

IMPEDANCE CIRCUIT IDENTIFICATION THROUGH EVOLUTIONARY ALGORITHMS

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Abstract: Impedance circuit identification through spectroscopy is used to characterize sensors. When the circuit topology is known, genetic algorithms can be used to obtain the circuit component values. Gene expression programming can be used to search for an adequate circuit topology. In this paper, an improved version of the impedance circuit identification based on gene expression programming and hybrid genetic algorithm is presented. Numerical results based on a real sensor are presented.

Key words: Impedance spectroscopy, circuit topology identification, genetic algorithms, gene expression programming.

1. INTRODUCTION

Impedance spectroscopy is used in different fields ranging from tissue characterization in biomedical application to electrochemical applications such as the study of fuel cells [1]. Other applications include monitoring of anti-corrosion coatings [2] and sensor modeling such as of a humidity sensor [3]. The first step in performing impedance spectroscopy consists on obtaining the impedance spectral response. This can be accomplished either by using an impedance vector-analyzer or through a two-channel data acquisition system where a sine-fitting algorithm can be used to extract the impedance magnitude and phase [4]. An improved version of this algorithm, called 7-parameter sine-fitting, has since been proposed [5].

Usually, some knowledge of the underlying processes is needed to suitably choose a circuit topology that models the process under study therefore fitting the acquired spectral data. The Complex Non-Linear Least Squares (CNLS) method is then used to obtain the circuit parameters of the chosen model. Since the CNLS is time consuming and sensitive to the starting search values, a new approach [6] based on an hybrid genetic algorithm [7] was proposed. This approach was recently used to characterize a viscosity measurement system [8].

In [9], Gene Expression Programming (GEP) was proposed as a method to search for a suitable circuit topology without any prior knowledge of the equivalent circuit [10]. In that work, a basic genetic algorithm was used to estimate the values of the circuit components. A different approach, based on GEP and cultural algorithms, was used in the modeling of electrochemical phenomena [11].

In this work, we use GEP to obtain the circuit topology, but then an improved version of the genetic algorithm to

obtain the circuit parameter values is used. A more effective fitness function is also tested in this paper. In order to make the numerical simulations more realistic, measurement uncertainty is considered for the amplitude and phase impedance data. This algorithm is also applied to impedance measurements performed on the circuit that models the humidity sensor presented in [12].

2. EVOLUTIONARY ALGORITHMS

The equivalent circuit identification from impedance spectroscopy involves identifying the circuit topology and then optimizing the values of each component in that circuit. This is accomplished in two steps; (i) first, a GEP implementation is used to identify potential circuit network topologies that can model the measured impedance; (ii) secondly, a hybrid genetic algorithm is applied to each topology to obtain the values of the components that minimize the cost function. In the next subsections these two algorithms are presented.

2.1. Equivalent Impedance Parameters Identification

For a given circuit topology the optimization of the component values is performed using an hybrid genetic algorithm [6]. Initially, a population of M chromosomes is created. Each chromosome is composed by the values of each component in the current circuit topology. The fitness of each chromosome is usually evaluated through the cost function

$$\varepsilon = \frac{1}{P} \sum_{i=1}^P \frac{|\bar{Z}(\omega_i) - \bar{Z}_{est}(\omega_i)|^2}{|\bar{Z}(\omega_i)|^2} \quad (1)$$

where $\bar{Z}(\omega_i)$ is the measured impedance at angular frequencies $\omega_i = 2\pi f_i$, $\bar{Z}_{est}(\omega_i)$ is the estimated impedance obtained with the component values in the chromosome and P is the number of measured frequency points. However, it was found that the frequency points in the resonance region had little weight in the final value of the cost function, which led to having good candidate circuits being discarded by the genetic algorithm. A different cost function that does not suffer from these problems was therefore used

$$\varepsilon = \frac{1}{P} \sum_{i=1}^P \frac{|\bar{Z}(\omega_i) - \bar{Z}_{est}(\omega_i)|^2}{|\bar{Z}_{est}(\omega_i)|^2} \quad (2)$$

The fitness of each chromosome is used to evolve the population based on survival of the fittest, where the fittest elements have a better chance of reproducing and therefore propagate their characteristics into next generations. Just like a biological population, there is reproduction and mutation which is vital to create population diversity. This algorithm is very efficient in finding the region of the absolute minimum of (2) even when the search space is vast and local minima are present nearby. However, it takes a long time to find the actual minimum, so a Gauss-Newton method is applied using the final results of the genetic algorithm as starting values for the Gauss-Newton method.

