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Design and Realization of an Electronic Load for a PEM Fuel Cell

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***Abstract*—**In order to further understand the behavior of PEM fuel cell and optimize their performance, it is necessary to perform measurements in real time. The internal impedance measurement by electrochemical impedance spectroscopy (EIS) is of great importance. In this work, we present the impedance measurement method of a PEM fuel cell by electrochemical impedance spectroscopy method and the realization steps of electronic load for this measuring technique implementation. The theoretical results are obtained from the simulation of software PSPICE® and experimental tests are carried out using the Ballard Nexa™ PEM fuel cell system.

***Keywords*—**Electronic load, MOS transistor, PEM fuel cell, Impedance measurement, Electrochemical Impedance Spectroscopy (EIS).

I. Introduction

FUEL cells appear as one of the alternative energy for the future, in addition to other renewable energies because they do not generate pollutants. While the principle of the fuel cell is relatively old, their development has greatly increased in recent years from technological progress to environmental awareness and soaring prices of fossil energy.

A fuel cell is an electrochemical device; its study requires multidisciplinary knowledge. Nevertheless, it has the disadvantage of the price to the kWh which stems from its more or less short lifetime. Indeed, the membranes are subject to thermodynamic constraints that accelerate their decline. One of the ways for the status of the membranes is the measurement of the impedance of these cells. We are interested in the measurement of complex impedance of the stack by impedance spectroscopy, which informs us about the evolution of the state of the cells constituting the heart of cell. This study is part of a more global research work which is the study of membrane degradation over time and depending on its use and the influence of the water management on the state of cell degradation; this project is in fact to instrumentalize the fuel cell.

II. Simulation of the Method of Measurement of the Impedance of the PEM Fuel Cell

A. Choice of the PEM Fuel Cell

Our study will involve a fuel cell proton exchange membrane (PEM) from BALLARD Nexa™ fuel cell system with a power of 1200 W [1]. It is fully automated, highly integrated and can supply a current to 46 A at full power for a voltage of 26 V and a minimum current of 0.7 A for an open circuit voltage of 48 V. The stack is composed of a total of 47 cells which can provide an individual voltage between 0.6 V and 1 V depending on the power requested. We are aiming at realizing an electronic load with its control for the said PEM fuel cell; the load must support a current of 46 A. This current is debited by the stack; its load voltage is approximately 26 V, giving an output power equal to 1196 W. The sizing of this load will concern the selection of transistors, resistors and heat sinks. During the operation of a fuel cell, it may have a variation of the internal impedance caused by the humidifying state of the membrane; this variation affects the efficiency and the lifetime of the stack. To do this, it is necessary to make measurements in real time. There exist electrochemical methods such as internal impedance measurement and the non-electrochemical methods to characterize the stack in a global manner.

Our choice was concerned with the use of an electrochemical method that is the impedance spectroscopy (IS). In fact this choice method is non-invasive to the stack, does not influence its functioning and does not change its characteristics; it rather allows us to better understand the physical effects that occur in this type of generator. To implement this method we need to make measurements on the stack in load from which the obligation of an adjustable load. 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 principle of measurement by the method of electrochemical impedance spectroscopy (EIS) is the superposition of a low amplitude signal with the output voltage of the stack while delivering the desired current [2], [3]. The first solution was a major inconvenience; it does not represent an adjustable resistor. It is difficult to maintain a constant current during a variation of the output voltage of the stack. Therefore, we chose to use the electronic components and realize an electronic load using the MOS transistors. This electronic load carried out for the measurement of the impedance must impose a DC current debited by the fuel cell during the measurement. In this case, we have reached an electronic load that supports a current of 25 A and a voltage of 30 V to be a power of 750 W. This sizing ensures a safety margin of 240 W from the power debited by the PEM fuel cell

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from Nexa™ Ballard 1200 W. For the measurement and display of the internal impedance of the fuel cell, we used the LabVIEW® software and data acquisition card connected to a computer to save the measurements and show the experimental results.

