Project Work Report

Fuel cell

Course of Hydrogen Technologies

Prof. Paolo Colbertaldo

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Group Members

Agostino Francesca	10868686
Chiarolini Simone	10802237
Dewynter Manon	10948467
Piuri Simone	10659447

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1 Abstract

In the current report, a discussion of the experimental laboratory attended during the Hydrogen Technologies course is presented. The subject of the experiments is a PEMFC system which is an innovative and promising device that allows to produce and exploit energy from hydrogen. The fuel cell used during the lab is a small-scale model which employs hydrogen provided to produce electricity. The analysis includes the preliminary mosfet characterisation and the performance measurements of the PEMFC. The performance analysis takes into account the V-I curve and the power curve. The paper also includes a critical analysis of which mistakes could have occurred during the measurements.

2 Introduction

The imminent and necessary energy transition led the technology development to investigate new forms of power production that permit to minimize CO_2 emissions.

A valid alternative to fossil fuels is hydrogen which has recently attracted significant attention for its high energy density, on a weight basis. The main problem with hydrogen is the low density that makes complex and expensive systems necessary.

The hydrogen application that is getting more interest is the transport application which uses a fuel cell connected to an electric motor to produce power. The transport sector accounts for 1/3 of the GHG emissions. For this reason, their reduction would have a major impact. The constraints of this application are the limited storage available on board and the need for a distributed refuelling.

A fuel cell is an electrochemical cell that converts the chemical energy of a fuel, in this case, hydrogen, and an oxidizing agent, often oxygen, into electricity through redox reactions. The fuel cell can produce electricity as long as hydrogen and oxygen are supplied.

The aim of the analysis is to investigate the performance of a small-scale fuel cell used for educational purposes. The analysis includes the V-I curve and the P-I curve. The measurements are made using an Arduino circuit and after a preliminary characterisation of the mosfet.

Initially, a brief description of the system is presented, with an explanation of every component of our circuit. The second chapter illustrates the circuit scheme and investigates the results regarding the mosfet characterisation and the fuel cell analysis. The last chapters discuss the results and compare the 3 measurements that are done commenting on the accuracy and the possible problems.

3 System understanding

3.1 Project description

The project is part of the laboratory work of the course "Hydrogen Technologies" which consists of the analysis of a small-scale PEM fuel cell. The aim of the project is to build a system capable of measuring the parameters which allow the analysis of the fuel cell performance.

3.2 The context

Fuel cells are an innovative and promising system that allows to produce and exploit energy from hydrogen. Hydrogen is becoming an important energy vector in renewable energy production and fuel cells are the most encouraging technology. The recent success of hydrogen as a fuel is due to the highest weight-based energy density equal to 33.3 Wh/g. The oxidation of hydrogen is very easy under neat ambient conditions of temperature and pressure and also using air at the cathode the system has zero emission because the only products are electricity, heat and water.

3.3 Components of the system

The fuel cell at disposal is a small-scale model which is used for educational purposes. This system needs hydrogen filling which is available thanks to the pairing with a PEM electrolyzer.

3.3.1 Fuel cell

Fuel cells are electrochemical systems which use the chemical energy of hydrogen to cleanly and efficiently produce electricity. The process description is reported in the **Figure 1**.

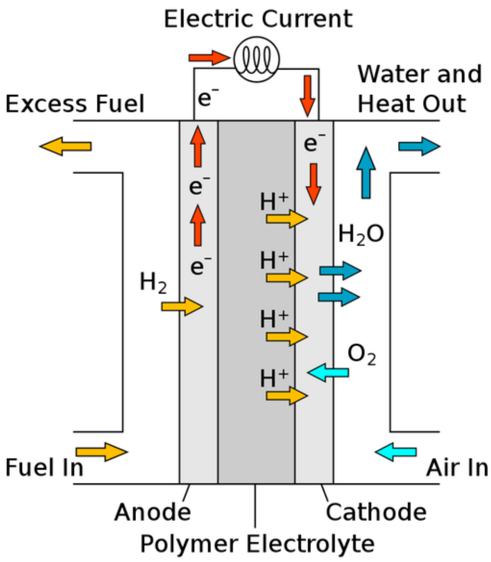

Figure 1: PEM fuel cell

Hydrogen is fed to the anode while oxygen or air is fed to the cathode. The fuel, hydrogen, is oxidized at the anode to produce protons and electrons following the reaction (Hydrogen oxidation reaction HOR) [1]:

$$H_2 = 2H^+ + 2e^- \tag{1}$$

Where the corresponding anode thermodynamic potential is $E^0_- = 0.00$ V vs SHE (under standard conditions). The protons can go through the hydrated PEM to reach the cathode as hydronium ions. The electrons travel along an external circuit to reach the cathode. The protons and the oxygen react with the electrons in the cathode following the oxygen reduction reaction(ORR) [2]:

$$\frac{1}{2}O_2 + 2H^+ + 2e^- = H_2O \tag{2}$$

Where the corresponding cathode potential is $E^0_+ = 1.229$ V vs SHE.

The overall reaction of an hydrogen PEMFC is [2]:

$$\frac{1}{2}O_2 + H_2 = H_2O \tag{3}$$

The standard equilibrium electromotive force is equal to 1.229 V.

The PEMFC are suitable for smaller scale applications such as transportation. It allows continuous operation, high power density and relatively low temperature operation. The most critical component is the catalyst layer which requires a platinum-based catalyst that is needed to minimize the energy loss due to the oxygen reduction in the cathode. The performances critically depend on the membrane resistance to proton flow which is minimized by a thin membrane. The membrane and catalyst degradation leads to low durability of the system which is the most challenging aspect of the PEMFC development [1] [2] [3].

3.3.2 Arduino

Arduino is an open-source electronics platform based on easy-to-use hardware and software. Arduino boards can read inputs, such as sensors, and turn them into an output. Arduino was invented by the Ivrea Interaction Design Institute and it is aimed at students without a background in electronics and programming. The **Figure 2** show us the Arduino UNO board pinout diagram.

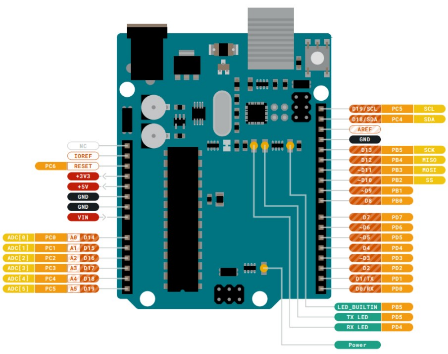

Figure 2: Arduino UNO Rev 3 pinout diagram

The analogue pins (A0-A5) read a signal from an analogue sensor and convert it into a digital value that can be read by the board microprocessor. The digital pins (D0-D13) are input/output pins to read or write logical values (0 or 1). When the "~" symbol is present the pin can generate a pulse width modulation (PWM) as the output signal. The power pins supply a constant output voltage and the ground pins are used to ground the circuit. The Arduino IDE contains a text editor for writing the code which allows it to connect and communicate with the Arduino hardware. The Arduino code is written using C++ [4] [5].

3.3.3 INA219

The INA 219 is a current sensor that allows us to measure the current, voltage and power of a circuit. It is an I2C supported interface based on zero drift and bi-directional current/power monitoring module. The sensor module is provided with 0.1 Ω and a 1% shunt resistor to fulfil the requirements of current measurements. The sensor can measure DC voltage up to 26V.

