End-of-Degree Project

Degree in Industrial Engineering

Bench designing for the integration of fuel cells into electric vehicles

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The comittee judging the Project indicated above is comprised of the following members:

President:

Chair:

Secretary:

They agree to grant this project a grade of:

Sevilla, 2022

Tribunal Secretary

A mi familia

A mis maestros

Acknowledgments

A mi madre, hermanas y amigos por enseñarme y darle sentido a mi vida, aguantarme y apoyarme en todo lo que me propongo. Gracias a Carlos Bordons y a Juan José Márquez por su paciencia y ayuda ofrecida durante este trabajo. También a Carlos Naz por su ayuda con el programa y consejos dados durante el curso. Y gracias a mi padre por darme fuerzas todos los días.

Javier Martínez-Pais Gonzalez

Sevilla, 2022

Resumen

En el presente trabajo se pretende integrar una pila de combustible NEXA1200(PEMFC) en un vehículo eléctrico que dispone de una batería y cuatro motores, uno por rueda. Para investigar posibles estrategias de gestión de la energía se propone el diseño de una bancada formada por una pila de combustible y un convertidor elevador de tensión. Además, se dispone de una carga electrónica, fuente de alimentación y posibilidad de conectar baterías. Inicialmente se diseña una estrategia que tiene como fin aumentar la autonomía del vehículo y conservar la vida útil de la pila. Dicho vehículo, llamado FOX, y el material fue proporcionado por el Departmaento de Ingeniería de Sistemas y Automática de la ETSI.

Abstract

In the present project it is pretended to integrate a NEXA1200 fuel cell (PEMFC) in an electric vehicle which has one batterie and four motors, one by wheel. To investigate possible energy management strategies, the design of a bench formed by a fuel cell and a voltage booster converter is proposed. In addition, an electronic load, power supply and the possibility of connecting batteries are available. Initially, a strategy is designed that aims to increase the autonomy of the vehicle and the fuel life will be preserved. The vehicle, named FOX, and all the material was provided by the Systems and Automatics Engineering Department of ETSI.

Índice

CHART INDEX

FIGURE INDEX

Notación

PEMFC	Protochange membrane fuel cell
UinSP	Input voltage reference
UinAV	Input voltage actual value
UoutSP	Output voltage reference
UoutAV	Output voltage actual value
IinSP	Input current reference
IinAV	Input current actual value
IoutSP	Output current reference
IoutAV	Output current actual value
CO2	Carbon dioxide
INTA	Instituto Nacional de Técnica Aeroespacial
CAN	Controller Area Network
NI-DAQmx	National Intrument's current-generation data acquisition driver

1 INTRODUCTION

When there is no energy, there is no color, no shape, no life.

- Michelangelo Merisi da Caravaggio -

During this introducción the problem to study and the objectives to accomplish will be presented. Lastly, there will be a description of the strategy followed to achieve those objectives.

1.1 General motivations

In the 1880s, Karl Benz builded the first vehicle with a internal combustion motor (ICE). In 1888 the first long trip (about 100km long) was accomplished by his wife, showing that personal transport could be done in this type of vehicles. [1]

As of today, the number of vehicles is growing continuously. In figure 1.1. we see the evolution of the vehicle numbers existing worldwide and in Europe. In 2012, there were 449 vehicles for every 1000 people, indicated by the Organisation Internationale des Constructeurs d'Automobiles (OICA). [2]

On the other hand, this fact means that 16% of the CO2 human emissions come from the road transport section. This quantity of emissions is only overcome by the electric generation and calefaction section. [3]

That is why the main objectives of the car industry is reducing these numbers. The electric vehicle is way of replacing the contentional motors. Meanwhile batteries, Ultra Capacitor (UC)s and fuel cells are becoming the new energy sources, without forgetting the hydrogen cells. In this regard, China is one of the main stakeholders and promoters of this kind of energy source. [4]

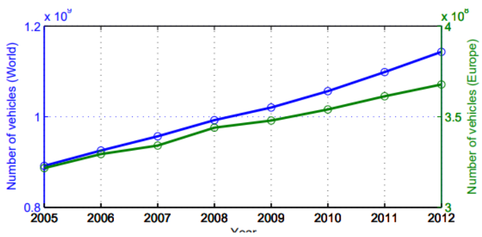

Figure 1.1. Number of vehicles in the world and in Europe

1.2 Description of the problem

It is looked for integrating the NEXA 1200 proton exchange membrane fuel cell (PEMFC) into a bench which will be used to test several and different control designs and algorithms, with an intermediate stage with a boost-elevator converter where the voltage will be elevated to the necessary values required to fulfill the requisites of a hybrid car.

Previously, there was a LabView and C++ program which was asked by INTA to control a different hybrid vehicle, called MELEX. The working method of this program was using 2 devices and CAN communication, with the control part implemented in C++. Here there was also an intermediate stage with a boost-elevator converter. The objective was integrating it into the MELEX.

Figure 1.2. General scheme of the circuit.

In this case, because designing a bench to integrate the system, the circuit will look like Figure 1-3, where the electric charge will simulate the car. This way, it will be easier, safer, and less laborious to test control designs and algorithms, since it will not be required to implement them in the FOX first.

The working method of this bench will be only using one computer where:

- The PEMFC will be given the orders of turning on and off or reseting, while being able to see all the information related to it. If any error occurs, the description and the code will be shown.
- The converter setpoints will be written before and through the test, with the information and values being shown in real-time.

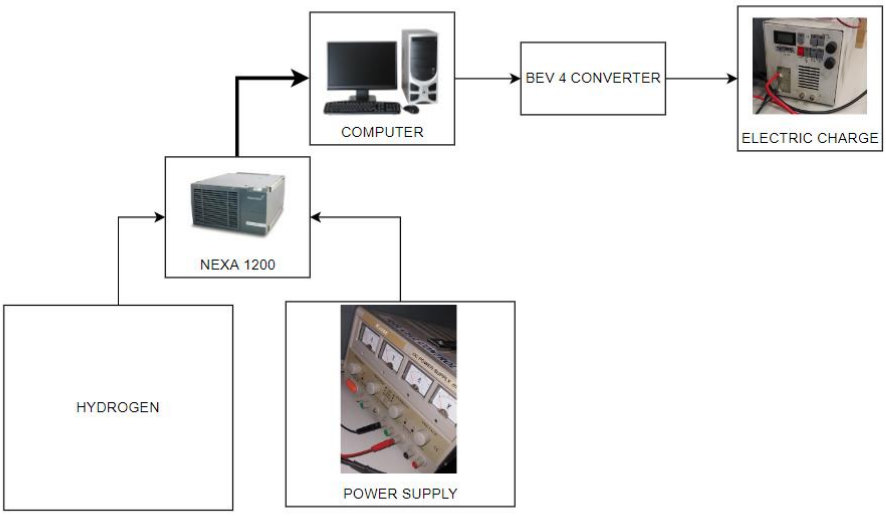

Figure 1-3. Bench scheme circuit

In the University of Seville, the thesis of David Marcos*: Contributions to power management and dynamics in hybrid vehicles* [7] started the research of the hybrid hydrogen vehicles which have been focused on the FOX car, its properties, and several control strategies. There have been several TFGs have been related to the FOX vehicle, which studied controlling the vehicle dynamics [10] and traction and stability [9] of the FOX wheels. In this case, we are gathering some of the work done related to the batteries and PEMFC integration, making adjustments to adapt the software and, after that, accomplishing only leaving the part of plugging the necessary devices into the vehicle and making it run.

1.3 Objectives

For doing this TFG we will be helped with a LabView program that was made for another car (MELEX) to INTA a couple years ago. Therefore, our main objective developing a program to integrate the operation of the fuel cell connected to a load a battery. Specifically:

- Adjusting the LabView program so it can be used to send orders through the program and not needing another device that controlled the system through C++
- Doing the power control part so it can regulate the voltage and intensity that comes out of the converter and that will pass to the FOX.

1.4 Followed Strategy to achieve the goals

When talking about how the problem can be solved, we have to look at 2 parts: redoing the LabView program so that it is adjusted to the FOX and PEMFC necessities and design the power-elevator control part.

Lastly, dealing with errors and solving or adapting to them was crucial during this TFG, specially with LabView versions and having to search different driver versions so the Data Adquisition Cards could be use and are able to give us the correct data.

1.4.1 Program Used

In this part, the program that was made a couple years for the MELEX vehicle which was asked by INTA will be used as a help to create the new algorithm.

For adjusting it to the objective that was aimed for, a couple of changes had to be made, from implementing the new DAQmx functions and creating the algorithm to re-doing the CAN communication. All these changes that were made will be talked about later in Chapter 4.

In Figures 1-4 and 1-4.2 of the interface can be seen; the first one was re-done so the fuel cell could be started, stopped or reseted and the next one is the converter-part, where the set-points can be adjusted.

1.5 TFG Adaptation

When this TFG was started the main idea was to replicate the FOX vehicles system (which Will be talked about later) using two PC-104 (an embedded computer), its ECU and the supervisor. There were some logistic problems when asking for them, so the main objective of this work document had to be changed and adapted to the logistic possibilities of the laboratory, resulting in this document.

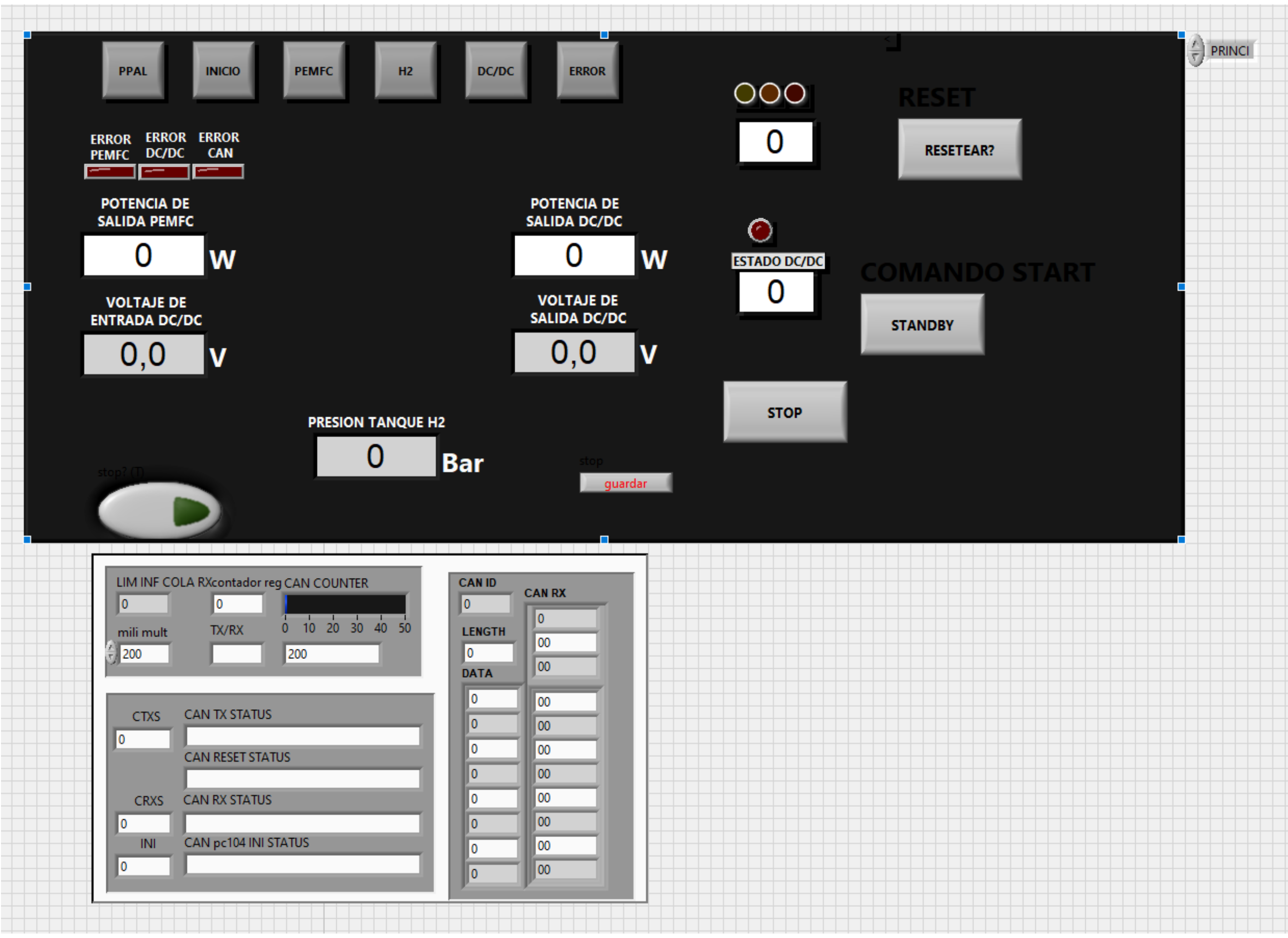

Figure 1-4. Interface of the LabView Program

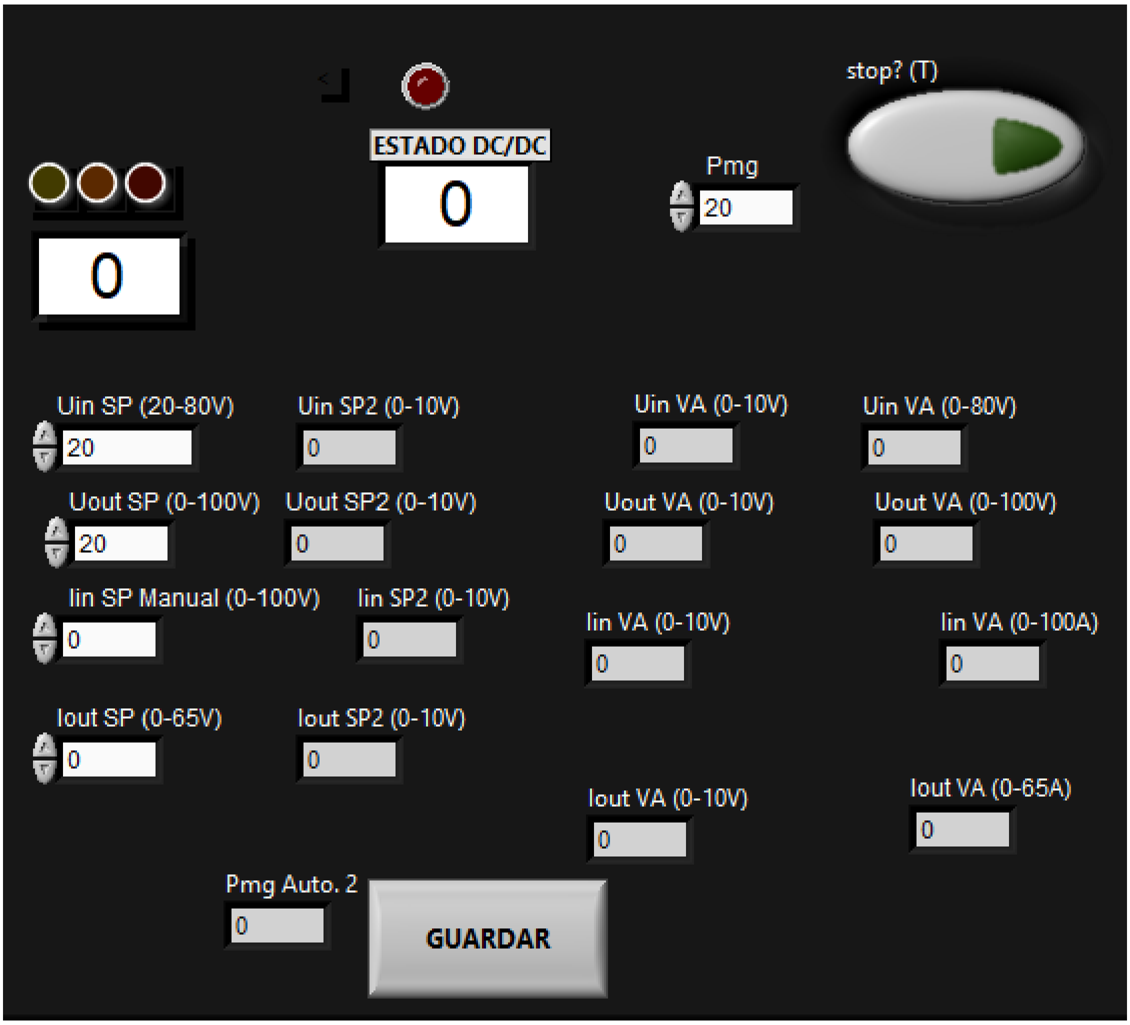

Figure 1-4.2 Interface of the LabView Program

2 STATE OF THE ART

"The people are the masters of the revolution in each country It cannot be exported nor imported".

-Kim Il Sung-

During this chapter a look will be taken into the characteristics of the devices that are going to be used to expose the knowledge and researchs that have been done with them that are closer to the objective of this work document. Firstly, it is looked at the FOX vehicle and the BEV4 Converter. Moreover, a look will be taken into the PEMFC and the integration of them into hybrid vehicles and the reasons behind it.

