International Conference on Control, Engineering & Information Technology (CEIT'14)
Proceedings - Copyright IPCO-2014, pp.103-108
ISSN 2356-5608

Design and Development of a Labview Application for the Measurement of the Complex Impedance of a Fuel Cell in Real Time

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***Abstract*—To optimize the performance of fuel cells and to deepen the knowledge of their behavior, it is necessary to make measurements in real time. To run such a measure, it is necessary to use specific software and hardware tools to instrumentation fuel cells. In this context, we presented the steps of designing and developing an application for the measurement of the complex impedance by electrochemical impedance spectroscopy method (EIS) using LabVIEW® software. The experimental results are obtained using a Ballard Nexa® PEM fuel cell, an electronic load produced in our laboratory and application developed by the LabVIEW® software.**

Keywords—Impedance Measurement; LabVIEW® Software; Electrochemical Impedance Spectroscopy (EIS); PEM Fuel Cell; Electronic Load

I. Introduction

Fuel cells are presented as a new source of electrical energy, they appear as one of alternative energy for the future because of these benefits that they do not generate pollutants. While the principle of the fuel cell is relatively old, their development has greatly increased in recent years through to technological progress, to environmental awareness and the soaring prices of fossil energy.

During the life cycle of a fuel cell, its performance tends to progressively degrade due to irreversible physical and chemical changes that occur in terms of its using and his age until it is no longer usable. Indeed, the membranes are subjected to the thermodynamic constraints that accelerate exhaustion. One way to know the state of the cells or membranes of a fuel cell is the measurement of the impedance of these cells. Here, we are interested in the measurement of complex impedance of a PEM fuel cell by the electrochemical impedance spectroscopy method (EIS), which tells us about the evolution of the state of the membranes forming the heart of the fuel cell. This method allows making measurements in real time during operation of the fuel cell. This study is part of a global research work that is the study of membrane degradation over time depending on its use and the influence of water management on the degradation of the state of the cells; the project consists in fact in instrumentalize the fuel cell.

II. The Study of the Method for Measuring the Impedance.

A fuel cell is an electrochemical system during the running. It can have a variation of the internal impedance due to the humidification state of the membrane. This variation affects the performance and lifetime of the stack. To do this, it is necessary to make measurements in real time. There exists electrochemical methods such as internal impedance measurement and the non-electrochemical methods to characterize the stack in a global manner.

In this work we have chosen to use an electrochemical method which is the impedance spectroscopy, this choice is due to the fact that this method is non-invasive to the fuel cell and does not influence its operation and does not change its characteristics.

This approach allows us to better understand the physical effects occurring in this type of generator. The impedance spectroscopy method has been used to characterize complex systems around an operating point where it can be considered that variations imposed resulted in a linear variation of the response. The principle of this method is to inject a signal. The most used one is sinusoidal, and it's compared to the output signal. The difference in magnitudes and phase shift between the input signal and the output signal allows us to deduce the value of the impedance at this frequency [1] [2]. By making other measurements at different frequencies, we obtain the impedance spectrum of the object studied. It is the complex impedance of the system as a function of frequency. The plot of this impedance is usually done in the Bode plot or in the Nyquist plot representing the imaginary part as a function of the real part.

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The internal impedance measurement of the fuel cell using the electrochemical impedance spectroscopy exists three methods:

- Potentiostatic method.
- Galvanostatic method.
- Load modulation method.

Our choice was the use of the load modulation method; this method is to vary the resistance of the load depending on the signal that we want to superimpose. Indeed, the complex impedance of the fuel cell can be measured by dividing the Fourier transformed of the voltage by the current from the stack to the frequency of measurement [3] [4] [5]. Fig. 1 shows the principle of load modulation method.

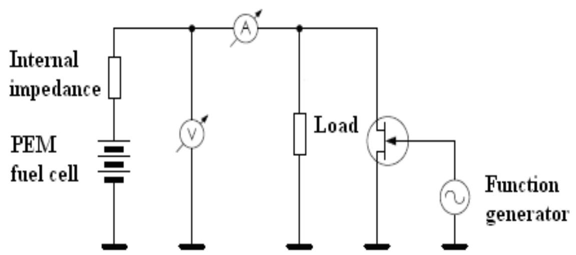

Fig. 1. Principle of the method of the load modulation.

