Polymer electrolyte fuel cells (PEFCs) remain a serious option to decarbonize the transport sector.\textsuperscript{1} To achieve higher efficiency and lower costs, several topics are still being investigated. One of them, water management, continues to be at the heart of fuel cell research.\textsuperscript{2} Indeed, some related challenges remain partially unanswered. Too little humidification of the membrane leads to low protonic conductivity and therefore suboptimal efficiency. Too much water can lead to flooding, gas starvation or inhomogeneous current density distribution which are all detrimental for the lifetime of the cell or for its operation.\textsuperscript{3,4} Additionally, inhomogeneous membrane hydration may also lead to local hot spots or in plane currents that also impairs the operation and lifetime of the cell. For these reasons, it is important to be able to measure the distribution of the humidification of the membrane.\textsuperscript{5} Ideally, such a diagnostic tool that could even act as an online control system of the PEFC stack needs to be non-invasive and simple in its application. However, no such techniques currently exists as the traditional impedance based methods such as electrical impedance spectroscopy (EIS), high frequency resistance (HFR) or current interrupt method only provide information on the average conductivity of the membrane.\textsuperscript{6} Other methods that provide spatial resolution of membrane conductivity, such as the segmented cell approach require either a specially designed flow field\textsuperscript{8–14} or an additional plate at the position of interest in the stack.\textsuperscript{15,16}

Alternative methods aiming to provide non-invasive local information about a fuel cell stack are being investigated such as external magnetic field measurements\textsuperscript{17} or electrical impedometry tomography (EIT).\textsuperscript{18–20} The magnetic field resulting from the current in a fuel cell stack can be probed with external sensor to provide information on the local current density. Additionally, the application of EIT to PEFCs was proposed\textsuperscript{18} to non-invasively monitor local membrane humidification conditions. The working principle of EIT\textsuperscript{18} is based on successive local alternating current injection and voltage measurements all around the cell thanks to numerous electrodes being placed around the object of interest. The AC amplitude of the boundary voltage measurements (performed on the outer surface of the flow fields in this case) are then related to the inner conductivity distribution of the cell. They represent the local HFR value but are difficult to interpret as their value depends on the electrode positions and the area they characterize is difficult to determine. EIT aims to calculate the inverse problem to obtain the conductivity distribution from boundary voltage measurements. Different methods can be used to solve the inverse problem and to reconstruct the conductivity distributions based on the voltage measurements.\textsuperscript{20} It is however challenging to apply EIT to fuel cells for different reasons: the complex mesh of a fuel cell stack geometry needs to be resolved with high level of details and it is therefore computationally expensive to perform calculations on it and interfacial contact resistance distribution are difficult to quantify to name a few. Therefore, this work focuses on an experimental approach and aims to relate local voltage variation to local membrane conductivity and thus on local membrane hydration and local relative humidity (RH) conditions based on reference measurements at well-defined RH conditions. It represents an intermediate step towards the application of EIT to PEFCs which allows to determine the local conductivity distribution of any cell in a fuel cell stack based only on surface AC current injections and voltage amplitude measurements without the extensive a-priori requirements to implement EIT on PEFCs. A complex multichannel AC current injection and voltage measurement instrumentation as needed for EIT measurements on PEFCs is implemented and described in detail. The instrumentation is used to implement the local non-invasive impedance measurement approach. To do so, local electrical stimulations are performed at homogeneous RH conditions over the whole cell area to build a relationship between RH and local voltage measurement. The local high frequency resistance of the membrane can then be determined at other conditions by interpolating between these reference measurements for each electrode combination. Finally, the sensitivity of the method to changes of the local membrane hydration is presented and discussed for different test conditions using inert nitrogen flow in anode and cathode flow fields.

