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59th ILMENAU SCIENTIFIC COLLOQUIUM
Technische Universität Ilmenau, 11 – 15 September 2017
URN: urn:nbn:de:gbv:ilm1-2017iwk-051:3

IMPEDANCE ANALYSER ERROR CORRECTION USING ARTIFICIAL NEURAL NETWORKS

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ABSTRACT

The basic difficulties associated with the impedance analyzers design as well as possible their solutions have been outlined in the paper. The article proves advantages of artificial neural networks for correction of frequency errors in impedance measurements. Error correction algorithm for auto-balancing measurement circuit based on neural networks has been developed. Various ways of algorithms implementation on different computing platforms have been considered. The advantages and disadvantages of neural networks vs. classical analytical models have been analyzed. It has been defined that the most promising approach for algorithmic correction based on neural networks are the following cases: impossibility to obtain expressions for correction algorithms analytically; absence of analytical model of measurement channel is given, availability of only experimental data.

Index Terms - impedance analyzers, frequency errors, algorithmic correction, artificial neural networks.

1. INTRODUCTION

Impedance (complex resistance) Z_x, as well as the inverse admittance value (complex conductivity) $Y_x = 1/ Z_x$, is a part of immittance term which is more general. Impedance and admittance reflect the same physical quantity from the formal point of view. Their choice is mainly determined by the convenience of interpreting the primary parameters of the substitution scheme of object under study: the impedance is used for serial two-element substitution schemes and admittance is used for parallel ones. More complex substitution schemes of the objects under study make equivalent measurements of impedance and admittance, and if necessary, the transition from Z_x to Y_x or vice versa, is carried out by recalculation at the results elaboration stage.

The vector (two-dimensional) nature of the impedance is more informative than investigations conducted by using direct current. Since real objects and processes are characterized by certain active and reactive components' dependencies on the frequency, the information about these objects' properties can be obtained by analyzing their frequency response to alternating current. Knowing the dependence on the impedance, a variety of physical quantities, such as humidity or corrosion, can be controlled indirectly. This approach is called impedance spectroscopy [1,2,3].

Impedance spectroscopy is currently widely used to study objects of non-electric nature, including biological ones. The biomedical measurements [4,5,6], the study of materials properties [2,3], in particular on micro and nano level [7,8], corrosion monitoring and diagnostics [9,10], control of the parameters of batteries and elements of electrochemical power sources [3,11] can be used as the examples.

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Measurement converters, built on the basis of operational amplifiers (op-amps) based on the auto-balancing circuit, have become widely used in modern impedance measurement instrumentation. Often called active measurement converters (AMC), they are characterized by a number of advantages, in particular, the linearity and stability of the conversion function, high sensitivity and speed, the possibility of creating the specified energy conditions on the investigated object. They also provide measurements both in impedance and in the admittance modes [13,14].

The main disadvantage of AMC is the occurrence of frequency errors due to the decrease in the op-amp gain with the increase in the frequency of the probe signal and increase of impact parasitic shunt capacity at op-amp input. There are several approaches to solve this problem. For example, Agilent, the manufacturer of many types of impedance meters, uses a structural method to reduce frequency errors at frequencies above 100 kHz. An auto-balancing circuit that consists of a zero-detector, in-phase and quadrature phase-sensitive detectors and a vector modulator is constructed to stabilize the op-amp gain [12]. By nature, the frequency errors of such a measurement converter are determined by lock-in loop [15]. [16] describes another structural method for reducing frequency errors, this time in a static structure of the measurement converter. The composition of the measuring channel, in addition to the specified zero-detectors, phase-sensitive detectors and a vector modulator, consists of numerical accumulators, which perform the function of integrators.

The above described structural methods for reducing the frequency error rely on the introduction of the hardware redundancy (additional elements) in the measurement channel of impedance analyzers. An alternative solution for expanding the AMC frequency band is the use of algorithmic correction of measurement results, which is based on simple computing operations [12,16]. Such a "software" approach to improving the metrological characteristics of measurement instrumentations is promising and expedient, considering the availability of computing tools and existing trends for their further improvement.

Special correction algorithms have been developed to reduce the frequency errors of active measurement converters [17]. The algorithmic correction implies:

- synthesis of correction algorithms based on the mathematical model of AMC, which means, analytical expressions, taking into account the influence of parasitic parameters and destabilizing factors;
- calculation correction terms using developed algorithms and adding them to the measurement results.