2.1 FOX Vehicle characteristics

The FOX car has its chasis as the racing car Silver Car S2 and under them it has 4 electric motors implemented on the wheels and the energy source, as it shows in Figure 2-1 and Figure 2-2:

Figure 2-1. Tubular Chassis Detail

The FOX car is an electric vehicle designed by the University of Seville. It is different from nowadays cars since it uses a PEMFC and electric batteries and has an electric motor in each wheel that is powered through a battery system, so it has all-wheel drive (power is applied to all 4 wheels). For this reason, it offers a lot of versatility when it comes to implementing control algorithms for vehicle traction and stability.

Referring to the motors, as it was said, it has all-wheel driver, so making control algorithms is easier and less laborious. Because of that, intermediate steps that transfer torque to the wheels, so the efficiency raises up considerably.

Talking about numbers, each motor has a 7kW power with a maximum transmitable torque of 8 N*m. These motors do not have brushes because this improves the speed-torque relationship, efficiency and reduces the need for maintenance, which is very common in the vehicle industry.

Lastly, the braking system consists of a disc brake independent of the motors, activated mechanically from the pedal, as is normal. This assures that they will work properly during testing.

Figure 2.2. FOX Vehicle

2.2 Electric Vehicles

The electric vehicle can be defined as a car which obtaines its movement power through stored electric energy liberation and is transmitted into one or more electric motors. These vehicles have a series of energy storage which the vehicle uses to generate its movement. The most used device for storage is batteries, but there exist other devices such as an energy auxiliar supplier like ultra capacitors or fuel cells.

Since the 90s, electric vehicles have developed fast in the vehicle industry. The main motivation for their use and development is minimizing the global warming and the dependance of the fossil fuels, even being able to become an alternative to reduce greenhouse gasses. In Figure 2-3 the comparation between the two types of vehicles when producing pollution is shown:

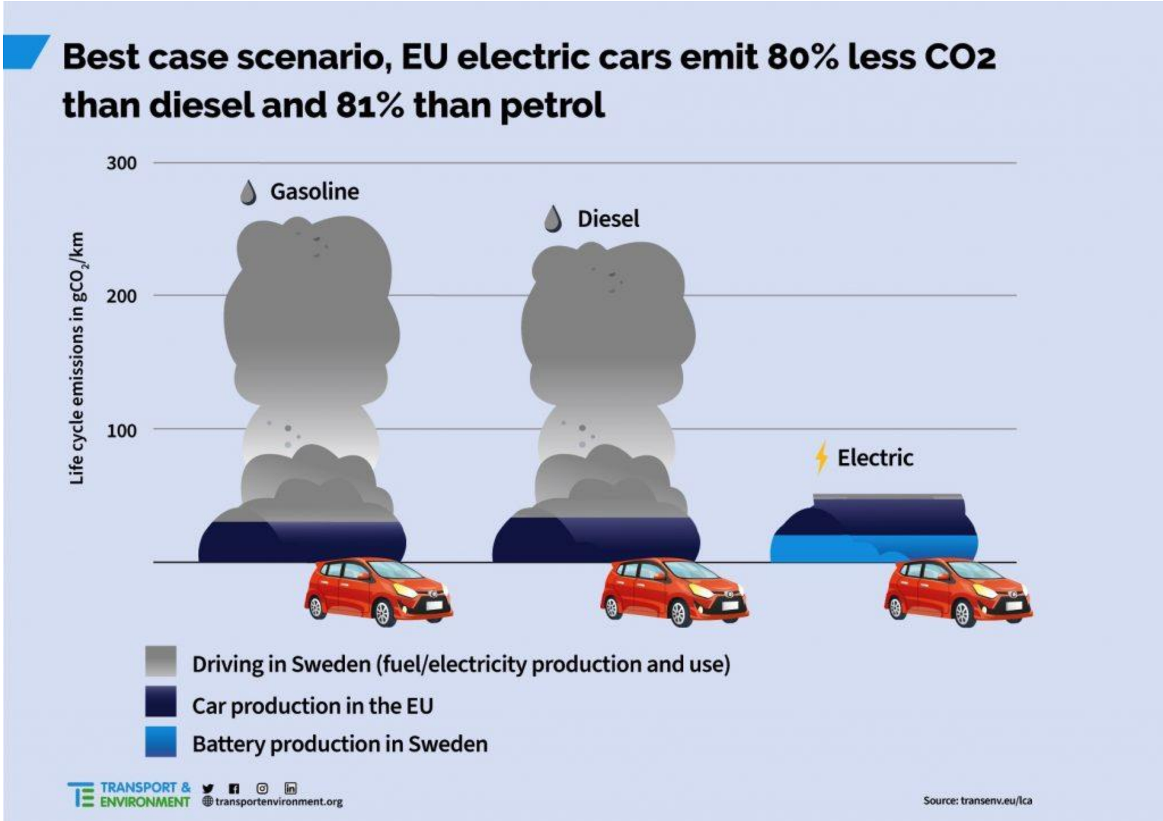

Figure 2-3. Pollution difference between electric and conventional cars [11]

On the other hand, the electric vehicles have to overcome the problem of the initial cost and the recharging battery time. The good part is that the initial cost is fastly amortized because of the low price of its maintenance (no need to buy special oils or lubricants to operate them) and recharging price. Electric cars also have a lower wastage of their breaks and the fact that they make almost no sound their motors do not suffer vibration, which also helps reducing acoustic pollution. [12]

2.3 Hybrid Vehicles

A hybrid vehicle consists of a car that has an electric and a thermal motor. With this combination the problem that the electric cars have, which is an excessive weight, size, and cost of the actual batteries, can be erased. The hybrid cars problem is that the pollution production is higher and the more expensive maintenance cost. Still, they are much promising than conventional cars, specially when being used only in cities. In Figure 2-4 an intern configuration of a hybrid vehicle can be seen:

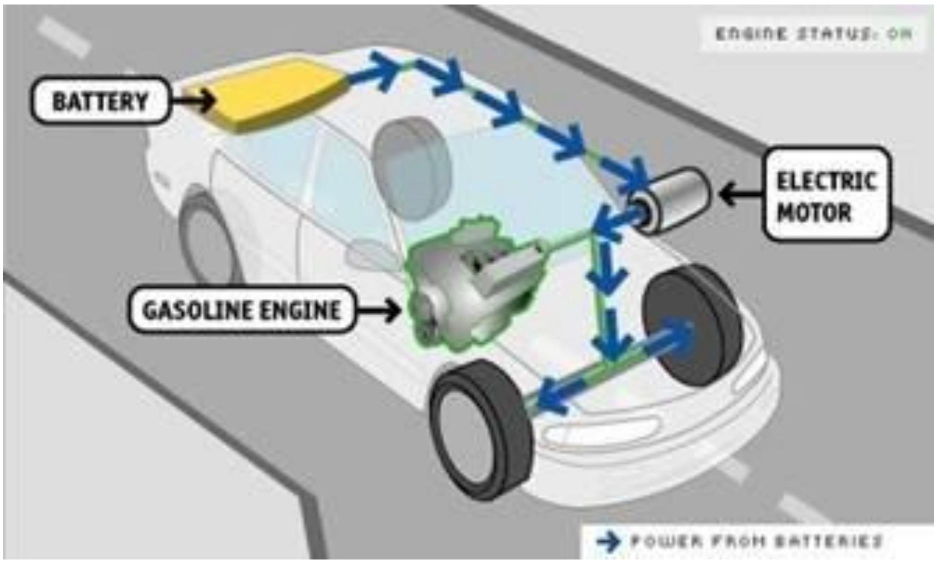

Figure 2-4. Hybrid vehicle configuration

Nowadays, enviroment worries have motivated managing projects that involve cars boosted electrically, and hybrid vehicles have been created to solve the autonomy problems that only electric vehicles have. In Figure 2-5 the configuration scheme of a hybrid vehicle with a generator installed is shown:

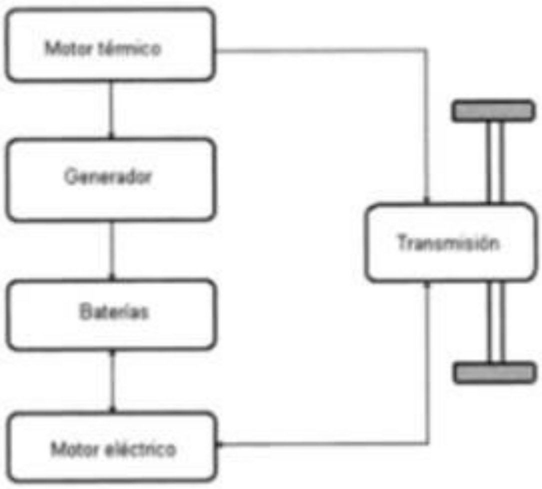

Figure 2-5. Hybrid vehicle configuration with independent generator

The generator can be expendable, which helps reducing the number of pieces that are needed but its efficiency will be lower. In this case the electric motor is used as a generator [13]. In Figure 2-6 the configuration scheme can be seen:

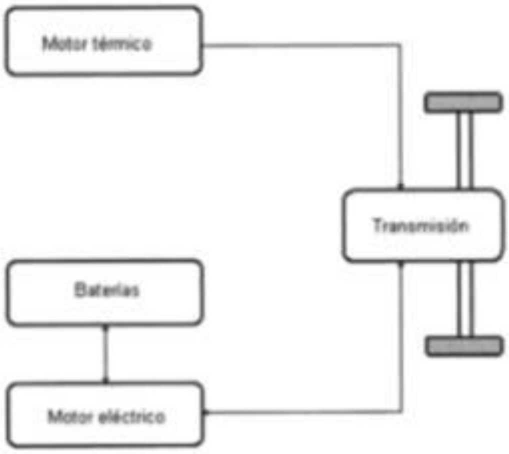

Figure 2-6. Hybrid vehicle configuration without independent generator

2.4 Fuel Cells

Fuel cells are elements that can transform, through an electrochemical nature, chemical energy into electrical energy. To do it they use the oxidizing-reducing reaction characteristics that allow the direct extraction of electricity. They stand out because of their high efficiency and their no greenhouse gases or pollution generation. While a conventional car has a efficiency around 35%, a car that uses its energy coming from a PEMFC can reach a global efficiency of 70%, so it is safe to assume that a hybrid car could cover double the distance than a conventional car.

The process of how a PEMFC works can be seen in Figure 2-7, and consists in:

- Hydrogen dissociation occurs at the anode and releases electrons.
- Then, the cathode produces the reduction in a similar way. To prevent contact, an electrolyte is inserted between them in the form of a membrane that allows the permeation of low-conductivity protons
- To complete the reaction, the anode and cathode are joined through an electrical circuit that allows the passage of electrons

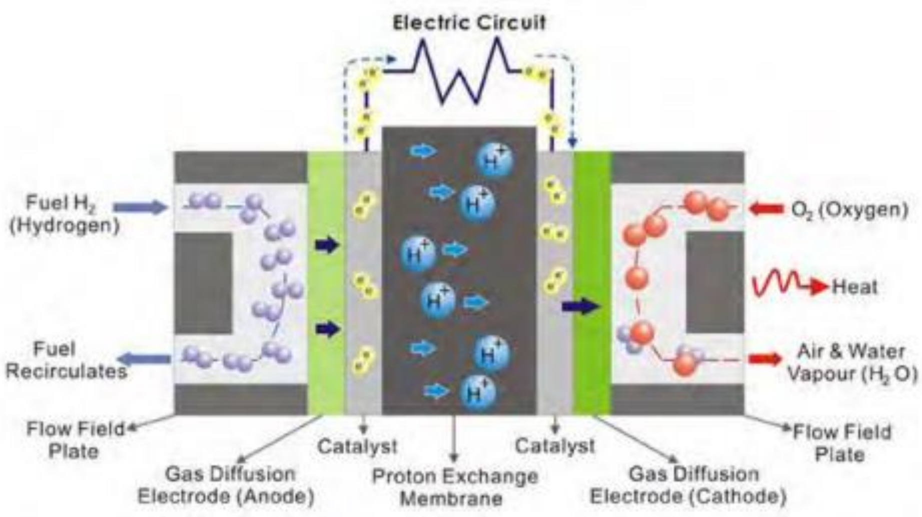

Figure 2-7. Functioning of a PEMFC [14]

The main problem of PEMFC is that hydrogen cannot be found in the environment in a pure way, that is why different process are needed to obtain it.

Fuel cells have yet not been widely implemented into the market because fabrication techniques are still expensive and quite laborious to elaborate, so they are not very accessible.

2.5 Fuel Cell Integration onto electric vehicles

Since the market is still dominated by internal-combustion motor vehicles, electric vehicles must get better in two aspects: the re-charge time and the duration of their autonomy. There's still the problem that if the rapid charge is used, the lifetime of the electric batteries will be shortened; specially if done regularly, being able to lose up 10% of its capacity in 5 years if fast-charge option is used often (more than 3 times a month). Instead, if this option is not used, its lifetime will not lose more than 2% of its capacity in those 5 years.

Thanks to the PEMFC development, hybrid cars that use a PEMFC and have electric batteries are offering much better benefits, like a 5-minute refueling time and 700km long autonomy. Also, it can much cheaper: a H2 kilogram can be equal to the energy given by 7 liters of diesel. [6]

The main problema right now is that there are still only a few models on sale. We can give a few examples: The Honda Clarity Fuel Cell is not even on sale in Spain, and the Hyundai Nexo is a SUV with hydrogen tanks that allow it to reach 666km of autonomy, which can be adquired on Spain. The thing is that ordinary people cannot buy this type of cars since there are not hydrogen-charge stations yet in Spain. [8]

Figure 2-8. Hyundai NEXO

This type of electric vehicles has a promising future, but some aspects are still left to upgrade: the PEMFC do not give enough power yet and their life span seems that, if not used well, can be shortened and during that shortening; the power that is given also is lowered.

2.6 DC/DC Boost Power Converter

DC/DC converters are used to obtain a stable voltage output without being affected by possible fluctuations at the input or at the connected electric charge. In this case a boost-converter consists of a power converter that steps up voltage (while stepping down current) from its input to its output. Boost convreters are highly nonlinear systems and a wide variety of linera and nonlinear control techniques for achieving good voltage regulation with large load variations have been explored.

Regarding its applications, they are often used in battery power systems. This is because they often stack cells in series to achieve higher voltage but, due to lack of space, this is not possible, so boost-converters can increase the voltage and reduce the number of cells. This is especially important since two battery-powered applications that use boost converters are used in hybrid electric vehicles. They are also used in phovoltaic cells. [15]

2.7 BEV4 Power Converter

Because of the low voltage that the PEMFC gives, an intermediate elevator phase is needed. Therefore, the BEV4 boost-converter is used. It works as a unidirectional 4kW boost-converter (Step-up). Its maximum output voltage is 100VDC, and the power-input and output use a common ground-system, so the boost-converter consists of two setp-up-levels working 180º phase shifted.

The output and input parameters can be adjusted by analog set points (10-V), where the analog ones inform about the actually existing values of the converter. The parameter options will be used in our control program and can be seen in the block diagram.

The converter always regulates on the parameter (Uin/Uout/Iin/Iout) reached first. It also has an internal temperature control and a fan which makes it cooling.

