

UNIVERSITÉ DE TECHNOLOGIE DE BELFORT-MONTBÉLIARD

Fuel cell and supercapacitors remote control car

Project report - A2011

Département d'Énergie et environnement

Master thesis

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Abbreviations

In this project some abbreviation will be used. These are the more frequently used:

DSP: Digital Signal Processor

ESC: Electronic Speed Control

FC: Fuel cell

H₂: Hydrogen

LED: Light Emitting Diode

LHV: Lower Heating Value

PEM: Proton Exchange Membrane

PEMFC: Proton Exchange Membrane Fuel Cell

PWM: Pulse Width Modulation

RC: Remote Control

SC: Supercapacitor or Supercapacitors

SD: Secure Digital card

Introduction

The energetic crisis and the actual fossil fuel dependant society make an alternative energy sources necessary. In a world where pollution is massively emitted and consumption has no end a cleaner energy source is needed. The hydrogen is a very good option because its use is very clean and is the more common element in the universe and also abundant in the earth. Nevertheless the hydrogen also has some disadvantages like high flammability, expensive obtaining and difficult storage.

To solve or decrease these disadvantages the hydrogen must work with other energy sources like supercapacitors. If newer technologies are developed, more investigation will be done and the hydrogen problems will be solved with time.

In this report of a 5 month project all the technological aspects involved in the conception and creation of a hydrogen car are explained.

Project aim

The purpose of this project is to make an approach of a real and nowadays car industry problem: Energy management of an electric hybrid car. The car in this project is five times smaller and its power needs are lower too, but the problem in managing the different power supplying sources remains. In this actual project the power supply sources are a 300 W fuel cell and a 29 F supercapacitor.

To make an accurate approach to the real problem the real requirements are tried to be accomplished:

- Same acceleration as Porsche 911GT: The speed reached by a remote control car won't be the same as the real car, but the acceleration of the car can be the same but in a lower speed. The Porsche 911GT reaches 100 km/h in 4,2 seconds ($a = 6,614 \text{ m/s}^2$), so this car would do the same if it could reach 100 km/h.
- Brake: The brake system is an essential system for any car and must guarantee a rapid stop of the car.
- Reverse gear: This is important to park a car and do some maneuvers occasionally.

Some of these requirements are essentials and others are not and there are also very difficult requirements and easier requirements. All of them are kept in mind while doing this research project.

Previous works summary

In this section all the works done previously are introduced briefly. Is because of these previous works that this project can be done. From the third to the seventh chapter, each chapter belongs to a different previous report. From the eighth chapter until the end of this report all the chapters belong to the work done during this semester.

1 Project history

Date	Students	Work
Spring 2009 (P2009)	PENELON Loic NOIRET Guillaume NAAMAN Raed	Preliminary study: Preliminary component sizing.
Fall 2009 (A2009)	AHMED EI'Had BOUDOUDOUH Soukaina FRITZ Thibaut	Components choice. Modeling and first simulations.
Spring 2010 (P2010)	ARCIN Marie-Adeline SELIG Thomas	Power components validation tests: Buck and supercapacitors.
Fall 2010 (A2010)	LEFEVRE Florian STOFLETH Mathieu VIAL Robin	Components ordering. Components placing. First vehicle tests.
Spring 2011 (P2011)	LEFEVRE Florian CADALEN Florence	Components placing continuation, vehicle testing and optimisation.
Fall 2011 (A2011)	MARTÍN Jordi	MicroAutoBox replacement by a DSP FC and SC optimisation Mechanical improvement Electromagnetic interferences solving
Spring 2012 (P2012)	Unknown	Regenerative brake system Reverse gear

2 First approach

2.1 Electrical architecture

The energy source of the vehicle is a 300 W fuel cell, precisely a PEMFC¹. A PEMFC use hydrogen and air to produce electricity, so no pollutant is emitted. Knowing that a fuel cell (FC) has a slow response time and that a frequent power variation needed for this case, another energy source is needed. The use of supercapacitors is a good solution (check A2009 report in French). The supercapacitors power density is quite high, can give the power needed to accelerate and also can stores the energy in a regenerative brake.

The FC will be connected to a 30 V bus by a buck converter. This one-way current converter allows regulating the current given by the FC and also protecting it when braking. The FC must be protected because if the regenerative brake system is implemented in the car the FC can't work in a reversible way.

This is the electrical architecture that is used when motor is working as a motor and even when the motor works as a generator.

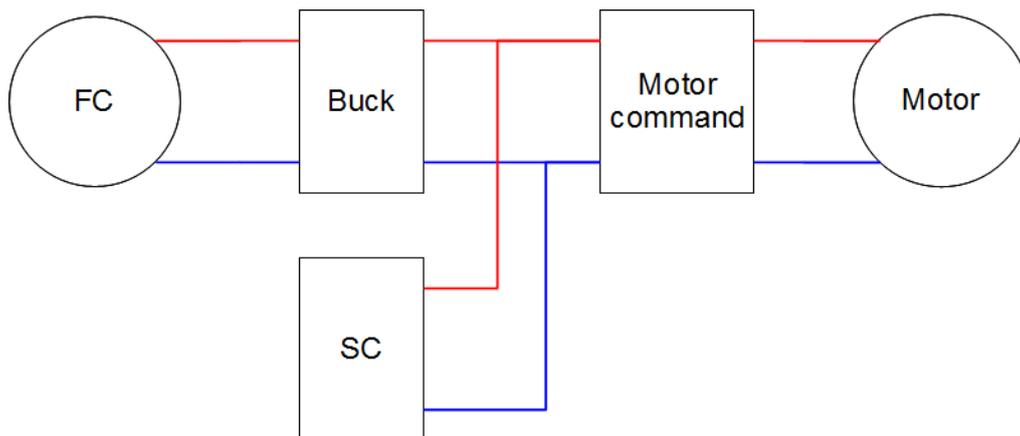


Figure 1: Electric car architecture

¹ Proton Exchange Membrane Fuel Cell

2.2 Performances

The remote control car must have the same acceleration as the Porsche 911 GT3 as previously said, from 0 to 100 km/h in 4,2 s, equivalent to an acceleration of $6,6138 \text{ m/s}^{-2}$

2.3 Bodywork

The car's bodywork used must be the one of Porsche 911 GT3, 1/5 scale. The restriction of the bodywork is to arrange all the components in a way that they fit in the car with the bodywork on.

3 Components sizing

The calculations in this section have been corrected from the previous reports because several mistakes have been found.

3.1 Steady state speed

First of all the overall efficiency must be estimated. In the previous reports 80% efficiency was estimated. To do such thing we must know all the systems between the FC and the wheels:

FC→Buck→Motor→Transmission→Wheels

No loses between systems are supposed. The most common efficiencies of each system are shown:

Buck: 90%

Motor: 80%

Transmission: 98% [1]

Now the overall efficiency is: $0,9 \cdot 0,80 \cdot 0,98 = 0,7497 \approx 0,75 = \eta_{global}$

Considering that the FC has a constant power of 300W and that the global efficiency (from the FC to the wheels) is 80% (see A2009 report), the propulsion power can be found:

$$P_p = P_{FC} \cdot \eta_{global} = 30 \cdot 0,8 = 240 W \quad (eq. 1)$$

Solving the static equilibrium equation the steady state speed is found:

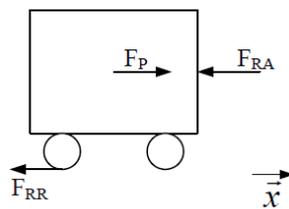


Figure 2: Car force distribution

Constant speed and horizontal plane rolling are supposed. These are the forces applied to the car (vertical forces are not shown because they cancel each other and don't help to find the steady state speed):

- Propulsion force: F_p
- Drag force : $F_D = \frac{1}{2} \rho_{air} \cdot A \cdot C_x \cdot S^2 \quad (eq. 2)$

