

## Electrochemical Impedance Spectroscopy (EIS): A Powerful and Cost-Effective Tool for Fuel Cell Diagnostics

Electrochemical Impedance Spectroscopy (EIS) is a powerful diagnostic tool that you can use to characterize limitations and improve the performance of fuel cells. There are three fundamental sources of voltage loss in fuel cells: charge transfer activation or “kinetic” losses, ion and electron transport or “ohmic” losses, and concentration or “mass transfer” losses. Among other factors, EIS is an experimental technique that can be used to separate and quantify these sources of polarization. By applying physically-sound equivalent circuit models wherein physiochemical processes occurring within the fuel cell are represented by a network of resistors, capacitors and inductors, you can extract meaningful qualitative and quantitative information regarding the sources of impedance within the fuel cell. EIS is useful for research and development of new materials and electrode structures, as well as for product verification and quality assurance in manufacturing operations.

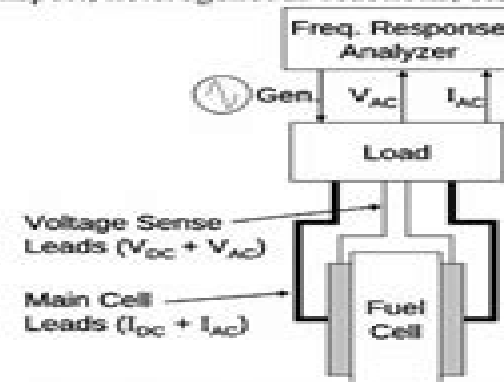
This article provides a quick primer on EIS with an introduction to its application in fuel cell testing and research.

### Instrumentation and measurement basics

During an impedance measurement, a frequency response analyzer (FRA) is used to impose a small amplitude AC signal to the fuel cell via the load (**Figure 1**). The AC voltage and current response of the fuel cell is analyzed by the FRA to determine the resistive, capacitive and inductive behavior - the impedance - of the cell at that particular frequency. Physicochemical processes occurring within the cell – electron & ion transport, gas & solid phase reactant transport, heterogeneous reactions, etc. – have different characteristic time-constants and therefore are exhibited at different AC frequencies. When conducted over a broad range of frequencies, impedance spectroscopy can be used to identify and quantify the impedance associated with these various processes.

#### Advantages of EIS:

- Measurements can be made under real-world fuel cell operating conditions, *e.g.*, open circuit voltage or under load (DC voltage or current).
- Multiple parameters can be determined from a single experiment.
- Relatively simple electrical measurement that can be automated.
- Can verify reaction models, and characterize bulk and interfacial properties of the system, *e.g.*, membrane resistance and electrocatalysts.
- Measurement is non-intrusive – does not substantially remove or disturb the system from its operating condition.
- A high precision measurement – the data signal can be averaged over time to improve the signal-to-noise ratio.



**Figure 1. Instrumentation for EIS of fuel cells.**

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**British Standards Institute Staff**



### **Scribner Associates Tutorial Electrochemical Impedance Spectroscopy Eis:**

*Tutorials in Electrochemical Technology: Impedance Spectroscopy*, An Introduction to Electrochemical Impedance Spectroscopy Ramanathan Srinivasan, Fathima Fasmin, 2021-05-03 This book covers the fundamental aspects and the application of electrochemical impedance spectroscopy EIS with emphasis on a step by step procedure for mechanistic analysis of data It enables the reader to learn the EIS technique correctly acquire data from a system of interest and effectively interpret the same Detailed illustrations of how to validate the impedance spectra use equivalent circuit analysis and identify the reaction mechanism from the impedance spectra are given supported by derivations and examples MATLAB programs for generating EIS data under various conditions are provided along with free online video lectures to enable easier learning Features Covers experimental details and nuances data validation method and two types of analysis using circuit analogy and mechanistic analysis Details observations such as inductive loops and negative resistances Includes a dedicated chapter on an emerging technique Nonlinear EIS including code in the supplementary material illustrating simulations Discusses diffusion constant phase element porous electrodes and films Contains exercise problems MATLAB codes PPT slide and illustrative examples This book is aimed at senior undergraduates and advanced graduates in chemical engineering analytical chemistry electrochemistry and spectroscopy

