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Study and Validation of a PEM Fuel Cell Complex Impedance Measurement System

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Abstract

Objectives: The objective of this work is the study and validation of the complex impedance measurement system for the PEM fuel cell using STM32F4 microcontroller. We present the technical method for measuring the PEM fuel cell complex impedance using this system. **Methods**: Among the problems of fuel cells development is still the reliability of their performances over time. The solution of this problem is the implementation of an efficient diagnostic method such as the complex impedance measurement of the cells in order to diagnose it in real time using the Electrochemical Impedance Spectroscopy method (EIS) which is used to diagnose complex electrochemical systems. **Findings:** To run the complex impedance measurement, it is necessary to use specific software and hardware tools for fuel cells. In this context, we presented the steps of implementation of the system for the measurement of the PEM fuel cell complex impedance. This test bench is realized around the Nexa Ballard PEM fuel cell, an electronic load and a measuring board based on the microcontroller STM32F4 connected to a computer collecting data processed by measurement application developed using LabVIEW® software. The obtained results validate the design of this measuring system. The contribution through the results in this work will be to obtain onboard diagnostic for a PEM fuel cell in the automotive transport field. **Application:** This system is so small that it can be implemented in an embedded system; it is less expensive than the industrial system for measuring the PEM fuel cell complex impedance.

Keywords: Complex Impedance Measurement, LabVIEW® Applications, PEM Fuel Cell, Real Time Diagnose, STM32F4 Microcontroller

1. Introduction

Fuel cell is a chemical energy transformer into electrical energy, so it is not a new technology and its working principle was discovered in[1,2]. At this time, fuel cells are experiencing increased interest both industrially and research. The industrial sectors (board electronics, transport, and stationary supply energy...) invest the development of this technology. To use fuel cell in a rational and efficient way, detailed knowledge of its constitution and its operation is required.

The basic principle of the PEM fuel cell is the inverse of the electrolysis; the hydrogen combines with oxygen to produce electricity, rejected heat and water. Through the operating cycle of PEM fuel cell, its performance tends to gradually deteriorate due to the chemical and physical changes of the cells involved in the use and function of his age until it more usable. The aging conditions of a PEM fuel cell and associated mechanisms remain to understand, even if significant progress studies were conducted. In addition to aging, the performance degradation may also take place over a very short time scale due in

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particular to a clogging or drying of the membranes. Such failures lead to reversible damage limited in time, which must be detected quickly to react via the system controller, so as not to lead to irreversible damage.

The data acquisition using experimental method has opened a wide variety of diagnostic techniques. It appears that the impedance spectroscopy remains the most appropriate, it is non-invasive and adapts well to the diagnosis of the fuel cell and its cells if it is done synchronously. In addition, it allows a separate study of various electrochemical phenomena. We interested to measure the complex impedance of the PEM fuel cell using impedance spectroscopy method, which informs about the evolution of the cells state. This method consists to superimposing sinusoidal signal around a continuous DC current value to be injected into the PEM fuel cell and to analyze response signal. It identifies the various parameters which are not accessible when direct measurements with a DC current. This work is a part of a global research work which is the study of the membrane degradation over time and the influence of the rejected water on the degradation of the cells states. Indeed, the aim of this work is the PEM fuel cell diagnosis. This paper is presented by five main sections. The Section 1 is introduction to this work. The Section 2 presents the theoretical study of the complex impedance measurement and the choice of the measurement method. In the Section 3 we will present the development of complex impedance measurement system. The Section 4 presents the results of this work; it serves to validate the design of our system for measure the complex impedance and we will finish this paper with the conclusion in the Section 5.

2. The Study of the Complex Impedance Measurement for PEM Fuel Cell

2.1 The Description of the PEM Fuel Cell

Proton Exchange Membrane (PEM) fuel cell is the stack that has attracted significant interests of research and developments in the transport sector. It has several advantages over other fuel cells since its characteristics include operation at low pressures and temperatures ranges and a specific polymer electrolyte membrane. Thus, we will use this type of fuel cell in our work. The PEM fuel cell is supplied with hydrogen and oxygen. The cell of a PEM fuel cell is physically comprised of three main elements; the solid electrolyte is the membrane, the two electrodes composed of a diffusion layer with an active layer and two bipolar plates.