With ρ_{air} : Air density [2],

$$\rho_{air} = 1,2 \text{ kg/m}^3$$

A: Reference area [3]², $A=0,0836 \text{ m}^2$

C_x : Drag coefficient, $C_x=0,34$

S: Steady state speed in m/s

- Rolling friction force [4]: $F_{RF} = \frac{f \cdot m \cdot g}{R}$ (eq. 3)

With m: Car mass, $m=16 \text{ kg}$

g: gravity, $g=9,81 \text{ m/s}^2$

f: Coefficient of rolling friction, $f=0,01$

R: Wheel radius, $R=0,0612 \text{ m}$

Static equation solving:

$$\sum \vec{F} = \vec{0} \quad (\text{eq. 4})$$

Over \vec{x} axis:

$$F_P = F_D + F_{RF} \quad (\text{eq. 5})$$

The car has 4 wheels, the 2 in front have a 0,0619 m radius and the 2 in the back have a 0,0605 m radius. An uniform weight distribution is considered, so the mean radius is 0,062 m.

$$P_P = F_p \cdot S \quad (\text{eq. 6})$$

then

$$P_P = 240 W = (F_D + F_{RF}) \cdot S \quad (\text{eq. 7})$$

Results: $S = 8,8905 \text{ m/s} = 32,0058 \text{ km/h}$

This speed is perfectly possible because the theoretical maximum speed is 42,22 km/h. This is known because the maximum motor rotation speed is voltage dependant:

$$\omega_{motor \max} = K_V \cdot U_{bus \max} = 305 \cdot 30 = 9150 \text{ min}^{-1} \quad (\text{eq. 8}) [5]$$

The gear ratio is 5:1, this means that for every 5 spins of the motor, the wheels do just one spin.

$$\omega_{wheel} = 9150 \text{ min}^{-1} / 5 = 1830 \text{ min}^{-1} \quad (\text{eq. 9})$$

$$S = \omega_{wheel} \cdot R \cdot \frac{1 \text{ min}}{60 \text{ s}} = 1830 \frac{\text{rev}}{\text{min}} \cdot \frac{2 \cdot \pi \text{ rad}}{1 \text{ rev}} \cdot 0,0612 \text{ m} \cdot \frac{1 \text{ min}}{60 \text{ s}} = 11,7282 \frac{\text{m}}{\text{s}} = 42,2215 \frac{\text{km}}{\text{h}} \quad (\text{eq. 10})$$

This happens because the motor used is an aeroplane motor and this means that the torque will be higher and the speed will be lower. Furthermore, the car has not a reverse gear by the same reason.

² $A = 0,22 * 0,38 = 0,0836$ (measured)

3.2 Power needs in transient state

Adding the acceleration into the previous equation and integrating the equation by the speed from 0 m/s to 8,8905 m/s with the Simpson integrating rule the needed power is obtained:

$$a = \frac{ds}{dt} \leftrightarrow dt = \frac{ds}{a} = \frac{8,8905 - 0}{6,614} = 1,3442 \text{ s} \quad (\text{eq. 11})$$

$$P_p = (F_D + F_{RF} + m \cdot a) \cdot S \quad (\text{eq. 12})$$

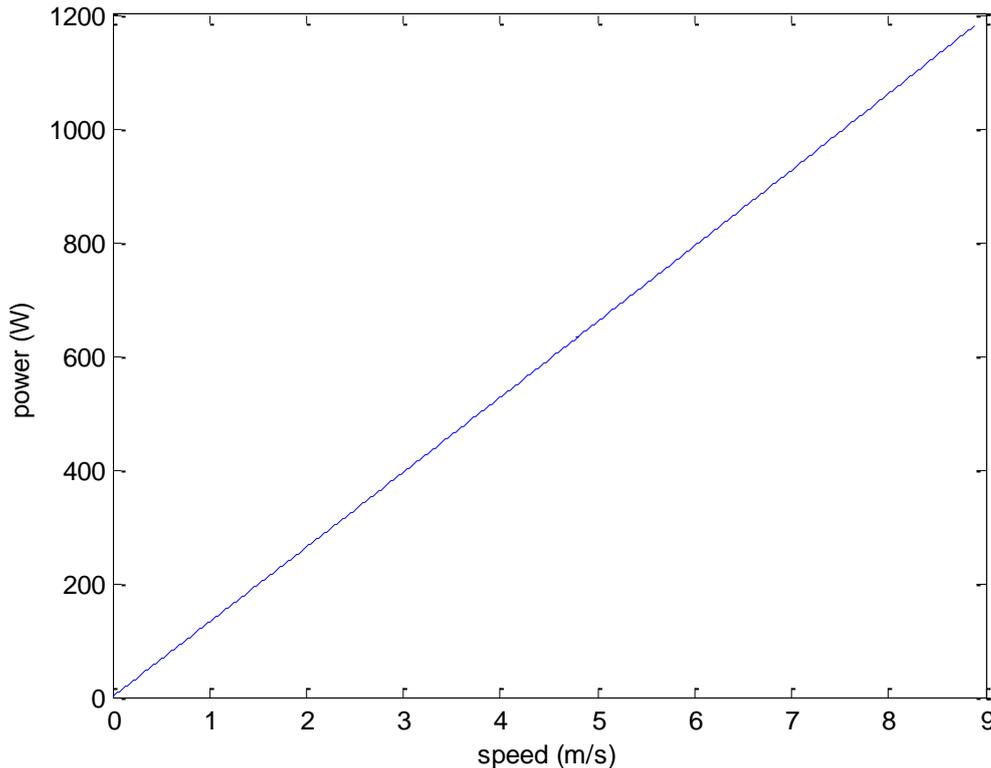


Figure 3: Power needs versus speed during acceleration

Maximum power (@8,8905 m/s) = 1.180,8 W

If the system efficiency is about 80%, the motor power must be at least $1.180,8/0,8 = 1.476$ W to provide the required power.

3.3 Energy requirements

With an acceleration of 6,614m/s², the car reaches its maximum speed in 1,3442 s. The power increase is considered as linear until its maximum value.

The energy needed for each acceleration process is the integral of the power equation used in the previous section:

$$\begin{aligned} & \int_{S_{start}}^{S_{finish}} \frac{1}{2} \cdot \rho_{air} \cdot A \cdot C_x \cdot S^3 + \frac{f \cdot m \cdot g}{R} \cdot S + m \cdot a \cdot S \, dS \\ &= \int_0^{8,8905} 0,5 \cdot 1,2 \cdot 0,0836 \cdot 0,34 \cdot S^3 + \frac{0,01 \cdot 16 \cdot 9,81}{0,0612} \cdot S + 16 \cdot 6,614 \cdot S \, dS \\ &= 5,222 \, J \end{aligned}$$

(eq. 13)

The energy storage systems used in the car must store at least 5,222 J to allow a complete acceleration.

4 Components selection (P2009)

4.1 Fuel cell

An Horizon H-300 fuel cell is used. Its nominal power is 300 W, its voltage stands between 36 and 69 V and the maximum current is 8 A. The entire and most recent documentation is available in digital version.

4.2 Buck

The buck PCB has been improved by Mr. Larioumlil, because the old one had serious problems while the car was in motion. This buck will make possible the fuel cell voltage decreasing until the continuous bus of 30 V. Due to several problems while developing the new buck version the buck hasn't been tested as much as desired.

4.3 Motor

The electric motor must accomplish the following requirements:

- Be capable of provide a large amount of operating modes ;
- Be compact and light;
- Has a high rotation speed.

The chosen motor is a brushless DC electric motor [6]. This motor is widely used in transportation because is powerful and light.

4.4 Motor controller

Like the motor it has to work between 11,1 V and 37 V and also has to supply enough power to the motor when acceleration peaks occurs. Its choice is decided by the motor.

If the regenerative brake system has to be set up this controller must be modified or replaced.

4.5 Supercapacitors

The chosen supercapacitors are made by Maxwell Technologies®. Their components are the bought in the market due to their performance and their reliability.

To adjust the supercapacitors performance characteristics and the motor requirements two BPAK0058 E015 B01 supercapacitors has been bought and connected in series. Each supercapacitor has a capacitance of 58 F and 15 V of initial voltage. This means that connected in series the equivalent supercapacitor has a 29 F capacitance and 30 V of initial voltage.