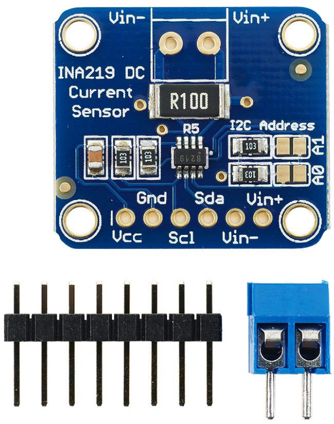

Figure 3: INA 219

It is possible to see from the **Figure 3** that the INA is equipped with 6 pins: VCC, GND, SCL, SDA, Vin- and Vin+. The VCC and GND pins are used for power supply and SCL and SDA pins are for the I2C communication. The Vin- and Vin+ pins have the goal to measure the voltage. Also, pins A0 and A1 are used for the I2C Address selection. The R100 is the current sensor resistor and finally, there is the INA 219 chip. Thanks to the wide voltage input range the sensor can be powered using the Arduino. The Arduino connection is shown in the **Figure 4**.

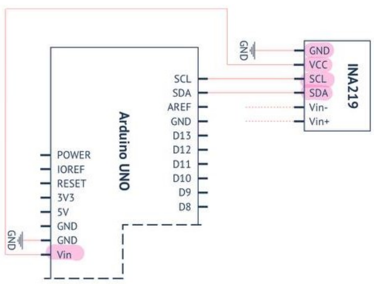

Figure 4: INA 219 connection with Arduino.

It is needed to connect the SDA and SCL pins to the corresponding pins in the Arduino UNO. The VCC pin is connected to the Vin pin on the analogue part of the Arduino UNO and finally the GND pin is connected to the ground. The connection with INA219 requires additional libraries such us <Adafruit_INA219.h> [6].

3.3.4 Mosfet

The Mosfet (Metal Oxide Semiconductor Field Effect Transistor) is a semiconductor device which is used for switching purposes and for the amplification of electronic signals. The device has 4 terminals: source(S), gate(G), drain(D) and body(B). Actually, is a three-terminal device because the body is connected to the source terminal. The Mosfet functioning is based on the electrical variations happening in the channel width and with the flow of carriers (electrons) which enter into the channel using the source terminal and exit through the drain terminal. The channel width is controlled by the voltage on the gate which is an electrode located between the source and the drain terminals and is insulated from the channel with a layer of metal oxide.

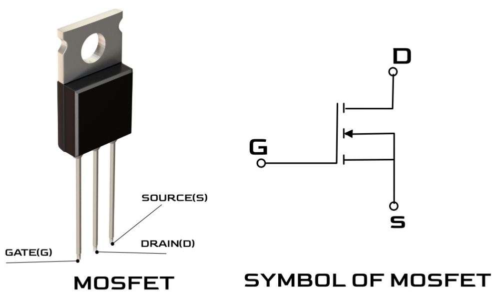

Figure 5: Mosfet scheme.

The advantage of this device is that generated enhanced efficiency even functioning at minimal voltage levels. The Mosfet is characterized by a high switching speed thanks to the increasing input impedance due to the absence of gate current. These devices can function even at minimal power level using minimal current. However, at overload voltage levels the device presents instabilities. The Mosfet find application in amplifiers and in the regulation of DC motors [7] [8].

3.3.5 Low pass filter

A low pass filter is a circuit which allows an easy passage to low-frequency signals and attenuates high-frequency signals. Low pass filters circuit can be composed by a resistor with either capacitors(RC filter) or inductors(RL filter). The one used in the project is the RC low pass filter and the circuit representation is showed in **Figure 6** [9].

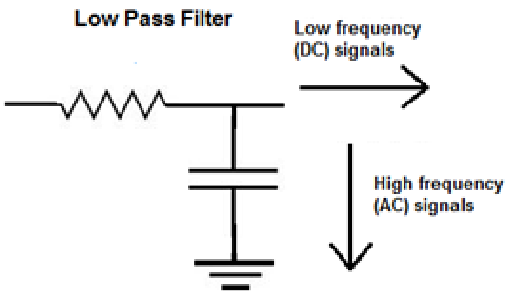

Figure 6: RC low pass filter.

The RC circuit is composed by a resistor that is in series with the input signal and by a capacitor in parallel to the input signal. The low pass filter is a reactive device which means that the resistance to signals depends on the frequency entering. The capacitor offers a very high resistance to low-frequency signal, instead a very low resistance to high-frequency signals. Therefore, the high-frequency signals will pass through the capacitor. The cut-off frequency of the filter determines which signals are allowed to pass as it is possible to see in **Figure 7** [10].

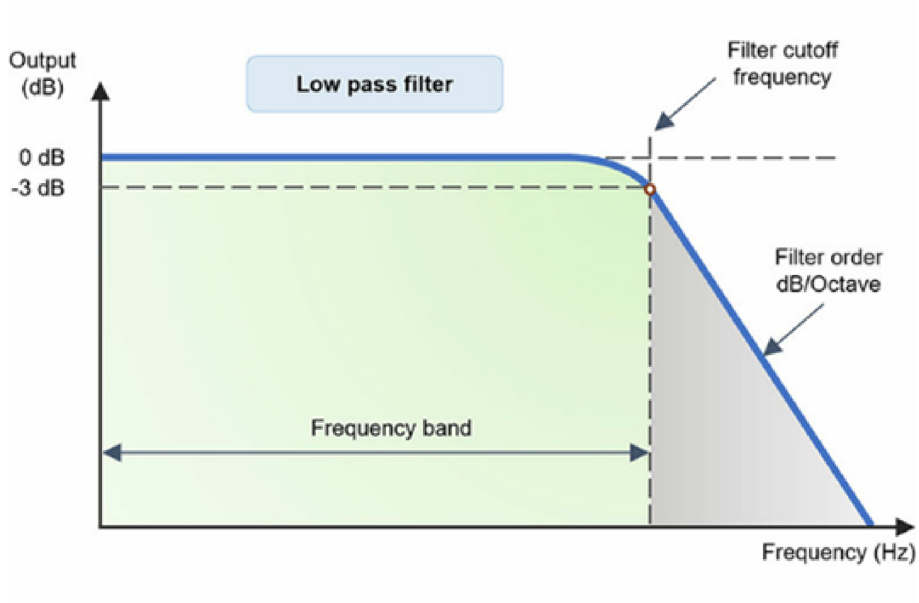

Figure 7: Low pass filter cut-off frequency.

4 Experiments

4.1 Mosfet characterisation

4.1.1 Circuit

As explained in **section 3**, the Mosfet is a transistor that can control the amount of current that flows into a circuit. This device is controlled using digital inputs and a low pass filter, connected in the configuration shown in **Figure 8**.
In order to measure the resistance of the Mosfet a multimeter is connected to the drain and source pin. In the first try of the experiment, the multimeter is connected to the Mosfet by directly placing the probes onto the source and drain pins. This resulted in a low accuracy of the measurement. To solve this problem, the connection is performed using additional cables that exploited the Arduino board, allowing for a more stable and accurate measurement.
Before any experiments on the fuel cell could be carried out, the Mosfet characterisation curve needed to be extrapolated. This curve relates the digital inputs, given through Arduino, to the resistance that the transistor applies on the circuit. For this reason, it is used in the Fuel cell experiment to obtain the polarization curve.