2.2. Impedance Network Topology Identification

The identification of the equivalent impedance network topology is performed using GEP. A set of N candidate circuit topologies are created and evolved using the genetic operators: replication, mutation, transposition and recombination [9]. Each candidate circuit is expressed as a linear gene which contains components (R, L and C) and operators (series and parallel). The gene is composed of a head of size h and a tail of size t , with $t = h + 1$. The head may contain components and operators while the tail is comprised only of components. This is fundamental to the operation of GEP since it guarantees under all circumstances a valid circuit topology.

Each gene is converted into a binary tree by filling it in a breadth-first fashion as proposed in [9]. This tree can then be recursively run to obtain the equivalent circuit. In fact, in our coding the binary tree is completely bypassed and is only used to help visualize the circuit topology. The hybrid genetic algorithm is then executed for each candidate topology gene to optimize its component values and the fitness of the circuit is used by the genetic operators to evolve the circuit topologies. Although the genes are of fixed length, its coding region varies, thus resulting in trees of different sizes and complexity. This means that GEP can add branches to the circuit or eliminate them, while searching for the circuit that best fits the measured data.

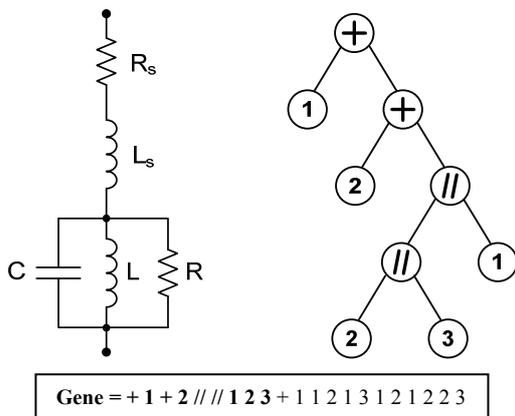


Fig. 1. Example of circuit topology and corresponding binary tree along with coding gene for GEP with $h + t = 21$. The coding region is shown in bold and ends at position 9.

Figure 1 shows an electric circuit that will be used as test impedance in the numerical results. The GEP gene that codes this circuit is presented along with the corresponding binary tree. The numbers in the tree leaves correspond to the type of component R, L or C for 1, 2 or 3, respectively.

3. NUMERICAL RESULTS

In this section, the circuit in Figure 1 is used to test the algorithm described in the previous section under realistic conditions. The spectral response of this impedance with $R_s = 10 \Omega$, $R = 1000 \Omega$, $L_s = L = 1 \text{ mH}$ and $C = 1 \mu\text{F}$ was calculated for only $P = 10$ frequency points in the range $[0,1 ; 10]$ kHz and random errors were included in the data to simulate real measurement conditions, with an uncertainty of 0.08% in the impedance magnitude and 0.05° in its phase. The encoding gene chosen by the algorithm is presented in Figure 2 along with its corresponding binary tree. The resulting equivalent circuit is presented in Figure 3, along with the corresponding component values.

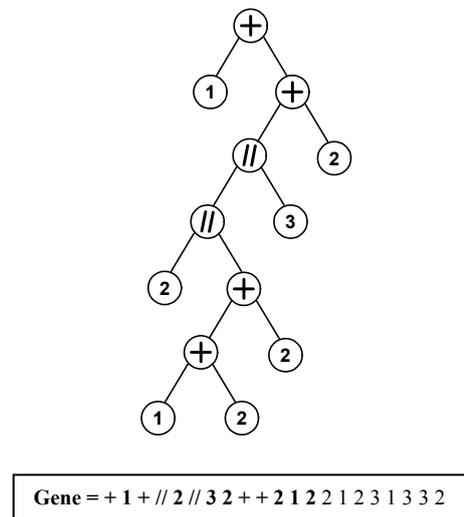


Fig. 2. Encoding gene (in bold) and corresponding binary tree obtained by GEP and hybrid genetic algorithm for the impedance in Figure 1 with $R_s = 10 \Omega$, $R = 1000 \Omega$, $L_s = L = 1 \text{ mH}$ and $C = 1 \mu\text{F}$.

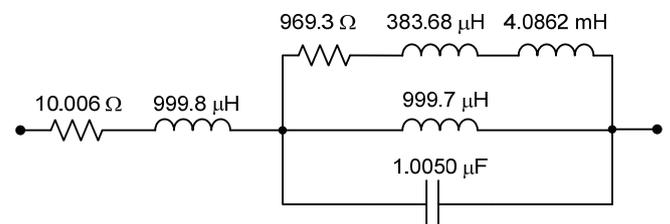


Fig. 3. Circuit topology and component values corresponding to the binary tree shown in Figure 2.