The principle of operation of the PEM fuel cell is based on the reverse process of electrolysis of water. The hydrogen and the oxygen reacting to produce electricity, water, heat in accordance with equations of the electrochemical reactions[2–6].

The anode reaction is (oxidation):

$$H_2 \rightarrow 2H^+ + 2e^- \quad (1)$$

The cathode reaction is (reduction):

$$½\, O_2 + 2H^+ + 2\, e^- \rightarrow H_2O \quad (2)$$

The chemical to electrical energy conversion is based on the electrochemical reactions taking place in the PEM fuel cell. Figure 1 shows the principle of the reactions in the fuel cell.

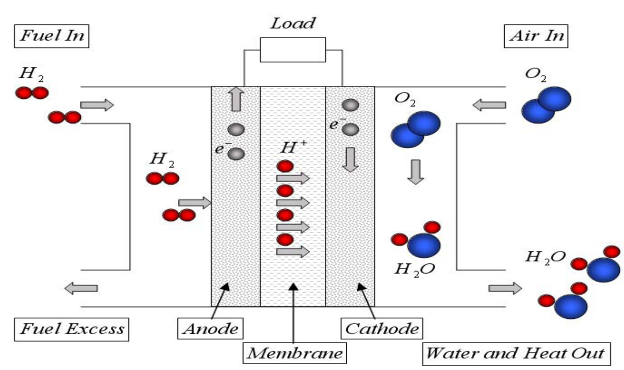

Figure 1. Principle of the PEM fuel cell electrochemical reactions[6].

The fuel cell contains as electrolyte the Nafion membrane. In the anode, hydrogen is decomposed into electrons and protons (oxidation). The membrane that is impermeable to gases, allows only the passage of hydrogen protons ions H^+. The electrons are conducted from the anode to the cathode through an external circuit through an electrical load. At the cathode the oxygen combines (reduction) with the hydrogen protons and electrons to produce water and heat.

The main role of the membrane or the electrolyte is the transfer of H+ protons from the anode to the cathode.

The conductivity of the membrane depends on the hydration and humidification condition; its value varies from 3 mΩ to 2.3Ω[7].

The modeling of the complex impedance is realized by the equivalent electrical circuits which are based on experimental readings (the impedance spectra), reflecting the behavior of the fuel cell. The equivalent impedances are used to determine the electrochemical parameters (the membrane resistance, the double layer capacitance, connections and charge transfer resistance ...) or to analyze the internal behavior of the fuel cell as the influence of the humidification and the drying of the membrane and also for observing the behavior of the fuel cell in the presence of CO in hydrogen[8,9].

When the fuel cell supplies a current flowing through an external circuit, the voltage across the fuel cell is lower than the theoretical potential[10,11]. This is due to different voltage drops generally referred polarizations losses η which is the activation polarization loss (η_{act}), ohmic polarization loss (η_{ohm}) and concentration polarization loss (η_{con}). The output voltage of the stack (V_{Stack}) can be introduced as follows[12,13]:

$$V_{Stack} = N_{cell}(E_{rev} - \eta_{act} - \eta_{ohm} - \eta_{con}) \quad (3)$$

where, E_{rev} is the theoretical potential for the one cell of the PEM fuel cell is about 1.23 V in the standard conditions of temperature 25°C, and partial gas pressure 1 bar, it's the Nernst Law[10,11], N_{cell} is the number of cells of the stack of the PEM fuel cell.

In this work, we used a Nexa PEM fuel cell from Ballard with a power of 1200W[14]. This PEM fuel cell is a module that does not require maintenance, fully automated and highly integrated and its composed of a 47 cells each capable to give a load voltage of 26V to a maximum current of 46A and an empty load voltage of 42V for minimum current of 0.7A.