B. Measurement Method

We distinguish three methods to measure the impedance of the stack using the impedance spectroscopy:

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

We have used the load modulation method for its great advantages. This method consists of varying the load resistor according to the signal that is to be superimposed. Indeed, the complex impedance of the fuel cell can be measured by dividing the Fourier transform of the voltage by the current from the stack to the frequency of measurement [4]-[6].

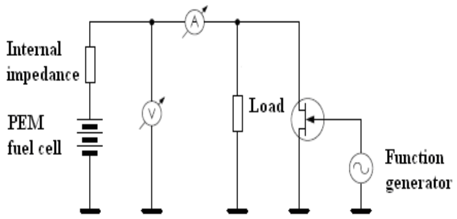

Fig. 1 Principle of the method of the load modulation [4], [5]

Fig. 1 shows the principle of the load modulation method, the choice of this method was motivated by the passivity of the technique that does not inject electrical energy to the stack. The other two techniques, potentiostatic and galvanostatic are more active, which could damage or reverse the chemical reactions at fuel cell. In order to get a correct result of this approach, the current response must be linear. The fuel cell is in priori a non-linear and non-stationary system. Therefore, we can determine the impedance using low-amplitude perturbations around a point operation which is assumed stationary. The superimposed signal is a sine voltage which can be written as following [4]-[7]:

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

The amplitude used in most applications does not generally exceed 10 mV to ensure that the current response is linear, so the expression of the current response is [4], [5], [7]:

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

θ represents the phase difference between the current and voltage.

The impedance around the operating point (I_0, V_0) that is the Fourier transform of the voltage divided by that of the current has the value:

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

While 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 [2]-[6]. 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, defined for a series of values of the frequency of the waves of current and voltage that can be represented on a Nyquist plot or Bode diagram. For the implementation of the load modulation technique, we must choose the load which is the essential element of the impedance measurement. The choice fell on type MOS transistors that are going to assume the role of variable resistance and can support the current debited by the stack, they constitute the essential elements of the realized electronic load. The linear operating region is defined in the current-voltage diagram of the MOS transistor. Indeed, since the gate-source voltage (V_{GS}) is greater than the threshold voltage (V_{th}) and the drain-source voltage (V_{DS}) is higher than the pinch-off voltage (V_p), the current depends only on the gate -source [8], [9]:

$$I_{DS} = \frac{K}{2}(V_{GS} - V_{th})^2 \quad (5)$$

$$K = \mu_n C_{ox} \frac{W}{L} \quad (6)$$

where μn: the charge-carrier effective mobility.
C_{ox}: the gate oxide capacitance per unit area.
W: the gate width.
L: the gate length.

It is noticeable from (5) that we can obtain a variable current in the circuit controlling the gate with variation of the gate voltage (VGS) where we impose the current delivered by the fuel cell. The structural capacity of the transistor who takes the time to charge and discharge limits the speed of the transistor. Studies carried out on the stack showed the need to impose current references. So it is indispensable to carry a current regulation. Thus we need to design a circuit that imposes the control voltage necessary for the current desired.

C. Simulations

The electrical model representing the different components of the fuel cell supplying the load is given in Fig. 3 where the variable load is represented by a MOS transistor with a controlled DC voltage source (V_{gs}). The impedance of internal cell is represented by the simplified Randles circuit (R_M = 10mΩ, R_T = 90mΩ, C_{DC} = 300μF), these values correspond to those found in the internal impedance of a real PEM fuel cell [7], [9]-[11]. The diagram of the simulation under PSPICE® is presented in Fig. 2.

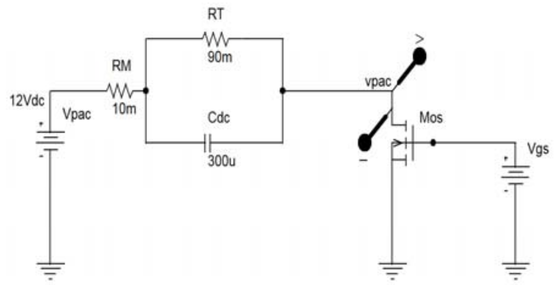

Fig. 2 Diagram of internal cell with the load

To maintain a constant current across the load, we inject a voltage greater than threshold Vth. The load becomes variable in function of the injected voltage and we observe that the voltage across the load varies according to the current.

