An Effective and Robust Self-developed Method in Support of Measuring the Cole-Cole Parameters

Lili Nadasdi, Nina Gyorfi, Attila Toth, Mihaly Klincsik, Zoltan Sari, Bojan Kuljic, Akos Odry, Peter Odry, Zoltan Vizvari

***Abstract*—**The Cole-Cole model is the fundamental mathematical model regarding the Electrical Impedance Spectrum, which is primarily applied to evaluate the majority of the data extracted by this type of measurement method. Since Electrical Impedance Spectrum measurements play a distinguished role in support of our research team, we are now in possession of a self-developed instrument and a self-developed data extracting method. These techniques ensure the extraction of the Cole-Cole model parameters are outstandingly effective and robust. This article intends to demonstrate the strength of the self-developed methods by presenting an experimental measurement method.

***Keywords*—** Electrical Impedance Spectrum Measurement, Cole-Cole model parameters

I. Introduction

The Electrical Impedance Spectrum as a material analysis method is a technique applied wide-spread throughout several fields of sciences. In addition to medicine and pharmaceutics, this procedure can also be effective in detecting environmental or geophysical resources. Furthermore, it is an efficient material analysis method not only for human and animal tissues but also for plants, including s different kinds of vegetables and fruits. The following section intends to show several meaningful examples.

By applying the induced polarization method and the Cole-Cole model jointly, it can be described how surface resistance is dependent upon the geological environment. Garcia-Fiscals and Flores intended to specify the model parameters by combining the procedure with other geoelectric measurement methods (spectral and frequency domain induced polarization and transient electromagnetic methods) [1]. Multi-layer earth structures including their spatial distribution can be determined in the use of this method [2].

In plant tissue studies, impedance data are extracted from fruit samples [3]. In this case, the Cole-Cole model is calibrated by means of an active electric circuit system to determine the parameters, and, following this, the data acquired are analysed using assistance from other measurement methods. In apple sample studies, different impedance values were recorded at different frequencies and the unknown Cole-Cole model parameters were determined by the often-referred to, Flower Pollination Algorithm (FPA) [4].

In cases regarding animal and human tissue studies, the tissue resistance given to certain stimuli is specified by the technique [5]. These intratissue resistance differences can be revealed by the circuit models. These differences, however, may also be detected by the deviation of the distribution of relaxation times [6]. Studying muscle tissues, prior to or following force exertion for instance, the biceps muscle tissues show different impedance values [7]. Moreover, the impedance values of tumorous and healthy breast tissues are different [8]. Impedance alterations may also be associated with the age of the tissues [9]. In diagnostics, distinctly in the role regarding imaging, the Cole-Cole model is applied for specification [10]. Examining the impedance of the blood by observing the erythrocytes provides an opportunity to monitor blood clot formation [11]. Additionally, it plays a crucial role in developing artificial tissues to substitute given human tissue since reproduction can only be performed if their electric features precisely match one another [12].

Although the Cole-Cole model proves to be efficient in several fields of sciences, no unified measurement evaluating procedure has been developed to extract parameters regarding material features. Thus, applying this technique, the biggest

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Lili Nadasdi is with the Department of Environmental Engineering, Faculty of Engineering and Information Technology, University of Pécs, Boszorkány u. 2, H-7624 Pécs, Hungary (e-mail: nadasdililike@gmail.com).

Nina Gyorfi is with the Department of Environmental Engineering, Faculty of Engineering and Information Technology, University of Pécs, Boszorkány u. 2, H-7624 Pécs, Hungary (e-mail: gyorfinina@gmail.com).

A. Toth is with the Institute of Physiology, Medical School, University of Pécs, Szigeti str 12, H-7624 Pécs, Hungary (e-mail: attila.toth@aok.pte.hu).

M. Klincsik is with the Department of Mathematics, Faculty of Engineering and Information Technology, University of Pécs, Boszorkány u. 2, H-7624 Pécs, Hungary (e-mail: klincsik@mik.pte.hu).

Z. Sari is with the Department of Information Technology, Faculty of Engineering and Information Technology, University of Pécs, Boszorkány u. 2, H-7624 Pécs, Hungary,(e-mail: sari.zoltan@mik.pte.hu)

Bojan Kuljic is with the College of Applied Sciences, Subotica Tech, Marka Oreškoviċa 16, 24000 Subotica, Serbia (e-mail: bojan@vts.su.ac.rs)

Akos Odry is with the Institute of Information Technology, University of Dunaujvaros, Táncsics M. u. 1/A, H-2401 Dunaújváros, Hungary (e-mail: odrya@uniduna.hu).

P. Odry is with the Institute of Information Technology, University of Dunaujvaros, Táncsics M. u. 1/A, H-2401 Dunaújváros, Hungary (e-mail: podry@uniduna.hu).