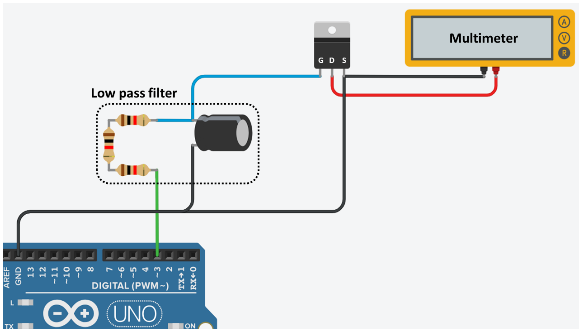

Figure 8: Mosfet circuit

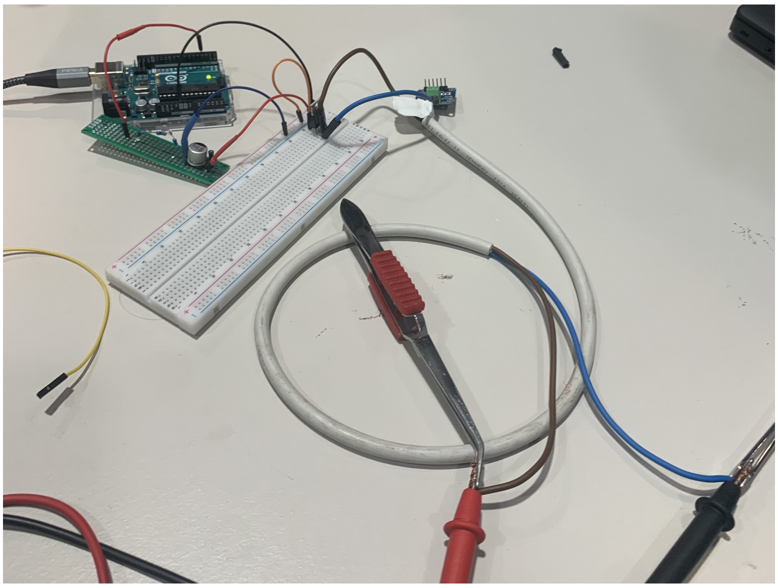

Figure 9: Real Circuit

4.1.2 Code

The code utilized for the characterization curve of the Mosfet is the one reported in **Figure 10**. It is decided to implement an algorithm, in which, the signals passed to the Mosfet are manually written on the keyboard. In this way, the time steps and the values can be decided each time, allowing a better understanding of the obtained results.

```
void loop() {

  while(a==0){
   a = Serial.parseInt();
  }

 if(a>0 && a<=255){
  analogWrite(Pin_Out,a);
  Serial.println(a);
 }
 else{
   Serial.println("Error");
 }
 a=0;
 }
```

Figure 10: Mosfet characterization code

4.1.3 Experiment

The results from the experiment are summarized in **Table 1**. Here, only part of the data gathered during the experiment is shown in order to give a sense of the conversion trend between bits and Ohm.

bits	Ohm [Ω]
140	9370
150	800
160	170
170	45
180	13.2
190	4
200	1.7
210	1.1
220	0.8
230 to 250	0.7
255	0.6

Table 1: Conversion from bits to Ohm of the Mosfet's resistance

In **Figure 11** the complete curve is shown. It's possible to see how the value of resistance is very high for low bits values. This is the reason why the data is gathered only in the range of 140 to 255 bits, which is the operative range of the Mosfet.
The curve shows a very steep decrease in resistance in the range 140 to 150 bits, going from 9370 Ω to 800 Ω. For higher bit values the curve decreases until it reaches an almost stable point around 200 bits.

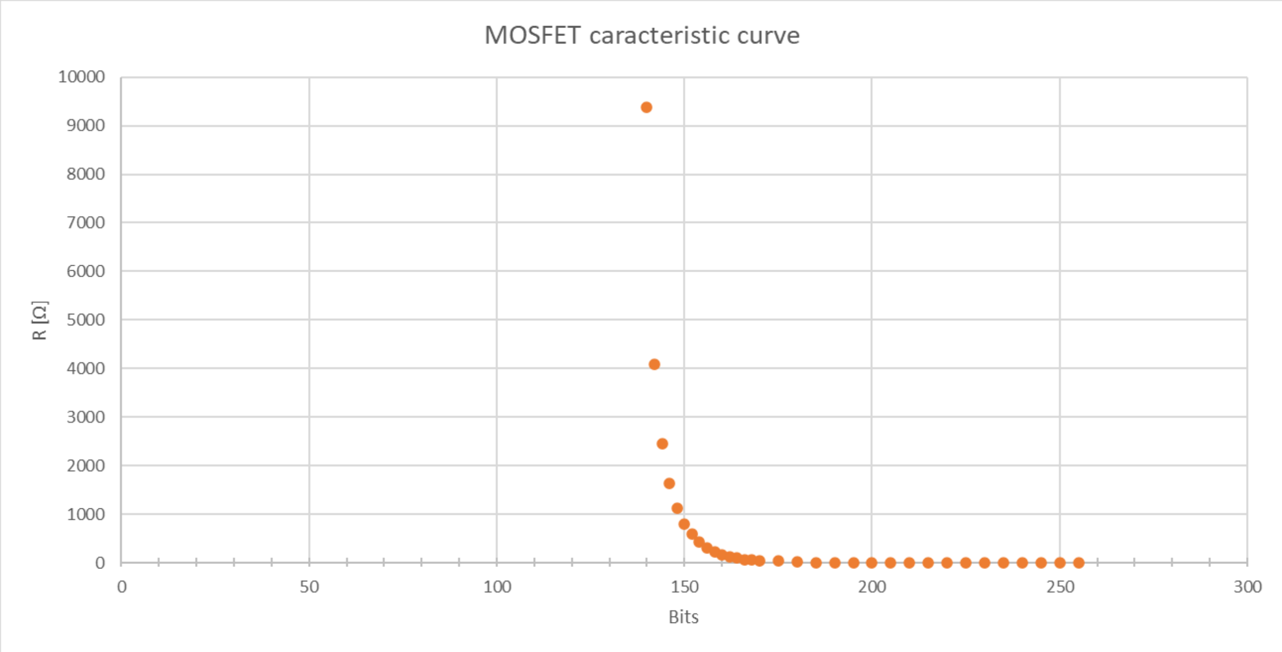

Figure 11: Complete Mosfet characterization curve

Figure 12 shows in more details the part of the curve from 160 to 255 bits, where the values of resistance reach the most common operative values.