However, this approach is characterized by a number of difficulties, in particular, it is not always possible to obtain analytical expressions that will ensure that the measurement results are corrected with the required precision, therefore it is necessary to solve a system of complex nonlinear equations for this. In this case, it is expedient to use other variants of algorithmic correction implementation, for example, with the help of machine learning techniques [18,19,20,21].

The purpose of this article is to study the possibility of using artificial neural networks (ANNs) to correct the impedance measurement results, as well as a comparative assessment of the efficiency of this approach to the classical one, which is based on the application of deterministic correction algorithms, obtained analytically.

2. ACTIVE MEASUREMENT CONVERTER BASED ON THE AUTO-BALANCING CIRCUIT

The active measurement converter is the main element of impedance analyzers' measurement channel. This is where an impedance (passive value) is converted into a proportional complex voltage under the action of a harmonical probe signal. The general view of the impedance measurement converter based on the auto-balancing circuit (method) is shown in Fig. 1.

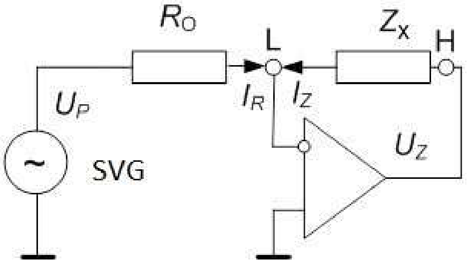

Figure 1 Active measurement converter based on the auto-balancing circuit

The essence of the method is to stabilize the current through the investigated object using the reference resistor R_0 and to form the complex voltage proportional to the impedance:

$$\dot{U}_Z = -\dot{I}_R \dot{Z}_X = -\frac{\dot{U}_P}{R_O} \dot{Z}_X \tag{1}$$

However, given expression does not consider the influence of the real op-amp parameters and the feedback loop. The second one is especially noticed when the probe signal frequency increases and causes errors which can reach tens of percent. These impacts are taken into account by so-called low-signal model of active measurement converter, which is described by the following expression [22,23]:

$$\dot{H} = -\frac{\dot{U}_Z}{\dot{U}_P} = P + jQ = \ldots$$

$$= \frac{-\dfrac{\dot{Z}_X}{R_O} + \left(\dfrac{1}{A_0} + j\dfrac{f}{f_T}\right)\dfrac{R_{OUT}}{R_O}}{1 + \left(\dfrac{1}{A_0} + j\dfrac{f}{f_T}\right)\left[\left(1 + \dfrac{\dot{Z}_X}{R_O} + \dfrac{\dot{Z}_X}{\dot{Z}_P}\right)\left(1 + \dfrac{R_{OUT}}{\dot{Z}_L}\right) + \dfrac{R_{OUT}}{R_O} + \dfrac{R_{OUT}}{\dot{Z}_P}\right]} \tag{2}$$

U_P and U_Z are probe and output (measuring) voltage; P and Q – in-phase and quadrature AMC output signal components (preliminary results of impedance measurement); A_0 – operational amplifier open-loop DC gain; f_T and f – operational amplifier unity-gain bandwidth and probe signal frequency respectively; R_{OUT} – op-amp's output resistance; Z_L – the load resistance; $Z_P=Z_D||Z_{S-}$ - shunt impedance created by differential input impedance Z_D and common-mode impedance Z_{S-} of op-amp; R_0 – the resistance of the converter's reference resistor; Z_X – impedance of the investigated object.

This expression is bulky, therefore, during the derivation of expressions for algorithmic correction, a number of simplifications were made, which, as shown in [17], had no significant effect on the adequacy of the model. Since the impedance is a complex value, a separate expression was obtained for each component:

- for the active component
$$R = \frac{P + C\dfrac{P^2+Q^2}{K} - Q\dfrac{1+D}{K} - \dfrac{P^2+Q^2}{K^2}}{1 + 2\dfrac{PC+Q}{K} + \dfrac{P^2+Q^2}{K^2}\left(1+C^2\right)} \tag{3, a}$$

- for the reactive component
$$X = \frac{Q + \dfrac{P^2+Q^2}{K} + P\dfrac{1+D}{K} + \dfrac{D}{K} + C\dfrac{P^2+Q^2}{K^2}}{1 + 2\dfrac{PC+Q}{K} + \dfrac{P^2+Q^2}{K^2}\left(1+C^2\right)} \tag{3, b}$$

$K = f_T/f$ is the ratio of unity-gain bandwidth and probe signal frequency; $D = R_{OUT}/R_0$ the ratio of the op-amp output resistance to the reference resistor value R_0; $C = 2\pi f C_{IN} R_0$ op-amp time constant by the input capacitance C_{IN} for the reference resistor R_0.
Each parameter displays one of the three main sources of AMC frequency error: K – decrease in op-amp gain; D – the direct passage of the signal is due to a nonzero output impedance of the op-amp; C – bypassing the op-amp differential and common-mode resistances with the input capacity.