**Experimental**

**Fuel cell stack.**—A short stack from SwissHydrogen (Fribourg, Switzerland) is used as test object for this study. It is composed of six cells of 200 cm\textsuperscript{2} active area each and parallel flow field channels. The stack is fed in counter flow configuration with humidified nitrogen on both the anode and the cathode side. The stack is liquid cooled and its temperature is controlled by a thermostat (Huber Pilot One CC 415) and the inlet gas lines are heated in order to avoid any condensation. Two RH sensors (VAISALA HMT310) are mounted
at the outlet of both the cathode and the anode. The different components are shown schematically and in pictures in Fig. 1.

**Local HFR acquisition system.**—The method presented in this manuscript relies on the application of multiple so-called stimulation patterns to the cell of interest in the fuel cell stack. One stimulation pattern corresponds to two electrodes that supply the AC current and the two electrodes that probe the voltage response. The method requires therefore a significant amount of hardware described below: electrodes that contact the cell, a system to position and hold these electrodes, a signal generation and acquisition system to supply current to any pair of electrodes and a voltage measurement system to measure the voltage across any pair of electrodes. The resulting voltages also have to be interpreted and analyzed in a specific way described below.

**Electrodes.**—Dedicated electrodes that enable to contact the cell’s outer flow field surface and to supply current or to probe voltage were implemented for the fuel cell stack. The electrodes have to be able to contact the outer surface of a single flow field at specific positions. A positioning system was designed to accurately place and contact the electrodes on the side of the flow field. It is a 3D printed structure made of non-conductive material with dedicated holes for the electrodes support that is clamped to the stack’s end plates. Spring-loaded pins (GKS-912–0532 from INGUN) are placed in their support (KS-11230 from INGUN) and contact the flow field while the pin’s support provide the interface to the signal generation and acquisition system. As shown in sub Figs. 1c–1d, the pins contact the outer surface of the flow fields. The low signal amplitude (only a few microvolts) probing the electrodes has to be transferred to the data acquisition system in a way that does not change its value or affect its accuracy. For these reasons, shielded coaxial cables (LEMO 00) are chosen to help reduce the noise from the environment.

**Signal generation and acquisition system.**—A dedicated signal generation and acquisition system with components in PXI standard from National Instruments (NI) was implemented to supply current and probe voltage across any pair of electrodes. It includes the following modules:

- High accuracy voltage measurement module (error below 1 microvolt at 10000 samples per second) with eight Analog to Digital Converters (ADCs) and four channels per ADC for a maximum of 32 channels (one channel is defined as one positive wire and one negative wire): NI PXIe-4309.
- Current injection module with 8 channels and up to 20 mA per channel: NI PXIe-4322.
- 512 crosspoints matrix switch to switch the current source to all the electrodes: NI PXIe-2532B.

To maximize the accuracy of the system, the voltage probed by the electrodes is directly read by the voltage measurement module, bypassing the matrix switch. In order to be able to measure the voltage difference all around the cell, it is necessary to introduce one reference voltage probe electrode per voltage difference all around the cell, it is necessary to introduce one reference voltage probe electrode per voltage difference all around the cell, it is necessary to introduce one reference voltage probe electrode per voltage difference all around the cell, it is necessary to introduce one reference voltage probe electrode per voltage difference all around the cell.

During the measurement, current is injected in two neighboring flow fields, through the membrane plane. The current spreading both in plane and through plane induces an in-plane potential distribution. The voltage amplitudes are measured in plane on the same flow field. The measured voltage amplitudes are a function of the resistance on the path of the current and the electrodes position. By doing so, the measured voltage amplitudes will stay independent of the cell voltage during cell operation and the maximum accuracy of the measurement device’s smallest voltage range can be exploited. The current is supplied as 100 consecutive sine waves with an amplitude of 20 mA at a frequency of 1 kHz. The AC voltage perturbation is measured at a sample rate of 100 samples per sine. A sine wave is fitted through all sample points to determine the voltage amplitude, the offset and the phase shift with high accuracy.21