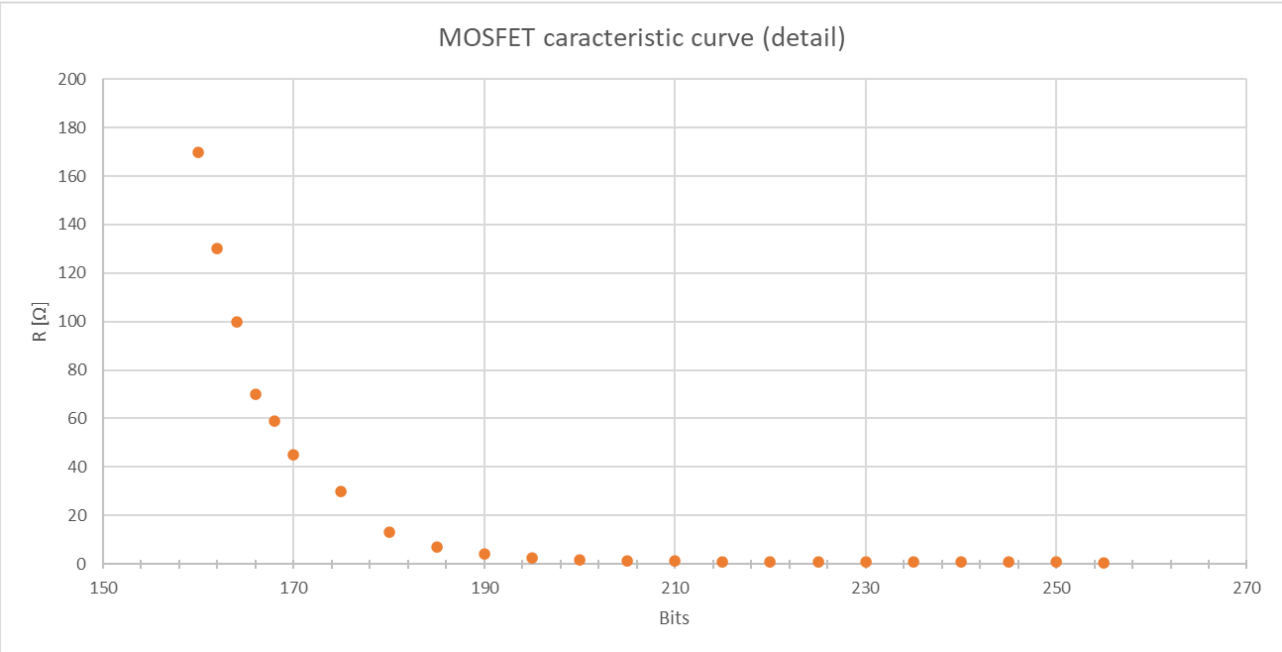

Figure 12: Detail of the Mosfet characterization curve, from 160 to 255 bits

4.2 Fuel cell experiments

4.2.1 Circuit

For the characterization of the Fuel cell's polarization curve, two parameters are needed, current and voltage. In order to get them, it is decided to put in series INA with the Mosfet, obtaining the current, and to use the analog port A0 to get the Fuel cell's voltage. With this configuration it was possible to modify the load and calculate simultaneously the resulting variation of current and voltage.

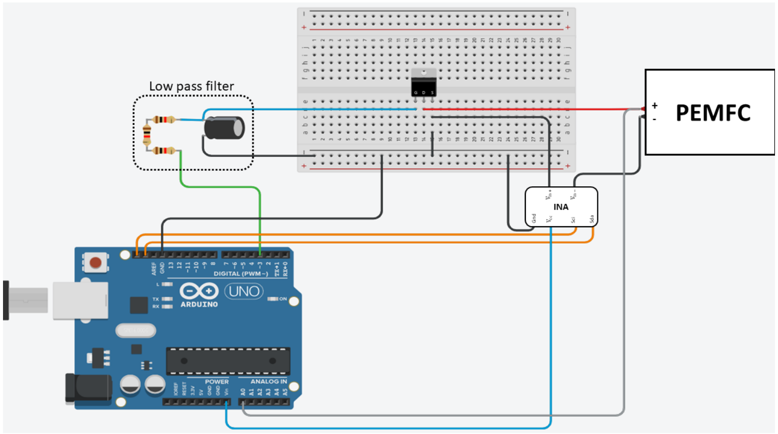

Figure 13: Circuit

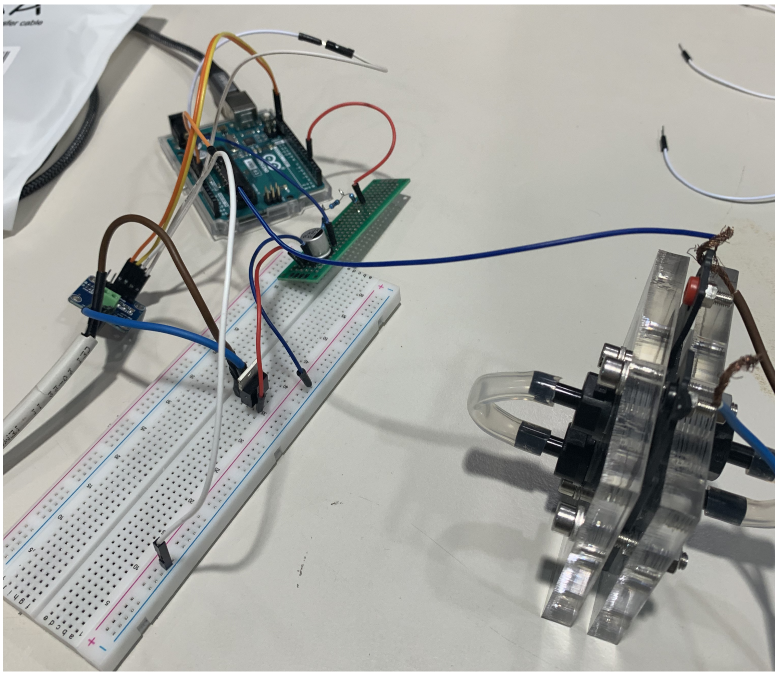

Figure 14: Real Circuit

4.2.2 Code

The code adopted for the measurement of current and voltage is implemented with the same procedure used in **Section 4.1.3**. Therefore, the signal passed to the Mosfet is given by keyboard input, and every 0.5 s the system calculate voltage and current till a new signal is sent. The code print voltage, current and pin signal separated by semicolons, allowing an easier post process.

```
void loop() {

  control=mosfet;

  while(control==mosfet || mosfet==0){
    delay(500);
    value = analogRead(Pin_V);
    voltage = value*V_max/1023;
    current_mA = ina219.getCurrent_mA();

    Serial.print(voltage);
    Serial.print(" ;");
    Serial.print(current_mA);
    Serial.print(" ;");
    Serial.println(control);

    mosfet = Serial.parseInt();

  }
  analogWrite(Pin_3,mosfet);
}
```

Figure 15: Final code

4.2.3 Experiments

Three experiments are performed that consist in getting the voltage and the current of the fuel cell applying different resistance to the Mosfet. In the first one the resistance varies from 140 to 255 bits by step of 10, which means from 9370 Ω to 0.6 Ω. This is the data range of interest, as explained in the previous part. Here is the I-V curve which that results from the first experiment.

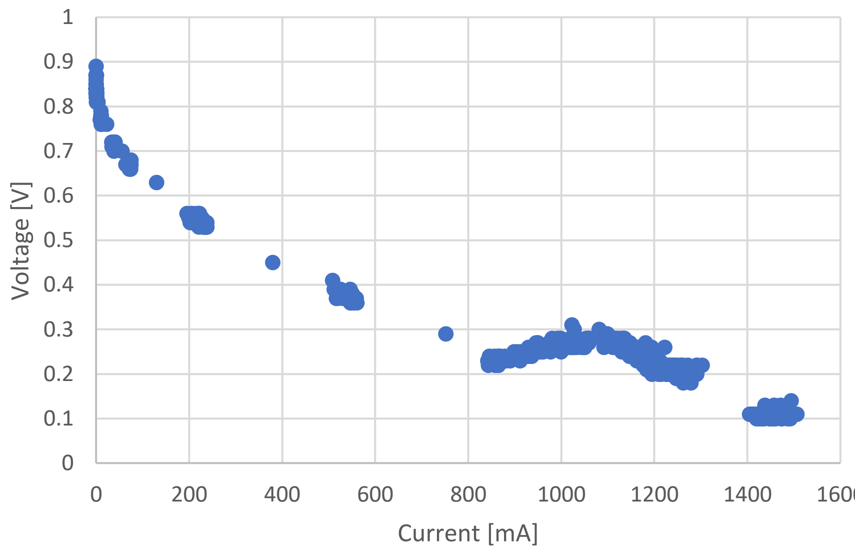

Figure 16: I-V characteristic curve of the fuel cell, from 9370 Ω to 0.6 Ω (1^{st} experiment).