The choice of this method was motivated by the passivity of this technique that does not inject electrical energy to the fuel cell. The other two techniques are more active, which could damage or reverse the chemical reactions at the fuel cell. In order for this method to give a correct result it is necessary that the current response is linear. The fuel cell is in a priori a nonlinear and non-stationary system. Thus we can determine the complex impedance by injecting small amplitude perturbations around an operating point represented by a fixed current which is assumed stationary [3] [4] [6] [7].

The superimposed signal is a sine voltage which can be written as following:

$$V(t) = V_{DC} + V_0 \sin(\omega t) \quad (1)$$

The injected signal V_0 is generally low amplitude for the current response remains linear, so the expression of the current response is:

$$I(t) = I_{DC} + I_0 \sin(\omega t + \theta) \quad (2)$$

θ represents the phase difference between the current and voltage.

The impedance around the operating point (I_{DC}, V_{DC}) is a voltage divided by the current value and admits as:

$$Z(\omega) = \frac{V_0}{I_0} e^{j\theta} \quad (3)$$

Where V_0 and I_0 are the amplitudes of the superimposed voltage ripple and the current passing through it, θ is the phase difference between the sinusoidal perturbations of voltage and current [3-7].

This impedance can be written in the form of a complex number which appears real and imaginary parts:

$$Z(\omega) = \mathrm{Re}(Z(\omega)) + j\,\mathrm{Im}(Z(\omega)) \quad (4)$$

This impedance is defined by a series of values of the frequency of current and voltage signals which can be represented on the Nyquist or Bode plot.

To implement this method, we must make measurements on the fuel cell during the operation to a load, hence the obligation to have an adjustable current load to multiply measurements at different value of the current supplied by the fuel cell, for this we propose two solutions:

- The use of a network of resistors representing a passive load.
- The use of semiconductor components commanded representing an active load.

The first solution has the disadvantage that it does not represent an adjustable resistance. Furthermore, it is difficult to maintain a fixed current during a variation of the output voltage of the fuel cell. Therefore, we chose the second solution that uses semiconductor components to realize an electronic load using MOSFETs. This electronic load prepared for the impedance measurement should require a continuous current to be debited by the fuel cell during the measurement. In this case we realized an electronic load which supports a current of 25A and a voltage of 30 V thus a power of 750 W. For the measurement and display of the complex impedance of the cell, we used the LabVIEW software and data acquisition card from National Instruments NI-9205 connected to a computer to record the measurements and visualize the experimental results.

Fig. 2 shows the block diagram of the electronic load proposed; it describes the various stages that make up the electronic load, the control and the acquisition module for the impedance measurement.

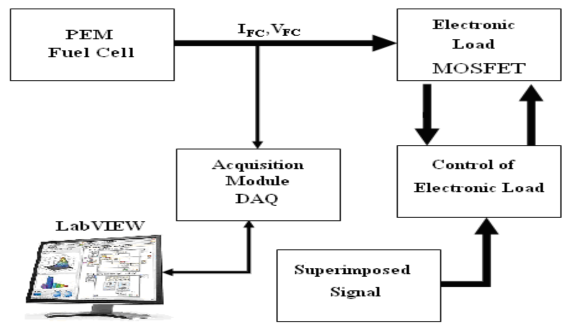

Fig. 2. Block diagram of the electronic load.

The block PEM fuel cell is one that debits the current to be supported by the electronic load, MOSFETs function as a variable resistor controlling voltage. The superimposed signal

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block ensures the injection of the perturbation sinusoidal signal to measure the complex impedance by the principle of electrochemical impedance spectroscopy (EIS), LabVIEW is one that will save the results of the measurement of the complex impedance of the fuel cell through a DAQ card to a file that can be used to view and compare the results found by others in the literature.