To prevent an early deterioration of the supercapacitors and extend as much as possible its life, the equivalent supercapacitor doesn't have to be discharged under 15 V when operating.

5 Modeling and simulating (A2009)

5.1 Global representation

The whole system is represented by the following diagram in Matlab Simulink®:

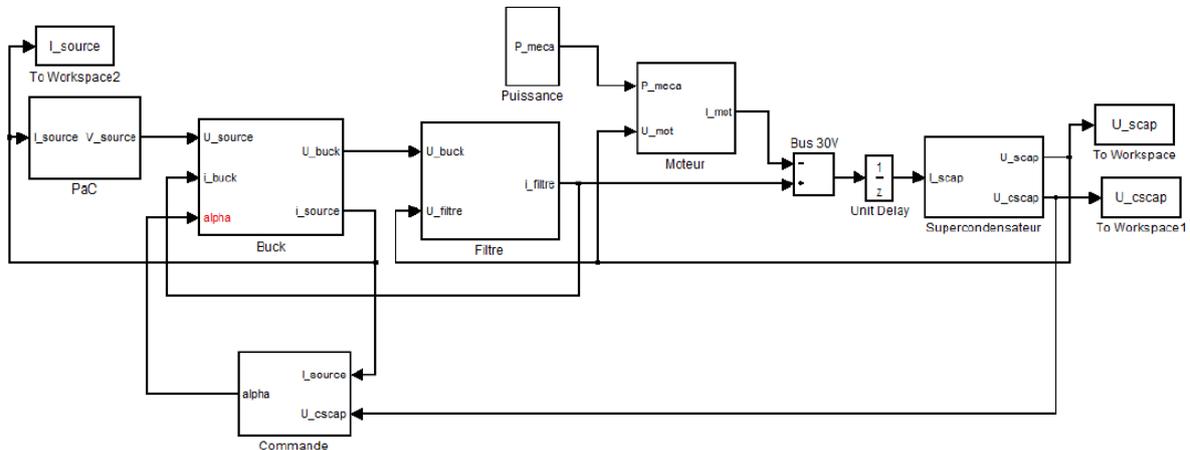


Figure 4: System flowchart

All the mathematics equations of the blocs are available in French in the 2009 Fall report.

The buck command is explained as follows:

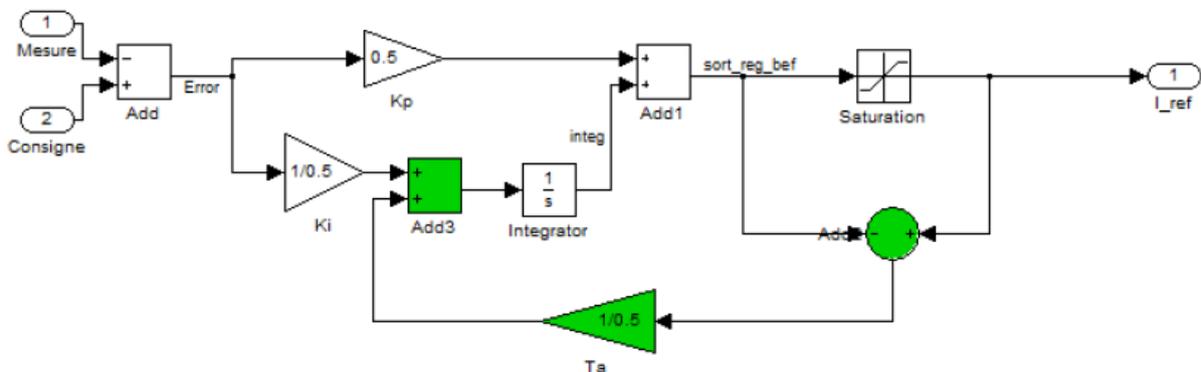


Figure 5: Alpha buck calculation from measured bus voltage

5.2 Results

To work with the previous system model and obtain some useful results, some parameters must be entered. To know those parameters like FC reaction time a simulation has been automated.

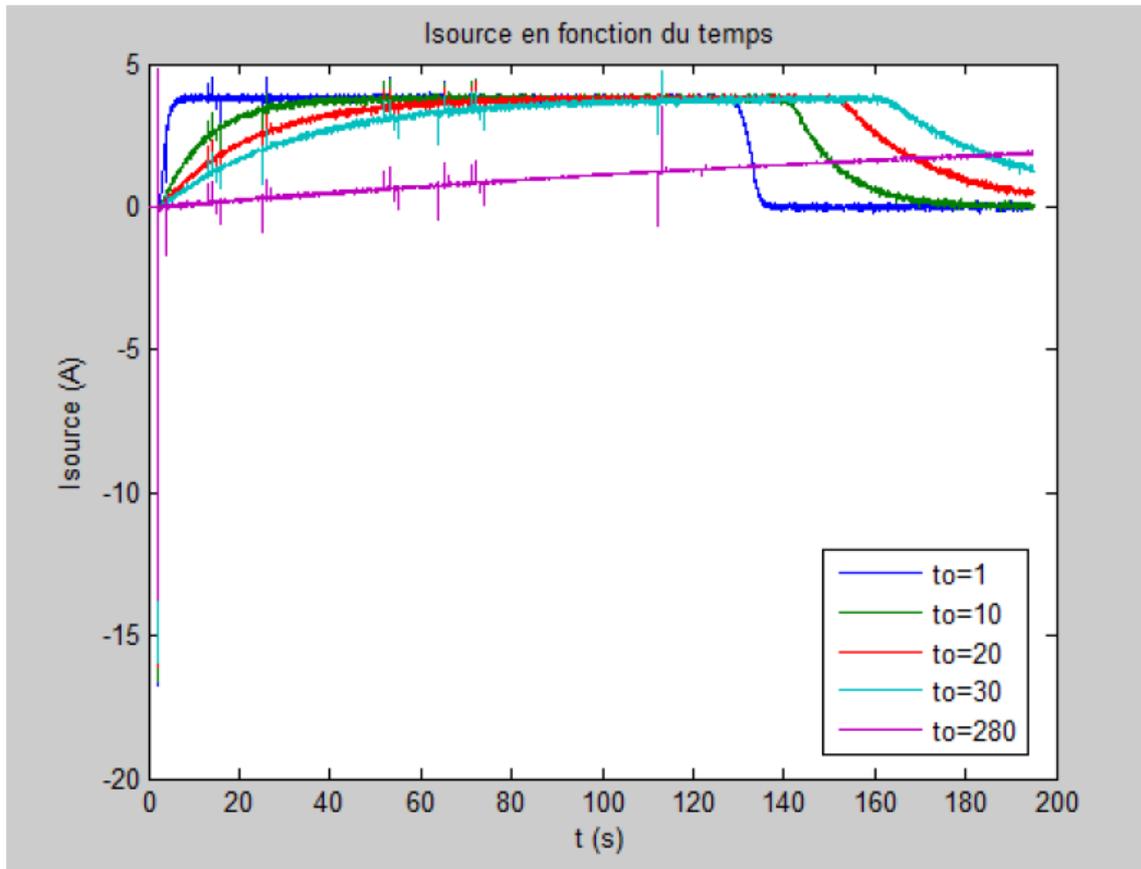


Figure 6: FC given current in function of time for different “ τ_o ” (τ_o) values.

What can be seen in this figure is logical, the more “ τ_o ” the more inertia the system has. A $\tau_o = 10$ s has been considered the most reasonable for this fuel cell, because the current rises slowly and regularly.