Additionally, the HFR of the cell of interest is also measured with the same system by supplying an AC current (120 mA at 1 kHz by connecting six current supply channels in parallel in the matrix switch) through the end plates and measuring the voltage response using two electrodes on neighboring flow fields. The two voltage sense electrodes are located both at about the center in the along the channel direction. Sub Fig. 1a shows a simplified schematic representation of the current setup with a reduced amount of the connections. All channels of the current supply module are connected to the matrix switch such that the AC current signal can be injected into any combination of the electrodes besides the two reference voltage probes. This way, it is also possible to combine multiple channels from the current supply module within the matrix switch to supply more than 20 mA. The other end of the matrix switch as well as the voltage measurement module are connected to a PCB. The PCB provides the hard-wired junctions needed to connect the PXI modules with the electrodes attached to the fuel cell stack. Four electrode connections are shown in sub Fig. 1a. Channel 1 and 2 of the matrix switch are connected to electrodes on the bottom flow field, which are also connected to the channels 1 and 2 of the first ADC (there are four channels per ADC but only 2 are shown as example in the scheme). The other pole of these channels are connected to the reference voltage probe at the bottom flow field. Similarly, channels 31 and 32 of the matrix switch are connected to electrodes on the top flow field and to the channels 1 and 2 of the fifth ADC. In total 30 channels of the matrix switch are connected to 30 electrodes at both the bottom and top flow field (the two remaining channels are used to supply current to the end plate for the global cell HFR measurement), which are linked to the ADC 1 to 4 and 5 to 8 of the voltage measurement module, respectively. The matrix switch, voltage measurement module and current supply module are integrated in a chassis which is controlled by a measurement PC.

**Local HFR interpretation.**—To acquire local HFR information, current is injected through the membrane via the flow field outer surface and the induced voltage is measured. The set of four electrodes that supply the current and probe the voltage is named stimulation pattern. Four stimulation patterns are chosen to characterize four domains along the channel direction.

Each of the measurement is individually calibrated with known inlet gases humidity conditions. For this purpose, nitrogen is used on both the anode and the cathode side in order to have controlled humidity conditions with no electrochemical operation of the stack. Constant RH conditions at the inlet of both anode and cathode are used to establish different homogeneous levels of humidity in the membrane as the stack is operated in counter-flow configuration. The four stimulation patterns are applied one after the other through each RH step. This allows to create a lookup table with the voltage values corresponding to different RH conditions for the four domains from cathode inlet to cathode outlet. Then, when new conditions are set or when the stack would be operated, one can simply use the lookup table on the newly measured voltage value to interpolate back the actual humidity condition. Using the cell’s global HFR values based on the endplate current injection a second lookup table is created that relates the local voltage amplitudes with the measured cell HFR at each RH condition. This allows to determine quantitative local HFR values and their distribution in the cell.

The reference measurements furthermore cancel out effects unrelated to cell humidification such as contact resistance.
Figure 1. (a) Schematic representation of the signal generation (current supply module and matrix switch) and the acquisition (voltage measurement module) system, the PCB for hardwired connections between the electrodes at the flow field and the modules of in the PXI chassis. (b) Overview picture of the main components. (c) Close-up picture of the pins including: in gold on the left, the pin’s support and the pins, in black in the middle, the frame to position the pins clamped to the compressing plate and in grey on the right, the flow fields that are contacted by the pins. (d) Schematic of the pin positioning system.
However, it is therefore required to perform the reference measurements at different RH conditions at least once before actual measurements and repeat them from time to time for recalibration.

**Model based stimulation pattern selection.**—The finite element model described in Ref. 18 is used to calculate the distribution of the current through the membrane to verify the assumption that local AC current injection can provide local HFR information. It uses EIDORS\(^{22}\) to solve the continuum Kirchhoff’s law on a mesh of finite element and to visualize the path of the current through the membrane and the resulting potential. It includes a simplified fuel cell geometry with a given conductivity for each component. A current of 20 mA is supplied using the same electrodes locations as on the real stack and the equations are solved by EIDORS.