3. DEVELOPMENT OF ALGORITHMIC CORRECTION BASED ON ANN

ANN is able to approximate elementary mathematical functions of almost any level of complexity. Thus, instead of polynomial expression (2) ANN based error correction means matrix multiplication of input data and network's weights. To model more complex dependencies dot products can be passed through non-linear activation function and after that multiplied with the weights of the next layer. The last layer is usually named as output and the others are called hidden. Structure of the simplest ANN is presented on the image below.

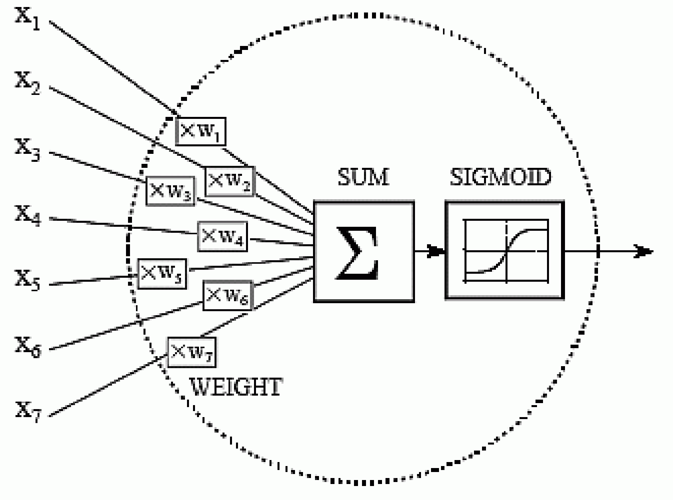

Figure 2. Artificial neural network with one neuron [24]

Experiments have been made in Matlab using Neural Network Toolbox. Design flow of ANN based algorithmic correction can be splitted in the following stages:

- data preparation;
- initialization;
- training (calibration);
- testing (accuracy evaluation).

At first stage train and test data sets should be prepared. Both sets have identical structure and include pairs of input and target (output) vectors, also called samples. Each input vector consists of six quantities f, P, Q, ft, C_{in}, R_0 and additional constant that equals one (typical machine learning trick for better performance). Each target vector consists of two quantities R, X. Train set includes 10 batches with 10 thousand samples in each. Test set includes one batch with 1 million samples. Quantities f, ft, C_{in}, R_0, R, X are randomly generated using uniform distribution. Quantities P, Q have been calculated according to (2).
On the initialization stage ANN of given type and architecture are being created. Initial values of weights are random. All necessary parameters for training and testing should also be set.
Experiments have been performed using feedforward type ANN (multi-layer perceptron). This type has linear activation function in the output layer and non-linear activation function (sigmoid) in hidden layers. Two ANN have been trained separately for resistance and

reactance correction. Networks have the same structure of two hidden layer with 50 neurons in each one (Figure 3).

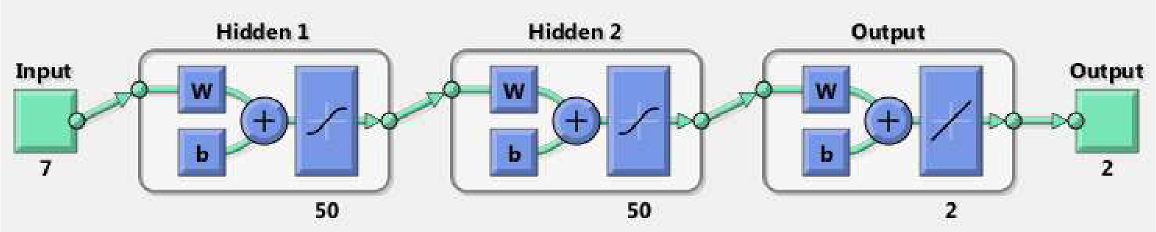

Figure 3. Feedforward ANN with two hidden layers

Following training and testing parameters were chosen:

- training algorithm: Bayesian regularization [25];
- number of iterations: 500 for each batch;
- maximal cross-validation error: 10;
- minimal gradient: 10^{-8};
- training accuracy: mse.