First of all, some values are missing, so the accuracy must be increase in the next experiments in the current measurement between 200 and 800 mA, which corresponds to the resistance values between 220 and 230 bits. Afterwards, the I-V curve increases around 1100 mA instead of decreasing continuously.

One consequence of this phenomenon can be noticed in the Power vs Current curve (P(I)) in **Figure 17**. Power should continuously increase until a maximum and then decrease, instead a local minimum is reached around 800 mA of current.

In this first experiment the maximum power reached is 324 mW at 1100 mA. According to the fuel cell's guide, it should reach 800 mW at 1500 mA.

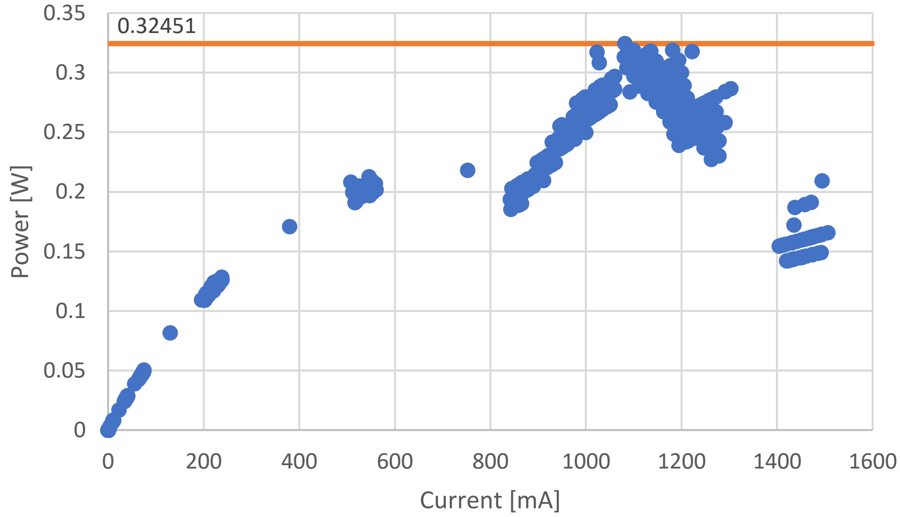

Figure 17: P(I) of the fuel cell, from 9370 Ω to 0.6 Ω(1^{st} experiment).

The two other measurements are intended to correct this increase of voltage in the I-V curve and to complete our set of results between 200 and 800 mA, as said before.

In the second experiment the resistance varies from 220 to 250 by step of 5 bits. These results are much more coherent because the I-V curve (**Figure 18**) is still decreasing, and I-P curve (**Figure 19**) looks like a parabolic curve, as expected. Anyway, the maximum power obtained, 391 mW at 1100 mA, is still far from the theoretical value.

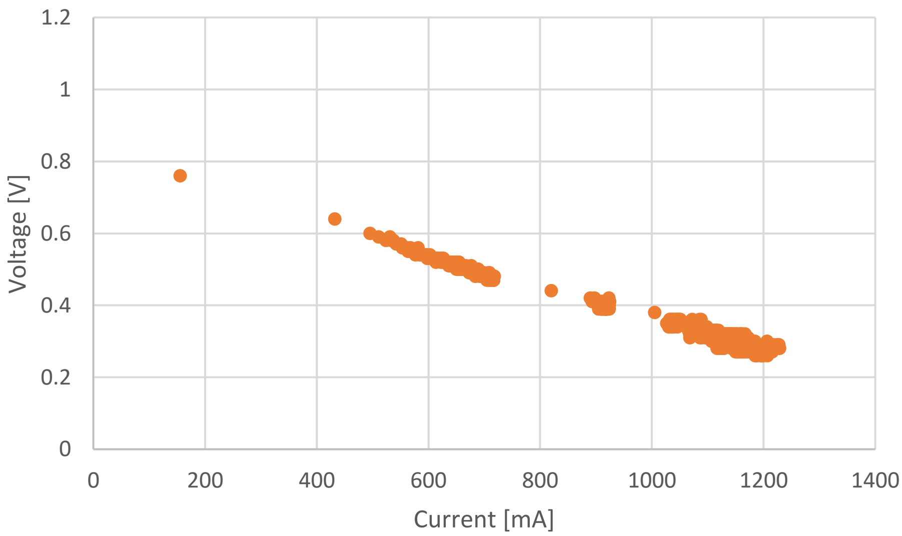

Figure 18: I-V characteristic curve of the fuel cell, from 0.8 Ω to 0.6 Ω(2^{nd} experiment).

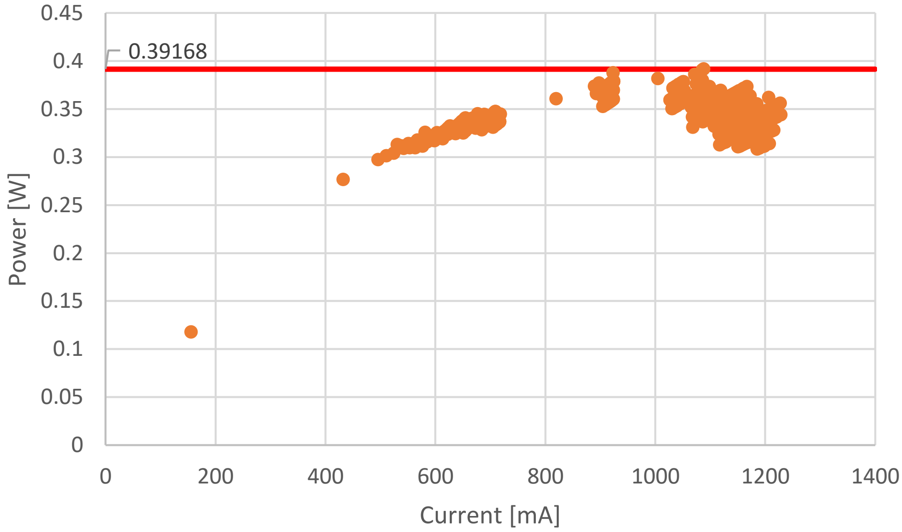

Figure 19: P(I) of the fuel cell, from 0.8 Ω to 0.6 Ω(2^{nd} experiment).

The accuracy of the measurement should be increased again between 220 and 230 bits, which is the goal of the third experiment (**Figure 20** and **Figure 21**), where it is collected data every two bits. Here, the maximum power obtained is 393 mW at 894 mA.

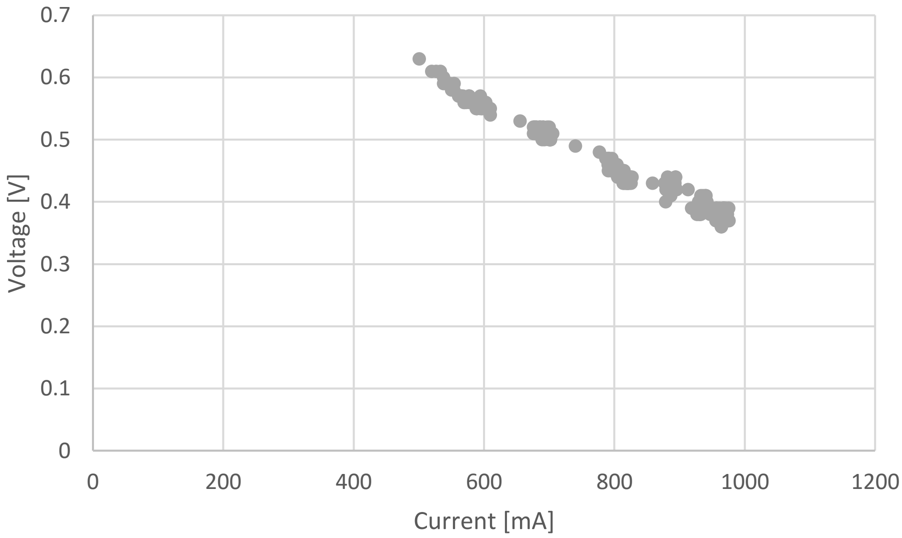

Figure 20: I-V characteristic curve of the fuel cell, from 0.8 Ω to 0.7 Ω(3^{rd} experiment).