**Experimental conditions.**—Figure 2 shows the different protocols used in this study. In Fig. 2a, the protocol to obtain the reference measurements is represented: it includes nine different RH steps from 46% to 98% RH. Each condition is held for one hour to let the cell reach a steady state. Figure 2b shows the test protocol including the following conditions:

- Constant RH on one side and gradually increasing RH on the other side (60 to 750 min).
- Constant and symmetrical RH conditions (different than the reference cases; 800 to 1050 min).
- Asymmetrical RH conditions with varying mass flow rate (1100 to 1900 min).

The stack is being dried with a lower RH (42%) between each of these test cases. Each step is executed for one hour. The test protocol is repeated three times in order to obtain statistical evidence and quantify the reproducibility of the method.

**Results and Discussion**

Four stimulation patterns were chosen to characterize four different zones along the channel of the fuel cell. The four electrodes located close to the active area of the cell are used to supply current and the same electrode positions but in the other flow field of the cell are used to sink the current (as shown in Fig. 3a with the colored circles). The voltage measurement is between the neighboring electrode (on the same flow field) (as shown in Fig. 3a with the grey circles with colored edges) and the corresponding reference voltage probe electrode (as shown in Fig. 3a with the grey circle). The through the membrane plane current distribution was calculated based on the voltage/RH relationship calibration. It includes a finite element and to visualize the path of the current through the membrane and the resulting potential. It includes a simplified fuel cell geometry with a given conductivity for each component. A current of 20 mA is supplied using the same electrodes locations as on the real stack and the equations are solved by EIDORS.

**Interpretation of local voltages.**—Figure 3b shows the voltage amplitude response to the changes in RH of the calibration data for the different stimulation patterns representing the zones shown in Fig. 3a. As the membrane conductivity increases with increasing RH because of water absorption,\(^{23}\) the measured voltage amplitudes decrease as the local resistances decrease. A similar behavior is observed for all of the four stimulation patterns even though the dependency of the voltage amplitudes on RH is not the same. The absolute value of the measured voltage amplitudes and their dependency on the RH depend on different parameters:

- The amplitude of the supplied current.
- The area of the membrane being probed which may differ depending on where the current is supplied as displayed in Fig. 3a.
- The geometry and the conductivity of the flow field, GDL and membrane (and the contact resistance between them) as they will dictate the path of the current and the contribution of the membrane resistance with respect to the other contributions (contact resistance and flow field resistance).
- The position of the two voltage measurement electrodes. As shown by the equipotential lines in Fig. 3a, if they are both far away from the current supply zone, the value will be very low and if one is close to the current supply zone and the other is far, the value will be higher.

All of these parameters influencing the voltage measurement values make it very difficult to interpret them without reference measurements. A linear interpolation between the measured calibration RH conditions is therefore used to calculate the local RH. For a new measurement with unknown RH conditions, the voltage reading can be translated into the RH at each location along the channel based on the voltage/RH relationship calibration.

The RH representation is shown because it is easy to relate the test cases and the reference cases. However, 50% of RH means that the membrane hydration is at a level similar to an inlet flow of nitrogen in the channel of 50% humidity during calibration. During cell operation the product water will result in a mismatch to this membrane hydration and channel RH relationship. Therefore, also a
local HFR scale is introduced: it allows a quantitative analysis and it enables the comparison of the local HFR distribution to the global cell HFR. Figure 3c shows the relationship between the voltage amplitudes of the four stimulation patterns and the overall cell HFR for each of the nine RH conditions. The same interpolation between the calibration values can be done for the local HFR values as described for the local RH values. The HFR of the cells was found to be higher than expected for sub-50 um membranes used in the stack, which was due to degradation of the stack that was in a state near end of life. For this proof-of-principle study consisting of in situ tests only, the state of health of the stack and its actual HFR range are considered as irrelevant.