Figure 2-9. BEV4 Converter Views

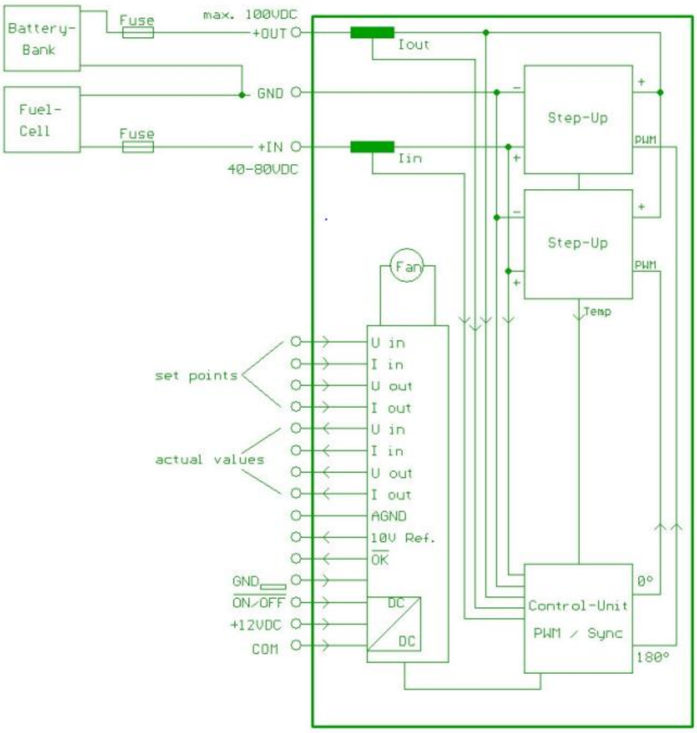

Figure 2.10. BEV4 Boost-Converter Block Diagram

PARAMETER	VALUE @25°C unless otherwise noted	NOTE
Input Side		
Input Power	4kW	fuel cell
Input Voltage	20-80VDC	
Max. Input Current	80A	
Capacity	Typ. 3630µF 100V	
Output Side		
Output Voltage	Input Voltage...100VDC	
Output Current	0-65A	
Capacity	Typ. 1980µF 160V	
Electronic parameters		
Switching frequency	Approx. 105kHz per stage (Summary 210kHz)	1. Step-up => 0° 2. Step-up => 180°
IN-U-Ripple / Spikes (BW 20MHz)	Typ. 200mVpp / 400mVpp	@ Iin = 100A / Uin = 45V / Uout = 80V
OUT-U-Ripple / Spikes (BW 20MHz)	Typ. 100mVpp / 300mVpp	
Soft Start OFF->ON	Nominal values reached after ≤ 300ms	
Static regulation - steady-state control accuracy - Voltage measuring accuracy - Current measuring accuracy	 ≤ ±1% < ±2% < ±5%	
Dynamic regulation	Compare „6. Step-Responce“	
Efficiency	Typ. 98,0%	@ Iin = 50A / Uin = 45V / Uout = 80V
	Typ. 97,4%	@ Iin = 100A / Uin = 45V / Uout = 80V
Auxiliary-Supply	12VDC ±15% 1A (2A$_{peak}$)	Start-up internal DC/DC-Converter typ. 9,5V
Auxiliary-Power	Nom. ≤15W During start-up typ. 24W	 FAN start-up current

Galvanic-Isolation	Isolation-Voltage between all Grounds: 1000VDC No isolation between Power IN and OUT	5x Ground-systems: • Power => GND • Analog => AGND • Auxiliary => COM • ON/OFF => $GND_{ON/OFF}$ • Mounting plate
Isolation resistance	> 1MΩ between all Ground systems	
Thermal protection (semiconductors)	Typ. 110°C	Reducing pulse-width
Internal output voltage limit	Typ. 110VDC	
Protections	- Undervoltage adj. by Vinsp - Overload adj. by Iinsp - I-limit per stage approx. 65A (Step-up 1&2) - Inverse current (blocked by Step-up Diodes) - *Short-circut => ext. fuse	* direct short circuit at the output may lead to damage of the internal diodes => use a Bypass-Diode (+Uin => +Uout) if shorts circuits are possible
Working temperature	-15°C to +40°C	
Relative humidity	**95%**	
Cooling	Forced air cooling	Papst 612NHH (2 pcs.)
Measurements (actual-value „av“)	Vin, Vout, Iin, Iout	Vin 0-10V ≙ 0-80V Vout 0-10V ≙ 0-100V Iin 0-10V ≙ 0-100A Iout 0-10V ≙ 0-65A
Control (set-point „sp“)	Vin, Vout, Iin, Iout	Vin 0-10V ≙ 0-80V Vout 0-10V ≙ 0-100V Iin 0-10V ≙ 0-100A Iout 0-10V ≙ 0-65A
Enable	ON/OFF	ON 12V ±15% (<4mA) / OFF 0V or open
Output resistance measurements	All analog outputs have a serial protection resistor of 1kΩ	
Input resistance control	1MΩ	Analog Inputs
Reference voltage	10V ±1% max. 4mA load	
Alarm signal	Open Collector ≤ 30V / ≤ 100mA	0V => regulation-loop OK open => out of regulation
Approval		
EMI	CE mark	
EMC	2004/104/EC directive	
Enclosure		
Dimension	265 x 134 x 85 mm	Without bolts
Terminals	- 2x 8pol Weidmüller SLD RM5,08mm (Interface) - M8 screw terminals (power-line)	
Weight	2,7kg	

Subject to technical changes

Table 2-1. BEV4 Converter Specifications [18]

2.8 LabView

Laboratory Virtual Instrument Engineering Workbench (LabView) is a system-deisgn platform and development environment for a visual programming language from National Instruments.

LabView integrates the creation of user interfaces into the development cycle. Every program has 3 components:

- Block diagram: this is where the programming occurs, and the different block functions are connected.
- Front panel: the front panel can be seen as the interface between the human and the program during the operation time. LabView allows to change values in real time to see different possibilities in a short period of time.
- Connector pane: this is used to represent the VI in the block diagrams of other, callings VIs (Virtual Instruments).

LabView can be used to perform a huge number of mathematical and logic functions. It can also interface to code developed in other languages, through DLLs.NET assemblies, and run-time interpreters, for example, MATLAB.

It also offers several benefits when working with it: Extensive support for interfacing to devices; a compiler that produces native code for the CPU platform with a run-time motor that calls these chunks and therefore allows a better performance. It also provides large libraries with multiple functions for data acquisition, signal generation, mathematics… [16]

As general applications and what is most commonly used for, 4 main purposes exist:

- Automated Manufacturing test of a system or component.
- Automated Product design validation of a system/component.
- Control and/or monitoring of a machine/piece of industrial equipment/process.
- Condicition monitoring of a machine/piece of industrial equipment.

LabView has been widely adopted in the automated test realm, essentially becoming the standard option in that application space, whereas more recently it's been gaining traction within the realm of industrial embedded monitoring and control. [20]

For this TFG LabView was chosen since it offers a really good work with data acquisition functions, which were very important during the tests. It also gives the possibility of changing values in real-time during a test so different regulations could be done in a short period of time.

3 FUEL CELL CHARACTERIZATION

Without a goal in mind, a man cannot manage his own life, much less the lives of others.

- Gengis Khan -

During this chapter, a characterization of the NEXA 1200 PEMFC will be made. Because of the several years that the PEMFC has not been used or turnt on, a characterization of its state through obtaining a polarization curve will be done. In the following points a little bit of its functioning will be explained, and a previous characterization done will be given. Then, later, how the test was done and what the results were will be listed, with the conclusion that can be extracted.

3.1 NEXA 1200 PEMFC

The Nexa1200 is a fully integrated fuel cell. It belongs to a generation of modules based on Ballard's FC GenTM 1020 ACS stacks. The interfaces can be found in the back part of the cell. In terms of communication CAN is used and with our software we can initiate, reset, and stop the cell.

In the following table we can see the specifications for the NEXA 1200 given by the manufacturer:

Designation	**Definition**	**Specification**
Physical specifications	Dimensions (H x W x D)	220 x 400 x 550 mm
	Weight	22 kg
	Protection Type	IP22
Output Power	Output voltage	20-36 VDC
	Rated current	65 (max.)
	Rated output	1200 W (5-25ºC)
	Rated output	1000 W (35ºC)

Designation	Definition	Specification
Combustible		H2, hydrogen gas
	Minimum purity	4.0 (=99.99%)
	Allowable presion input	1…15 bar
	Hydrogen consumption	15 NL/min
Electric supply	Minimum power input	110 WDC
	Power supply	12…36 VDC
	Oxygen	Atmosferic oxygen
	Volumen flow	Max 335 m3 / h
	Oxygen concentration	18 % at minimum
	Environmental pressure	700-1100 mbar
	Temperature	5…35ºC
	Water in the form of vapor contained in escape gases at nominal power	550 g / h
Operative enviroment	Functioning place	Dry, inside labs
	Ambiental Temperature	5…35ºC
	Relative humidity	0-95% … No condensation
Storage	Ambiental Temperature	3…30ºC
Transport	Ambiental Temperature	-40… +70ºC

Table 3-1. Technical specification of the PEMFC [19]

And in the following graphic we can see the polarization curve theorically:

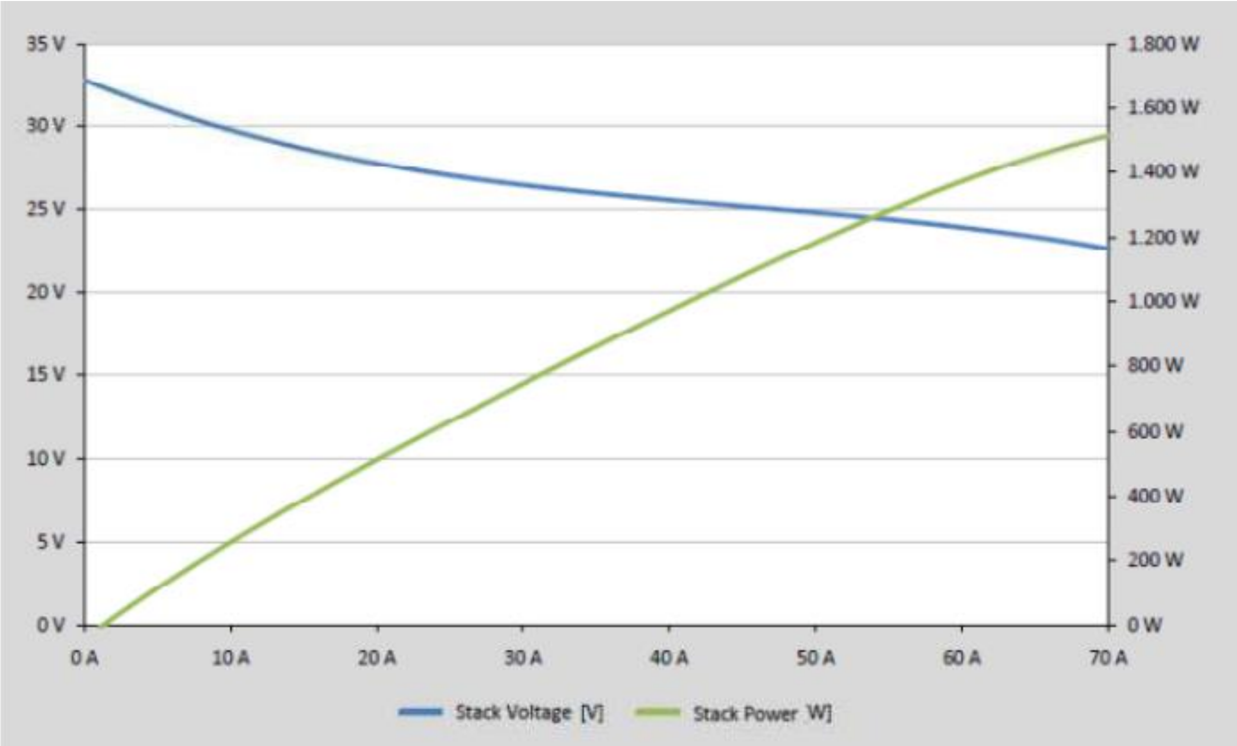

Figure 3-1. PEMFC polarization curve (theorical)

There was a End-of-Master work document where a characterization of the PEMFC in [5], with the same objective that had this part of the chapter.

These are the results that were obtained:

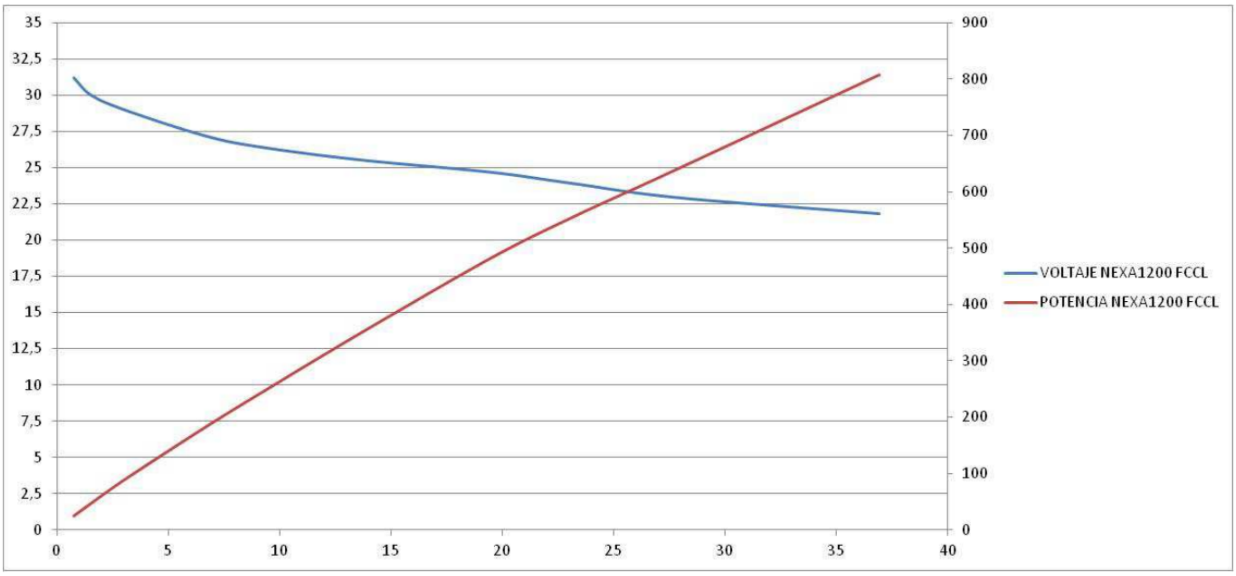

Figure 3-2. PEMFC polarization curve in 2014

The curves are different and that the power giving capacity has lowered, so it is expected that in this characterization the result will be even lower.

3.2 Characterization Test

3.2.1 Theoretical Framework

The PEMFC, thanks to the continous flow of fuel and oxidizing, can produce a chemical reaction controled to supply electric current to an external circuit.

The voltage given and the generated power is determined by its polarization curve, where the temperature and antiquity of the PEMFC can influence, as we saw earlier.

3.2.2 Test procedure

To make this characterization we have to use different devices: The NEXA1200, a computer with the proper software installed (our LabView program) with the right CAN wire, a diode, an auxiliary electric battery (to help the cell start), a load relay and an electric charge which could simulate the throttle of the car. The right hydrogen wires and valves will be necessary to carry out this test, too. A scheme of the connections can be seen in Figure 1-3.

To generate power the program made was asked for the following set points:

- UinSP= 25 V
- UoutSP=30 V
- Iin=90 A
- Iout=65 A

This way the program regulates Uout and the demand can be elevated as time passes (electric charge) as well as the power generated, while the input voltage (Uin) will slowly reduce. Uout will not change throughout the course of the characterization.

Because of the time that the cell has been inactive it was started with a low demand for a couple minutes so it could hydrate again slowly. After that we started increasing the charge, so the fuel cell power increased, too.

During the test, it was secured that the fuel cell voltage wasn't below 20 V because it it the minimum that it needs to be functioning and to not damage in any way the cell.

Once everything was set, the test consisted in increasing the asked charge between 3-5 A every 3-4 minutes. At first, the increased charge was 5 A every 4 minutes until voltage input reached its maximum capacity. Then, every 3 minutes the asked charge rose 3A until itw as felt that the maximum power without being damaged or hurt was being given. After that, in a shorter period of time the charge slowly decreased until it reached a normal state of functioning.

To make the converter part, we implemented the part of the program which its algorithm was designed in a previous TFM in C++, in which a low-level heuristic control is performed [6]. In Figure 3-3 the algorithm can be seen:

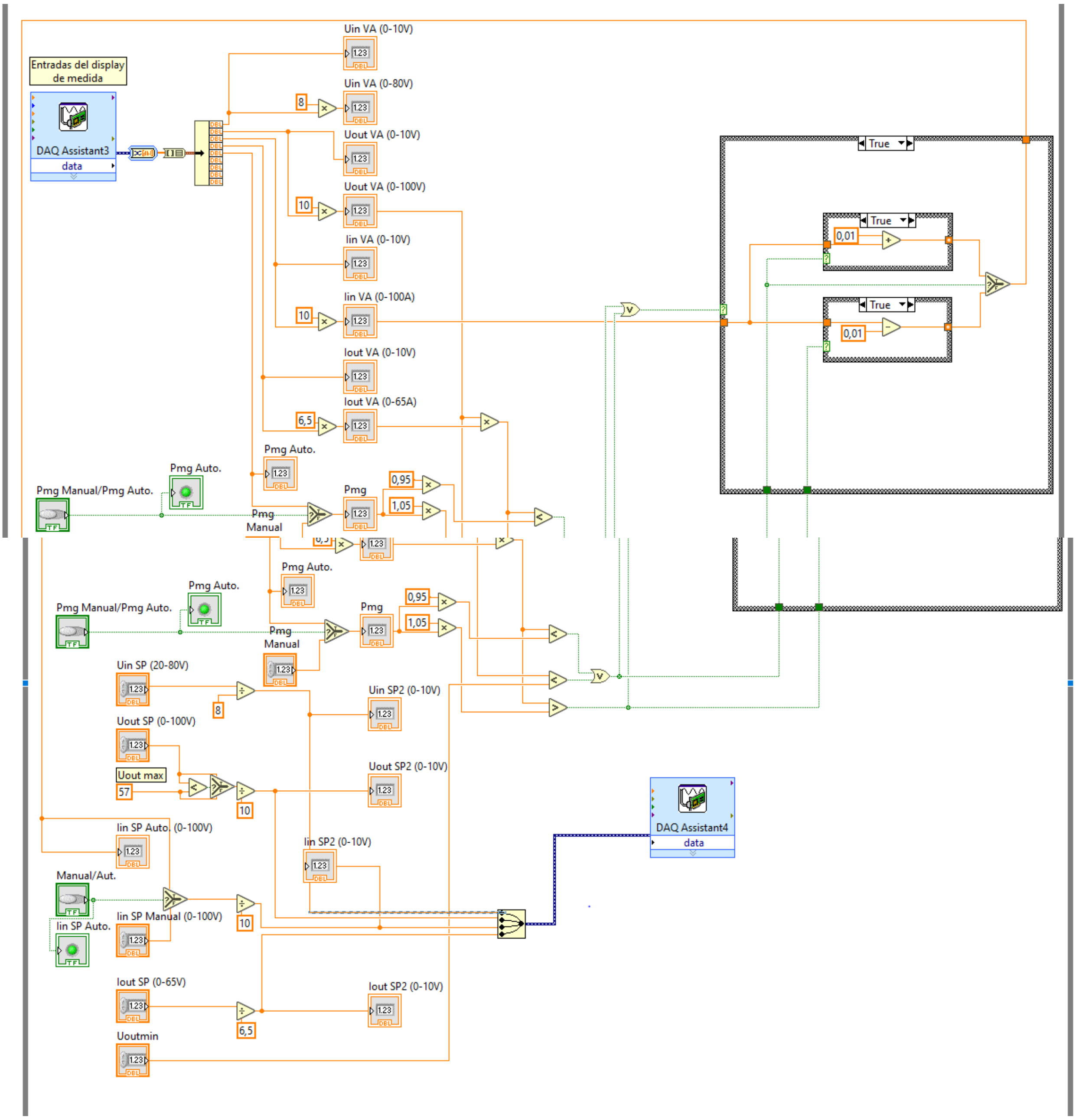

Figure 3-3. Boost-Converter Algorithm Part

This program was one used for a test. The final program is in BOSS_SUPERVISOR, which will be showed later.