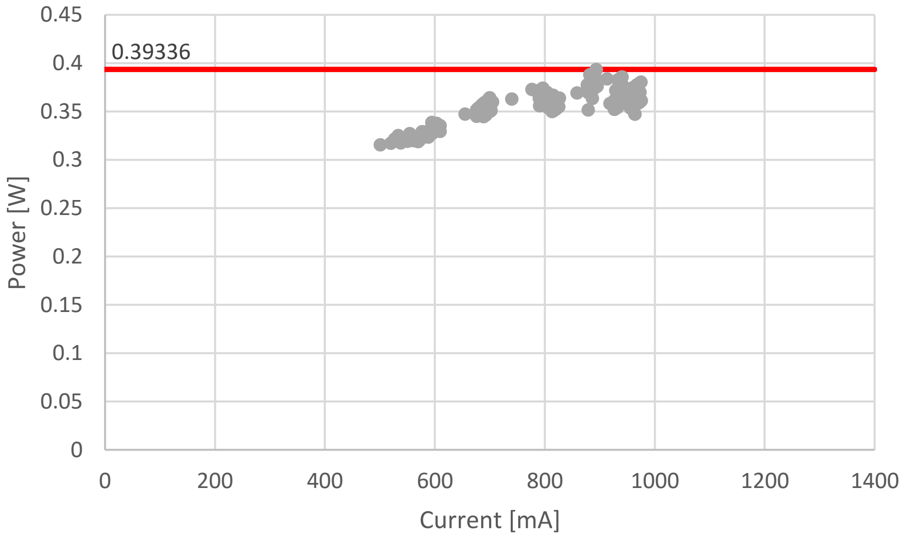

Figure 21: P(I) curve of the fuel cell, from 0.8 Ω to 0.7 Ω(3^{rd} experiment).

5 Discussion

Comparing the three experiments together, it is possible to say that the first measurement is the one that has the lowest accuracy. The second and third instead are very coherent and repeatable. To sum up, the maximum power obtained with these 3 experiments is 393 mW at 894 mA which is lower than the theoretical value (800 mW at 1500 mA, from the Fuel Cell guide).

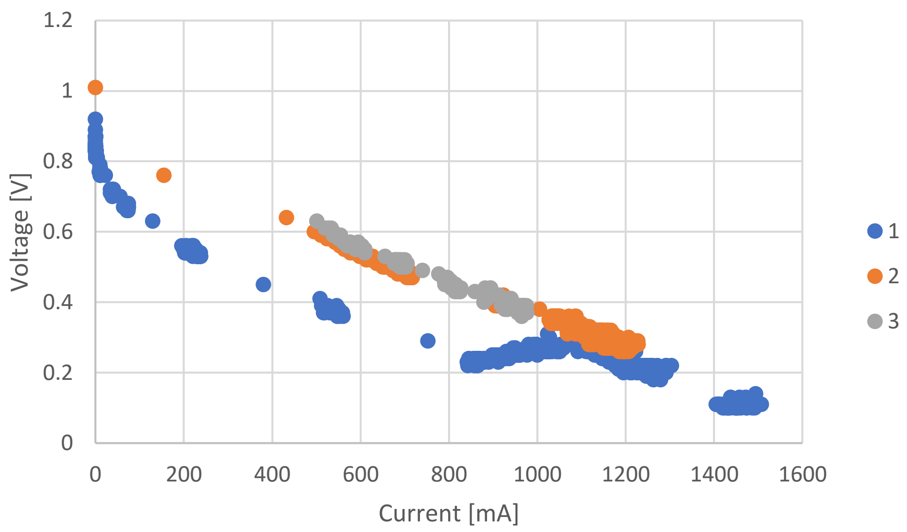

Figure 22: I-V characteristic curve of the fuel cell (all the experiments).

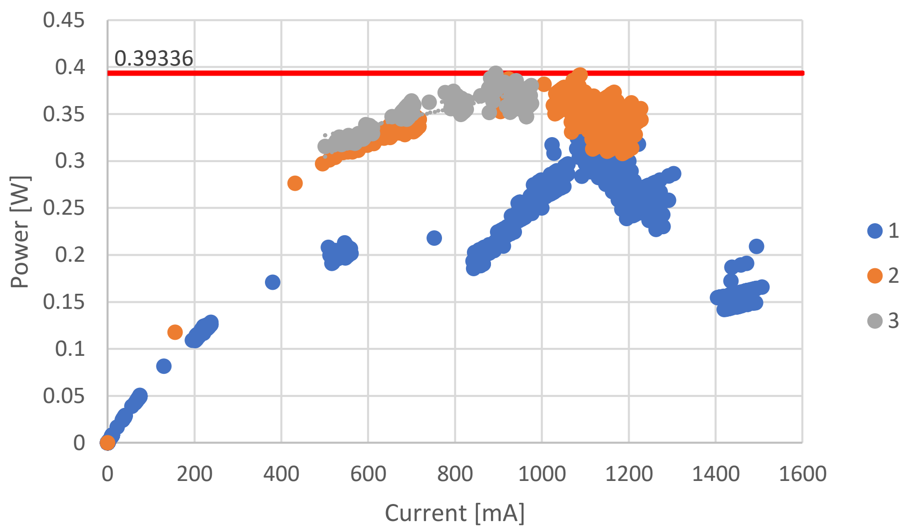

Figure 23: P(I) curve of the fuel cell (all the experiments).

In fact, during these experiments, the voltage measured through Arduino was approximately half than the one measured with the multi-meter directly at the fuel cell's terminals. Here are presented the differences of voltage obtained between Arduino and the direct measurement with the multimeter, for the 2 first experiments in function of the resistance.

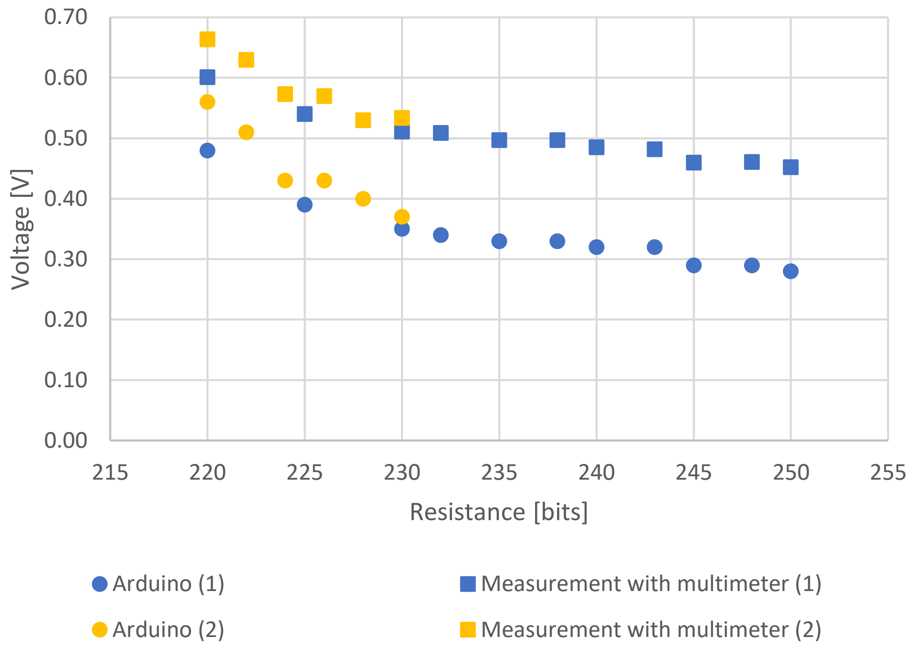

Figure 24: Difference of voltage between Arduino and the multimeter in function of the resistance.