Reproducibility.—First, the reproducibility of the approach is assessed by applying symmetrical and constant RH inlet conditions at different levels than in the calibration protocol and comparing the results with the set point, the RH sensors data and the cell HFR data. The calculated and known RH distributions are compared for symmetrical RH conditions as shown in Fig. 4a. The dashed lines are to be compared with the dotted lines of the same color and the RH sensor data. The dotted lines represent the along the channel RH distribution expected from the symmetrical RH set point. The filled circles represent the reconstructed value for each of the four stimulation patterns and the dashed lines are the second order polynomial fit through the four points and represent the reconstructed RH distribution. The x-axis error bars represent the uncertainty in the exact location along the channel that each measurement characterizes. There is a very good match of the calculated RH distribution with the expected one from the set point. The error stays below 1% in all the tested cases. The comparison with the outlet RH sensor data shows a slight offset of around 3.5 RH percentage point in all the cases. It is assumed to be an error of the sensor despite their thorough calibration as they also show the same mismatch with the set point.

The results of the same experiment with the local HFR representation are displayed in Fig. 4b. In this representation, the local HFR distribution is to be compared with the global cell HFR shown with the dotted line. There again, the match is very good with an error below 1% for all of the tested cases. The results are shown as the mean of three experiments with y-axis error bars showing the range of the measurements in these three experiments. The reproducibility is excellent and the error bars are therefore not visible at this scale.

Sensitivity.—RH distributions determined for non-symmetrical conditions are shown in Figs. 5a and 5b. The y-axis representing the RH is meant as the membrane hydration corresponding to nitrogen being flushed on both sides at the same RH. In each experiment, the inlet humidity of either the cathode(5a) or the anode(5b) is kept constant at 50% RH while on the other side, the humidity is increased from 50 to 90% in 10 percentage points steps. As the stack is connected in a counter-flow configuration, those asymmetric RH inlet conditions lead to a gradient in humidity along the channel as the membrane equilibrates the humidity between anode and cathode.

In the RH representation, for this specific example of same mass flow rate at anode and cathode, the membrane hydration at the inlet where the feed gas RH is kept constant shows little change while the membrane hydration at the other inlet is gradually increasing. Comparing the determined outlet RH to the RH sensor data shows a good match of the general behavior. There is however still an
offset similar to the one already shown in the constant symmetrical RH case. Additionally, in the case where the anode inlet is kept constant, there is almost no change in the measured RH while the RH sensor shows around 2 percentage point increase at each RH step. This mismatch can be explained by the fact that the exact localization along the channel of the four stimulation patterns is uncertain. The localization are chosen at the position of the electrodes but as current spreads through a zone of a few square centimeters, it is challenging to accurately assign a precise location for each of the stimulation patterns.

In the local HFR representation, one can compare the parallel sum average of the local HFR distribution and the global cell HFR displayed in dotted lines. In the first case where the anode inlet RH is kept constant, the error between the cell HFR and the average distribution ranges from 0.9 to 7.4% and the second case where the cathode RH is kept constant, the error ranges from 0.4 to 5.4%. The match is quite good and the error can again be explained by the uncertain location of the four stimulation patterns. Again, the results are highly reproducible in all the cases and do not allow to distinguish the error bars at this scale.

Figure 4 shows the RH and HFR distribution in a case where there is a high inlet RH (89%) on one side and a low RH (51%) on the other side for varying mass flow rates. Indeed, different mass flow rates and therefore different gas velocities in the channels lead
to different shapes of the humidity profiles. It is important to note that when the mass flow rates are equal on both sides, the gas velocity in the anode channels is twice the gas velocity of the cathode because of the channel design difference between anode and cathode. It is clear from both experiments that the RH of the side with the highest mass flow rate is dominating the average humidity. When the MFR on the wet anode side is twice the MFR on the dry cathode side (Fig. 6a), around 70% of the cell area is above 85% RH. Similarly, when the MFR on the dry cathode side is twice the MFR on the wet anode side, around 60% of the cell is below 60% RH. A similar behavior can be seen when the cathode is wet and the anode is dry (Fig. 6b). The shape of the distribution slightly differs because the cell is not symmetrical (different channel geometries and GDL dimensions). Both in Figs. 6a and 6b, the RH profiles tend to be flatter at the inlet where the MFR is higher than the other inlet.