2.2 The Description of the Complex Impedance Measuring Method

During the life cycle of a PEM fuel cell, it tends to deteriorate gradually due to irreversible chemical and physical changes that occur depending on the use and its age until they are no more usable. In fact, the membranes are subjected to the thermodynamic constraints which accelerate fatigue. To know the state of the PEM fuel cell membranes, we used the complex impedance measurement method, the advantage of this method is too improved understand the effects physical occurring in the PEM fuel cell.

Two methods are to consider for measuring the complex impedance:

– A measurement without load, this method that does not provide much information.
– A load measurement when the fuel cell operates dynamically. In this work, we have chosen this case.

In this work we have chosen to use an electrochemical method, due to the detail that this method is not invasive to the fuel cell, does not disturbed its function and do not change its characteristics. We measured the PEM fuel cell complex impedance using the EIS method, which expresses the evolution of the membranes states.

The EIS allows characterizing more or less complex systems. Around an operating point, we can consider that the imposed changes have a linear variation response. Among the existing methods for the diagnosis of the fuel cell, this is the most commonly used. It allows to follow the variation of the complex impedance of the fuel cell and secondly to observe transport phenomena material and transfer of charges to the electrodes[15–17]. The measurement principle of this method consists to superimpose a low amplitude signal to the output voltage of fuel cell while it delivers the desired current. For electrochemical devices such as fuel cell, the controlled signal is a current (or a voltage); therefore, the received signal is a voltage (current respectively). The complex impedance plot is generally presented in the Nyquist plan submitted by the imaginary part as a function of the real part.

To measuring the PEM fuel cell complex impedance using the electrochemical impedance spectroscopy, we can be use three methods; galvanostatic method, potentiostatic method and load modulation method. Our choice fell on the load modulation method; this choice is forced by the passivity of this method which does not inject directly the electrical signal to fuel cell. This method consists to change the resistance of the load based that it is preferred to superimpose. In effect, the complex impedance can be measured by dividing the voltage by the current across the PEM fuel cell[18–20]. Figure 2 shows principle of the load modulation method.

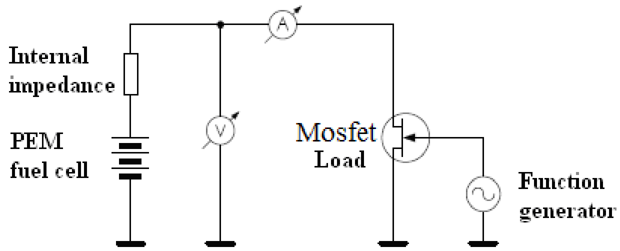

Figure 2. Principle of the load modulation method.

To give a result using this method, the DC current response should be linear. The PEM fuel cell is a priori nonlinear and no stationary system. So, we can measure the complex impedance by injecting a small perturbation signal around operating point presented by a fixed current which is supposed stationary[18,19,21].

The imposed signal is a sine wave voltage as following:

$$V(t) = V_{DC} + V_0 \sin(\omega t) \tag{4}$$

V_0 is the injected signal and its generally low amplitude for the linear DC current response, consequently the expression of the DC current response is:

$$I(t) = I_{DC} + I_0 \sin(\omega t + \theta) \tag{5}$$

θ: Phase difference between voltage and current.

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

$$Z(\omega) = \frac{V_0}{I_0} e^{j\theta} \tag{6}$$

where, V_0 and I_0 are the amplitudes of the imposed sine wave voltage and the sine wave current passing through it, θ is the phase difference between current and voltage[19–24]. This complex impedance can be written as that appears imaginary part and real part:

$$Z(\omega) = R(Z) + j\,\mathrm{Im}(Z) \tag{7}$$

The progress of such measures is shown schematically in Figure 3. Firstly, it imposes the parameters of the measure that is necessarily to 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 the signal of the measurement frequency is required and the measurement is performed. After measuring the whole spectrum, the initial parameters can be changed and the measurement starts again.