The difference of voltage is bigger during the 1^{st} experiment than during the 2^{nd} one. This is explained by the fact that before the first measurement, the purge of the cell was not sufficient so a lower voltage, higher current and lower power are obtained. On the contrary, before the second experiment, a better purge of the cell was realised, so the voltage measured is higher. To sum up, the purge was necessary to have high voltage and high power, and without a sufficient purge, the values obtained were not performing well. In addition analyzing the value in **Figure 24** it is clear that the values measured using Arduino are far from the one measured with the multimeter. The gap between these two measurements range are presented in **Figure 25**.

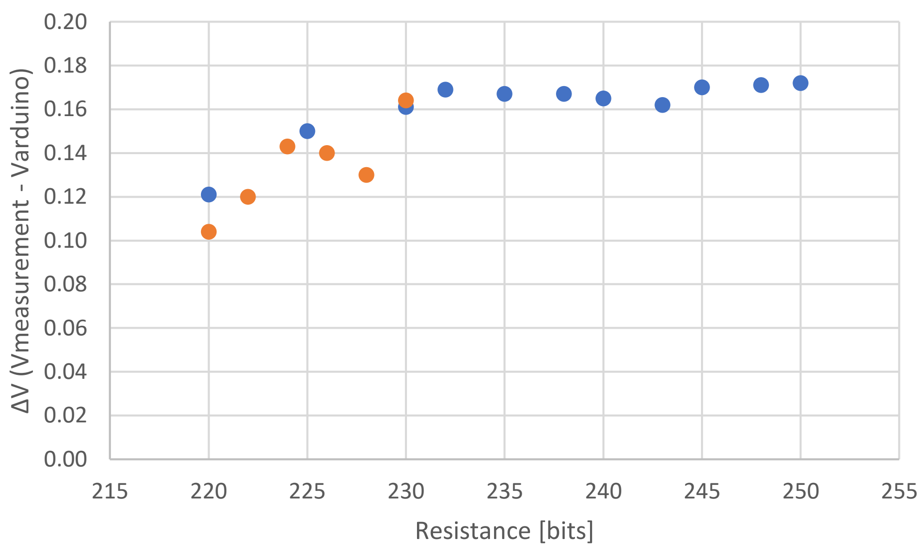

Figure 25: $\Delta V (= V_{measurement} - V_{Arduino})$ in function of the resistance.

The mean value of the gaps is around 0.17 V.

A consequent measurement of the voltage difference across the INA219 leads to the conclusion that this component is the cause of this lack of accuracy because the value measured was around 0.2 V. This latter value is very similar to the gap between the Arduino values and the multimeter values. Consequently, the full circuit is reassembled to measure the voltage using a configuration which connects directly the anode of the PEMFC to the Arduino ground. The connection with the PEMFC is inverted: the Anode is directly connected to the source terminal of the Mosfet and the cathode is connected to the INA219. The resulting values are showed in the **Figure 26**.

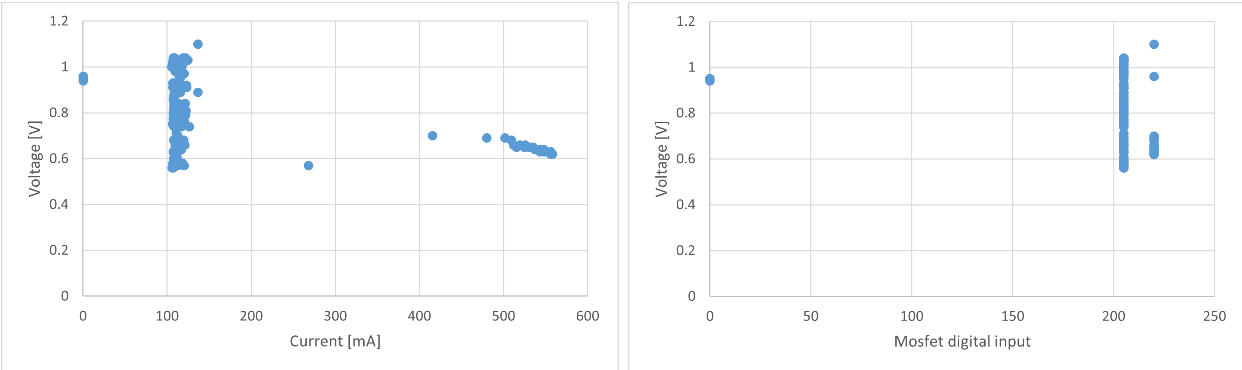

Figure 26: Measurement results

It's evident that the values obtained are not useful because at the value 205 bits the voltage is oscillating so the results are not stable. It can be assumed that are present some problems with the second circuit configuration because of the instability. Therefore it is not possible to state what is the real cause of the lack of accuracy.

6 Conclusions

To go further, the interpolation curve of both the voltage (**Figure 27**) and the power (**Figure 28**) in function of the current are calculated. In order to have the best fit as possible, the interpolation curves are computed using the data of the experiments 2 and 3.

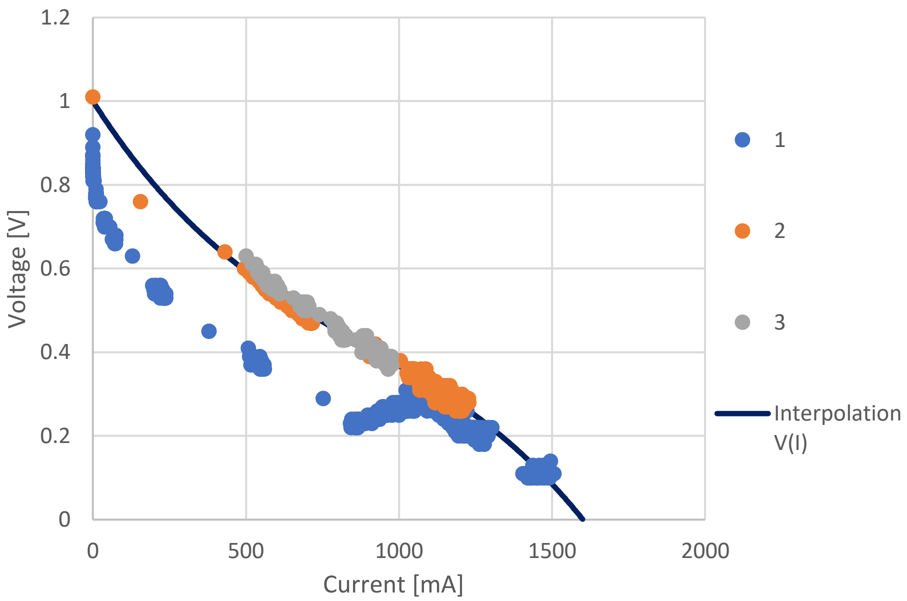

Figure 27: Polarization curve interpolation

The interpolation curve of the voltage is calculated using a polynomial function of order 3: $y = -3,16 \cdot 10^{-10} \cdot x^3 + 8,34 \cdot 10^{-07} \cdot x^2 - 1,15 \cdot 10^{-03} \cdot x + 1,0$. The correlation coefficient obtained for this fit is $r^2 = 0,987$.