Z. Vizvari is with the Department of Environmental Engineering, Faculty of Engineering and Information Technology, University of Pécs, Boszorkány u. 2, H-7624 Pécs, Hungary (e-mail: vizvari.zoltan@mik.pte.hu).

uncertainty factor arises from data extraction. Additionally, the appearance of the simplest empirical methods [18], two-measurements-only solutions were offered in support of the problem regarding several fields by using the Wien bridge oscillator [13]. The Cole-Cole impedance data can also be evaluated by introducing several algorithms (e.g. FPA, Moth-flame Optimization Algorithm, etc. [14]). Furthermore, the relationship among the different positioning of the electrodes and the alterations of the parameters are investigated [15]. Other researchers endeavoured to extract the medians of the parameters by stochastic methods (Markov chain, Monte Carlo method) and estimated the parameter values deterministically (Gauss Newton method) [16]. The Bayes approach, a stochastic method out of the plenty, also attempted to gain the Cole-Cole parameters [17]. Researchers, however, have pointed out the problem of residual impedance, the neglection, of which, leads to an imprecise measurement [19]. This explains why the techniques discussed above do not result entirely toward acquiring precise values. A program package was introduced in 2014, which had been developed for evaluating mathematical models regarding different Electrical Impedance Spectrum measurements [20].

II. Theoretical Background

The Cole-Cole model is a non-linear model using electric RC-coupling analogy. The model and the extracted values from the multi-frequent domain electric impedance measurements provide a good-fit function, the electronic equivalent of which is illustrated by Fig. 1.

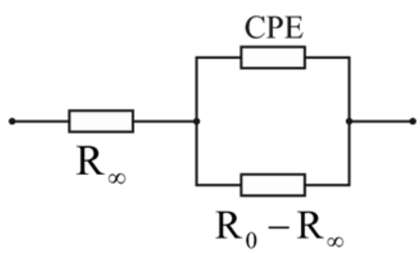

Figure 1 Cole-Cole model in biological measurements [20]

Fig. 1. depicts the non-linear, equivalent electric circuit element, the commonly-referred to, constant phase element (CPE) regarding the measured electrolyte diffusion features appear [20] and also two resistors R∞ and R0 – R∞. Here, index 0 represents the resistance measured in DC, while ∞ refers to the resistance measured in the infinite frequency range. The mathematical representation of the impedance of the coupling is described by the following complex function:

$$Z(j\omega) = R_\infty + \frac{R_0 - R_\infty}{1 + (j\omega\tau)^\alpha} \quad (1)$$

When $\alpha \neq 1$, the function implies an extremely difficult mathematical problem, the unified application of which, as it was discussed above, is not possible based on the present knowledge of science.

III. Material and Methods

A linear system has been developed to represent the estimated values of the Cole-Cole model. In this case, when $\alpha = 1$, CPE becomes a simple capacitor (Debye-model) [1]. The RC parameters include the following: R_∞ = 1 kOhm, R_0 - R_∞ = 10 kOhm, while the value of the capacitor is C = 1 uF. The resistors are ultra-precise resistors with less than 2 ppm thermic coefficients and 1% tolerance [21]. The tolerance of the capacitors is 5%, while the thermic coefficient is 200 ppm/°C [22].

A. The Measurement Method Applied

The experiment was performed using a self-developed multifunctional instrument, which can also be used regarding EIS and EIT measurements. The instrument [23] is capable of measuring impedance, impedance spectra, and Fast Fourier Transform (FFT) spectra on each channel independently. The excitation was a monochromatic sine wave in a frequency range between 1 mHz to 100 kHz, with a Total Harmonic Distortion + Noise (THD+N) greater than 100 dB. The maximum noise levels in the frequency range 0.1 Hz to 40 kHz are 150 fA eff for the current, while 1.5 µV eff for the voltage. The range of applicable excitations is 110 dB in both current-generator and voltage-generator modes with maximum values of 10 mA peak to peak and 10 V peak to peak, respectively. The signals are digitalized by the receiver board applying 24-bit Analog-Digital (AD) converters and additionally processed using the digital platform controlled by the PC. During precise impedance calculations, (48 bit) resolution for both real and imaginary parts, all operations regarding signal manipulations and parameter extractions are performed in the digital domain. One of the most important features regarding sensitivity representative of the equipment is the accuracy of 1 ppm for amplitude and 0.01° for phase. Fig. 3 depicts the customized instrument.

Figure 2 The measuring instrument

The entire measurement procedure is implemented using PC software referred to as Embedded System for Impedance Measurement (ESIM). The ESIM displays the results on the screen and it is capable of saving all measurement data, whether on a Secure Digital (SD) card or Hard Disk Drive (HDD). Interestingly, the measurement system is independently operational without the use of a PC.