Electrochemical Impedance Spectroscopy and its Applications Andrzej Lasia, 2014-06-17 This book presents a complete overview of the powerful but often misused technique of Electrochemical Impedance Spectroscopy EIS The book presents a systematic and complete overview of EIS The book carefully describes EIS and its application in studies of electrocatalytic reactions and other electrochemical processes of practical interest This book is directed towards graduate students and researchers in Electrochemistry Concepts are illustrated through detailed graphics and numerous examples The book also includes practice problems Additional materials and solutions are available online

**Electrochemical Impedance Spectroscopy** Mark E. Orazem, Bernard Tribollet, 2017-04-24 Provides fundamentals needed to apply impedance spectroscopy to a broad range of applications with emphasis on obtaining physically meaningful insights from measurements Emphasizes fundamentals applicable to a broad range of applications including corrosion biomedical devices semiconductors batteries fuel cells coatings analytical chemistry electrocatalysis materials and sensors Provides illustrative examples throughout the text that show how the principles are applied to common impedance problems New Edition has improved pedagogy with more than twice the number of examples New Edition has more in depth treatment of background material needed to understand impedance spectroscopy including electrochemistry complex variables and differential equations New Edition includes expanded treatment of the influence of mass transport and kinetics and reflects recent advances in understanding frequency dispersion and constant phase elements

**Fast Electrochemical Impedance Spectroscopy** Pavle Boškoski, Andrej Debenjak, Biljana Mileva Boshkoska, 2017-05-07 This book offers a review of electrochemical impedance spectroscopy EIS and its application in online

condition monitoring of electrochemical devices focusing on the practicalities of performing fast and accurate EIS The first part of the book addresses the theoretical aspects of the fast EIS technique including stochastic excitation signals time frequency signal processing and statistical analysis of impedance measurements The second part presents an application of the fast EIS technique for condition monitoring and evaluates the performance of the proposed fast EIS methodology in three different types of electrochemical devices a Li ion battery a Li S cell and a polymer electrolyte membrane PEM fuel cell Uniquely in addition to theoretical aspects the book provides practical guidelines for implementation commissioning and exploitation of EIS for condition monitoring of electrochemical devices making it a valuable resource for practicing engineers as well as researchers

**Impedance Spectroscopy** Vadim F. Lvovich, 2015-11-30 This book presents a balance of theoretical considerations and practical problem solving of electrochemical impedance spectroscopy This book incorporates the results of the last two decades of research on the theories and applications of impedance spectroscopy including more detailed reviews of the impedance methods applications in industrial colloids biomedical sensors and devices and supercapacitive polymeric films The book covers all of the topics needed to help readers quickly grasp how to apply their knowledge of impedance spectroscopy methods to their own research problems It also helps the reader identify whether impedance spectroscopy may be an appropriate method for their particular research problem This includes understanding how to correctly make impedance measurements interpret the results compare results with expected previously published results form similar chemical systems and use correct mathematical formulas to verify the accuracy of the data Unique features of the book include theoretical considerations for dealing with modeling equivalent circuits and equations in the complex domain review of impedance instrumentation best measurement methods for particular systems and alerts to potential sources of errors equations and circuit diagrams for the most widely used impedance models and applications figures depicting impedance spectra of typical materials and devices extensive references to the scientific literature for more information on particular topics and current research and a review of related techniques and impedance spectroscopy modifications

**Electrochemical Impedance Spectroscopy** Marwa El-Azazy, Mart Min, Paul Annus, 2020

*Electrochemical Impedance* John R. Scully, 1993 The collection of twenty seven papers published has been grouped into six major categories corrosion process characterization and modeling applications of Kramers Kronig transformations for evaluating the validity of data corrosion and its inhibition by either corrosion products of specially added inhibitors corrosion of aluminum and aluminum alloys corrosion of steel in soils and concrete and evaluation of coatings on metal substrates