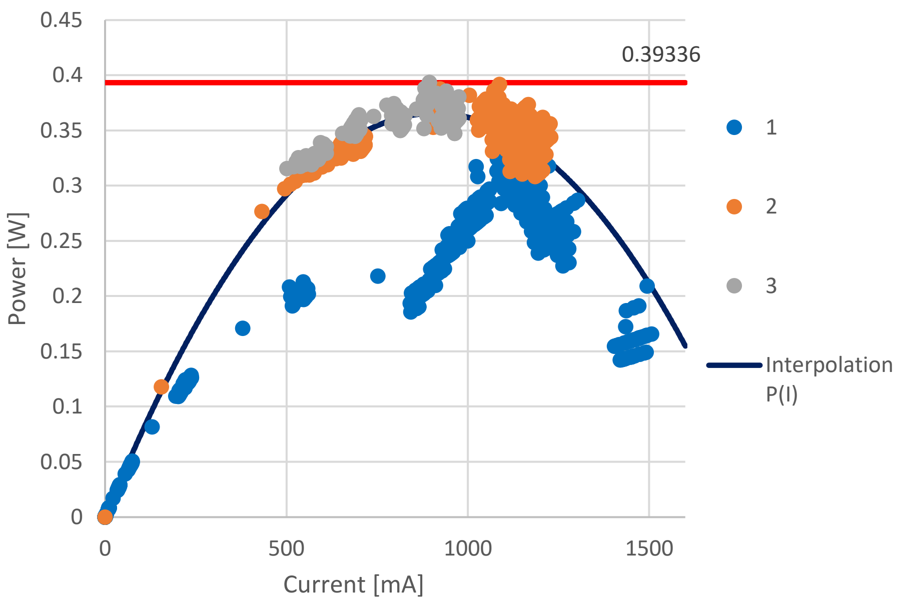

Figure 28: Power curve interpolation

The interpolation curve of the power was calculated using a polynomial function of order 2: $y = -4,42 \cdot 10^{-07} \cdot x^2 + 8,04 \cdot 10^{-04} \cdot x - 8,06 \cdot 10^{-05}$. The correlation coefficient obtained for this fit is $r^2 = 0,995$.

Then, using the polarization curve of the voltage vs the current, the electrochemical efficiency of our system (**Figure 29** and **Equation 4**) is calculated.

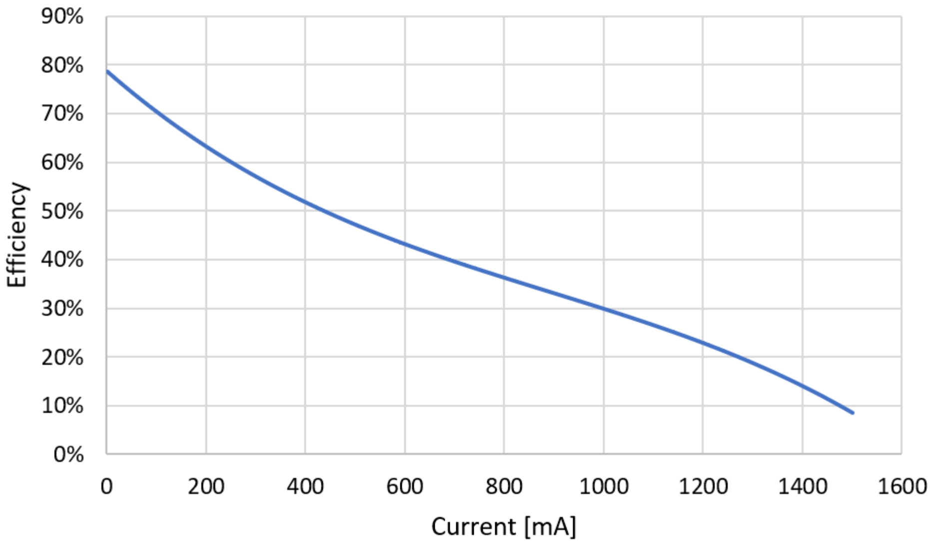

Figure 29: Efficiency

The electrochemical efficiency is calculated using the following equation:

$$\eta = \frac{\Delta V}{E_{EQ}} \tag{4}$$

with ΔV the voltage get from the interpolation of polarization curve and $E_{EQ} = 1.23$ V vs SHE, the equilibrium potential. The behaviour of the efficiency curve is the one expected.

From the approximated measurement of the INA219 in the first circuit it is possible to assume that this component can be the source of the accuracy but it can't be said with certainty.

Future research could be conducted on a deeper analysis of the measurement error generated by the INA. Two possible directions of study could be: to establish a more accurate measurement system, improving the connection between components but maintaining the same circuit; otherwise, it could be possible to rearrange the circuit in order to perform the measurement bypassing the INA, eliminating the mistake.

A Author Statement

Chiarolini Simone: Methodology, Investigation, Data Curation, Writing, Visualization.
Piuri Simone: Methodology, Hardware, Software, Investigation, Data Curation, Visualization.
Agostino Francesca: Methodology, Investigation, Data Curation, Writing, Visualization.
Dewynter Manon: Methodology, Software, Investigation, Data Curation, Writing, Visualization.

References

[1] *Electrochemistry Encyclopedia PEM fuel cells*. URL: https://knowledge.electrochem.org/encycl/art-f04-fuel-cells-pem.htm (visited on 05/30/2023).

[2] *Fuel Cells*. en. URL: https://www.energy.gov/eere/fuelcells/fuel-cells (visited on 05/30/2023).

[3] *Fuel cell - Energy Education*. en. URL: https://energyeducation.ca/encyclopedia/Fuel_cell (visited on 05/30/2023).

[4] *What is Arduino? — Arduino Documentation*. URL: https://docs.arduino.cc/learn/starting-guide/whats-arduino (visited on 05/30/2023).

[5] Engr Fahad. *INA219 Current Sensor with Arduino circuit and code explained*. en-US. June 2021. URL: https://www.electroniclinic.com/ina219-current-sensor-with-arduino-circuit-and-code-explained/ (visited on 05/30/2023).

[6] *INA219 High Side DC Current Sensor (26V ±3.2A)*. en. URL: https://store.fut-electronics.com/products/ina219-high-side-dc-current-sensor-26v-3-2a (visited on 05/30/2023).

[7] Lesics. *How does a MOSFET work?* en. URL: https://www.lesics.com/how-does-a-mosfet-work.html (visited on 05/30/2023).

[8] Tarun Agarwal. *What is the MOSFET: Basics, Working Principle and Applications*. en-US. Oct. 2013. URL: https://www.elprocus.com/mosfet-as-a-switch-circuit-diagram-free-circuits/ (visited on 05/30/2023).

[9] *Low Pass Filter- Explained*. URL: http://www.learningaboutelectronics.com/Articles/Low-pass-filter.php (visited on 05/30/2023).

[10] *Filter (electronics) — Kistler*. URL: https://www.kistler.com/INT/it/filter-electronics-/C00000109 (visited on 05/30/2023).