The supercapacitors have to be modelled also, so this is what can be seen in the next graph:

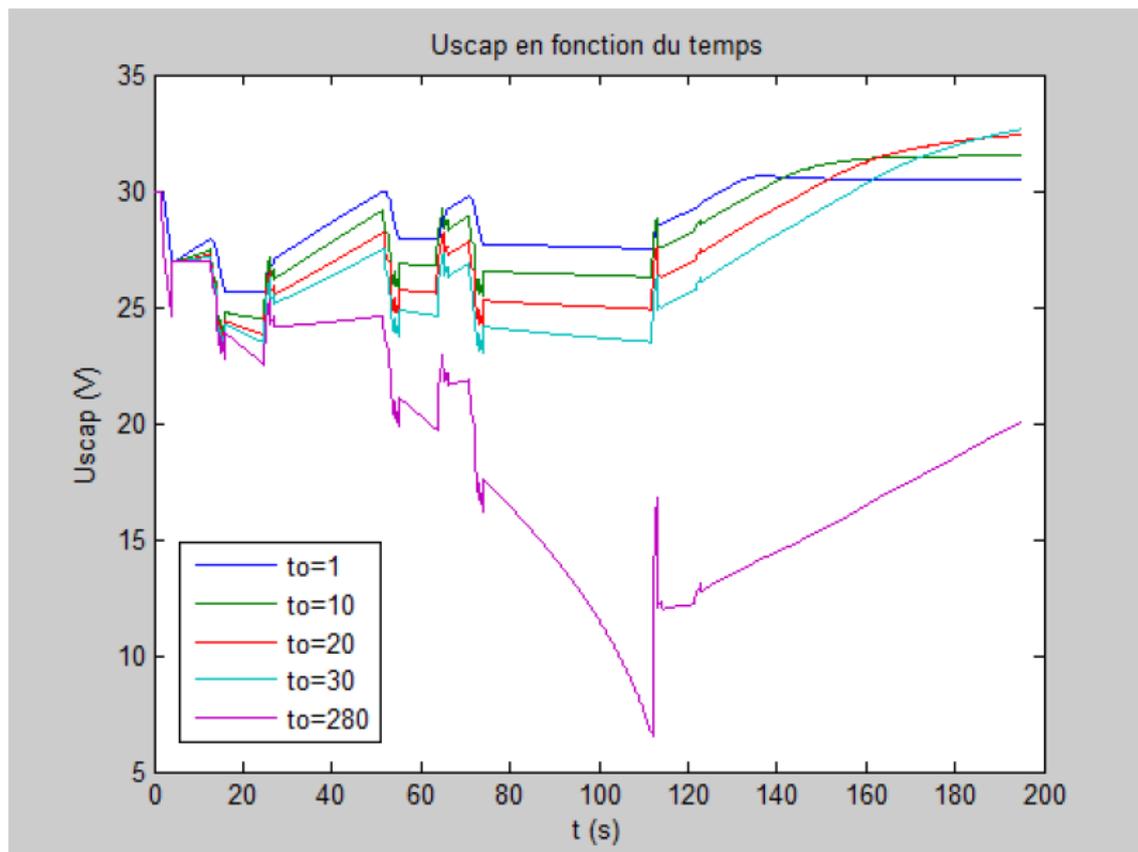


Figure 7: Voltage between supercapacitors terminals in function of time for different values of FC "to" (τ_o).

An obvious fact can be deduced from this graph: The slower the fuel cell is the more energy the supercapacitors must provide and the lower voltage they have in function of time. Anyway the supercapacitors voltage must be between 15 V and 30 V due to their specification. This is why a limitation must be imposed: the time constant must be low enough to maintain the voltage over 15 V but high enough to use the supercapacitors stored energy.

To optimise the supercapacitors operating range, when protecting them of overvoltage, might be interesting settle the "to" value in real time or simply deactivate the fuel cell in some occasions due to oversizing of supercapacitors. A better knowing of the fuel cell characteristics, precisely its starting and stopping times obtained by real tests, will permit to choose the best adapted command typology.

A solution that won't be implemented yet consists in not using the fuel cell and change the buck duty cycle³ according to the following criterion defined arbitrarily:

- Deactivation when the bus voltage is higher or equal to 30 V.
- Activation when the bus voltage is lower than 20 V.

³ Duty cycle: Ratio between the pulse duration (or pulse width) and the period

The command flowchart is represented in Figure 4.

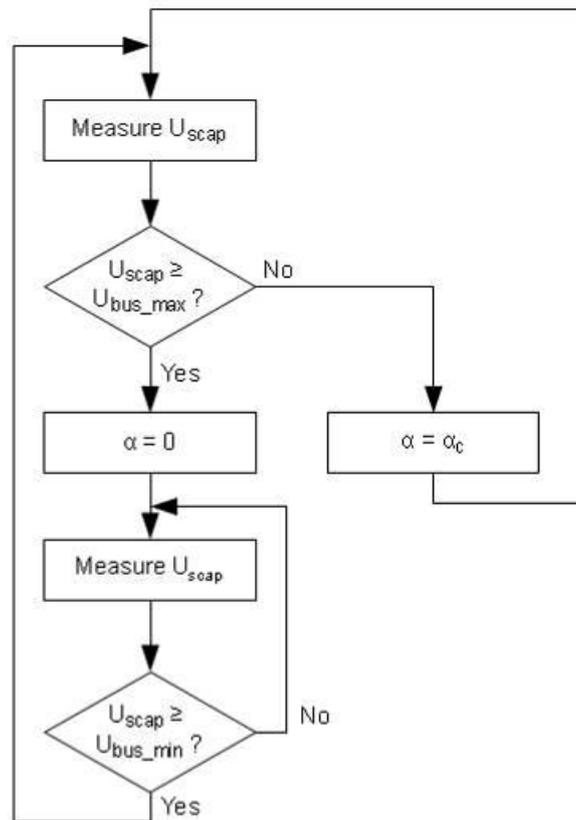


Figure 8: Flowchart when not using the fuel cell

5.3 Buck command

The buck operation must satisfy some requirements imposed by different components:

- Supply a 30 V voltage to the continuous bus
- Must be controlled by current
- Maintain supercapacitors terminals between 15 V and 30 V when operating

Work with a supercapacitors voltage under 15 V must be avoided when the car is running and the supercapacitors are charged and discharged frequently, if not supercapacitors performance and useful life will decrease.

The students of the semester P2010 have worked with another buck than the used nowadays. Nevertheless their results are still valid. They commanded the buck in two ways:

- Filtered current command
- Voltage command

5.4 Filtered current command

The control has been made in the following way: the used load current is measured, that current is filtered and this filtered current is the reference current for the buck.

Then the best time constant is searched to have a constant voltage in supercapacitors terminals. Here is the results obtained by $\tau = 1,5$ s.

- In blue: Load demanded current (A)
- In green: Measured current in buck's output (A)

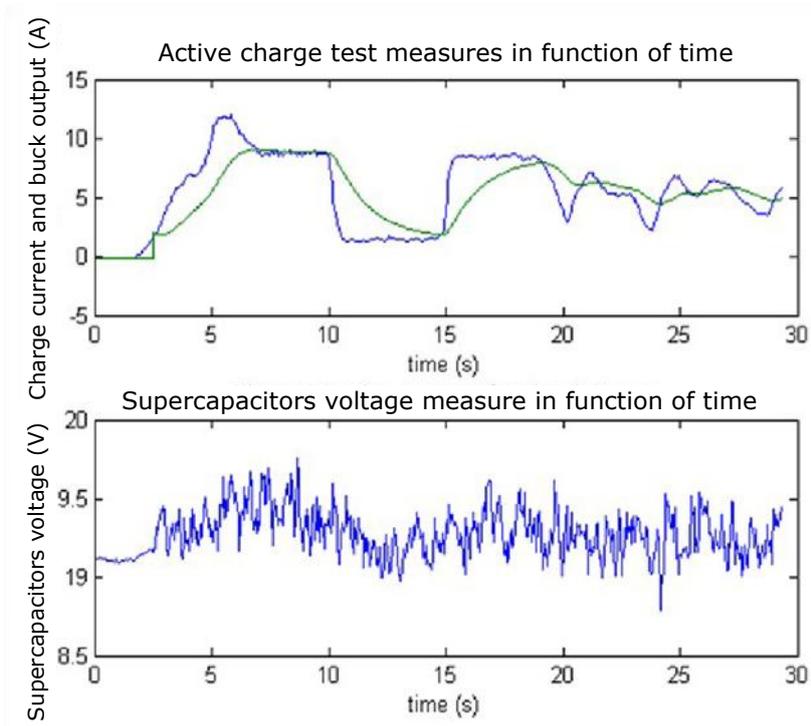


Figure 9: Filtered current command $\tau = 1,5$

These curves analysis allows affirming that this control type works. However it doesn't allows assuring that the voltage in supercapacitors terminals keeps between 15 and 30 V. To do that another current control system must be used to ensure that the voltage has the proper value, but this will increase the control complexity.