In order to connect the devices, the following steps were made:

The following photos are details of the connections and devices for the test that was done:

1- The CAN wire is connected to the computer that is executing the program.

2- The power supply helps the PEMFC start; once the PEMFC has started, it is not necessary anymore.

3- The charge is used to simulate the throttle of the car and is the one that, while moving in the polarization curve range, asks for power.

4- The load relay acts as a security device if it detects a high value of voltage or current.

Figure 3-4. CAN Connection

a

Figure 3-5. Power Supply

Figure 3-6. Charge

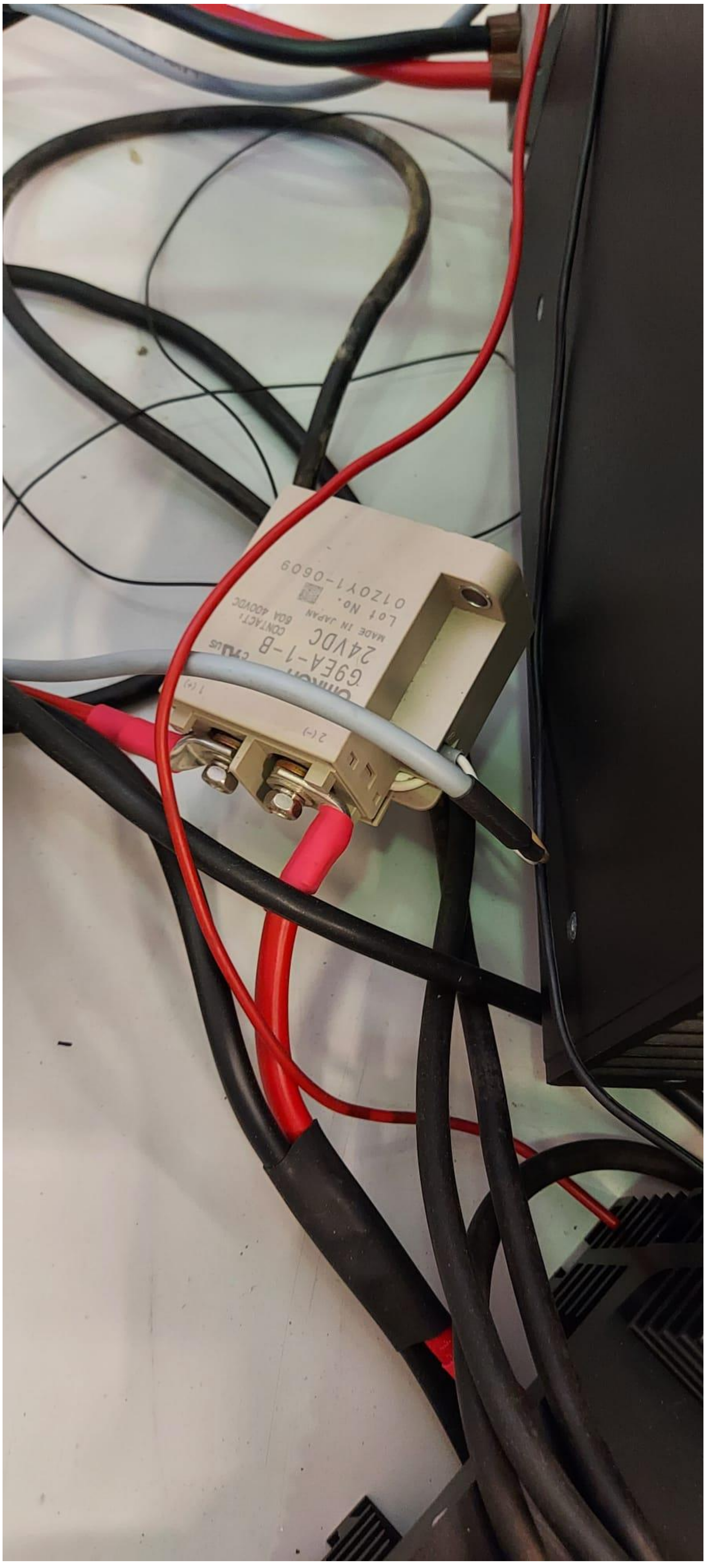

Figure 3-6. Load Relay

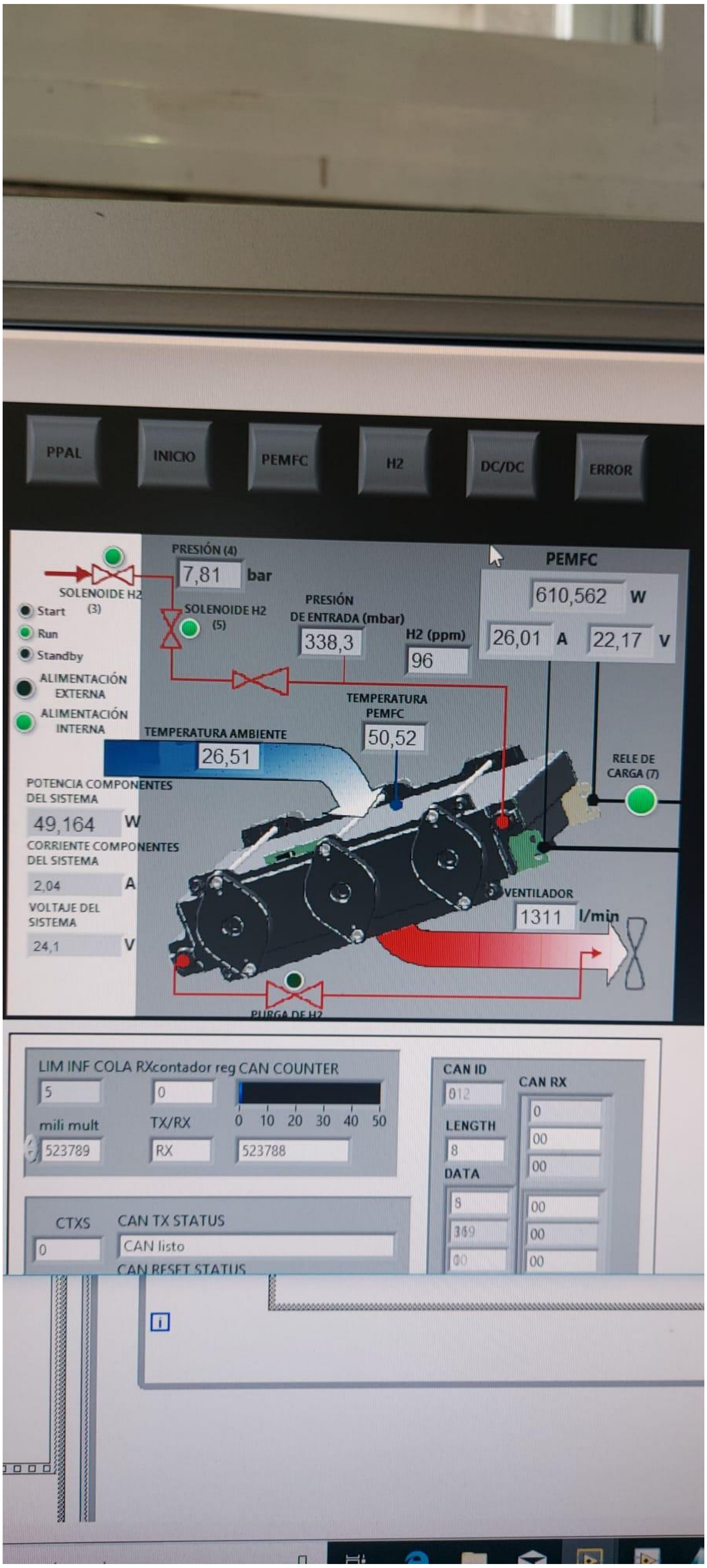

Figure 3-7. LabView PEMFC Interface

3.2.3 Results

In Figures 3-9 and 3-10 the NEXA 1200 generated power and voltage can be seen:

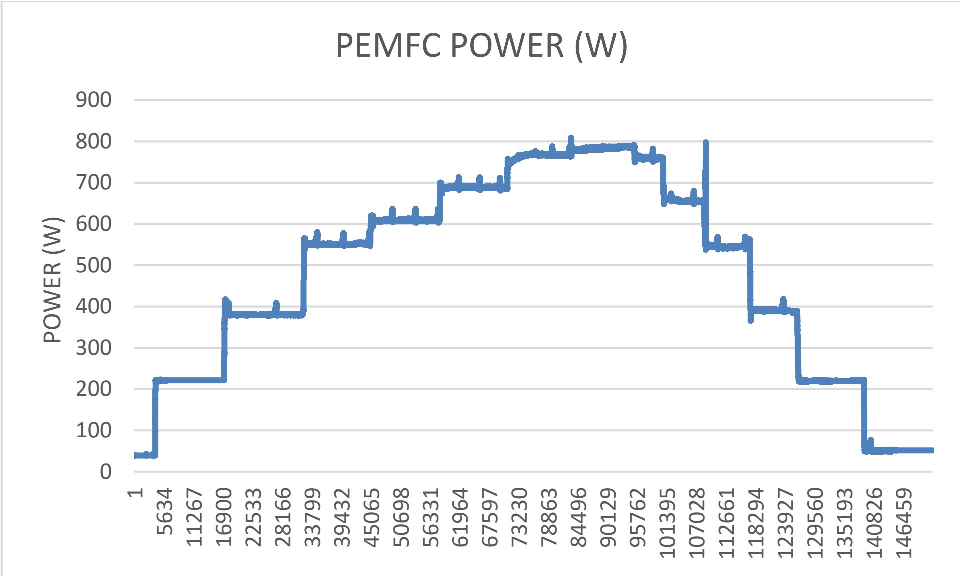

Figure 3-9. NEXA 1200 POWER

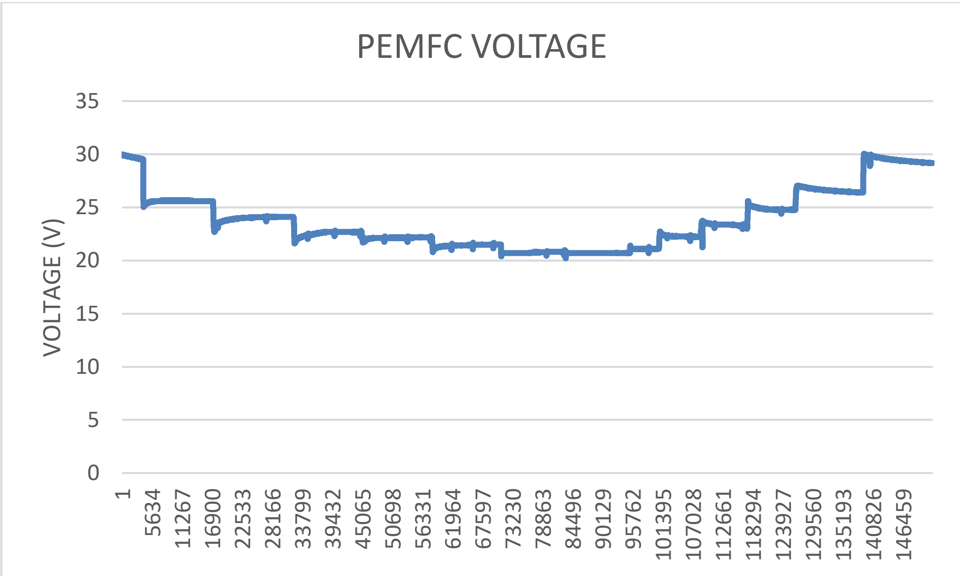

Figure 3-10. NEXA 1200 Voltage

As a result of these two figures, in figure 3-11 the polarization curve can be seen. In this case the results are displayed with a piramydal structure because big changes could affect negatively to the health of the PEMFC. Regarding the spikes that can be seen in figures 3-10 and 3-9, they are caused by the PEMFC, which makes periodic purges of H2 that result in voltage spikes.

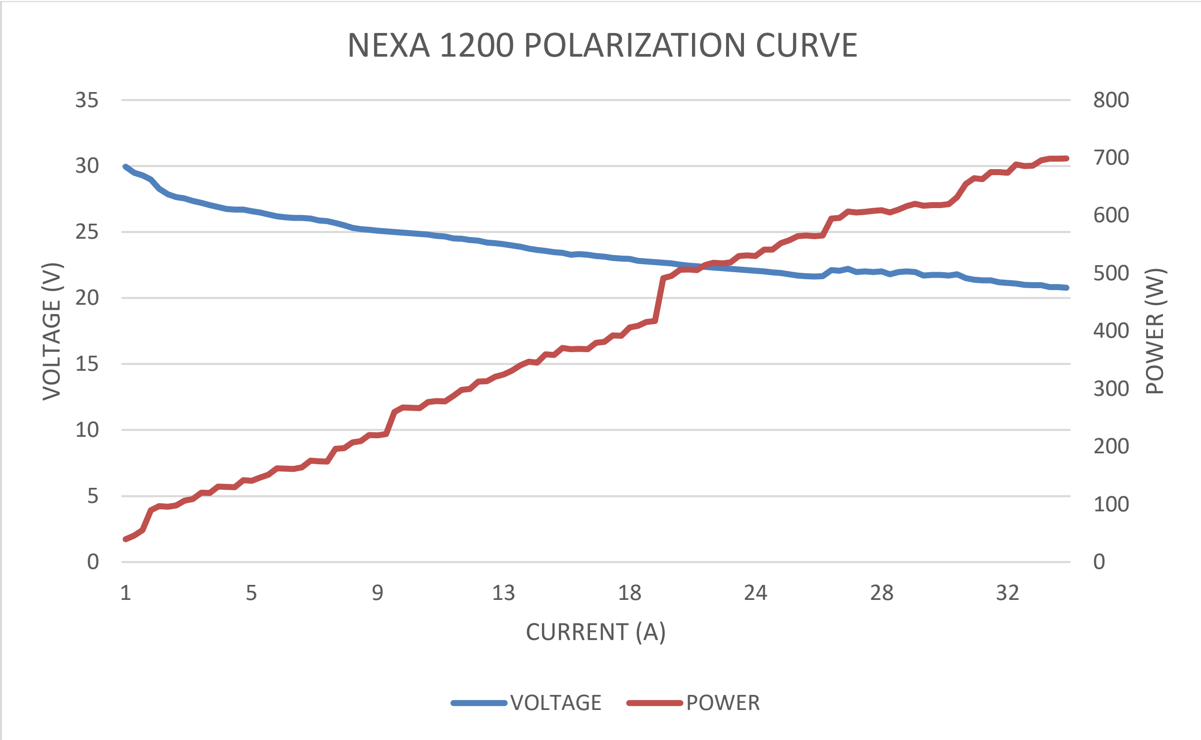

Figure 3-11. NEXA 1200 PEMFC Polarization curve

3.2.4 Conclusions

When comparing it to the previous polarization curves (Figures 3-1 and 3.2) it is noticeable that the maximum power that the PEMFC can give is less. In the previous curves the maximum power giving values were around 1600W and almost 850W, while in the most recent the maximum power that the PEMFC gave was 700W. This is because of the deterioration that has occur as time passed. In this characterization, the maximum current reached was also minor than in the previous one because of the logistic possibilities that were available in the laboratory but should be careful since the minimum value of 20V could be trespassed and could damage the PEMFC.

The expectations of the power giving capacities were right and have been reduced, which can be expected for future PEMFC characterizations.

4 LabView Program Designing

The fundamental problem of communication is that of reproducing at one point either exactly or approximately a message selected at another point.

Claude Shannon, 1948

During this chapter, an explanation about the remodeling of the previous LabView program with the objective of erasing the needing of 2 devices and the design of a comfortable test bench will be given.

Also, how the program works and the function of each part of the program will be explained.

4.1 General

As said in the introduction, a couple years ago INTA asked for a program that could be used to operate with the fuel cell. Therefore, the previous program that it is being used was created. The program consisted of a LabView part and a C++ and all worked via CAN. The LabView program would receive the data, then send them to the C++ control code, that did all the work and would send the data again and again. This program was elaborated by Juan José Márquez Quintero, Carlos Montero and David Marcos about 10 years ago.

In this case, all the work will be (or tried to be, in the next section the problems will be explained) in one program:

- The CAN is still used to get the data from the fuel cell, but from now on orders can be given directly from the LabView program, like turn on, off… Without the need of a second device. Also, the function of adquiring data was changed and the previous functions aren't needed.
- The data adquisition is done through the DAQmx drivers and the two cards that will be connected to the computer and the fuel cell. One card is used to the setpoints and the other one is connected to acquire the real values. This part had to be added to the program, not like the other one, that was re-modeled.