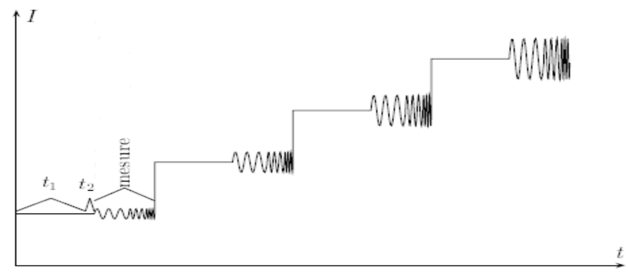

Figure 3. Measurement spectrum method of the complex impedance.

The objective of the load modulation use is to measure the complex impedance of the PEM fuel cell in load, since it is a method that providing information of the status of various components of the fuel cell system, the most researchers in this domain use the impedance spectroscopy method which was well developed in recent years. To implement this method, we must have hardware and software tools and primarily an impedance measurement system and an electronic load. Therefore, a complex impedance test bench must be made and dimensioned.

3. The Development of Complex Impedance Measurement System

This part of the work is a description of the different measurement mechanisms implemented for experimental data of the complex impedance measurement. A test bench is made around the Nexa Ballard fuel cell and an electronic load carried by our own resources[25]. To this is added a measuring board based on the microcontroller STM32F4 connected to a computer collecting data which will be stored and processed by a measurement application developed with LabVIEW® software.

To implement the load modulation method, we must make measurements on the Nexa fuel cell during operation of the load, then the obligation to have an adjustable current load to multiply measurements at different values of the current supplied by the fuel cell. In fact, to do this, two solutions are proposed:

– Using network of resistors present passive load.
– Using a controlled semiconductor components present active load.

Primary solution has the disadvantage that it does not present an adjustable resistance. Furthermore, it is hard to preserve a fixed DC current during the variation of the output voltage of the PEM fuel cell. So, our chosen are the second solution that uses semiconductor components to make an electronic load using MOSFETs. This realized electronic load[26] for measuring the PEM fuel cell complex impedance, should require a DC voltage and current debited by the PEM fuel cell for the period of measurement.

Figure 4 shows the block diagram of the test bench proposed; it describes the various stages that make up the electronic load, the control and the acquisition module for the impedance measurement system.

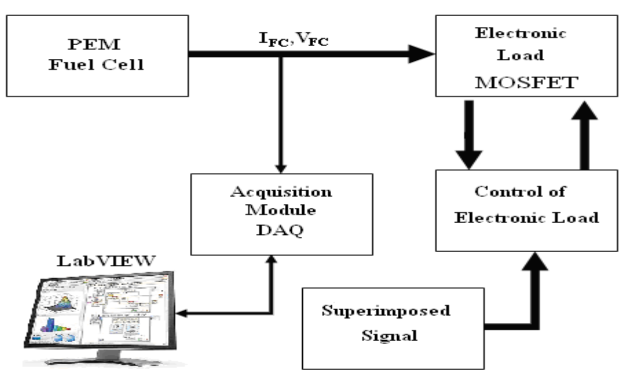

Figure 4. Block diagram of the impedance measurement system proposed.

The PEM fuel cell block is one that debits the current to be supported by the electronic load, MOSFETs work as a variable resistor controlling voltage. The PEM fuel cell will be described in the experimental work. The superimposed signal block ensures the injection of the perturbation sinusoidal signal to measure the complex impedance using the principle of EIS method with load modulation, LabVIEW that saves the measurement results of the complex impedances through the microcontroller STM32F4 in a file that can be used to view and compare the experimental results.

In this work, we realized a system based on the STM32F4 microcontroller that can process and analyze the data collected in real time from the Nexa PEM fuel cell, with the aim to develop a test bench designed to measure the complex impedance and make it more standard and independent of any industrial system. Our aim is to achieve an onboard measurement system that can be installed on any fuel cell system. The measurement module of our solution is based on a microcontroller STM32F4 capable to perform complex calculations for measuring the complex impedance and to supervise the display of the frequency spectrum via the USB port through a LabVIEW graphical interface in a computer.