5.5 Voltage command

A voltage command it can be also possible. To do that the active load demanded power must be changed and then the supercapacitors voltage and current are observed. A dynamic profile, that corresponds to a typical profile for this car has been done to make a simulation.

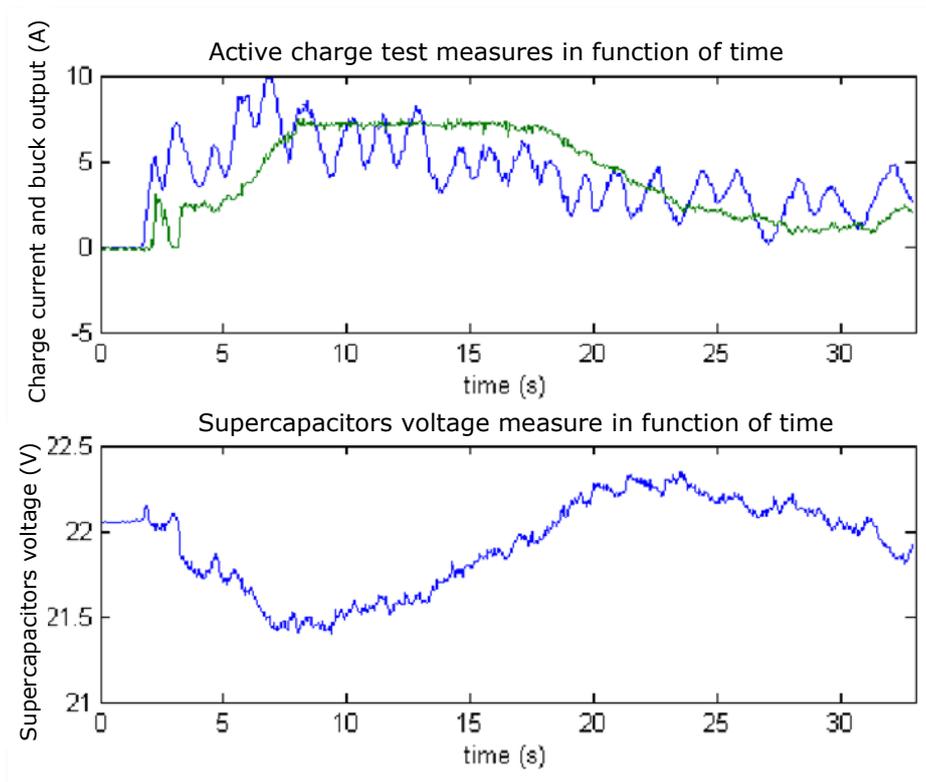


Figure 10: Voltage command

- Blue: Active load demanded current
- Green: Buck current

In the first graph the slow reaction time of the fuel cell can be observed, but it was what has been expected. Indeed the fuel cell can't change its given current as fast as we want. The best solution is to provide the current as steadily as possible.

The first current peak of the fuel cell is caused because of PWM signal starts. This peak won't be considered because during car operating the fuel cell is meant to work continuously.

The second curve corresponds to supercapacitors voltage response in time. The voltage doesn't vary too much even in a dynamic use. A voltage stabilisation was programmed and expected around 22 V, and that's what has been obtained. So the voltage response is satisfying although the small variations caused by electromagnetic interferences that hasn't been considered while doing this analysis.

5.6 Summary

The filtered current command works quite well but it has some limitations because of uncontrolled supercapacitors voltage. The voltage command has solved this issue. However the voltage command has also its limitations as in the case of a dynamic regime the demanded fuel cell current is superior than its maximal current and the supercapacitors discharges too much. This is why the motor power needs will be controlled due to avoid the supercapacitors voltage to reach the 15 V by giving less power until the fuel cell has charged the supercapacitors to its optimal level.

6 Components ordering (A2010)

6.1 Fuel cell

The FC⁴ has been ordered by Mr. Blunier. Is the H-300 fuel cell model from Horizon enterprise. Its power is 300 W and the operating range is between 36 and 69 V and between 0 and 8 A. The most recent manual in a digital format has been obtained during this semester (A2011).

This FC is slightly different than the previous used FC. This one has its fans in a side and not in the top, that allows to place some components upon the fuel cell, and the fans works in extraction and not in impulsion.



Figure 11: H-300 Fuel cell

The FC is delivered with its controller. The controller it manage the whole FC, so for this project the FC is just a voltage source with a quite high constant time.

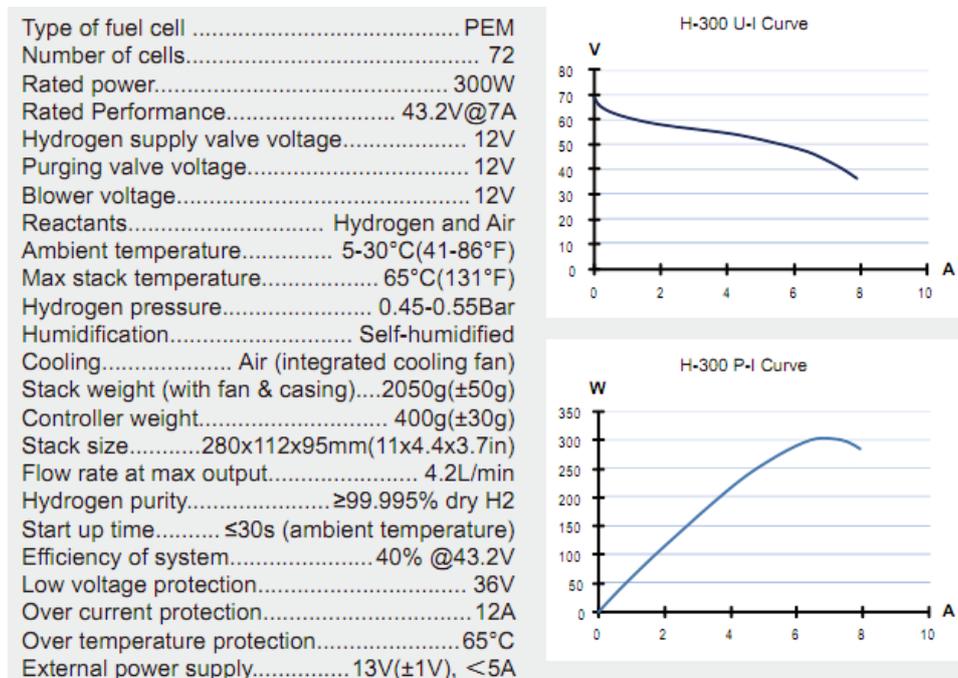


Figure 12: H-300 fuel cell technical specification and performance characteristics

⁴ FC: Fuel cell

6.2 Hydrogen supply

The FC must work in a narrow range of pressure of hydrogen. The hydrogen tank has a high pressure, too excessively high for the FC.

A pressure regulation valve is needed to reduce the tank pressure to a suitable pressure for the FC. In order to know and modify the input FC pressure a manometer have to be placed. The requirements are shown in the next table:

Component	Role	Demands
Hydrogen tank « Ovonic® Solid Hydrogen Storage Canister Model 7G250B-NPT / 7G555B-NPT »	Provide energy by delivering hydrogen	Refilling pressure: between 10 and 17 bars.
Pressure regulation valve	Pressure reduction	Has to bear up to 17 bar in input and has to reduce that pressure between 0,45 and 0,55 bar.
Manometer	Allow a precise pressure adjustment	Must read pressures between 0 and 1 bar.
Piping and joints	Transport the hydrogen from the tank to the FC. Ensure the purge of the FC.	Proper hydrogen transport by the car chassis.
Fuel Cell H300 Horizon Fuel Cell	Electricity production	Operate with an hydrogen pressure between 0,45 and 0,55 bar

The chosen solution is a pressure regulation valve and two manometers (input pressure and output pressure) from Heliocentris and the joints from Swagelok.