Subsequently, we replaced the DC source voltage Vgs by a sinusoidal voltage source and observe the response of the current and the voltage across the transistor according to the sinusoidal voltage. A simulation example under PSPICE® is given in Fig. 3. We applied a sinusoidal signal of 1 kHz frequency.

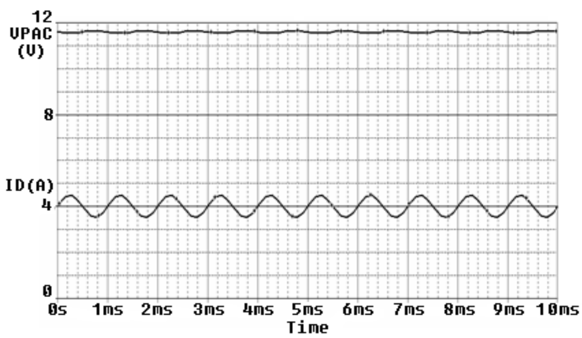

Fig. 3 Representation of a sinusoidal signal with frequency 1 kHz and the signal across the transistor Vpac

By observing these two curves we see that the current and the voltage in the load are out of shift phase. The applied sinusoidal signal is in phase with the load current. The response of the injected signal is a current that oscillates around 4 A for a transistor. The voltage across the load oscillates around 11.5 V while the voltage of the stack is 12 V the voltage drop is due to the presence of the internal impedance. This voltage drop equals to the product of the value of internal impedance by the current supplied.

In the following we present the frequency analysis of the schematic of the control current of the load, the purpose of this analysis is to plot the Nyquist diagram to observe the elements that constitute the model chosen for the fuel cell. To do this, we vary the frequency of the injected signal and we observe the complex impedance of the applied model. To execute this type of analysis under PSPICE® is used AC Sweep mode. The frequency of the simulated signal varies from 10 mHz to 50 kHz. Fig. 4 shows the Nyquist plot simulation under PSPICE® of the complex impedance of the fuel cell.

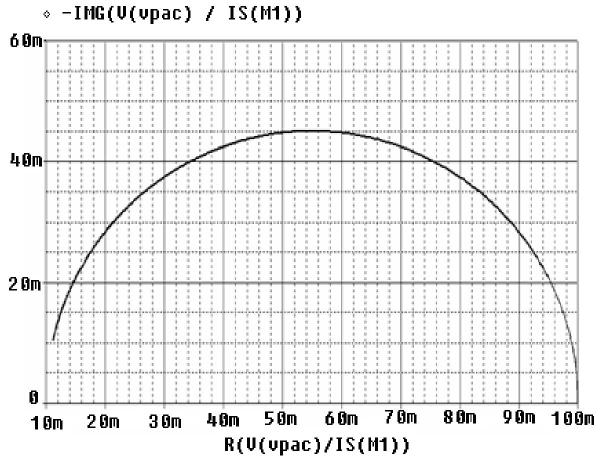

Fig. 4 Representation of the Nyquist plot simulation

This simulation then confirms the use of the electronic load because we have not disturbed the directed signal injected to the stack which is isolated by the gate of the transistor. However, Walkiewicz et al. [12] used a measuring bench by the potentiostatic method by injecting directly the perturbation signal to the stack for the measurement of the same impedance of the anode and cathode separately by measuring the voltage with a reference electrode, but our simulation results agree well with those found by Walkiewicz et al.

III. Design and Dimensioning of the Electronic Load

The aim of this work is to realize an electronic load with its control. It must support a current of 25 A and a power of 750 W delivered by the PEM fuel cell. The size of this load will mainly concern the choice of transistors, resistors and heat sinks.