4.1.1 Problems

It has to be said that because of the versions and drivers that were available in the computer with the DAQmx cards installed; this program could not be done in just one program. The CAN communication only worked on the 32-bit version and the DAQmx functions could only be used in the 64-bit version.

When remodeling the LabView program, it was found that the DAQmx functions could only be used in the LabView 2016 64-bit version. Several times different DAQmx drivers were installed in the 32-bit version, but also the lack of Internet connection was another problem since the NI Package manager could not be used. Different offline install packages were transfered with the help of another computer but none of them were enough to solve the problem.

It was also tried to install drivers on the 64 bit-version, but after some research it was found that the CAN functions can only work in the 32 bit-version.

Therefore, with these limitations 2 similar programs were used:

- One with the CAN communications where the information related to the PEMFC is shown.
- One with the boost-converter part, where the values that are given by the data acquisition cards are shown on screen.

The programs could be run at the same time to adquire the data necessary for the tests and characterization of the PEMFC.

To use the bench, a computer with LabView 2015-32 bit and LabView 2016-64 bit versions were needed, as well as a CAN wire that connects the computer and the PEMFC. Lastly, the data acquisitions cards are necessary to use the converter part. They were installed through wire to the computer.

4.2 Sub-programs change

In this part a look will be taken into the programs that needed a change excepting BOSS_SUPERVISOR, which will be talked about later. Also, a explanation of each sub-program functioning will be given.

4.2.1 BOSS_TXTraductor

This part of the program is in charge of «translating» the signals that arrive through buttons or data and translate them to communicate with the cell. The functioning is simple: it receives a signal and uses CAN to write an order (this will be seen in BOSS_TX) on the PEMFC.

For example, if the button RUN is pressed, FC START will be turned on and, therefore, the subprogram BOSS_TXTraductor will give the order to the PEMFC through CAN. To know what values must be written on CAN, the NEXA1200 manual was used.

The job of this function is sending the hexadecimal message to BOSS_TXCARGAMSG, that compresses everything into one signal and does a simple task, so it cannot be simplified (Figure 4-1). It sends the message to BOSS_TX, that is explained in one of the following parts.

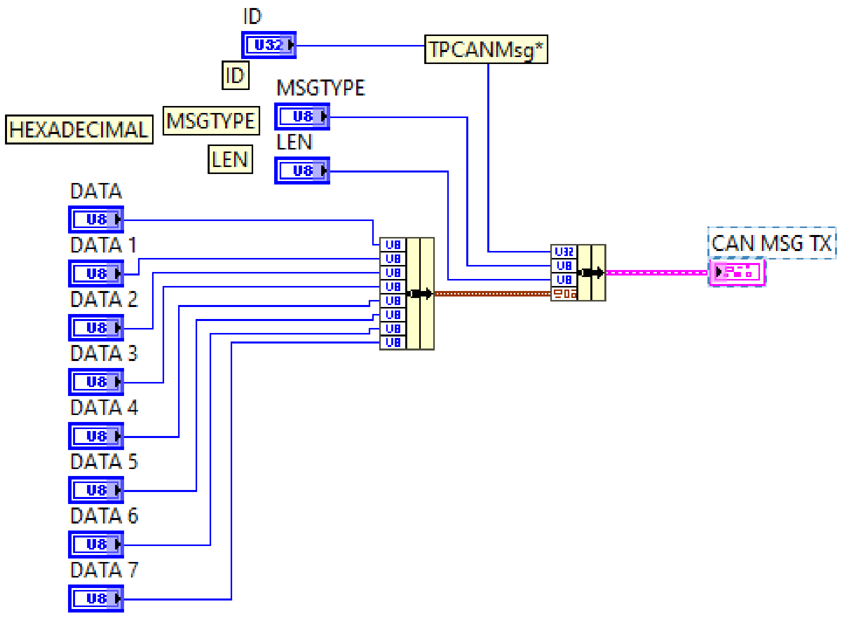

Figure 4-1. BOSS_CARGAMSG

Regarding this part, unnecesary signals were removed and the signals regarding the RUN, STOP and RESET were changed. The final result can be seen in Figure 4.2:

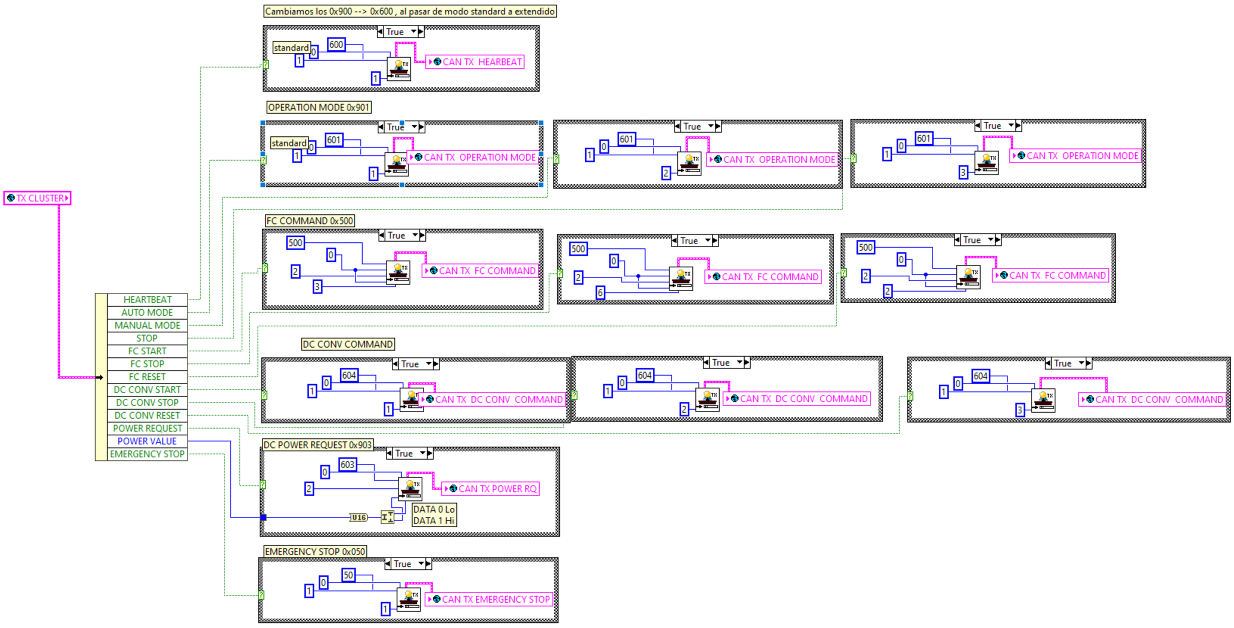

Figure 4-2. BOSS_TXTRADUCTOR

4.2.2 BOSS_TX

In this part the whole program had to be redone. The program itself could not send CAN messages and the PCAN_Write function had to be used as a help to manage the problem. Finally, with some changes in the window part + the front part, the program could send messages. The function of this subprogram is basically receiving through BOSS_TXTraductor the compressed order and trough the function PCAN_WRITE (that uses CAN communication), which is provided by LabView. In Figures 4-3 and 4-4 the Block Diagram and Front Panel can be seen.

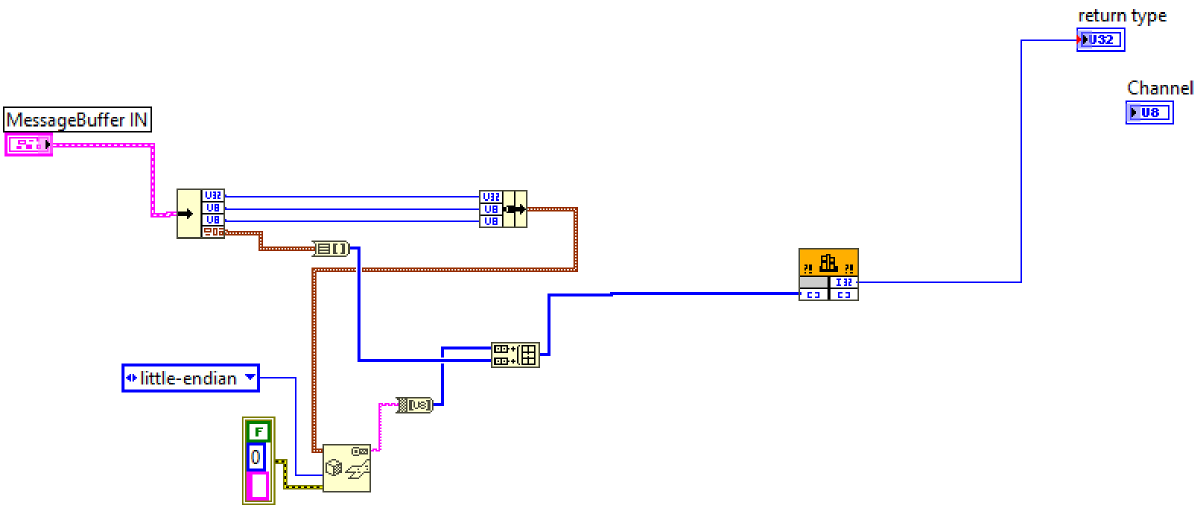

Figure 4-3. BOSS_TX Block Diagram

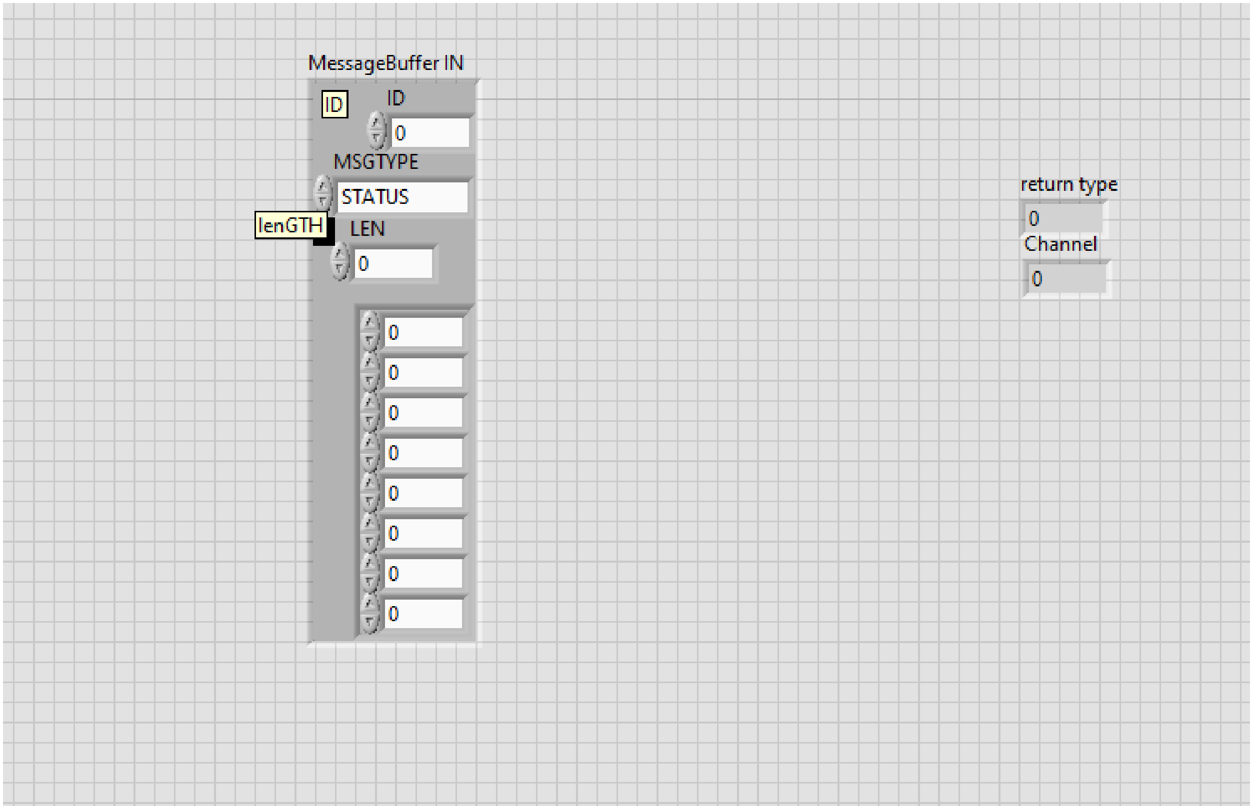

Figure 4-4. BOSS_TX Front Panel

4.2.3 Other programs

Regarding the left programs, changes were almost not needed; instead, several unnecessary signals were removed and, as said in the beginning, the functions BOSS_REGISTRO_VAR_INICIO, BOSS_REGISTRO_VAR and BOSS_TIME were not needed anymore since another acquiring data function was implemented.

The useful functions will be listed down below with a photo of its command window:

- BOSS_RX: This function is in charge of reading the CAN Messages that come from the PEMFC. Everything is done thanks to the PCAN_READ function that is given by LabView, as it can be seen in Figure 4-5.

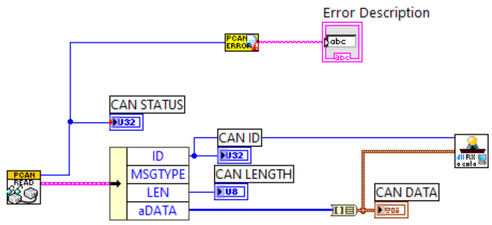

Figure 4-5. BOSS_RX Command Window

- BOSS_RXCOLA: This function does the unique part of sending the data to the BOSS_RXTRADUCTOR and showing the ID in the interface, as it can be seen in Figure 4-6.

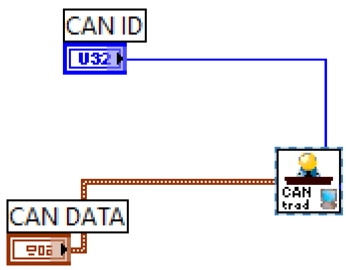

Figure 4-6. BOSS_RXCOLA Command Window

- BOSS_RXTRADUCTOR: This program is the one that load all the values sent by the ECU (Motor Control Unit) and send them to the RX_CLUSTER, which is the global variable that helps reading the names and also shows them in the GLOBAL_BOSS function, where all the values can be seen. A part of the algorithm is showed in Figure 4-7 since it translates all the values that are read. Basically, every signal that is received through numbers is given a tag, so it is easier to manipulate and worked with.

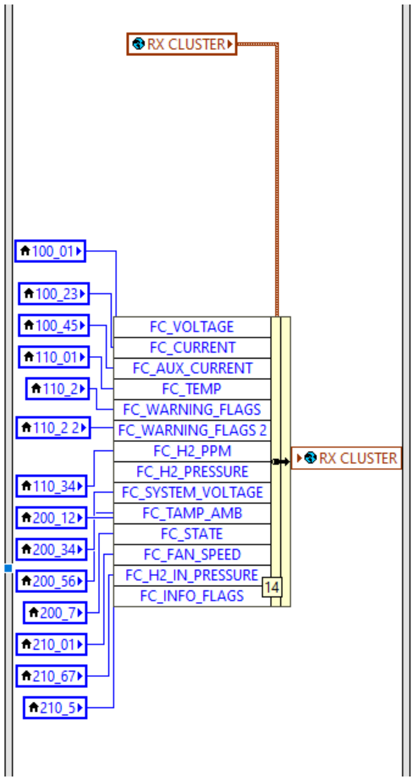

Figure 4-7. BOSS_RXTRADUCTOR

- GLOBAL_BOSS: As said in the earlier point, part is the part where all the values of the variables can be seen. It doesn't really do anything but show the values and other important information. Again, only one part is shown in Figure 4-8 since the front panel is very large.