Although the equivalent circuit does not have the same topology as the original impedance circuit, the effect of the two series inductors in the total impedance is negligible in the frequency range under study, as can be seen in Figure 4 and Figure 5 where the spectral response of the two circuits is shown. Different runs of the algorithm yield different

equivalent circuits, but always in good agreement with the spectral response of the original circuit. Note that, even without any measured point in the resonance region, the algorithm still finds a correct equivalent circuit.

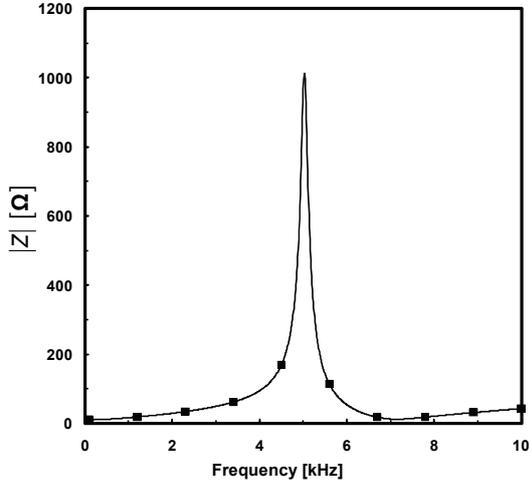


Fig. 4. Impedance magnitude of the circuit in Figure 1 (squares) versus the estimated impedance magnitude corresponding to the circuit in Figure 3 (line).

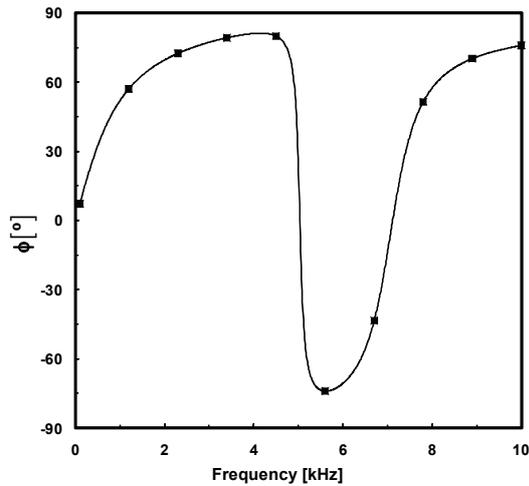


Fig. 5. Impedance phase of the circuit in Figure 1 (squares) versus the estimated impedance phase corresponding to the circuit in Figure 3 (line).

4. EXPERIMENTAL RESULTS

The next step in testing the developed algorithm is to evaluate its performance when applied to real measured data. The measurements were performed in the circuit shown in Figure 6 that models a humidity sensor [12]. The component values of the equivalent circuit of the sensor change with relative humidity, and as in [6], we consider the case corresponding to a relative humidity RH = 54 %. The component values are presented in Table 1.

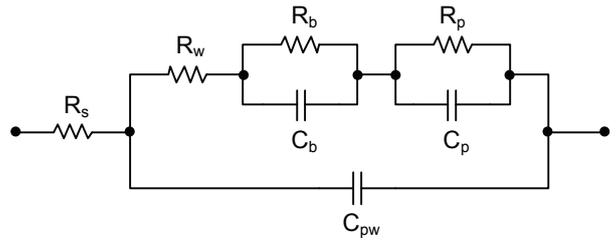
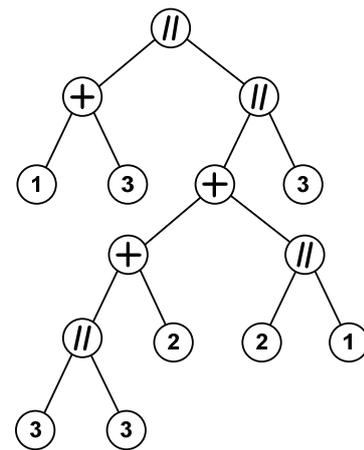


Fig. 6. Humidity sensor equivalent circuit. The component values change with relative humidity [12].

Table 1 – Component values for the humidity sensor equivalent circuit at RH = 54 %

Component	Value
R_s	1.18 Ω
R_w	624.5 Ω
R_b	30 M Ω
R_p	120.97 k Ω
C_b	0.68 μ F
C_p	2.32 μ F
C_{pw}	5.87 nF

The circuit in Figure 6 with the component values shown in Table 1 was assembled and its spectral response was measured. We chose $P = 11$ logarithmic spaced frequency points in the range $[1; 10^5]$ Hz. The presented algorithm was then applied to these measurements to find the equivalent circuit and respective component values. Figure 7 shows an example of the encoding gene and the respective binary tree that was found by the algorithm. Figure 8 presents the corresponding equivalent circuit including the component values.