The design of this module is to process signals from the voltage and current across the Nexa fuel cell to collect the data and draw the charts needed for the complex impedance. The application developed is based primarily on complex calculations of the FFT by a microcontroller STM32F4. This application consists of two main parts, the first part is for programming the microcontroller STM32F4 and the second part is for viewing and saving the results obtained using LabVIEW.

Figure 5 represents the "Front Panel" of the application developed using LabVIEW software in order to communicate the computer with the microcontroller STM32F4 to display and save the results of the complex impedance of the Nexa PEM fuel cell.

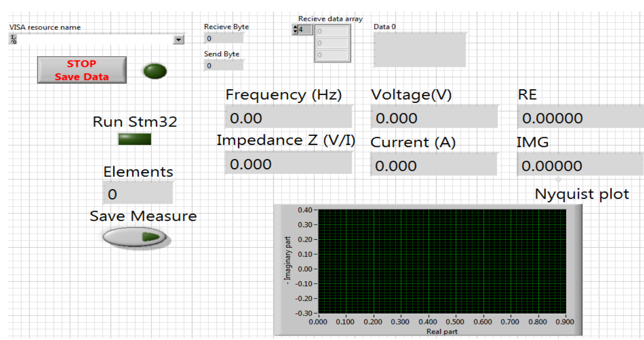

Figure 5. Front panel of the LabVIEW application developed for the complex impedance.

The main function of this application is the supervision and the save of the different parameters calculated by the microcontroller STM32F4 issues from the USB port.

Figure 6 shows the flowchart of the program developed in C language for microcontroller STM32F4 to measure the complex impedance. This part is the most important because it gives us a complex calculation of the various parameters needed.

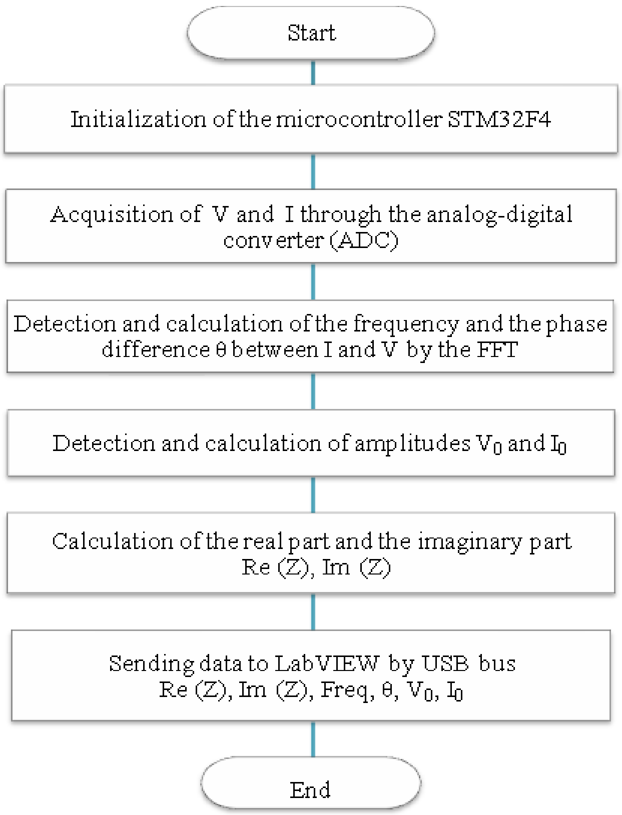

Figure 6. Flowchart of program C implemented in the microcontroller STM32F4.

This flowchart summarizes the different procedures and functions of the program developed in C language for measuring the complex impedance by STM32F4. The microcontroller initialization for the choice of hardware devices necessary for the measure execution. The next step is to acquire by the Analog Digital Converter (ADC) the current and the voltage across the Nexa fuel cell to extract the necessary information. The procedure for detecting the frequency and phase angle θ between I and V is completed by a calculation of the FFT, this procedure is based on the passage approach with zeros that is to start a timer and calculating the time of the passage of a periodic signal by the same value. The signal amplitude calculation procedure is based on the determination of the maximum amplitude of each sampled signal.