6.3 Supercapacitors

The Maxwell Technologies BPAK0058 E015 B01 supercapacitors are used in the car. Each SC has a capacitance of 58 F and a rated voltage of 15 V. They are connected in series, so the equivalent SC has a capacitance of 29 F and 30 V of rated voltage.

When operating the SC they are discharged up to half of their initial voltage, so the stored energy is :

$$E = \frac{1}{2}CU^2 = \frac{1}{2} \times 29 \times (30^2 - 15^2) = 9787,5J \quad (eq. 14)$$

The SC can bear up to 80 A during one second, so when they are fully charged (30 V) the maximum power is :

$$P_{max} = UI = 30 \times 80 = 2,4 \text{ kW} \quad (\text{eq. 15})$$

In continuous operation the SC can handle 20 A, so at 30 V the power is :

$$P_{cont} = UI = 30 \times 20 = 600 \text{ W} \quad (\text{eq. 16})$$



Figure 13: BPAK0058 E015 B01 Supercapacitor

6.4 Motor and controller

The ordered motor is a brushless motor and is usually used in aeromodelling. Its advantages are its reduced volume, its lightness and a wide range of operating voltages. The motor controller adapts the DC bus voltage and is programmable with a programming card included in the pack.

Fortunately it bears the required transient states and especially can work with a wide range of tension, from 11,1 V à 37 V.

Maximum power = 30 * 55 = 1.650 W



Figure 14: EPower E4130 300 brushless motor

CARACTERISTIQUES TECHNIQUES EP 4130 300		APPLICATIONS					
			Masse	Lipo	I Max	ESC	HELICE
Kv	305	TRAINER	5600g	8S	55A (60s)	EP 100HV	15x10
Nombre de Lipos	6-8						
Rendement Max.	88%						
Courant au Rd Max.	18-40A	ACRO	4600g	8S	55A (60s)	EP 100HV	15x12
Courant Max. (60s)	55A						
Courant à vide	1.0A	3D	3500g	6S	55A (60S)	EP 100A	18x10
Resistance Interne	79mOhm	3D	4000g	8S	55A (60s)	EP 100HV	18x8
Dimensions (Dia. x L)	49.8x65.5mm						
Axe	6mm	PLANEUR	6000g	6S	55A (60s)	EP 100A	18x12
Masse	385g						

Figure 15: EPower E4130 300 brushless motor technical specification



Figure 16: Epower ESC 100A HV brushless motor controller

6.5 Inductance

The inductance placed in the buck output must satisfy the next requirements:

- Maximum rippling current = 1 A ;
- Maximum switching frequency = 40 kHz ;
- Voltage = 30V.

$$\Delta i = \frac{U}{4.Ls.F} \Leftrightarrow Ls = \frac{U}{4.\Delta i.F} = 187,5 \mu H \quad (eq. 17)$$

The chosen inductance has a ferrite nucleus of 0,2 mH that allows to work with currents up to 10 A.



Figure 17 - 0,2 mH inductance

6.6 Components table

Material	Supplier	Characteristics
Hydrogen tank Model 7G250B-NPT / 7G555B-NPT	Already in the laboratory OVONIC www.energyconversiondevices.com Heliocentris Energiesysteme GmbH www.heliocentris.com	Refilling pressure between 10 and 17 bars
Pressure regulator with 2 fitted in manometers (input and output pressure)	Via : Systèmes Didactiques http://www.systemes- didactiques.fr/ 04 56 42 80 70 or direct contact : Sébastien BLANC sebastien.blanc@systemes- didactiques.fr 04 56 42 80 04 Swagelok Lyon : www.swagelok.com.fr	Input pressure between 0 and 21 bars Output pressure between 0 and 1 bars
Pipes and joints	Commercial : Olivier CHEVÉ 04 72 37 05 70 06 16 29 85 11 Fuel Cell Horizon Via :	Various joints
Fuel cell and its controller	N-GHY Enterprise: www.n- ghy.com Contact Robert RICAU : robert.ricau@n-ghy.com 06 87 74 41 93	Model H300 : 300 W Operating range: between 36 and 69 V Maximum supplied current: 8 A
Buck	Made by Mr. Larioumlil.	Decrease voltage Measures Each SC:
2 Supercapacitors BPAK0058 E015 B01	Maxwell Technologies http://www.maxwell.com/	58 F capacitance Operating range between 15 and 30 V
Inductance	Farnell	Value 0,2 mH

	http://fr.farnell.com/	Maximum rippling current 1 A Maximum switching frequency 40 kHz Voltage 30 V.
Epower ESC 100A HV Motor controller	GERB AIR http://www.gerb-air.fr/	Max 100 A
EPower E4130 300 motor	http://www.epproduct.com/webshop/contents/en-uk/d7_01.html 03 90 57 21 33	1.650 W Brushless DC
Gears	Fitted in the chassis	1/5 ratio
Support pieces	Made in the EE laboratory and the IMAP department	U for the FC: steel Motor support : aluminium.
Chassis	HOBBY CENTER ANGLET 05 59 03 35 88 http://www.hobbycenter.fr/	Porsche 911 GT3 RS 1/5 scale

7 Command tests and optimising (P2011)

7.1 Power supply board

The power supply board has been created by Mr. Larioumlil. It is placed on the back part of the vehicle near the motor. The board allows to connect the control board, the buck and the FC controller to the Lithium-Polymer battery at 12,6 V. The servos are powered by the motor controller.

1. Battery charger plug
2. 12,6 V plugs for the control board, buck and FC controller
3. Battery plug
4. Switch
5. I position: Car on
6. O position: Car off. Also for battery charging

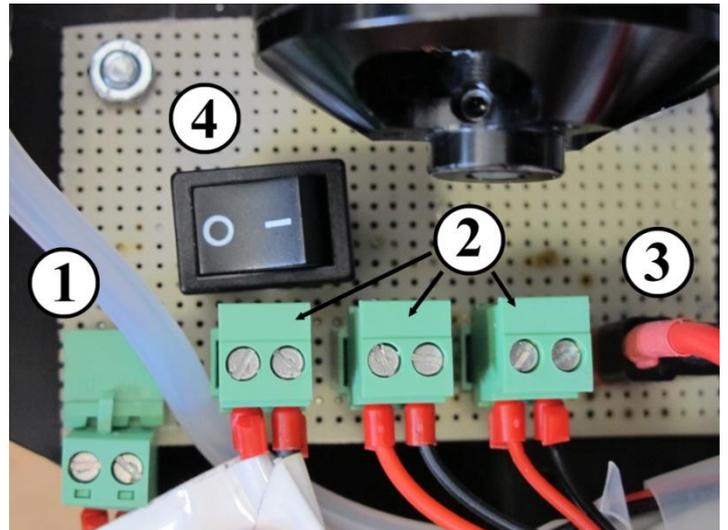


Figure 18: Power supply board

7.2 Fuel cell linking

During that semester the hydrogen linking was made. With the new linking no hydrogen leaks have been detected until now.



Figure 19: Manometers and hydrogen tank

7.3 Simulink®

To adjust the fuel cell current the alpha buck calculation is needed to send it to the buck and charge the SC according to its voltage. To do that first a current regulation is done and after that a voltage regulation will be done to get the desired current value.