B. The Data Extracting and Evaluating Methods Applied

By measuring the test circuit shown in Fig. 4, it is possible to perform a statistical estimation of the accuracy of the system and the data evaluation method by calculating the relative error (e) of the measured values, the correlation coefficient (R^2) and the Chi-square values (χ^2) for the model-fitting process.

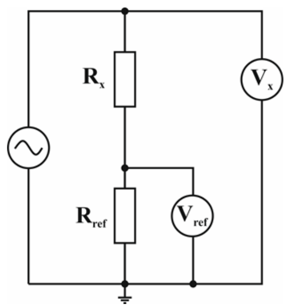

Figure 3 Passive test circuits (R_x symbolizes the measured Debye model circuit)

In order to test the advantages of the self-developed impedance measurement technique, the test arrangement depicted on Fig. 4. was used (the same arrangement as in [24]). According to the patented method, Rx can be calculated by the following formula:

$$R_x = R_{ref} \cdot \frac{V_x - V_{ref}}{V_{ref}} \qquad (2)$$

The EIS measurements were carried out by using lock-in averages in duration of 1 second at 100 distinct frequencies between 1 Hz and 10 kHz. In consideration of the evaluation regarding the measured frequency-impedance data-pairs, the Levenberg-Marqardt-based method, a non-linear optimization algorithm, was developed in a MatLab environment [25].

IV. RESULTS

These results demonstrate the capabilities and effectiveness of the entire equipment together with the data acquisition method. The error of impedance (R_x) values consists of two components: the constant error of analogue measuring channels and the resistor tolerance. The relative errors of the absolute value (Z) and phase (φ) of impedance are shown in the following formulae:

$$e_Z = 100 \cdot \frac{Z_i - Z}{Z}, \quad e_\varphi = 100 \cdot \frac{\varphi_i - \varphi}{\varphi}, \qquad (3)$$

in which e_Z and e_φ are the relative errors (%), Z_i and φ_i represent the measured values corresponding to the i-th channel (i = 1,...,8), while Z is the magnitude and φ is the phase of impedance (theoretical value based on equation (1), while α = 1). The results of EIS measurement can be seen in Fig. 5. The maximum relative error regarding the magnitude of the impedance (calculated for the entire frequency domain of the measurement) is 0.83%. Regarding the measured phase values, the maximum relative error is 0.42%.

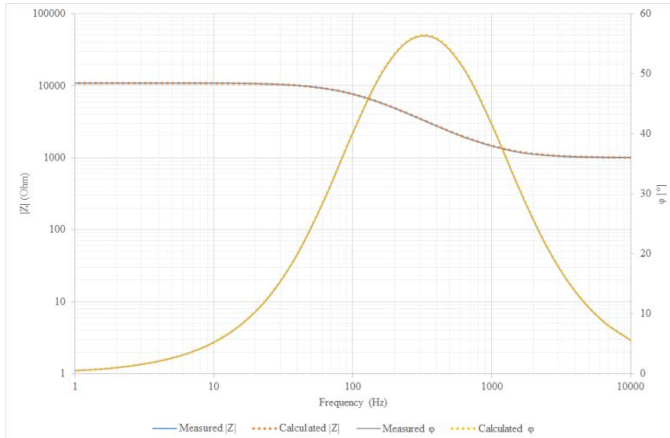

Figure 4 Result of EIS measurement performed on a test circuit compared to the theoretical values

The Table 1 depicts the results of a MatLab fit-algorithm. The relative error of the extracted model parameters is less than the tolerance of passive components.

Component name	Theoretical value	Extracted value	Relative error (%)
R_∞ (Ohm)	1 000	1004	0.4
R_0 - R_∞ (Ohm)	10 000	9 926	0.74
α (-)	1	0.9999	0.01
τ (sec)	0.01	0.01023	2.3

Table 1 The extracted model parameters compared to the theoretical value of components

The goodness of fit was measured using the R^2 value, which was 0.9999, while the χ^2 value was 0.32, which demonstrates the outstanding properties of the self-developed measurement system, the data recording method including the evaluation process.

V. CONCLUSION

This paper presents a widely used mathematical model, the Cole-Cole model, in support of Electrical Impedance Spectroscopy. Although there is a great need for the application of the model, there are no unified techniques currently available regarding evaluation, fitting, or the extraction of model parameters. Specifially, this the primary goal regarding our research, and supportive reasoning to why a self-developed complex Electrical Impedance Spectroscopy data recording and evaluation process are introduced here. The presented method incorporates every necessary element for effectively investigating, displaying, extracting and thoroughly evaluating the measured data. A test circuit is constructed for demonstrating the capabilities of the spectroscopy and the statistical properties regarding the proposed methodology. The test results performed on these circuits are able to demonstrate the impressive accuracy and stability of this system. Each test measurement value demonstrates how the measured error is less than the tolerance of the built-in resistors and capacitors. One of the main goals of this research is to pursue the development regarding specific applications in the near future in the effective application of the method presented in this paper.

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