Other parameters were set as default.

Training stage long for around 18 hours on CPU Intel Core i7-5500 (Windows operating system, 8 GB RAM).

4. RESULTS ANALYSIS AND COMPARISON

The next step after ANN models training is performance estimation on the test set. Also, correction accuracy should be compared with analytical models (3). Two types of errors have been chosen to report the results: maximum absolute error and mean square error (mse). As correction error is normally distributed, mean square error is estimated as standard deviation multiplied by factor 3. This allows to ensure probability of 0.997. Results of both types of algorithmic correction are presented in table 1.

Table 1. Comparison of algorithmic correction results

	Mean square error (P = 0.997), %		Maximum absolute error, %	
	ANN model	Analytical model	ANN model	Analytical model
R	0.0022	0.0037	0.0274	0.0244
X	0.0016	0.0032	0.0128	0.0155

As follows from the table, ANN tends to show slightly better results. Application of more complex ANN model (more layers and neurons) as well as input feature preprocessing (e.g. Z-scoring or logarithmic scale for frequency) theoretically allows to achieve even more significant improvement in correction efficiency. Nevertheless, proportional improvement of overall measurement accuracy on the real-life data is not expected. The reason for that is that impact of instrumentation errors (ΔP and ΔQ) will remain uncompensated.

For both cases correction takes a few dozens of microseconds. Both models are based on simple mathematical operations – multiplication and addition. Thus, they can be easily implemented on DSP or FPGA.

5. CONCLUSIONS

Impedance spectroscopy is the key to solving many problems that currently arise in a variety of fields: chemistry, medicine, ecology, semiconductor physics, material science. Modern impedance analyzers have to contain analog components, including those that are based on operational amplifiers. For example, the use of an operational amplifier in a measurement impedance-voltage converter provides high sensitivity and performance together with the stability of transfer function and the ability to create specified energy conditions on the studied object. However, the main problem that should be solved is the reduction of so-called frequency errors. This task should be performed with the use of algorithmic correction taking into account the availability of computing facilities.

The studies conducted showed the possibility of implementing algorithmic correction based on artificial neural networks. This approach allows the network to select the appropriate model weights independently at the learning stage, based on the input values and output values and the parameters of the measuring channel.

For the algorithmic correction development, feedforward type ANN with two hidden layers of 50 neurons in each one was used. The training set contained 10 batches with 10 thousand samples in each, and test set - 1 batch with a million samples. The training algorithm was Bayesian regularization, the number of iterations for each package was 500.

During the research, the following results were obtained:

- maximum absolute error does not exceed 0,027 % for the active component and 0,013 % for the reactive;
- mse for 0,997 confidence intervals are 0,0022 % and 0,0016 % for the active and reactive components correspondingly.

For comparison, using the analytical algorithmic correction approach based on a measuring converter mathematical model, the error values are as following:

- maximum absolute error for the active component – 0,024 % and for the reactive – 0,015 %;
- mse – 0,0037 % and 0,0032 % for the specified components.

As follows from the performed experiments, even the use of a rather simple artificial neural network provides comparable and even slightly more accurate results than the analytical model. Application of more complex ANN architectures for further reduction of errors is unjustified as the instrumental errors will not be corrected and thus will dominate over frequency errors.

Summarizing the obtained results, it should be noted that ANNs are preferable when:

- it is not possible to obtain correction algorithms expressions analytically from mathematical model;
- there is no mathematical model of the measurement channel, and only experimental data is available.

Also, ANNs may have an advantage in terms of the development cost. PC computing time is much cheaper than involving a qualified specialist into development of a mathematical model and analytical expressions for algorithmic correction.

The main disadvantage of algorithmic correction based on ANN is a complexity of the interpretation of the network weights. Based on the analytical expressions of algorithmic correction, it is possible to analyze what parameters of the measuring channel influence the device work and optimize them at the design stage instead. Another disadvantage of ANN is the lack of a distinct mathematical apparatus for accurately calculating the maximum possible values of uncorrected errors.

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