After obtaining the various parameters necessary, the microcontroller STM32F4 initiates the function for calculating the imaginary and real part based on cosine and sine calculations presented by the following equations and which are incorporated into this function.

$$\mathrm{Re}(Z) = \frac{V_0}{I_0}\cos(\theta) \qquad (8)$$

$$\mathrm{Im}(Z) = \frac{V_0}{I_0}\sin(\theta) \qquad (9)$$

Where:

- V_0: the amplitude of the voltage sampled.
- I_0: the amplitude of current sampled.
- θ: the phase difference.

Finally, when the microcontroller completes the calculations, it sends the results obtained by the USB bus for displaying by the LabVIEW application. This application allows us to visualize in real time the variation in various parameters of the Nexa fuel cell derived from calculations made by the STM32F4.

4. The Results and the Discussion

To confirm the exact operation of the complex impedance measurement system realized we carried out experimental tests on the Nexa PEM fuel cell[14]. For the verification of the measurement system, we used two applications developed in LabVIEW software and we used the National Instruments acquisition board NI-9205[27] and the measurement system by the microcontroller STM32F4. Figure 7 shows the picture of the test bench that is used to measure the complex impedance[25].

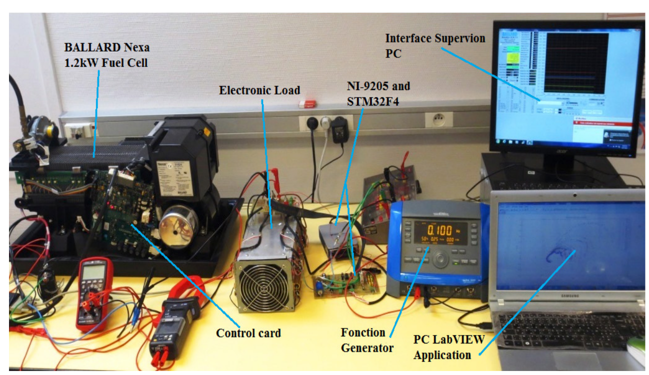

Figure 7. A photo of the realized test bench.

This test bench is composed of the proposed electronic load in the middle of picture, Nexa PEM fuel cell in the left, a function generator for injecting the perturbation signal, the acquisition system (NI-9205 and STM32F4) and the computer that integrates the applications developed in LabVIEW. In all of the tests, we injected a sinusoidal signal of frequency ranging from 0.1 Hz to 12 kHz and amplitude of 0.250 $V_{p\text{-}p}$ which is supplied by a function generator. The DC current to test the Nexa PEM fuel cell is starting 1 to 20A.

Figure 8 shows the Nyquist diagrams results of the complex impedances of the Nexa PEM fuel cell realized by the National Instruments NI-9205 and its applications[28].

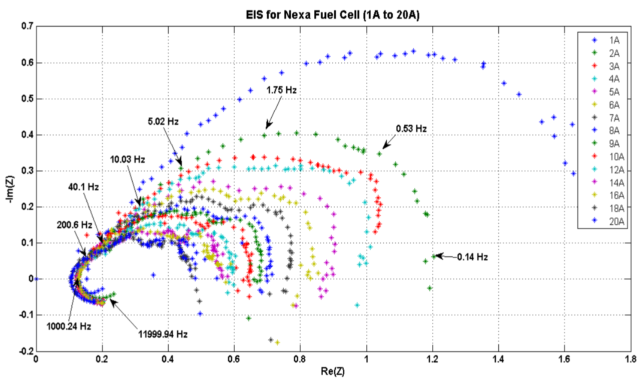

Figure 8. Nyquist diagrams of the Nexa PEM fuel cell[28].

In Figure 8, it is noted that the low frequencies are in the right and the high frequencies are in the left. In this figure, we observe that the Nyquist graphs are presented by 2 lobes. These lobes represent the different parts of the PEM fuel cell electrochemical operating; these parts present the losses in the PEM fuel cell system. The right lobes of the test curves are the sum of the losses that come about the cathode and anode, while the small lobe on the left presents the sum of the ohmic loss in the PEM fuel cell membrane. This loss is the sum of the ohmic resistors of each cell constituting the stack. The losses, which occur at the cathode and anode, influence directly on the mass transfer resistor which also reduces. The form of these curves of the complex impedances of these tests is in various researches results[17, 29–33].