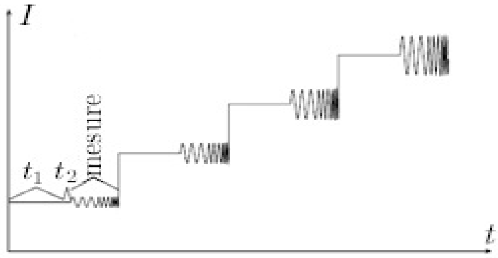

Fig. 3. Measurement of the spectrum at various levels of current as a function of time [8].

The unfolding of such a measure is shown schematically in Fig. 3. At first, it impose the parameters of the measure that is necessarily the current output, the fuel cell is allowed to stabilize for a time t_1. During the period t_2 which is approximately one second, the value of voltage and current are measured, subsequently a signal of the frequency measurement is required and the measurement is performed. After measuring the whole spectrum, the initial parameters can be changed and the measurement starts again. Each measurement value will be saved in a file using the LabVIEW software, this file can be used to compare the results we have found having different results. The maximum injected fuel cell rate is 12 kHz, in practice we had a problem adding perturbation frequency of approximately 50 kHz to the current and voltage signal measured at the terminals of the fuel cell. To get a good measurement of the complex impedance, we added a low pass filter which admits a cutoff frequency of 34 kHz higher than the maximum frequency of the injected signal; the filter is placed at the entrances to the LabVIEW DAQ.

These action steps are used by several industrial equipments such as Agilent® equipment or Gamry® for measuring the complex impedance for fuel cells.

III. The Measurement of the Complex Impedance with LabVIEW® Software

LabVIEW® is a graphical programming platform that helps in designing and testing of systems. It is an ideal software for any measurement or control systems. It includes tools that researchers need to build a wide variety of applications. In our case we used LabVIEW to measure, display the complex impedance with the method of impedance spectroscopy and draw the IV characteristic or polarization curve of the fuel cell using a data acquisition card from National Instruments. This acquisition card or DAQ samples the current and voltage debited by a fuel cell and sends the information of these variables to the software in order to perform the data processing required. The DAQ card from National Instruments NI-9205 [9] is composed of 32 channels of data type analog input with an input voltage signal of ± 10V range. This map includes an analog to digital converter with 16-bit resolution and a sampling rate of 250 kS / s. This card must be inserted into a frame of National Instrument NI CDAQ-9171 which is connected to the computer via a USB cable in order to process the data on the LabVIEW software. The choice of working with this card is due to the reason that it admits a high sampling rate in order to restore the proper shape of the signal voltage and current at the terminals of the stack, besides to its small size and simplicity connection with the computer. In this work we have developed two applications with LabVIEW software, the first to measure and display the complex impedance and the second to draw the polarization curve of the fuel cell.

A. The LabVIEW application for the measurement and display of the complex impedance

LabVIEW application for instrumentation is based on a graphic programming language. A LabVIEW program is composed of a front panel which is the user interface to display the values measured and a block diagram which is the heart of the program. Fig. 4 shows the block diagram of the application developed in LabVIEW to measure and display the complex impedance of the fuel cell.

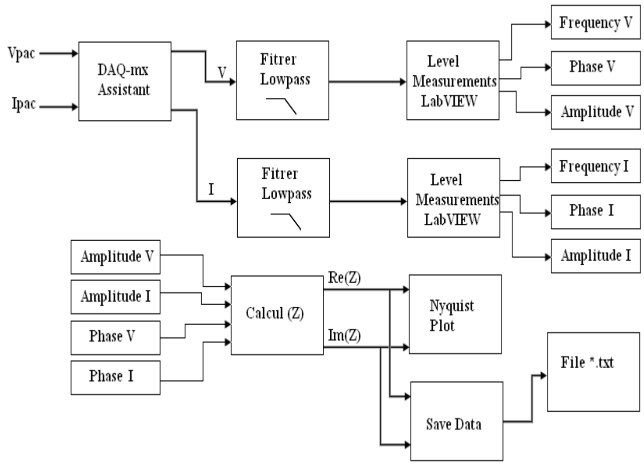

Fig. 4. Block diagram of the LabVIEW application for the measurement and display of the complex impedance

