applied sciences

MDPI

Editorial

Impedance Spectroscopy and Its Application in Measurement and Sensor Technology

Olfa Kanoun [1,*], Jörg Himmel [2] and Abdelhamid Errachid [3]

[1] Chair for Measurement and Sensor Technology, Department of Electrical Engineering and Information Technology, Technische Universität Chemnitz, 09111 Chemnitz, Germany
[2] Institute for Measurement and Automation, University of Applied Sciences Ruhr-West, 45479 Mühlheim, Germany
[3] Institute of Analytical Sciences (ISA)—UMR 5280, University Claude Bernard Lyon 1, 69100 Lyon, France
* Correspondence: olfa.kanoun@etit.tu-chemnitz.de

1. Introduction

Impedance spectroscopy is a key enabling measurement method that exploits the measurement of the complex impedance of a material or a system to characterize it or to track its changes over time. The method is used in several sectors of science and technology, ranging from classical material characterization to the characterization of devices and systems. It is non-invasive and applicable for in vitro and in vivo bio- and medical applications. At present, several sensor principles make use of impedance spectroscopy to improve measurement accuracy or to acquire more information from a sensor.

This Special Issue was introduced to collect the latest research findings in this field, in fundamentals, understanding, and applying impedance spectroscopy. Representative contributions on several aspects could be collected including system design aspects for field application, the characterization of materials and systems, and sensor design for a variety of applications.

2. Measurement System Design for Field Application

The design of measurement systems for impedance spectroscopy, as portable measurement systems or in embedded solutions, is important for field application; realizing portable solutions includes several challenges, e.g., due to the required frequency range, which varies considerably according to the type of application. Especially for the measurement of impedance spectra at very-low-frequency values down to a few mHz or even below, many challenges should be solved. In this context, Scandurra et al. [1] address the design, realization, and testing of a low-frequency impedance measurement platform. The realized system is portable, low-cost, and highly versatile. Signal generation and analysis are realized based on a personal computer and a soundboard. The implemented platform is adaptable to different applications with minimal effort.

For embedded impedance spectroscopy, the main challenges are due to limited processing capability and memory availability. To calculate impedance, an AC analysis of both currents and voltages has to be carried out. This can be realized with various methods. In [2], several methods are analyzed in terms of speed, memory requirements, amplitude measurement accuracy, and phase measurement accuracy. A. Y. Kallel et al. show that the linear sine fitting method reaches the highest accuracy in amplitude and phase determination but needs a high processing time and more memory capacity. Other methods, such as the Goertzel algorithm or fast Fourier transform with barycenter correction also have their merits under reduced calculation and storage resources.

3. Characterization of Materials and Systems

Impedance spectroscopy provides interesting possibilities to characterize materials based on their complex electrical behavior. The characterization of pharmaceutical materials

Citation: Kanoun, O.; Himmel, J.; Errachid, A. Impedance Spectroscopy and Its Application in Measurement and Sensor Technology. *Appl. Sci.* **2023**, *13*, 244. https://doi.org/10.3390/app13010244

Received: 19 December 2022
Accepted: 20 December 2022
Published: 25 December 2022

is essential for drug discovery, development, and evaluation. In [3], Vázquez-Nambo et al. carried out an EIS-based analysis in a wide frequency range from 20 Hz to 30 MHz of four drug formulations (trimethoprim/sulfamethoxazole $C_{14}H_{18}N_4O_3$-$C_{10}H_{11}N_3O_3$, ambroxol $C_{13}H_{18}Br_2N_2O.HCl$, metamizole sodium $C_{13}H_{16}N_3NaO_4S$, and ranitidine $C_{13}H_{22}N_4O_3S.HCl$). Based on arrays of linear R-C models, the different compounds could be differentiated.

For continuous production in the pharma industry, additional instrumentation to optimize material flow will be needed. Tableting manufacturing has high requirements concerning changes in flow conditions of raw materials, which may lead to a lack of reproducibility. In [4], M. Ghita et al. show how, with impedance spectroscopy supported by an online identification of generalized order parametric models, changes in material properties can be tracked by correlation of the model parameters. The proposed solution is easy to implement and provides significant added value to the pharmaceutical industry.

Battery cell characterization is also a classical use case for impedance spectroscopy. Due to the advancement of electro-mobility, the need for online diagnostic methods for batteries is increasing. State-of-health (SoH) estimation can be carried out based on a modeling approach. The most common method is thereby to model the acquired impedance spectrum with equivalent circuits and focus on the most sensitive parameters, namely the charge-transfer resistance. In [5], A. Y. Kallel et al. introduce a detailed model of a battery cell. Based on the physical meaning of the model parameters, a novel approach is proposed for SoH assessment combining parameters of the impedance spectrum by building the ratio of the solid electrolyte interphase (SEI) resistance to the total resistance of SEI and the charge transfer. This ratio characterizes the charge-transfer efficiency at the electrodes' surfaces and should decrease systematically with SoH and show a systematic correlation to the number of charging cycles on individual cell parameters, providing the basis of a novel online SoH assessment method.

4. Advanced Sensors

Impedimetric sensors are manifold and can be developed for manifold applications. In [6] K. Jin et al. realized an immune sensor for label-free and rapid detection of antigens with a low detection limit and a broad linear detection range of 0.01–10 ng/mL. The experimental results show that the realized impedimetric sensor based on PEN flexible materials is suitable for immunoassay experiments.