Current regulation

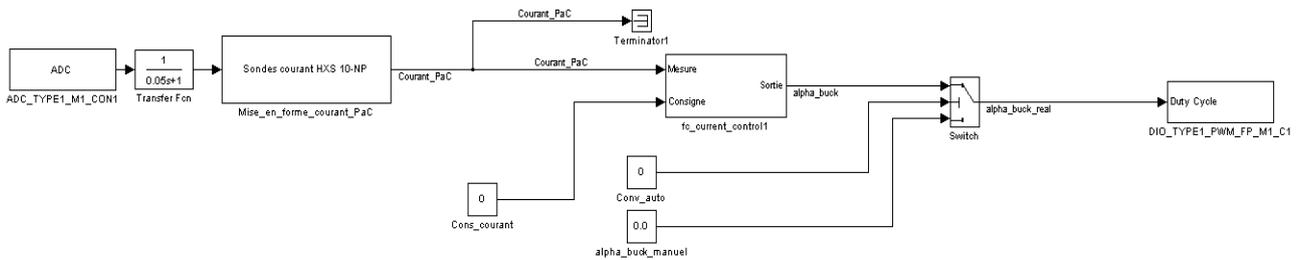


Figure 20: Simulink® current regulation

In this diagram the "Mise_en_forme_courant_PaC" (fuel cell current adjustment) block must be noticed because adjust the received values from the input to our control system.

The FC current goes to the "fc_current_control" that allows to provide the "alpha_buck_real" that will command the buck. This block is just a PI regulator with anti windup.

The switch allows the ControlDesk user to change the alpha value manually or automatically, but that variation is done manually must be done watching not to charge the SC over 30 V.

Voltage regulation

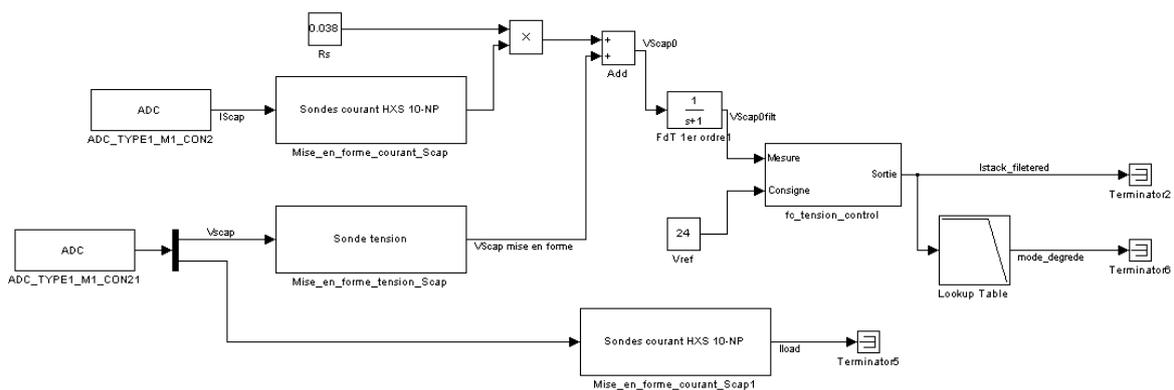


Figure 21: Simulink® voltage command

In this diagram the adjustment blocks are also present to adapt the buck sent signals to the control board received signals.

The SC voltage enters in the "fc_tension_control" that provides "Istack_filtered" which will be the reference current for the current regulation. The reference voltage "Vref" is fixed at 24 V to stabilize the SC voltage (this value is lower than 30 V to avoid overcharging). This way the more discharged the SC are the faster they will charge.

7.4 Mechanical aspects

Brake

Because of precedent motor damaging a mechanical brake has been mounted to improve the car safety. The new brake works fine, because while turning on the car an erroneous signal has been sent to the motor and the brake which made the joint breaking.

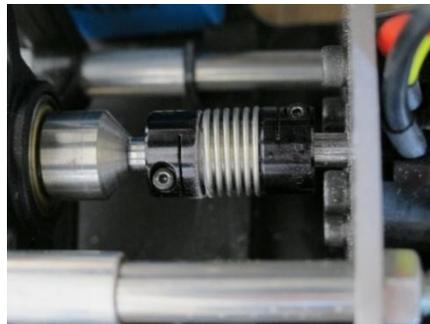


Figure 22: Broken joint before breaking

Fuel cell support

The fuel cell is sensitive to shocks and vibrations, so a soft fixing has been realised. To do it a support is made attaching it to the car chassis with 4 rubber silentblocs.

Three metallic plates have been done to keep the FC into the support and a foam rubber is placed between the top plate and the FC. Upon this plate some components can be placed (like the MicroAutoBox).

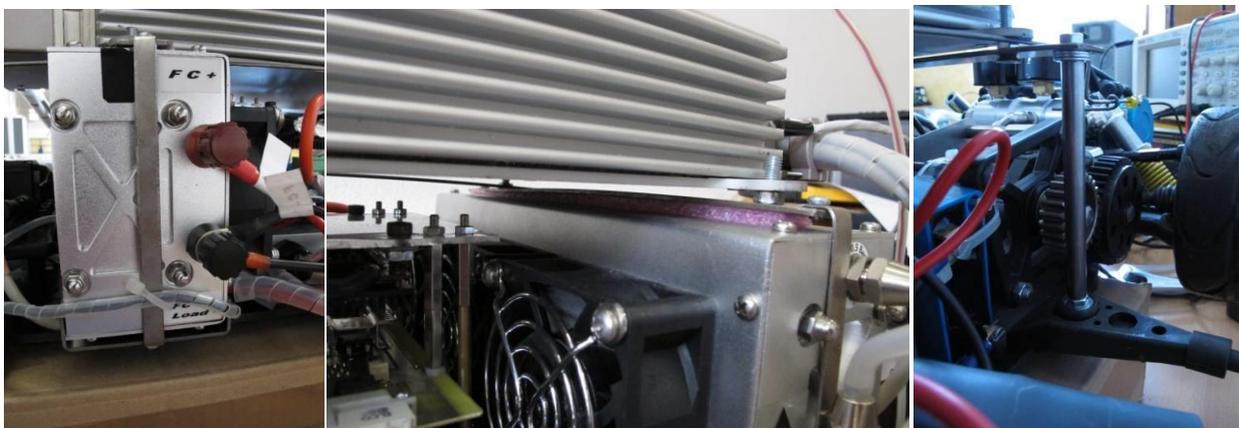


Figure 23: FC and MicroAutoBox support

7.5 Tests and simulations

Some tests and simulations have been done and here are the results.

Test 1

This test has been done with the SC, 3 batteries to replace the FC and an active load to replace the motor.

In the next figure the FC delivered current follows correctly the reference current.

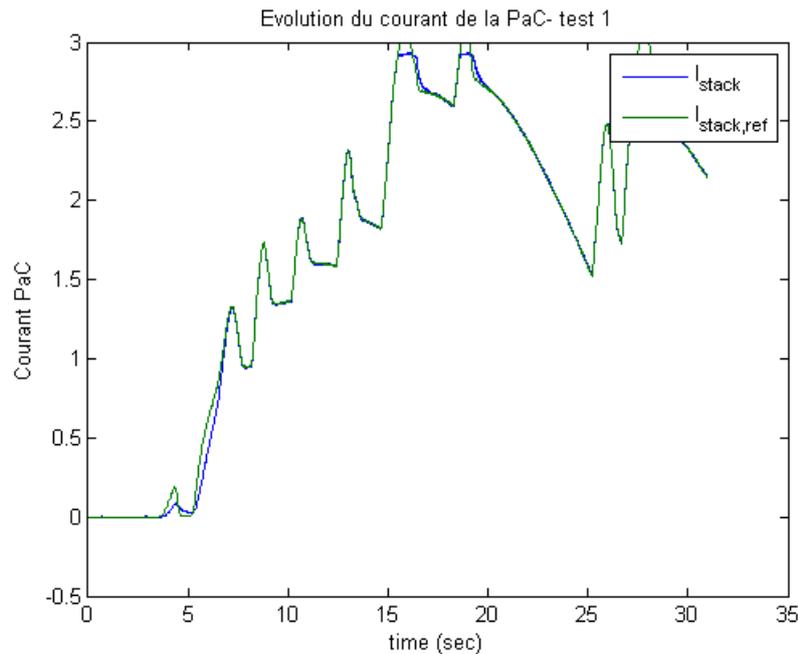


Figure 24: Fuel cell current evolution in time

Another test has been done and the SC charged until 25,5 V and each time the SC discharged the FC delivered a proportional current to charge the again. They charge until 25,5 V and not until 25 V due to filter's delays.