This application consists of multiple stages. We find the block "DAQ-mx Assistant" that integrates hardware driver of the data acquisition card from National Instruments NI-9205. The entry of this card is the signal voltage and current taken at the terminals of the fuel cell. Each signal is then fed to a digital low pass filter to form a good return signals picked. "Level Measurements" LabVIEW block is the one that calculates the parameters for the different measurement such as the frequency, amplitude and phase. To measure the complex impedance we need two essential parameters which are the amplitude and phase of the two signals of voltage and current sampled, the impedance is calculated according to in "(3)" "(4)" defined above. To calculate the real part Re(Z) and the imaginary part Im(Z) we must have V_0, I_0 and θ parameters.

$$\operatorname{Re}(Z) = \frac{V_0}{I_0}\cos(\theta) \qquad (5)$$

$$\operatorname{Im}(Z) = \frac{V_0}{I_0}\sin(\theta) \qquad (6)$$

With:

V_0: the amplitude of the voltage sampled.

I_0: the amplitude of current sampled.

θ: phase difference between the signals of voltage and current.

Equations (5) and (6) are integrated into the "calcul (Z)" block, this block allows us to calculate the real and imaginary parts of the complex impedance and draw them in a Nyquist plot and save these settings in a data file.

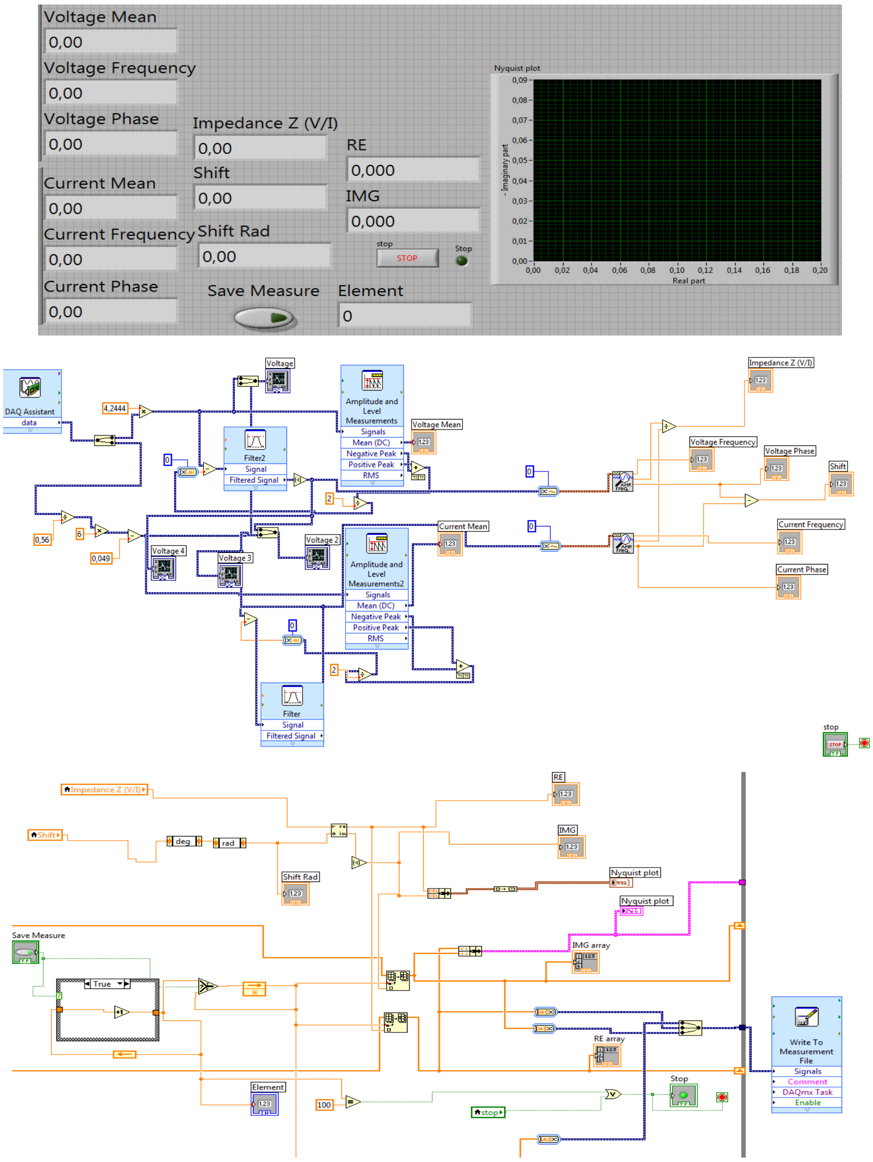

Fig. 5. Front panel and block diagram of the LabVIEW application developed.

Fig. 5 shows the graphical interface and the graph of the application developed by LabVIEW to make the measurement of the complex impedance, the interface is composed by a Nyquist graph to display each point of the impedance measured in real time. Digital indicator to display the different parameters of the voltage and current at the time of measurement (Voltage and average current, frequency of the signals, phase shift between the signals). In this interface we have integrated a button to save the measured points to a file that you can use it to display data from other software such as Microsoft Excel or MATLAB, the STOP button to stop the application at the end of the total measuring points of the complex impedance. For the execution of this interface, we have developed the block diagram of the LabVIEW application; it is the essential part of the application because it includes most of the blocks required for the data processing in order to perform the impedance measurement.