When comparing the RH distributions with the outlet RH sensors in Figs. 6a–6d, it is important to keep in mind that what is measured is the average of the membrane humidity and that there exists a through plane gradient of humidity from the membrane to the channel. The channel RH is therefore compared with the mean of the membrane RH and are not supposed to be perfectly equal. Moreover, the mismatch is mostly explained by the offset already discussed previously and the possible mispositioning of the measurement point which may need to be more towards the anode inlet.

Looking at the local HFR representation in Figs. 6c–6d, the error between the parallel sum average HFR obtained from the calculated distribution and the measured global cell HFR ranges from 1.9 to 7% when the anode RH is high and from 0.9 to 12.1% when the cathode RH is high. The highest error in Figs. 6c and 6d is reached in the case where the anode MFR is 4 l min⁻¹ and the cathode MFR is 8 l min⁻¹. Both those profiles exhibit a steep slope towards the anode inlet side and is therefore more prone to a mispositioning of the measurement closest to the anode inlet. This behavior seems to indicate that the measurement point closest to the anode inlet should be located more to the right: the parallel sum of the local HFRs would fit better the global cell HFR if this were the case. The exact localization of these measurements points will require further attention in the future.

Conclusions

A new noninvasive method, able to provide local HFR information in PEFCs is presented. It relies on local AC current injection and voltage measurements on the flow field’s outer surface made at different locations around the cell. For this purpose, a multichannel high accuracy signal generation and data acquisition system was designed and adapted for fuel cell application on a linear cell short stack.

The locally measured impedances depend on many parameters like membrane and catalyst layer hydration, the area the current crosses the membrane in through-plane direction due to in-plane conduction within the flow field plate and MEA, conductivity of the flow field plate and MEA, contact resistances between the different layers of the cells and the positioning of current injecting and sensing electrodes. In particular, the reading of the voltage probe electrodes is highly sensitive to their position on the flow field’s outer surface and difficult to interpret. The local impedance values of the individual electrode combinations are therefore calibrated vs homogeneous humidity conditions and global cell high frequency measurements which allow to conclude from the local impedance on the corresponding local RH or high frequency resistance in a localized domain near the current injecting electrodes on the flow field’s outer surface.

The applicability of the approach was confirmed using different symmetric inlet RH as well as asymmetrical RH conditions between anode and cathode without electrochemical cell operation. A very

Figure 6. (a)–(b) Reconstructed RH distribution for an asymmetrical RH condition at different mass flow rates. The y-axis RH representation corresponds to the local membrane hydration observed with nitrogen being flushed at the same RH in both flow fields. (c)–(d) Reconstructed HFR distribution for an asymmetrical RH condition at different mass flow rates.
good match between the obtained results and the values of the outlet RH sensors and to the global cell HFR was found. The sensitivity of the method was also demonstrated by depicting how the distribution of membrane hydration varies with the mass flow rate at constant asymmetrical RH conditions.

This work presents a proof of concept of the technique’s local sensitivity although some uncertainty on the exact localization of each measurement remains. However, more complex stimulation patterns combined with an in-depth analysis of the localization of their sensitivity could drastically increase the resolution and the robustness of the method. Future work will explore the approach to measure the local HFR distribution in operating fuel cells, increasing the spatial resolution and enable also two dimensional HFR distribution mapping. Furthermore, insights into the behavior in high humidity conditions seem possible by incorporating lower stimulation frequencies to enable and simplify local impedance spectroscopy without the need of segmented flow fields or stack inserts.

