens of hours) it stands significant reduction of the identification time. The identification error is on the level of 0,1-5% depending on element location in the structure of equivalent circuit of tested anticorrosion coating.

The authors are planning to work on algorithm improvement to increase identification accuracy and shorten measurement time. The identification error can be lowered by means of measurement frequency modification during the process of the coating monitoring. When the coating performance getting worse, the impedance of the object is decreasing – it means that the measurement frequencies are increasing and also measurement time can be shortened.

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