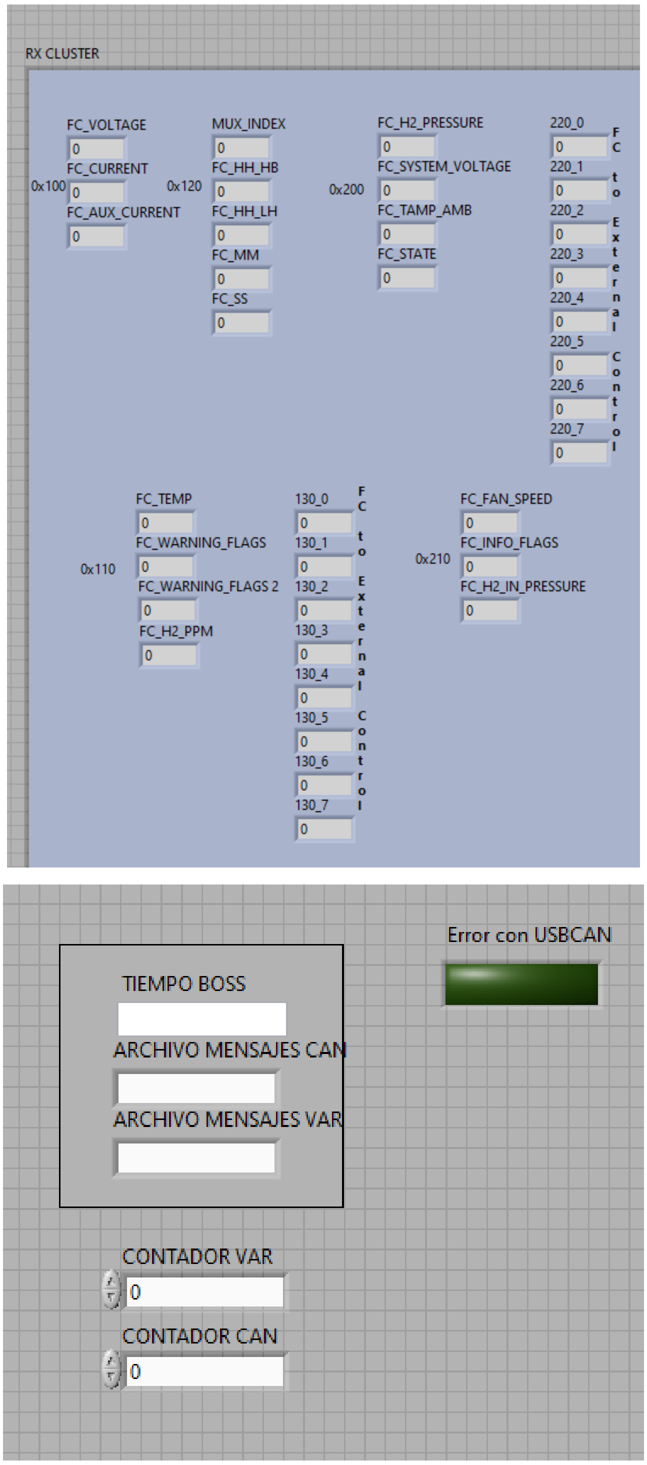

Figure 4-8. GLOBAL_BOSS

4.3 BOSS_SUPERVISOR

BOSS_SUPERVISOR can be looked at as the main program since it is where all the functions work together and is the one that will be runned when functioning.

To make this part properly working the program had to be changed, specially in the boost-converter part, since previously it all worked with CAN. To make it possible, the data acquisition functions were used thanks to the cards that were installed in the computer. With these functions the data could be read and the setpoints could be written. Once the functions were implemented, it was possible to work with the acquired data. The different values are extracted from the DAQ Assistant3 and are displayed in the Command Window. Then, the DAQ Asisstant below writes the setpoints that are desired by the tester. Finally, the control algorithm is implemented with a “Write to Measurement File” function, that is activated when the “Guardar” button is pressed, in order to acquire the data and use it to review the test results. The program can be seen in Figure 4-9.

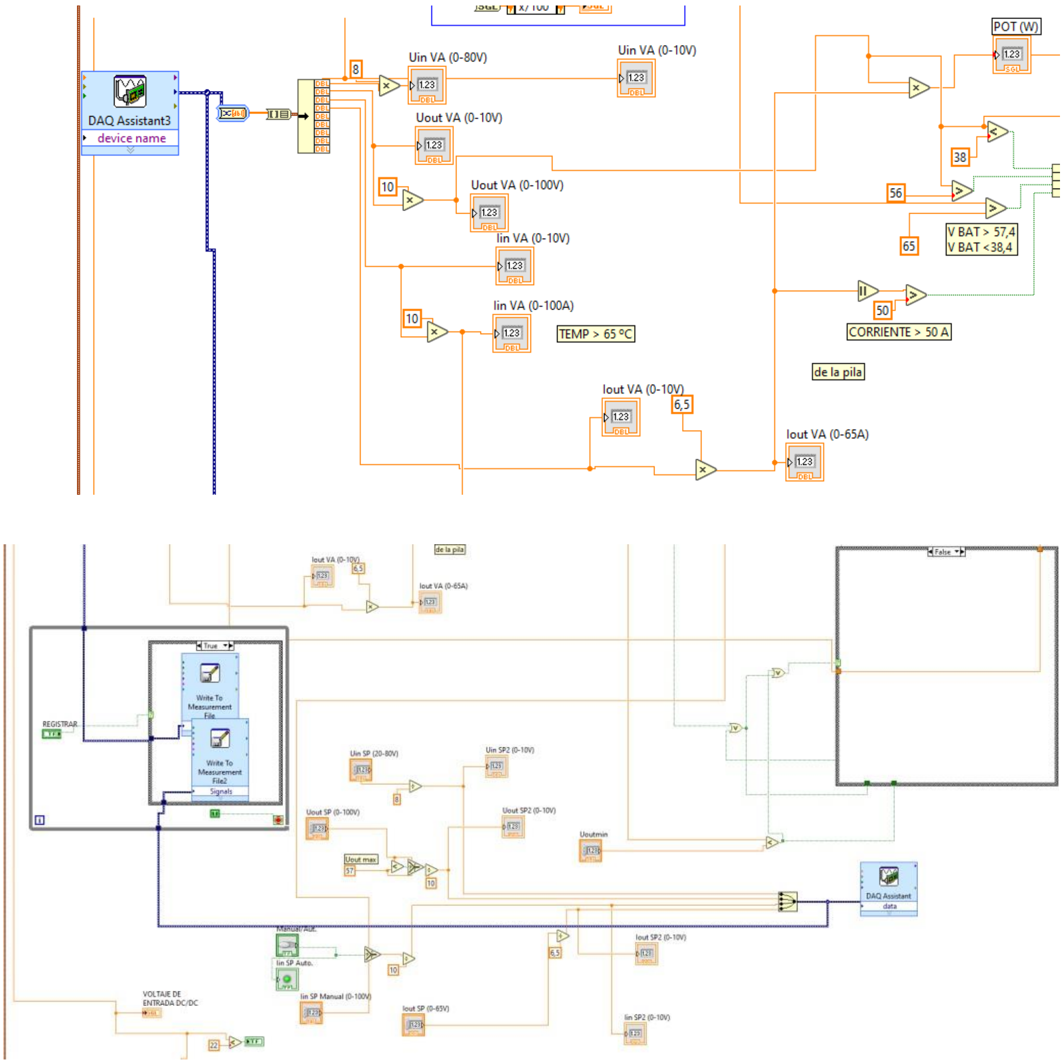

Figure 4-9. BOSS_Supervisor Control Part

The converter is the one that calculates the values needed in order to achieve the set points, regulating the first variable that reaches its set point.

To use this program the set points are written manually in the front pannel and can be changed while the converter is working. As said in the characterization of the converter, the first variable that reaches the set point will be the one regulated, so for the tests, that are coming up on the next chapter, will be our reference when knowing if theconverter is properly functioning. It is recommended to write the initial setpoints before running the program, so no damage can be done, and risks are not taken

BOSS_SUPERVISOR is in charge of everything since it runs all the programs that have been talked about earlier. The Front Panel has various tabs and each one has its function: reading the state of the PEMFC, reading the different data that it gives, using the converter part, reading errors, etc.

To correctly operate the program, a User’s Manual is attached at the bottom of the work document.

5 TESTS

The greatest danger for most of us is not that our goal istoo high and we will not reach it, but that it is too lowand we will achieve it.

-Miguel Angel-

DUring this chapter, an explanation about the remodeling of the previous LabView program with the objective of achieving the new goals

The tests will consist in setting every set point excepting one super high, it is done intentionally so the lowest one will always be the one regulated while the other values won't reach. In all these tests, only the set points vary, so the electric charge is always stable.

5.1 Regulating Uout

In this test the setpoints were:

- UinSP=25V
- UoutSP=25V
- IinSP=100A
- IoutSP=65A

The setpoints are set this way because these values are the highest that they can reach, but in no way it is looked for in these tests, because the PEMFC is not able to give the values and could be damaged. Uout is the lowest, so the actual value reaches first, and the other ones are calculated by the converter. In figure 5-1, the graph showing how the actual value follows the setpoint everytime it changes, except for one time because another value reaches and becomes regulated, which is the voltage input (Uin), as it can be seen in Figure 5-2:

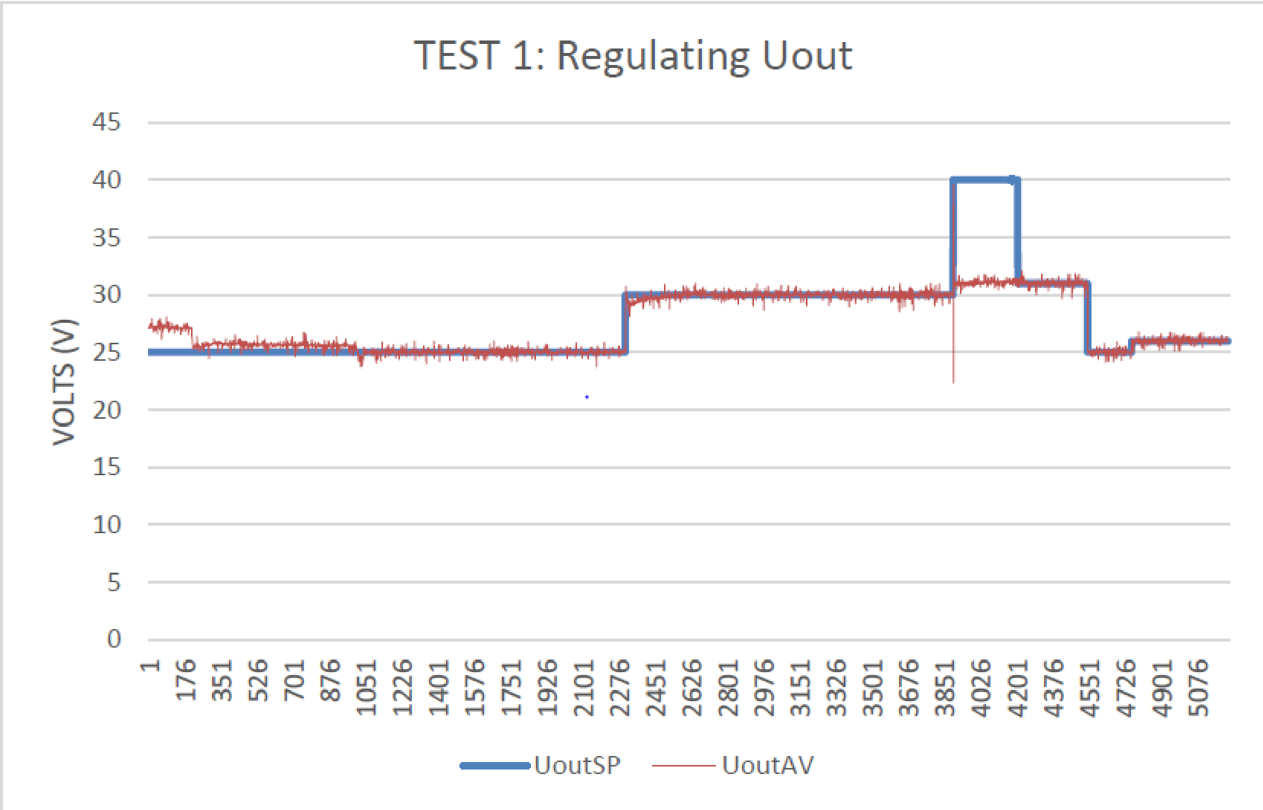

Figure 5.1. UoutSP and UoutAV graph

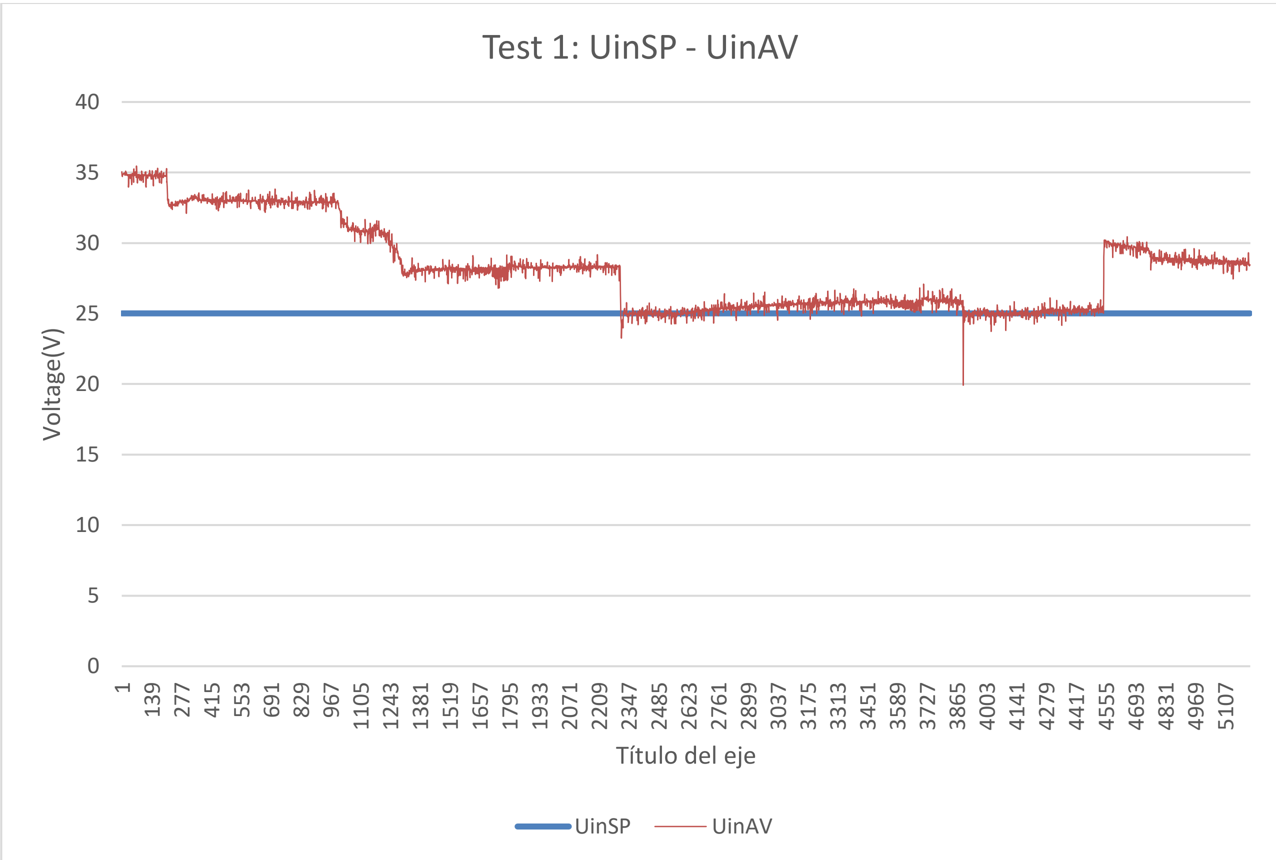

Figure 5-2. UinSP and UinAV graph

The converter works well regulating Uout and everytime the set point changes, the real value changes, too. It started with a UoutSP=25V and the UoutAV starts around 27V. When looking at the beginning, the actual value doesn't follow very well the set point, but the reason could be that this was the very first test done and the PEMFC wasn't used for a lot of time.

Regarding the other values, the Figure 5-3 shows them :

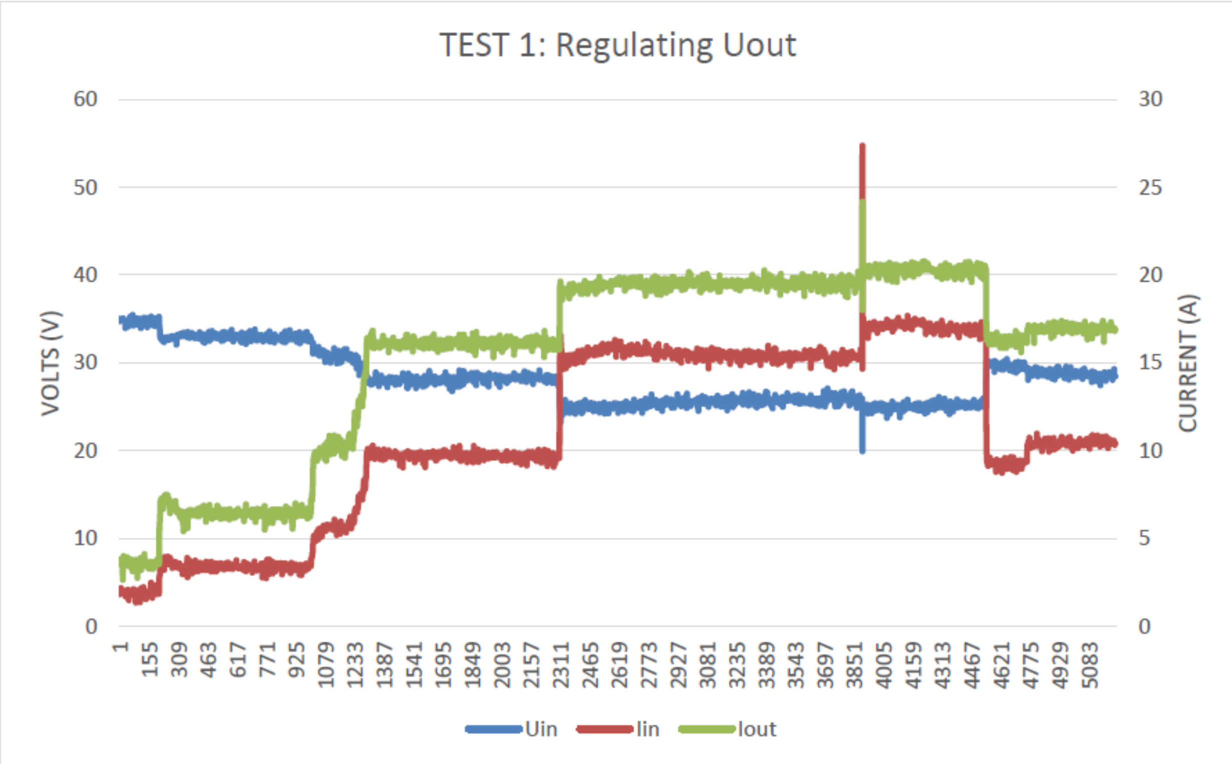

Figure 5-3. UinAV, IinAV and IoutAV graph

Everytime the setpoint changes, the other values do it, too, since the converter calculates the necessary value of the variables.