Acknowledgments

The authors would like to acknowledge the Swiss Federal Office of Energy (SFOE) for financial support under grant no. 501860-01, Patrick Pollet and his team for designing and assembling the printed circuit board, Thomas Gloor for the test bench hardware and software support and Felix Büchi for the valuable discussions and feedback (all PSI). Finally, the authors would also like to thank Evrem Yarkin from NI for the discussions and the support.

ORCID

A. Schuller https://orcid.org/0000-0001-5516-6743
T. J. Schmidt https://orcid.org/0000-0002-1636-367X
J. Eller https://orcid.org/0000-0002-9348-984X

References

1. S. Dunn, Int. J. Hydrogen Energy, 27, 235 (2002).
2. Y. Wang, K. S. Chen, J. Mishler, S. C. Cho, and X. C. Adroher, Appl. Energy, 88, 981 (2011).
3. W. Schmittinger and A. Vahidi, J. Power Sources, 180, 1 (2008).
4. H. Li et al., J. Power Sources, 178, 103 (2008).
5. P. Ren, P. Pei, Y. Li, Z. Wu, D. Chen, and S. Huang, Prog. Energy Combust. Sci., 80, 100859 (2020).
6. M. M. Mench (ed.), Fuel Cell Engines (Wiley, Hoboken, NJ) p. 453 (2008).
7. X. Yuan, H. Wang, J. Colin Sun, and J. Zhang, Int. J. Hydrogen Energy, 32, 4365 (2007).
8. N. Rajalakshmi, J. Power Sources, 112, 331 (2002).
9. S. J. C. Cleghorn, C. R. Derouin, M. S. Wilson, and S. Gottesfeld, J. Appl. Electrochem., 28, 663 (1998).
10. S. A. Freunberger, I. A. Schneider, P.-C. Sui, A. Wokaun, N. Djilali, and F. N. Büchi, J. Electrochem. Soc., 155, B704 (2008).
11. I. A. Schneider, H. Kuhn, A. Wokaun, and G. G. Scherer, J. Electrochem. Soc., 152, A2383 (2005).
12. D. Gerteisen, N. Zamel, C. Sadeler, F. Geiger, V. Ludwig, and C. Hebling, Int. J. Hydrogen Energy, 37, 7736 (2012).
13. X.-G. Yang, N. Burke, C.-Y. Wang, K. Tajiri, and K. Shinohara, J. Electrochem. Soc., 152, A759 (2005).
14. T. V. Reshetenko, G. Bender, K. Bethune, and R. Rocheleau, Electrochim. Acta, 56, 8700 (2011).
15. Splus, (http://splusplus.com/measurement/en/cslin.html) (accessed February 18, 2019).
16. Y.-H. Lai, K. M. Rahmooler, J. H. Hurst, R. S. Kukejja, M. Atwan, A. J. Maslyn, and C. S. Gittelman, J. Electrochem. Soc., 165, F3217 (2018).
17. M. Le, N. O. Chadebe, G. Cauldwell, S. Rosini, and Y. Buttel, J. Appl. Electrochem., 45, 667 (2015).
18. A. Schuller, T. J. Schmidt, and J. Eller, J. Electrochem. Soc., 169, 044525 (2022).
19. T. Murai and Y. Kagawa, IEEE Trans. Biomed. Eng., BME-32, 177 (1985).
20. A. Adler and D. Holder, Electrical Impedance Tomography: Methods, History and Applications (CRC Press, Boca Raton) 2nd ed. (2021).
21. P. Seibold, (2022), (https://mathworks.com/matlabcentral/fileexchange/66793-sinefitting), Retrieved April 4, 2022.
22. N. Polyporides and W. R. B. Lionheart, Meas. Sci. Technol., 13, 1871 (2002).
23. T. A. Zawodzinski, C. Derouin, S. Radzinski, R. J. Sherman, V. T. Smith, T. E. Springer, and S. Gottesfeld, J. Electrochem. Soc., 146, 1041 (1993).