A. *Choice of Transistors*

The MOS transistors are the most important parts of the assembly; they can resist to high powers. By increasing the number of transistors, the power distributed among all the transistors increases. In our case we have used twelve transistors, each transistor acts as a variable resistor and it must support a current that varies from 0 to 4 A and a voltage of 30 V, so that the maximum power is 120 W. These transistors are put in parallel for that each one conducts an acceptable current. To measure the current passing through each transistor we have added shunt resistors connected in series with those.

B. *Choices of Shunt Resistors*

The shunt resistors are connected in series with the transistors to allow the measurement of current through them. These resistors must have a very low value so as not to influence the current. The choice of a resistance is based on the knowledge of the reference voltage and the maximum current through the transistor.

We have:

- $| I_{max} | = 4$ A at a transistor,

- | $U_{consigne}$ | = | U_{Rshunt} | is a voltage variable from 0 to 2 V, so R_{shunt}t = 0.5 Ω.
- The power of a shunt resistor is P_{Rshunt} = 8 W.

Thus we needed twelve shunt resistors 0.5 Ω each can hold a power of 8 W. In practice, we used two shunt resistors 1 Ω connected in parallel to have a resistor of 0.5 Ω with a power of 50 W for each resistor.

C. Choice of Heat Sinks

To determine the size and type of the heat sinks, it is necessary to know the resistor which has the thermal resistor between the heat sink and its environment (Rth (h-a)) (a = ambient, h = heat sink). It is on the value of thermal resistor that manufacturers of heat sinks characterize their products in the catalogs. In this implementation, the choice of the heat sink is made for each transistor in the same way based on data from the data sheet of the selected transistor.

We have:

- Power dissipated by the chosen transistor is: Pd = 120 W.
- Junction temperature of the selected transistor: Tj = 175°C.
- Ambient air temperature: Ta = 25°C.
- Thermal resistor between the junction and the case of the selected transistor: Rth (j-case) = 0.95°C / W.
- Thermal resistor between the case and the heat sink of the selected transistor: Rth (case-h) = 0.24°C / W.

We must first calculate the value of the thermal resistor between the junction and ambient air Rth j-a desired. We then have:

$$Pd = \frac{Tj - Ta}{Rth(j - a)} \tag{7}$$

Therefore: $Rth(j-a) \approx 1.25°C/W$

Finally, we need to calculate the value of the thermal resistance between the radiator and its environment ambient air Rth (h-a).

$$\text{Rth(h - a)} = \text{Rth(j - a)} - [\text{Rth(j - case)} + \text{Rth(case - h)}] \tag{8}$$

The calculations we give a value of:

$$\text{Rth(h - a)} = 0.06\ °\text{C/W}.$$

The choice of the type of the heat sink for the final realization of the load is based on the value of the thermal resistance Rth (h-a).

D. Choice of the Current Control of the Load

Fig. 5 shows a diagram of the control current of the load, in this scheme we used an analog control based on the use of operational amplifiers; each transistor is controlled by an operational amplifier.

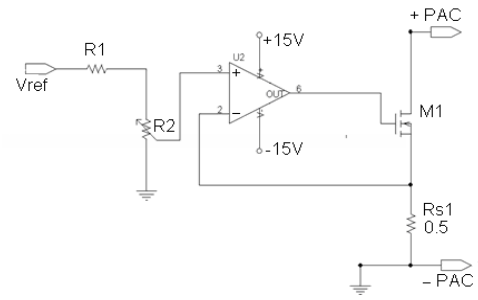

Fig. 5 Schematic of the current control of the load for a transistor

When we vary the voltage of the current reference, the amplifier will regulate the output voltage; so the reference voltage and the image voltage of the current relieved between terminals by the shunt resistor becomes equal. To impose the current that will be delivered by the stack, we used a resistor and a potentiometer. The latter is used to vary the voltage reference, thus variation of current. The entry of this stage denoted V_{ref} is a voltage that we injected to the stack to measure the impedance. To have a good precision level of imposed current to the stack, we chose to work with a multi-turn potentiometer.