5.2 Regulating Iin

To do this test the set point were:

- VinSP = 25V
- VoutSP= 30V
- IinSP= 22 A
- IoutSP= 65 A

Therefore, the variable IinAV will be the one regulated as we can see in Figure 5-4 :

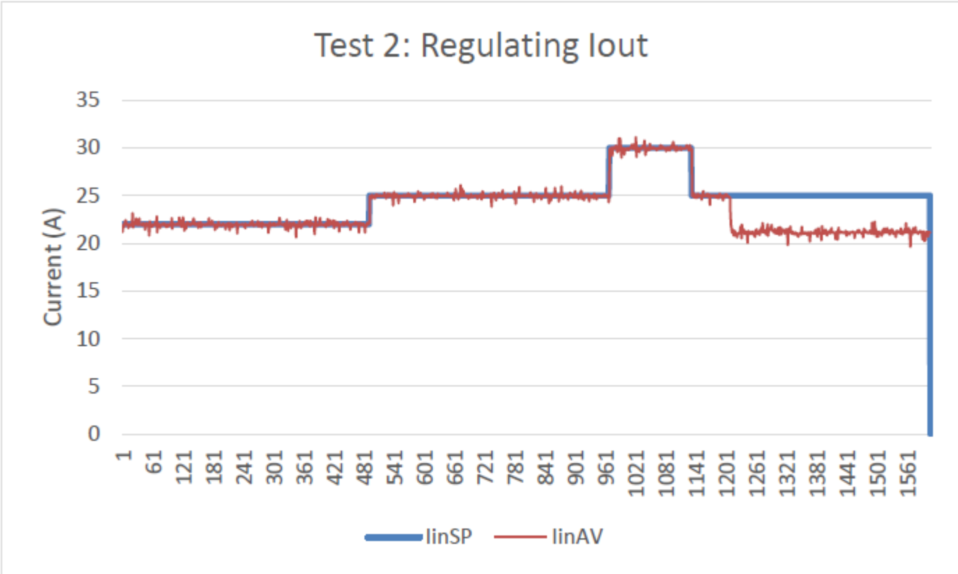

Figure 5-4. IinSP and IinAV graph

It can be seen that the set point and the actual value are the same almost until the end. This was done intentionally since it wanted to be proven that the variable regulated could change if the set points changed. In this case the one being regulated was Uout again. To do it the only thing to do was set the UoutSP to 26 V, as we can see in Figure 5-5:

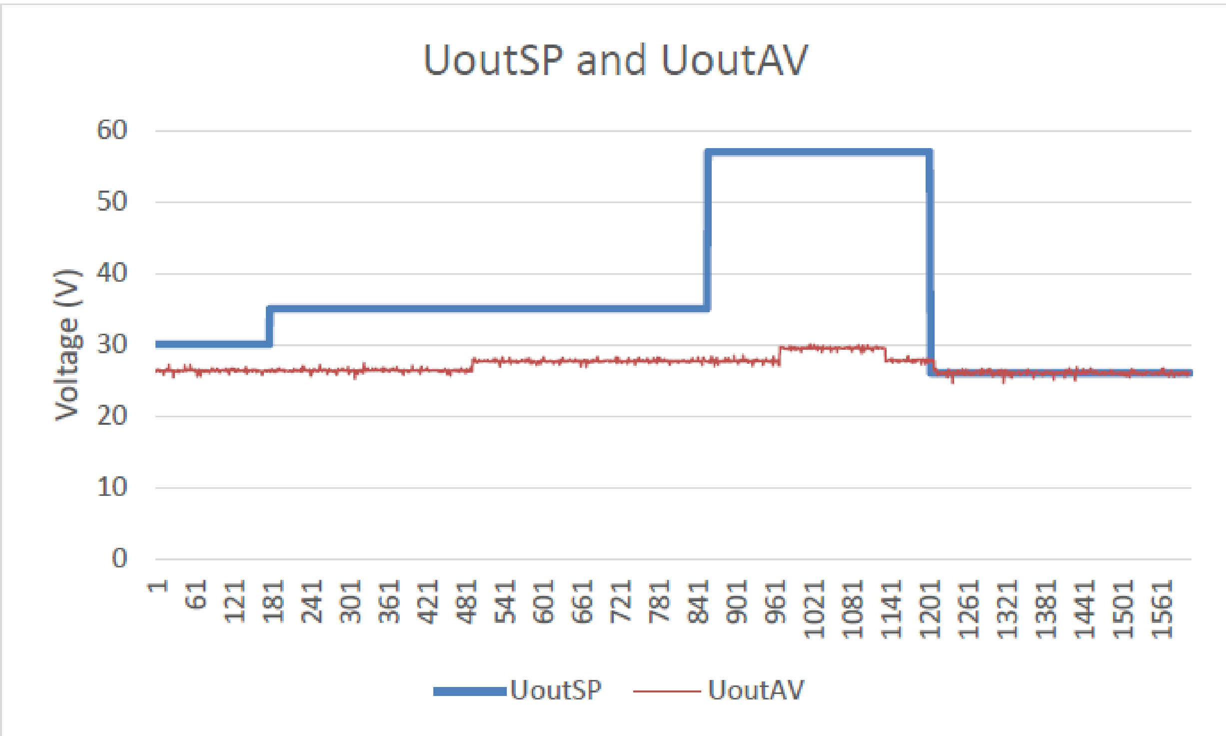

Figure 5-5. UoutSP and UoutAV

Once the Uout set point was set to a value where the current needed was lower than the set point, Uout became the regulated value.

5.3 Regulating Iout

For this test, the set points were:

- UinSP= 25 V
- UoutSP= 57 V
- IinSP= 80 A
- IoutSP= 16 A

Once the program was operating, Figure 5-6 shows Iout:

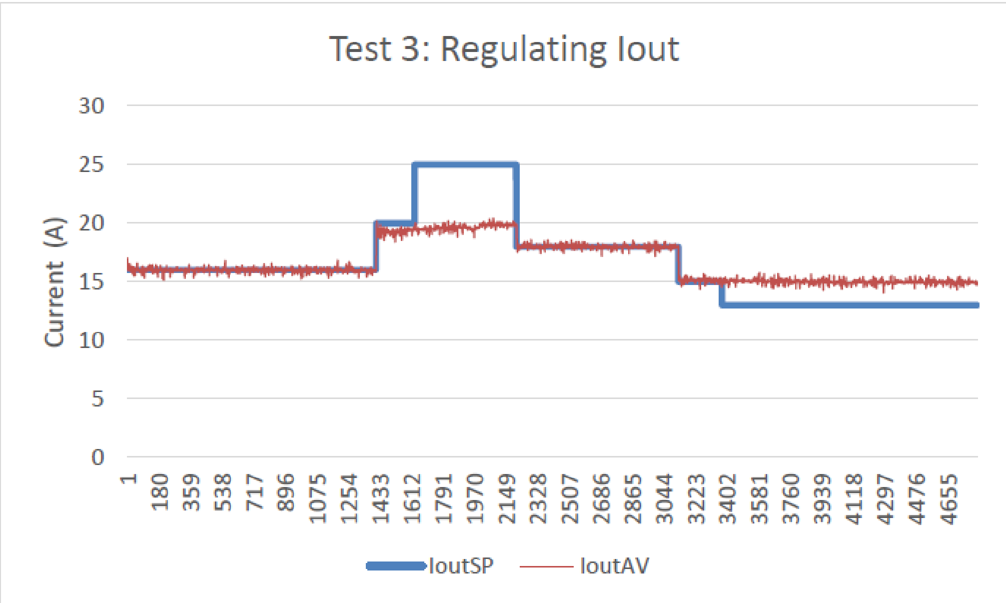

Figure 5-6. IoutSP and IoutAV graph

In this case the set point was changed to a very low value, and it produced that it could not lower it anymore. It looked like it was because the value Uout reached its minimum value of around 22-23V and could not be lowered anymore.

The other values also didn't change when the Iout set point was set to 13V, as it can be seen in Figure 5-7:

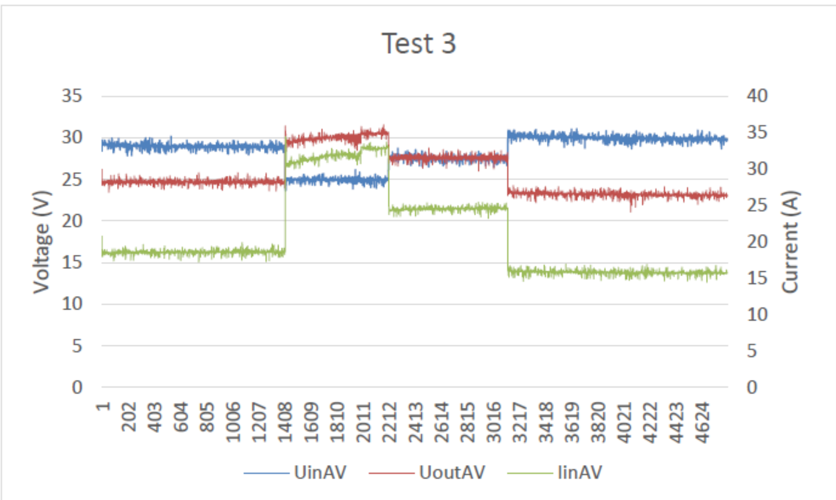

Figure 5-7. UinAV, UoutAV and IinAV graph

5.4 WLTP Drive Test

To simulate a real-life conduction, the WLTP (World Harmonized Light-duty Vehicle Test Procedure) will be done. It is known globally and is done to determine how much carbon dioxide produces and how much pollution fabricates. It is done to all types of vehicles: conventional, hybrids and only electric cars.

There are some types of WLTP test, and they are different from each other when talking about the maximum speed that they reach, and the time of the test. In this case, the WLTP class 1 cycle was done, and its curve can be seen in Figure 5-8.

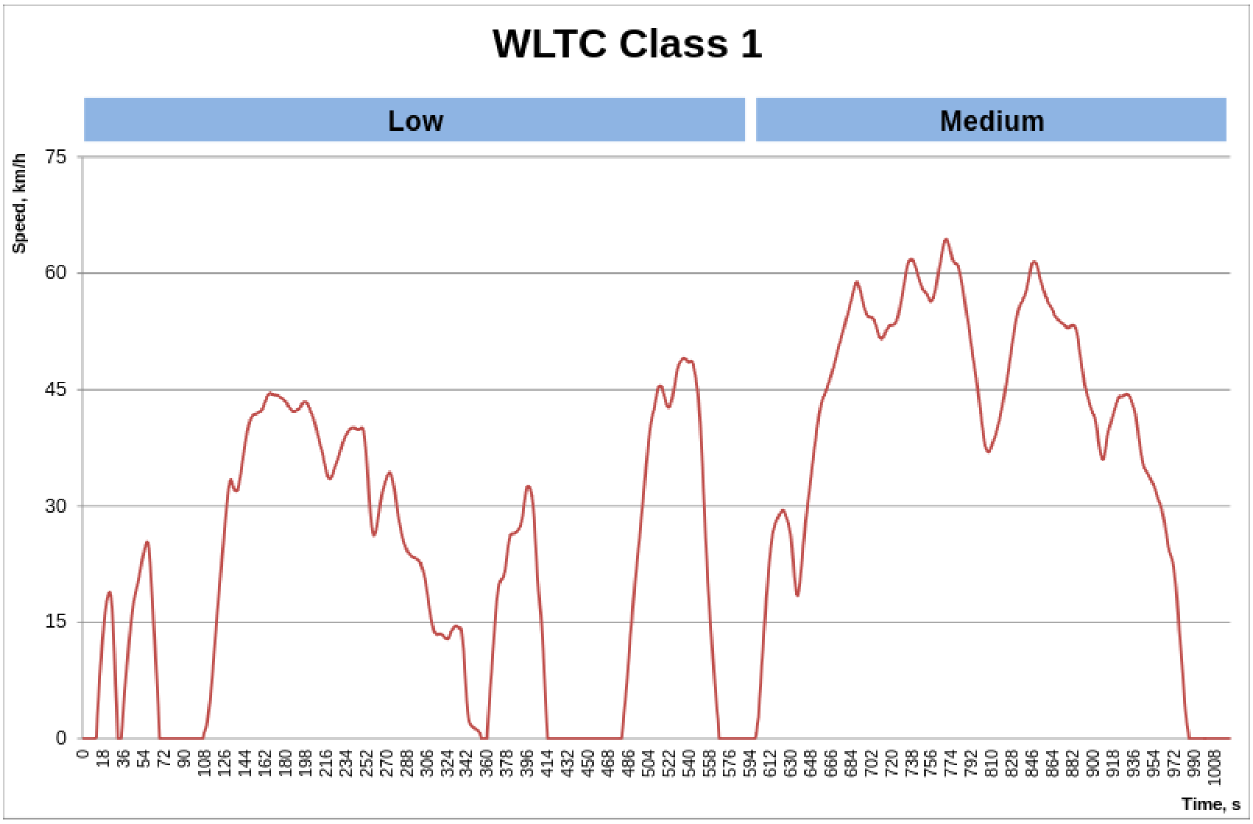

Figure 5-8. WLTP Class 1 [17]

To take on this test, Uout was regulated with a set point of 48V. This was done so the electric charge could be changing during the test with no problems. To know which current was necessary each second, Figure 5-7 was escalated, where the maximum speed would be the maximum power that the PEMFC has given during the last characterization, in this case around 800W. Then, using the formula:

$$P = VI$$

With V being 48V, the current needed I was deduced.

Once it was known the power needed each second, intervals of 30W each, starting from 30W, were created. This was done so that the electric charge didn't vary a lot and the values could be more precise. For example, from 31W to 60W, the current established was 0.8 A, and between 61W and 90W, the current established was 1.9 A, and so on. This way the values of the PEMFC and the BEV4 converter would be steadier. The current established was the maximum of each interval.

In Figures 5-9 and 5-10, the power obtained, and the voltage and current output are shown:

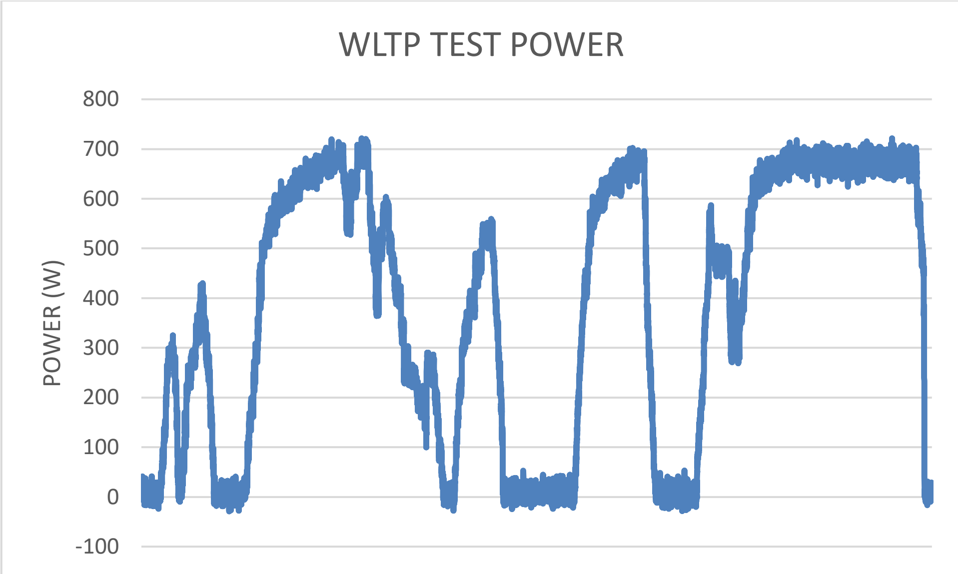

Figure 5-9. WLTP Test power

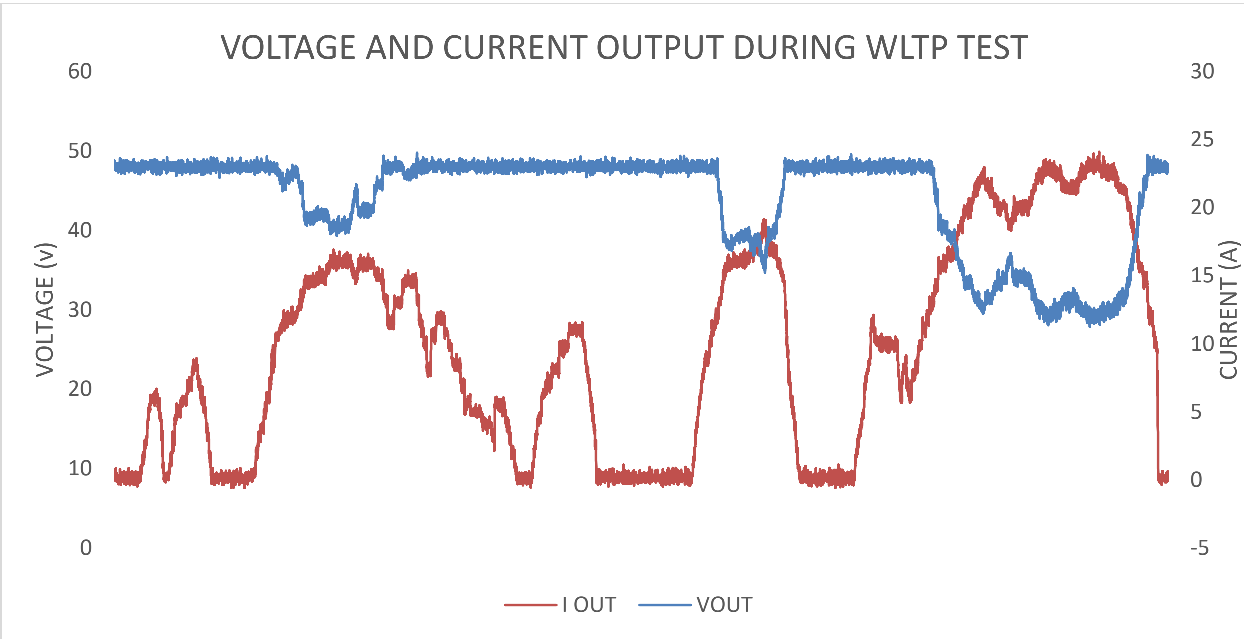

Figure 5-10. Voltage and Current Output

The test was taken on, but due to the electric charge problems appeared. It can be seen that the beginning was correct, but when test was at about 80% done, the electric charge started fuming and the option chosen was to terminate the test.