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B. The LabVIEW application for tracing the polarization curve

This application is used to draw the IV characteristic or polarization curve of a fuel cell, the principle of plotting of IV characteristic is to vary the current and sample the voltage across the corresponding fuel cell. Fig. 6 shows the block diagram of the LabVIEW application for tracing the IV characteristic, the "DAQ-mx Assistant" blocks and the low pass filter are the same used in the previous application. The "Basic DC/RMS LabVIEW" block is one that calculates and displays the numerical values of the sampled voltage and current at the terminals of the fuel cell.

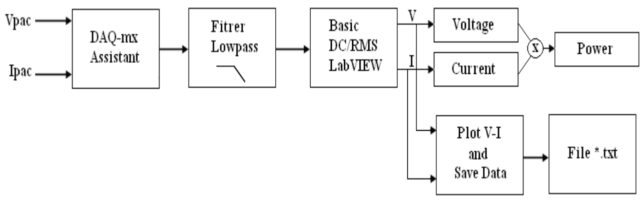

Fig. 6. Block diagram of the application for tracing the IV characteristic.

This application is composed of two digital indicators to display the voltage and current sampled across the fuel cell, a graph for plotting this feature and a button to save the collected data to a file. To run this application, we have developed the block diagram that integrates most of the blocks required for data processing.

The objective for the development of these applications is to have a thorough idea about the results of tests carried out by the electronic load and compare the results with other search results.

IV. THE EXPERIMENTAL WORK

To validate the correct operation of the two applications developed using a PEM fuel cell, the electronic load that we have realized supports a maximum power of 750 W and a function generator for injecting the disturbing signal to measure the complex impedance by electrochemical impedance spectroscopy. The PEM fuel cell used in the experiments is Ballard Nexa power 1.2 kW [10]. This fuel cell is a module that is fully automated and can provide current at full power 46 A at a voltage of 26 V, this stack is composed of a total of 47 cells may provide a single voltage range between 0.6V and 1V depending on the power required. The measurement made on the fuel cell represents the total impedance of the whole cell. In this work, we started testing by tracing the polarization curve of the PEM fuel cell Ballard Nexa 1.2 kW using the proposed electronic load and the application developed by the LabVIEW.

Fig. 7 shows the polarization curve of the PEM fuel cell Nexa. The principle of this test is to simultaneously measure the voltage and current supplied with the fuel cell using the developed application.