Gene = // + // 1 3 + 3 + // // 2 2 1 3 3 1 2 2 1 1 3

Fig. 7. Example of encoding gene (in bold) and corresponding binary tree obtained by GEP and hybrid genetic algorithm for the measured spectral response of the sensor equivalent circuit with RH = 54 %.

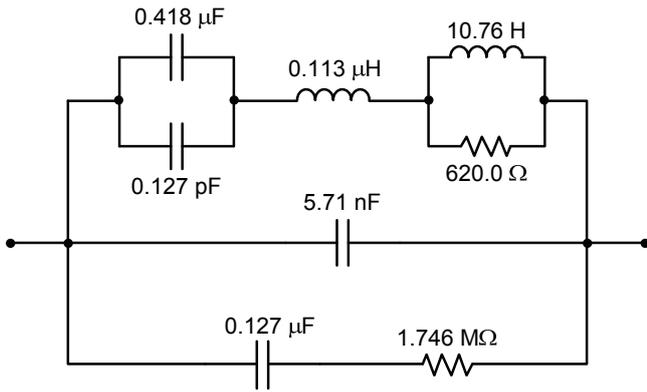


Fig. 8. Circuit topology and component values corresponding to the binary tree shown in Figure 7.

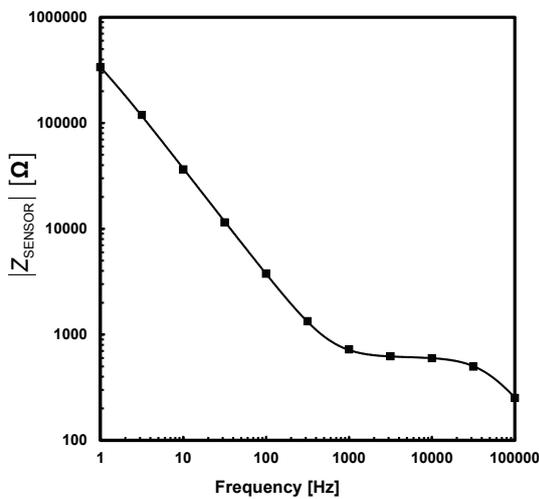


Fig. 9. Impedance magnitude of the circuit in Figure 6 (squares) versus the estimated impedance magnitude corresponding to the circuit in Figure 8 (line).

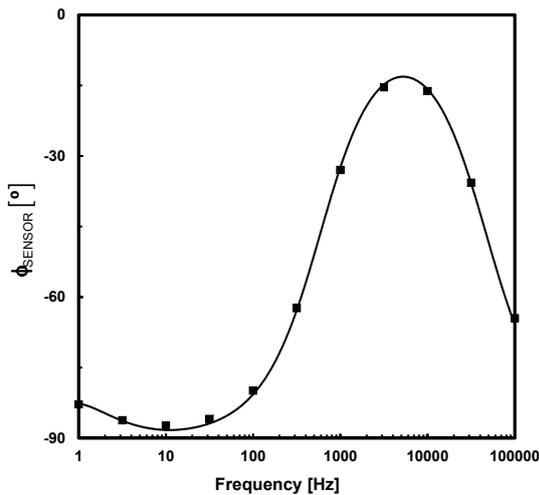


Fig. 10. Impedance phase of the circuit in Figure 6 (squares) versus the estimated impedance phase corresponding to the circuit in Figure 8 (line).

It was found that different runs of the algorithm on the measured data yielded different equivalent circuits that do not resemble the original circuit topology shown in Figure 6. However, as shown in Figure 9 and Figure 10, the spectral response of the obtained circuit closely matches the measurements performed on the original circuit. This allows us to conclude that the circuit in Figure 8 is equivalent to the original circuit, at least in the measured frequency range, although it might not be equivalent to sensor equivalent circuit at different relative humidity.

4. CONCLUSION

An improved version of impedance spectroscopy using evolutionary algorithms was presented where GEP is used to evolve the target circuit topology and an hybrid genetic algorithm is used to obtain the circuit component values. A different fitness function, which works well with impedance sweeps that include resonances, was proposed. Numerical results show that even with measurement uncertainties and few frequency measured values, the presented algorithm is capable of finding an equivalent circuit. The algorithm was also applied to measurements of a circuit that models a humidity sensor at a specific relative humidity. It was found that different runs of the algorithm yield different equivalent circuits that nonetheless closely match the measured spectral response, but might not be valid for other relative humidity values. We are currently developing a method for automatic simplification of the obtained circuits.

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