Electrochemical Impedance Spectroscopy: Modelling and Interpretation , 2013 *Electrochemical Impedance Spectroscopy* Jennie Brock, 2017 In Chapter One the authors review the recent developments in the field of electrochemical impedance spectroscopy discuss some of the challenges and compare EIS with the other relevant techniques The effect of storage time without use STWU in the supporting electrolyte solution on the conducting properties of poly o aminophenol

POAP film electrodes was studied in Chapter Two In Chapter Three the authors study the effect of the cerium content on the corrosion behavior of Al<sub>85</sub>Ce<sub>x</sub>Ni<sub>15-x</sub> x = 4, 5, 6, 7 and 10 amorphous alloys obtained by melt spinning

**Impedance Spectroscopy** Evgenij Barsoukov, J. Ross Macdonald, 2018-03-19 The Essential Reference for the Field Featuring Protocols Analysis Fundamentals and the Latest Advances Impedance Spectroscopy Theory Experiment and Applications provides a comprehensive reference for graduate students researchers and engineers working in electrochemistry physical chemistry and physics Covering both fundamentals concepts and practical applications this unique reference provides a level of understanding that allows immediate use of impedance spectroscopy methods Step by step experiment protocols with analysis guidance lend immediate relevance to general principles while extensive figures and equations aid in the understanding of complex concepts Detailed discussion includes the best measurement methods and identifying sources of error and theoretical considerations for modeling equivalent circuits and equations in the complex domain are provided for most subjects under investigation Written by a team of expert contributors this book provides a clear understanding of impedance spectroscopy in general as well as the essential skills needed to use it in specific applications Extensively updated to reflect the field's latest advances this new Third Edition Incorporates the latest research and provides coverage of new areas in which impedance spectroscopy is gaining importance Discusses the application of impedance spectroscopy to viscoelastic rubbery materials and biological systems Explores impedance spectroscopy applications in electrochemistry semiconductors solid electrolytes corrosion solid state devices and electrochemical power sources Examines both the theoretical and practical aspects and discusses when impedance spectroscopy is and is not the appropriate solution to an analysis problem Researchers and engineers will find value in the immediate practicality while students will appreciate the hands on approach to impedance spectroscopy methods Retaining the reputation it has gained over years as a primary reference Impedance Spectroscopy Theory Experiment and Applications once again present a comprehensive reference reflecting the current state of the field

Electrochemical Impedance Spectroscopy And Related Techniques: From Basics To Advanced Applications Laurence M Peter, 2023-12-14 This book begins by introducing the basic concepts of impedance to non specialist readers who may have only an elementary knowledge of physics and mathematics Mathematical concepts are explained clearly at appropriate points in a series of Theory Notes Subsequent chapters cover RCL resistor capacitor inductor circuits before developing the key ideas behind the application of impedance spectroscopy to electrochemical systems Circuit elements used to model electron transfer double layer charging and diffusion are described in detail along with Kramers Kronig testing of experimental data The book explains how potentiostats and frequency response analyzers work and evaluates a wealth of experimental data obtained either during the annual Bath impedance courses or in the laboratories of the author and his colleagues Topics covered include not only conventional electrochemical systems such as the rotating disc electrode and ultramicroelectrodes but also unconventional solar cells and the application of frequency

resolved techniques in spectroelectrochemistry Finally the last two chapters introduce techniques based on modulation of light intensity rather than voltage or current The book concludes with worked answers to the problems set out in earlier chapters

**Lecture Notes on Impedance Spectroscopy** Olfa Kanoun,2011-09-07 Impedance Spectroscopy is a powerful measurement method used in many application fields such as electro chemistry material science biology and medicine semiconductor industry and sensors Using the complex impedance at various frequencies increases the informational basis that can be gained during a measurement It helps to separate different ef *Electrochemical Impedance Spectroscopy (EIS) on Coated and Uncoated Metallic Specimens: Collection of data* ,2016

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Paints and Varnishes. Electrochemical Impedance Spectroscopy (EIS) on High-Impedance Coated Specimens. Processing and Analysis of Data from Dummy Cells British Standards Institute Staff,2009-11-30 Paints Varnishes Coatings Electrochemical methods Impedance measurement Spectroscopy Corrosion protection Data acquisition Data representation Test equipment Simulation Circuits

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