IV. Realization of the Electronic Load

A. Practical Realization

The electronic load must support a current of 25 A and a voltage of 30 V so a power of 750 W. The type of the chosen transistor is an N-MOSFET referenced IRFP150N [13]. According to its data sheet this type of transistor can support a current I_D = 42 A and a power P_{max} = 160 W and resistor drain - source ($R_{DS(on)}$) is in the order of 0.036 Ω. As we indicated earlier, for resistor shunts we used two 1 Ω resistors connected in parallel in order to have a resistance of 0.5 Ω.

For the choice of the heat sinks, the computation is effected with the data sheet of the transistor. To do this we must choose a heat sink with a thermal resistor with a value less than or equal to 0.06°C/W to ensure a good cooling of each transistor. This value of thermal resistor belongs to the family of high power heat sinks. In practice we have chosen four heat sinks Marston™, whose length is 300mm, its reference (890SP-03000-A-100).

To ensure good cooling components, on each of the two radiators we placed three transistors and six resistors. These resistors do not affect the calculation of the heat sink because they are shunt resistor heat sinks. The chosen heat sink admits a thermal resistor of 0.04°C/W. We have provided a margin of safety by the use of two parts of this type of radiator that will be screwed in together in parallel, with a fan for the heat that can be accumulated between the two radiators and thus optimize the cooling of transistors. Fig. 6 presents the technical characteristics of the realized electronic load.

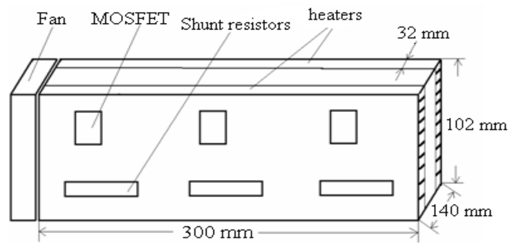

Fig. 6 Front view of the realized electronic load

B. Results and Discussion

To validate the correct operation of the electronic load, we used the Ballard Nexa™ PEM fuel cell system for testing. We used a power supply for the control board of the electronic load, a function generator for distributing the signal injected and a digital oscilloscope to verify the operation of the load. For current measurement we used a digital ampermeter. However for applications developed by LabVIEW® we used the acquisition card of National Instruments NI- 9205. Fig. 7 shows the test bench to validate the operation of the electronic load with the Ballard Nexa™ PEM fuel cell.

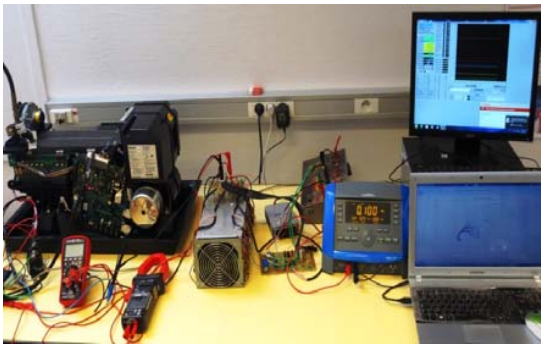

Fig. 7 Photo of the test bench of the electronic load with the Ballard Nexa™ PEM fuel cell

In this work, we started testing by tracing the polarization curve of the Ballard Nexa™ fuel cell using the proposed electronic load and the application of LabVIEW®.

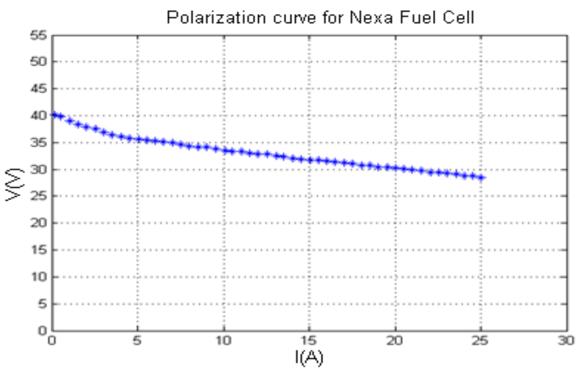

Fig. 8 Polarization curve for the Ballard Nexa™ PEM fuel cell with the proposed electronic load.