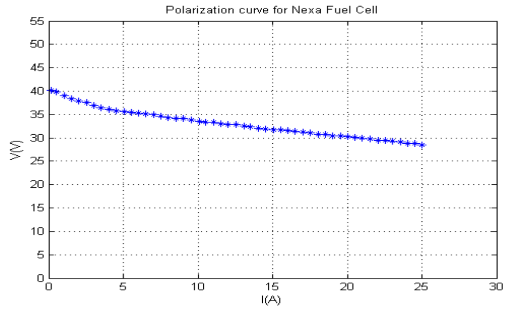

Fig. 7. Polarization curve of the Nexa PEM fuel cell.

It is observed in this curve two distinct areas, one for the low current corresponds to a voltage drop due to the activation overvoltage caused by the electron transfer to the cathode area and the second means for matching a current ohmic drop localized mainly in the membrane [11]. There is a third area that corresponds to high currents, it does not appear in this curve corresponding to a voltage drop due to the problems of reactant diffusion limited by the mass transport which causes a sudden drop in the fuel cell voltage.

Measuring the complex impedance by electrochemical impedance spectroscopy method requires hardware and software tools, for this we designed and produced an electronic load and we have developed a LabVIEW application to measure and display the complex impedance. The LabVIEW application notes data for the various tests and display them in a Nyquist plot. The current range for testing by Nexa PEM fuel cell is 1A, 5A, 10A, 16A and 20A. The frequency range used by the function generator for measuring ranges from 0.1 Hz to 12 kHz, usually for a PEM fuel cell frequency spectrum is selected from 1 Hz to 10 kHz [11]. The complex impedance measurement was made by an amplitude value for the perturbation signal of 0.25 V_{P-P}. A measure for this amplitude has no effect of perturbation on the fuel cell because it debit 41 V maximum empty. The testing of the fuel cell is made with a fixed hydrogen pressure equal to 5 bars. Fig. 8 shows the diagrams of the complex impedances of the Nexa PEM fuel cell.

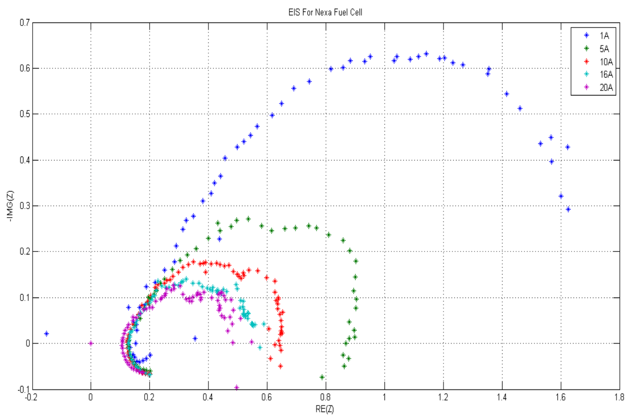

Fig. 8. Nyquist diagrams of the Nexa PEM fuel cell.

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It is noted in this figure that the low frequencies are on the right and the values of high frequencies are on the left. We observe in this figure in the form of Nyquist graphs that we form complex impedance represented by two lobes. These lobes correspond to different parts in the operating fuel cell; these parts are the losses in the stack. The right lobe of each test is the sum of the losses that occur at the cathode and anode cell fuel cell, while the small lobe on the left represents the total ohmic loss of the fuel cell. This loss is represented in the sum of the ohmic resistors of each cell constituting the fuel cell. The shape of the curves of complex impedances of these tests is in various researches [12], [13], [14], [15], [16], which confirms these tests and validates our design of both applications developed by LabVIEW software. Figure 9 shows an example of diagram of a Nyquist type fuel cell used by Wenhua Nexa H. Zhu et al [13].

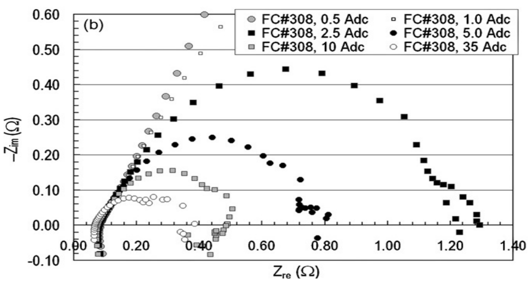

Fig. 9. Example of Nyquist diagrams of a Nexa PEM fuel cell found in other research [13].