For the detection of anal sphincter injuries occurring during natural deliveries, a rectal probe called the ONIRY Probe has been designed. In [7], M. Młyńczak et al. carried out clinical studies on twenty women after natural delivery who were enrolled in the study and divided into two groups referring to the stage of a perineal tear. Several diagnostic tests have been carried out in addition to impedance spectroscopy including three-dimensional endo-anal ultrasound, anorectal manometry, and physical examination as a reference. The results show that impedance spectroscopy is a promising diagnostic technique for anal sphincter injury detection.

The measurement of soil parameters can provide important information about the stability of earthwork structures. In [8], C. Clemens et al. propose the use of impedance spectroscopy to measure changes in density and volume caused by contact erosion. Experimental investigations show a correlation between the volume change of the soils and impedance values. Several investigations have proven that material transport can be detected by impedance spectroscopy.

5. Future of Impedance Spectroscopy

Although this Special Issue provides a good collection of advances in the field of impedance spectroscopy showing up-to-date methodology development and applications, further research is expected in the future. An increase in the demand for impedance spectroscopy-based devices in industrial applications can be observed today. Thereby, the need for portable and embedded measurement systems will also increase. There is a further trend towards the diversification of solutions for measurement and sensor technology. The non-invasiveness of the method and the possibility to track material and system states at relatively low costs also make it attractive for the control and quality improvement of processes in the environment and industry as with health monitoring and sensor applications [9].

Author Contributions: Conceptualization, O.K., A.E. and J.H.; methodology, O.K.; formal analysis, J.H.; investigation, O.K.; writing—original draft preparation, O.K.; writing—review and editing, J.H.; supervision, A.E. All authors have read and agreed to the published version of the manuscript.

Acknowledgments: This Special Issue has been initiated as an activity of the IEEE Technical Committee on Impedance Spectroscopy (TC-2) within the IEEE Instrumentation and Measurement Society during the International Workshop on Impedance Spectroscopy (IWIS), which takes place every year at Chemnitz University of Technology [10]. We thank all the authors for their valuable contributions and the peer reviewers for their tremendous efforts in reviewing the submissions to this Special Issue. The journal team are thanked for their tireless editorial support, quick responses, and management, which contributed to the high satisfaction of all contributors and the success of the Special Issue.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Scandurra, G.; Arena, A.; Cardillo, E.; Giusi, G.; Ciofi, C. Portable and Highly Versatile Impedance Meter for Very Low Frequency Measurements. *Appl. Sci.* **2021**, *11*, 8234. [CrossRef]
2. Kallel, A.Y.; Hu, Z.; Kanoun, O. Comparative Study of AC Signal Analysis Methods for Impedance Spectroscopy Implementation in Embedded Systems. *Appl. Sci.* **2022**, *12*, 591. [CrossRef]
3. Vázquez-Nambo, M.; Gutiérrez-Gnecchi, J.-A.; Reyes-Archundia, E.; Yang, W.; Rodriguez-Frias, M.-A.; Olivares-Rojas, J.-C.; Lorias-Espinoza, D. Experimental Study of Electrical Properties of Pharmaceutical Materials by Electrical Impedance Spectroscopy. *Appl. Sci.* **2020**, *10*, 6576. [CrossRef]
4. Ghita, M.; Birs, I.; Copot, D.; Nascu, I.; Ionescu, C.M. Impedance Spectroscopy Sensing Material Properties for Self-Tuning Ratio Control in Pharmaceutical Industry. *Appl. Sci.* **2022**, *12*, 509. [CrossRef]
5. Kallel, A.Y.; Petrychenko, V.; Kanoun, O. State-of-Health of Li-Ion Battery Estimation Based on the Efficiency of the Charge Transfer Extracted from Impedance Spectra. *Appl. Sci.* **2022**, *12*, 885. [CrossRef]
6. Jin, K.; Zhao, P.; Fang, W.; Zhai, Y.; Hu, S.; Ma, H.; Li, J. An Impedance Sensor in Detection of Immunoglobulin G with Interdigitated Electrodes on Flexible Substrate. *Appl. Sci.* **2020**, *10*, 4012. [CrossRef]
7. Młyńczak, M.; Rosoł, M.; Spinelli, A.; Dziki, A.; Wlaźlak, E.; Surkont, G.; Krzycka, M.; Pająk, P.; Dziki, Ł.; Mik, M.; et al. Obstetric Anal Sphincter Injury Detection Using Impedance Spectroscopy with the ONIRY Probe. *Appl. Sci.* **2021**, *11*, 637. [CrossRef]
8. Clemens, C.; Radschun, M.; Jobst, A.; Himmel, J.; Kanoun, O. Detection of Density Changes in Soils with Impedance Spectroscopy. *Appl. Sci.* **2021**, *11*, 1568. [CrossRef]
9. Kanoun, O.; Kallel, A.Y.; Nouri, H.; Atitallah, B.B.; Haddad, D.; Hu, Z.; Talbi, M.; Al-Hamry, A.; Munja, R.; Wendler, F.; et al. Impedance Spectroscopy: Applications, Advances and Future Trends. *IEEE Instrum. Meas. Mag.* **2022**, *25*, 11–21. [CrossRef]
10. International Workshop on Impedance Spectroscopy (IWIS). Available online: https://www.tu-chemnitz.de/etit/messtech/iwis/ (accessed on 19 December 2022).