Fig. 8 represents polarization curve for the Nexa™ fuel cell. The principle of this test is to measure simultaneously the voltage and the current of the fuel cell using the electronic load and the developed LabVIEW® application. This curve contains two distinct areas; one for the low currents that corresponds to a voltage drop due to the activation overvoltage caused by the electron transfer to the cathode, the second area represents to the median currents and corresponds to a localized ohmic fall mainly in the membrane [14]. There is a third area corresponding to the high currents, it does not appear on this graph and corresponds to a voltage drop due to problems of diffusion of reactants limited by the transport of material, which causes a sudden drop in the voltage of fuel cell.

The measurement of the complex impedance with the electrochemical impedance spectroscopy (EIS) method requires hardware and software tools. Thus we have designed and realized the electronic load and developed a LabVIEW® application to measure and display this complex impedance. The LabVIEW® application identifies the data for the various tests and displays them in a Nyquist plot. The current range for testing by Nexa™ PEM fuel cell varies from 1 A to 10 A in steps of 1 A and 10 A to 20 A in steps of 2 A. We performed a total of fifteen tests for different current values. The frequency used for measuring ranges from 0.1 Hz to 12 kHz, usually for a PEM fuel cell the frequency used is selected from 1Hz to 10 kHz [14]. The measure of the complex impedance was made by an amplitude value; the perturbation signal is equal to 150 mV. A measure of this amplitude has no disruptive effect on the fuel cell because it delivers maximum 41 V without load. The testing of the fuel cell is made with a fixed hydrogen pressure equal to 5 bars.

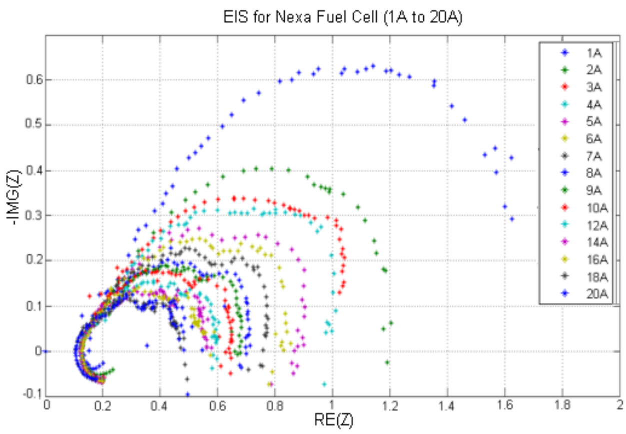

Fig. 9 Nyquist plots of the Ballard Nexa™ PEM fuel cell with the proposed electronic load for different currents.

Fig. 9 shows the Nyquist plots of the Nexa™ PEM fuel cell. It is noted in the figure that the low frequencies are on the right and the high frequencies are on the left. We noticed in this figure that we have a form of complex impedance represented by two lobes; these lobes correspond to the different parts operating in the fuel cell. The right lobe of each test represents the sum of the losses that intervene at the cathode and the anode of the fuel cell, while the smaller left lobe represents the total of the ohmic loss in the fuel cell. This loss is represented as the sum of the ohmic resistance of each cell of the stack. We note that these losses are the same for the fifteen tests realized with the Nexa™ PEM fuel cell. The form of the curves of these tests exist in various research works [15]-[17], which confirm these tests and validate the concept of the electronic load and the application developed by LabVIEW®. During these tests, we measured a quantity of the rejected water equivalent to 1165ml by the fuel cell.

V. Conclusion

In this paper, we presented the steps of design and implementation of an electronic load supporting a current of 25 A. This load will be integrated into a test bench for the measurement of the internal impedance of a PEM fuel cell has a power of 1200 W. The choice involves N-MOSFET transistors, heat sinks and the control current circuit of the electronic load. The experimental tests that carried with this electronic load have been tested on the Ballard Nexa™ PEM fuel cell and the results were satisfactory and agree well with those of the various searchers. This validates the choice of the method for measuring the internal impedance and the realization of the electronic load. Finally, this electronic load realized, is simple to prepare and presents a very interesting and economic ratio for the research.

Acknowledgments

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