We note that our results join the results found by these researchers. They used a fuel cell of the same family is the Ballard Nexa a power of 1.2 kW and a measurement bench at Gamry that Gamry FC350 ™ is a tester which integrates an electronic load industrial and system for measuring and displaying the Nyquist plot using the same measuring principle which is the electrochemical impedance spectroscopy(EIS).

V. CONCLUSION

In this work, we have used the LabVIEW software to develop an application for measuring the complex impedance by electrochemical impedance spectroscopy method. This application allows us to avoid the use of industrial equipment that is expensive and cumbersome. We found the same experimental results with the use of industrial equipment.

ACKNOWLEDGMENT

This work was supported by the LR-ACS laboratory of FST in Tunisia, the DRIVE laboratory of the ISAT at Nevers in France and the LIEN laboratory from University Henri Poincaré at Nancy in France.

REFERENCES

[1] Comparison of fuel cell electrolyte, resistance measurement techniques: The magazine of Fuel Cell Business and Technology, Avril/Mai2005

[2] C. Gabrielli: Mesures d'impédance. Techniques de l'Ingénieur, 10 avr 1994, PE2210-1:20.

[3] W. Merida, D. Harrington, G.F. Mclean, and N. Djilali: Hardware Development for Impedance Spectroscopy on a 4-cell PEMFC Stack Under load. Proceedings of the XIV Canadian Hydrogen Conference, Canada, 2002.

[4] G. Raposa. Fuel cell magazine- Performing AC impedance measuremùents on fuel cells. Agilent technologies, 2003.

[5] K.R. Cooper et M. Smith: Electrical test methods for on-line fuel cell ohmic resistance measurement, Journal of Power Sources 160:1088–1095, 2006.

[6] El-Hassane AGLZIM, Amar ROUANE, Mustapha NADI and Djilali KOURTICHE: Signal Processing for the Impedance Measurement on an Electrochemical Generator. Sensors & Transducers Journal, Vol. 90, Special Issue, April 2008, pp. 150-159.

[7] Basics of Electrochemical Impedance Spectroscopy: Application Note, Rev 1.0 9/3/2010, Gamry Instruments, Inc.

[8] Wolfgang Friede: Modeling and characterization of a PEM Fuel cell, Thesis, Institut National Polytechnique de Lorraine, France, 2003.

[9] NI-9205 Analog Input Module User's Manuel: National Instruments, 2013. http://sine.ni.com/nips/cds/view/p/lang/en/nid/208800 (2013).

[10] Nexa Power Module User's Manuel: Ballard Power Systems, 2003.

[11] J.Deseure, Pierre-Xavier Thivel ,M.Marchesiello : Methods for characterization of a fuel cell, Publication Notes, Université Joseph Fourrier de GRENOBLE, CNRS, France ,2008.

[12] S.WALKIEWICZ: Impedance spectroscopy study of fuel cell proton exchange membrane. DEA, Institut National Polytechnique de Grenoble, France, 2001.

[13] W.H. Zhu, Robert U. Payne, Bruce J. Tatarchuk : PEM stack test and analysis in a power system at operational load via ac impedance , Journal of Power Sources, 169, p. 211–217, 2007S.

[14] M. Pérez-page, V.Pérez-Herranz : Study of the electrochimical behaviour of a 300 W PEM fuel cell stack by Electrochimical Impedance Spectroscopy, International journal of Hydrogen Energy(2013).

[15] Xiao-Zi Yuan, Chaojie Song, Haijiang Wang, Jiujun Zhang, Electrochemical Impedance Spectroscopy in PEM Fuel Cells : Fundamentals and Applications , Books, ISBN978-1848828452, 2009.

[16] N. Fouquet, C. Doulet, C. Nouillant, G. Dauphin-Tanguy and B. Ould-Bouamama: Model based PEM fuel cell state-of-health monitoring via ac impedance measurements, Journal of Power Sources 159 (2006) 905–913.

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