In Figure 5-10, it can be noticed that during the test the value of 48V in Vout was not steady. The cause is thought to be that the electric charge, which could regulate limit the voltage, decreased it in order to increase the charge that was being asked. That's why when passing the limit of around 12A the voltage started decreasing, being most noticeable at the final stages, when the fuming started.

It is though that the PEMFC could have performed better with a more optimal electric charge, since this one limited the power that it was giving.

It could also have performed better with a lower voltage output of around 36V, since this one may have been too high, but at the highest current askings the same problem may have appeared.

Another first though was that the electric charge could have limited the power since it has a maximum power output giving of 1000W, but this was discarded since the maximum power reached was 700W.

6 CONCLUSIONS AND FUTURE INVESTIGATION LINES

"Habit is master of all things."- Julius Caesar -

6.1 Conclusions regarding the work document

It can be said that the PEMFC and the BEV4 converter were succesfully implemented into the computer with the DAQmx cards that were installed. The LabView program was succesfully re-modeled and, even though the software gave problems because of the drivers and LabView versions, the system was upgraded in terms of hardware, since only one device was needed, not two, like in the past, where every communication was done through CAN and a C++ code was used to run the control part. In this TFG the communications were changed, the NIDAQmx functions were used, and a new algorithm was implemented, resulting in a less laborious and safer testing site, since it is not necessary implementing the hardware onto the FOX vehicle.

The converter worked as thought and the tests were done successfully where regulating was proved to function correctly and the characterization of the PEMFC was done again to prove that its life span and power-giving capacities were slowly downgrading. The WLTP Class 1, which is a global car test, was done to demonstrate that the PEMFC, with proper connection and devices, can work as an hybrid car, offering a large range of power with a stable voltage.

6.1 Future lines of research

It is highly recommended that the following TFGs done related to the FOX implement different and uprograded hardwares: batteries, a new electric charge...

With this TFG finished, the following research lines are proposed:

- After the implementation of the hardware and the software upgrade, the connection of the device used with the DAQmx cards, the PEMFC and the BEV4 Boost converter to the FOX vehicle is proposed since is the next and final step of making this system work in real life.
- A study about how to improve the BEV4 boost-converter system or implementing another similar hardware with the objective of giving higher voltage and therefore upgrading the system is recommended.

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APPENDIX A. USER MANUAL

BENCH TESTING PROGRAM USER MANUAL

1. Introduction

1.1 Objective

To provide support to users that use the LabView bench test program and to inform about the necessary connections and steps to do so. To use the PEMFC and the converter together the program that has to be used and the one that will be explained how to below will be BOSS_SUPERVISOR. There exists two versions, wich will be talked about below.

1.2 Requirements

- Windows 7 Computer with LabView 2015-32 bit and LabView 2016-64 bit version
- PEMFC NEXA1200
- BEV4 Converter
- CAN wire (USB adaption)
- H2 valve and supplier
- Electric charge or batteries
- 2 Power Suppliers
- DAQmx cards

2. Connection procedure

To connect the devices correctly, the following steps have to be made:

1- Turning on the computer with the DAQmx cards installed and configured and pluging in the electric charge and power supplier. Connect the CAN wire to the computer. To see the necessary values to supply the PEMFC see the NEXA1200 and BEV4 manual.

2- Connect one electric supplier to the PEMFC and another one to the BEV4 converter. Set the values without turning it on.

3- Connecting the BEV4 converter to the PEMFC, to the electric charge and to the DAQmx cards. To see the connections see the BEV4 manual.

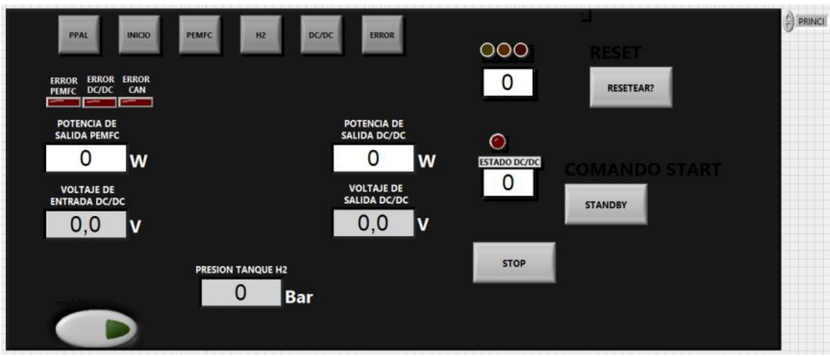
4- Turn on the electric supplier and open the hydrogen valve.

5- Follow “Test Procedure”

3. Program Information

In this chapter every screen that shows will be explained, but first it has to be said that the LabView 2015-32 bit version will be used to extract and see information from the PEMFC and the other version will be used to extract the data from the data acquisition cards that are installed in the computer. Also, the screens that its explanation is not given will be because they will not be necessary to operate the bench.

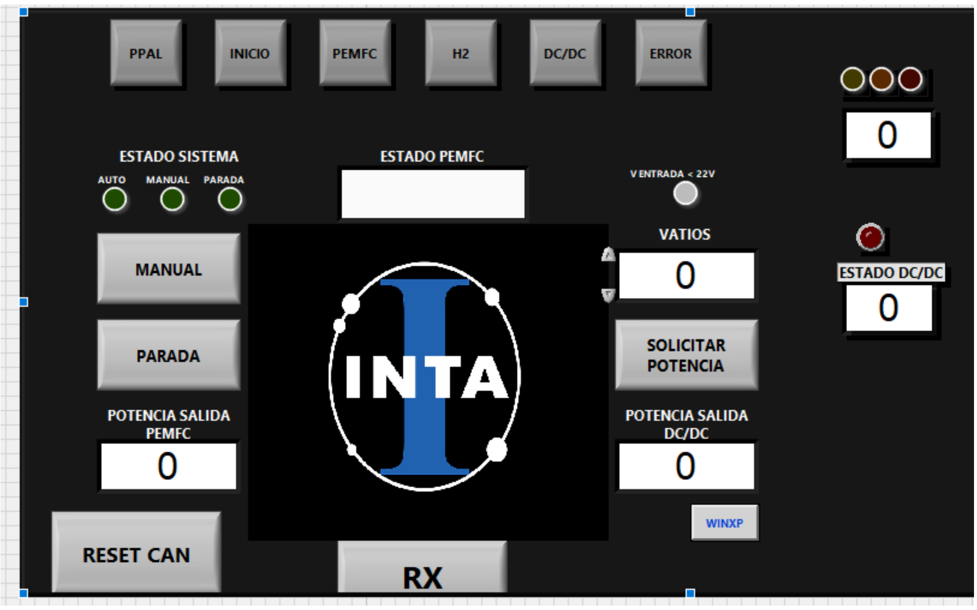
3.1 LabView 2015-32 bit screens



PPAL Screen

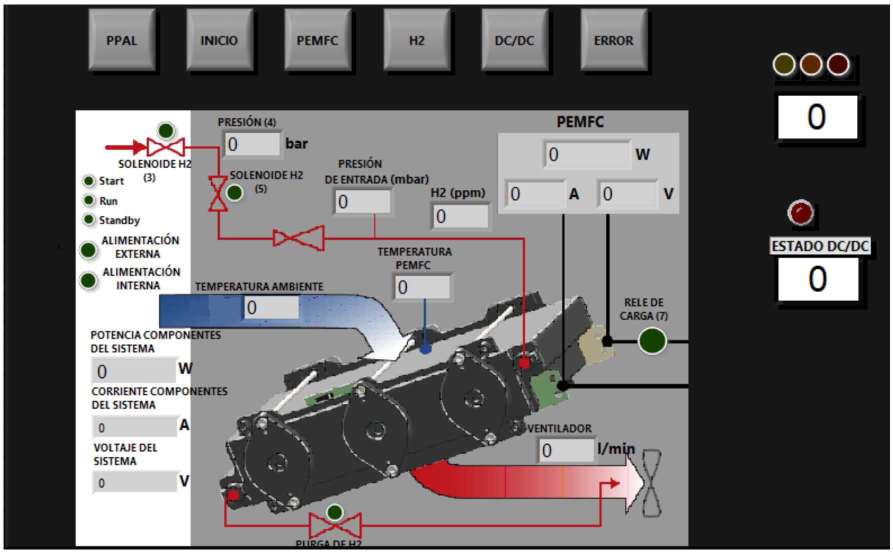
This will be the first screen that pops up when opening the program, and it is used to order the actions of RUN (click "standby" to run the PEMFC), RESET (click "RESETEAR?") and STOP (click "STOP). Also if errors regarding CAN happen the light below ERROR CAN will be turn red.

The button that is at the bottom-left part of the screen is the responsible for stopping the program.



INICIO Screen

In this screen the state of the PEMFC will be shown, as well as the power that exits the PEMFC. It is very important to know that the RX button is the responsible for reading the values of the PEMFC, so it has to be activated when wanting to see the data.

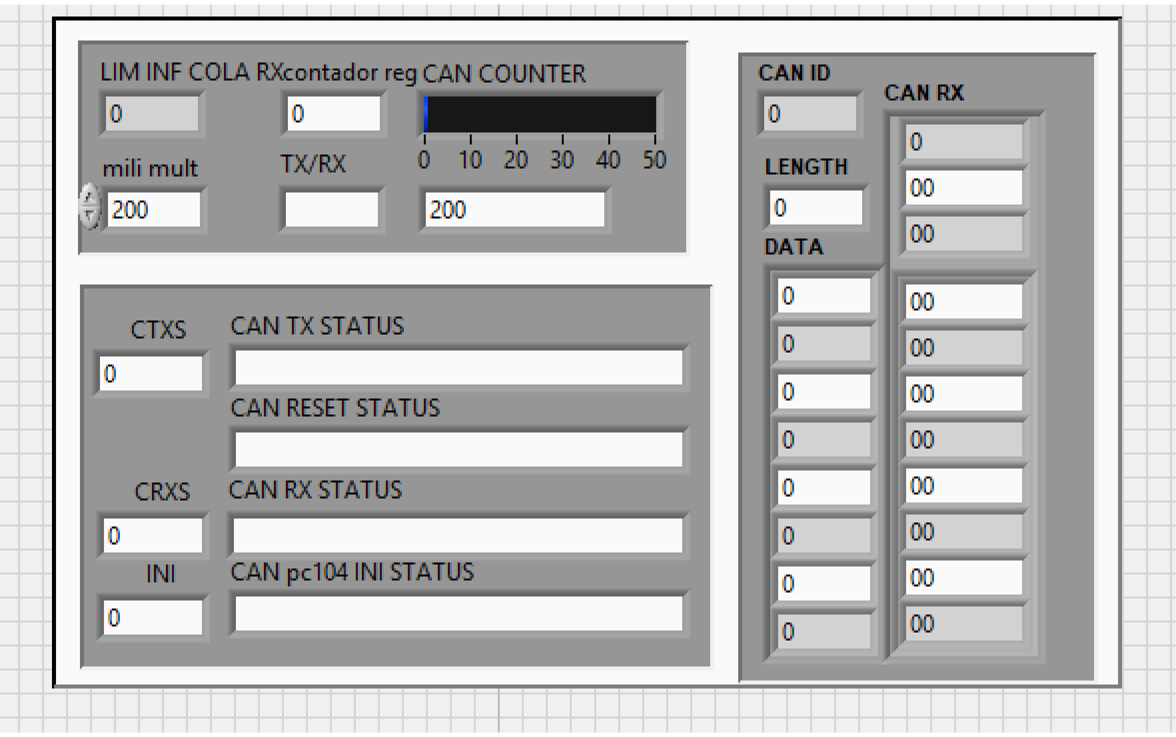


PEMFC Screen

This screen is just informative of the different values that the PEMFC offers.

ERROR Screen

This screen shows the description of every error that happens relating to CAN and its code, so it is helpful when CAN doesn't communicate correctly.

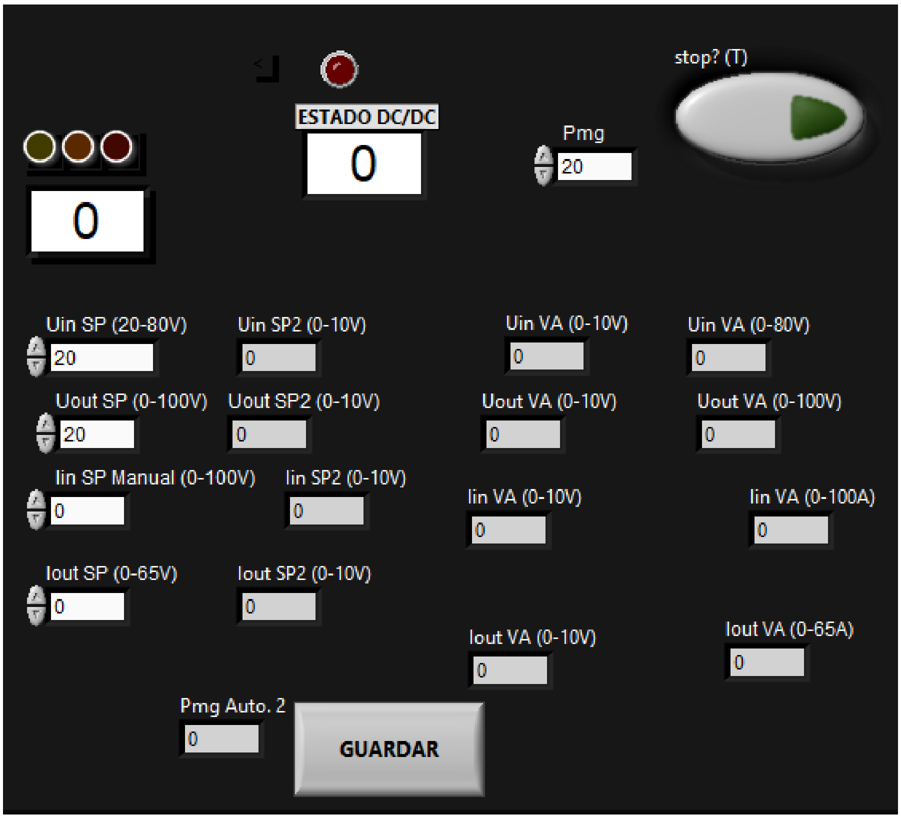


STATUS Front Pannel Part

This Pannel will always be below the interface and it is informative. The TX/RX informs if CAN is transmitting or receiving information, and in the right the information about the data can be seen. Below the TX/RX part the status of the TX CAN and the RX CAN can be seen, too. This is informative in case there exists any error.

3.2 LabView 2016-64 bit screen

For this part only one screen is relevant and that is the DC/DC converter part.



DC/DC Screen

This screen is used to write the setpoints wanted to test the converter. The left part is where the setpoints are written and in the right part the values can be read. The button "GUARDAR" will acquire the data in a .xls file.

4. Test procedure

To use the workbench, it is recommended to configure the acquire data function that can be found in the Command window so the file is easier to find.

The steps, one everything is connected correctly and turned on, are:

1- Write the desired setpoints on the 2016 program.

2- Start running both programs.

3- Ordering the PEMFC to run on the 2015 program.. If the PEMFC was on ERROR state, it must be reset first.

4- Once the PEMFC is running, the respective data will be showing in both programs.

5- If wanted, press the button "GUARDAR" to acquire data.

6- When finished, press "GUARDAR" again so it stops.

7- Finally, pressing STOP on the 2015 program and shut down both of them.