The aim of this part of the work is to compare and validate the results obtained by the measurement card with the STM32F4 microcontroller and the NI-9205 card to validate the concept of the proposed test bench and perform experimental tests on the Nexa PEM fuel cell in order to have an embedded measurement system independently of any industrial system.

Figure 9 shows a comparison of multiple Nyquist diagrams for the current values 3, 5, 7, 10 and 15A achieved by both measuring systems.

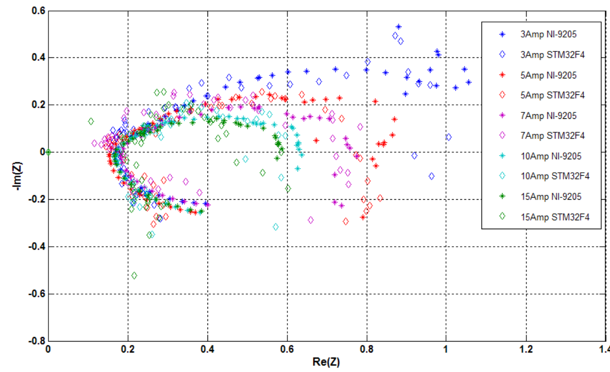

Figure 9. Comparison of multiple Nyquist plots for different values of current.

We see a small offset between the results obtained by these two systems; this offset is due to some differences in the design of each system. For the NI-9205 card is the LabVIEW software which acts to perform complex calculations but for STM32F4 card is itself performs all calculations and LabVIEW is used only for the supervision the results.

Figure 10 shows two Nyquist plots for the current value of 10A that are achieved by both measurement systems the STM32F4 and the NI-9205 from National Instruments. We see a small offset between the results obtained by these two systems.

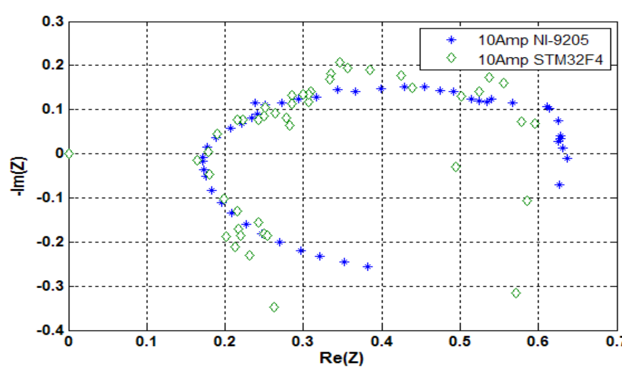

Figure 10. Comparison of Nyquist plots for STM32F4 and NI-9205 of 10A.

The objective in the development of these applications is to have a comprehensive idea about the test results carried out using the complex impedance measurement system and the realized electronic load to validation of the results obtained by these two systems to make the measurement of the complex impedance more standard and independent of any industrial system in order to have an embedded measurement system for a PEM fuel cell.

5. Conclusion

In this paper, we presented the complex impedance measurement system for the Nexa PEM fuel cell system. The chosen method is the Electrochemical Impedance Spectroscopy (EIS) that has the advantage that not to influence the functioning of the PEM fuel cell system when it delivers DC voltage and current. Then we have also presentation of the development of the complex impedance measurement system for PEM fuel cell and its make a measurement of the complex impedance and determine its characteristics. Also, we presented the comparison of the results between two systems (NI-9205 and STM32F4) designed to measure the complex impedance of the Nexa PEM fuel cell.

In this work, we have used the STM32F4 and LabVIEW® software to develop an application for measuring and displaying the complex impedance. 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. Also, we found the same results in comparison with those two systems the NI-9205 and the STM32F4. We can say that our contribution through the results obtained in this work will be to obtain onboard diagnostic for à PEM fuel cell in the domain of automotive transport.

6. Acknowledgement

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