Test 2

Here the SC reaction has been tested with an important current delivering. Unfortunately the battery current was limited to 3 A while the FC deliver 7 A. With this restriction the SC spends many time to recharge.

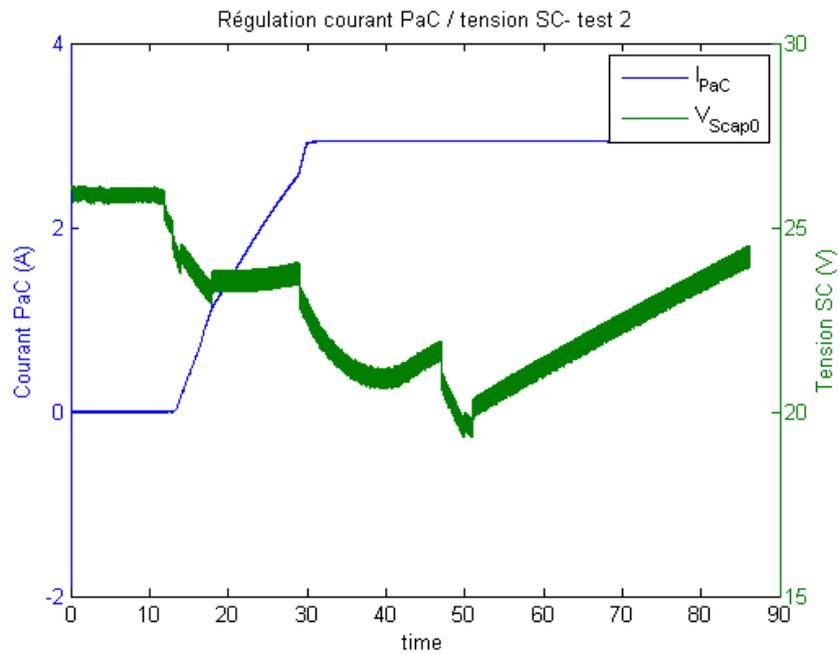


Figure 25: Current (blue) and voltage (green) evolution after discharge

Fuel cell with current drop

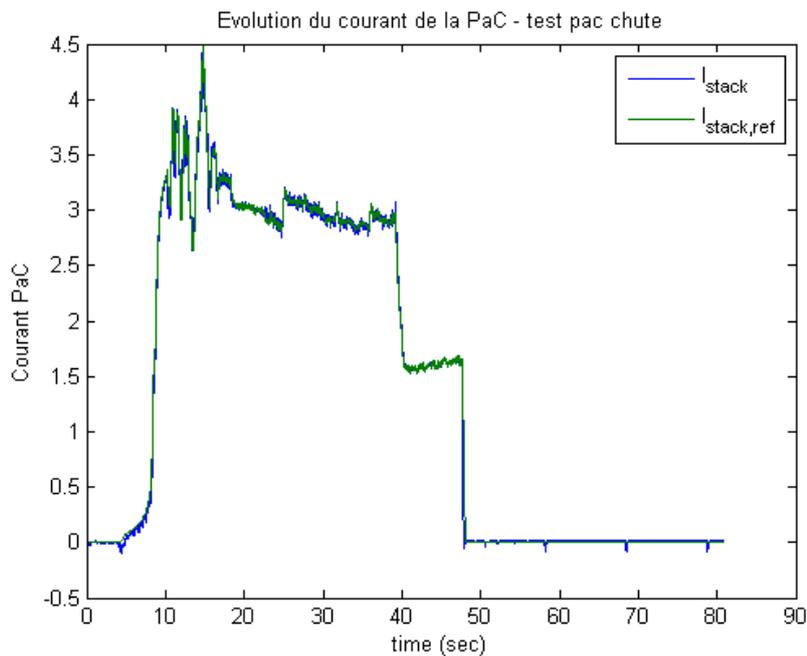


Figure 26: Fuel cell current

In this figure the fuel cell follows the reference signal correctly, but sometimes big variations happens. To understand that the next figure must be observed:

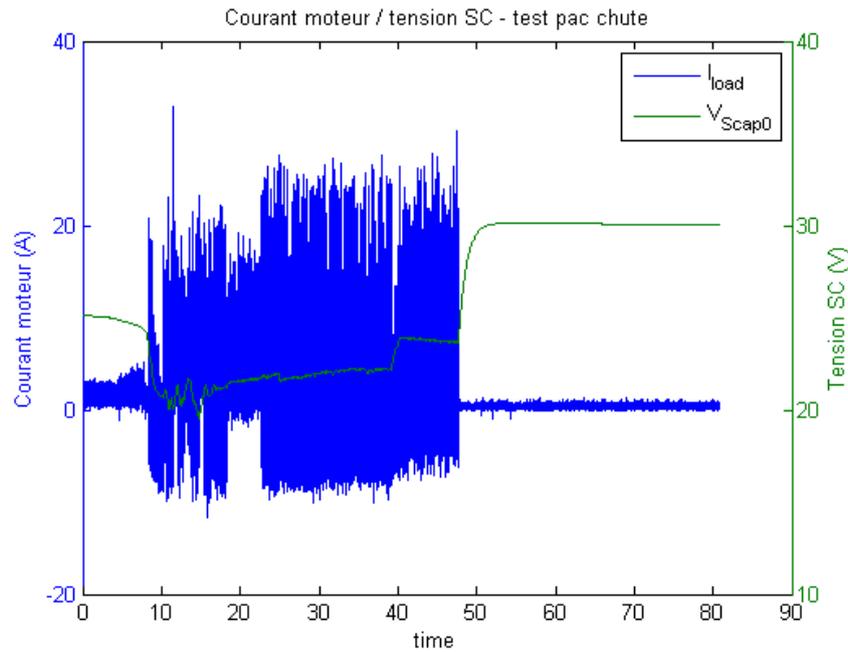


Figure 27: Motor current (blue) and SC voltage (green)

It can be clearly seen a SC voltage drop when the motor needs many power. When the fuel cell must supply more power some interference is observed. The SC voltage had to remain in the same place and increase progressively.

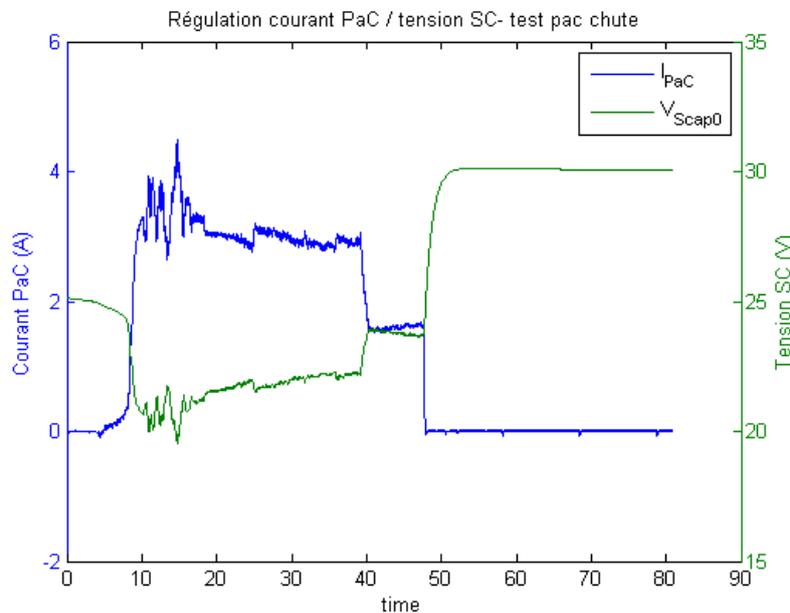


Figure 28: FC current (blue) and SC voltage (green)

In the last figure a rapid SC voltage rising is shown as well as a voltage distortion. When the system is turned off the SC get their real value. It was evident that a perturbation happens when an important current is delivered by the FC.

Power supply without drop

To reduce that problem the FC has been replaced by a power supply. The programmed control works perfectly.

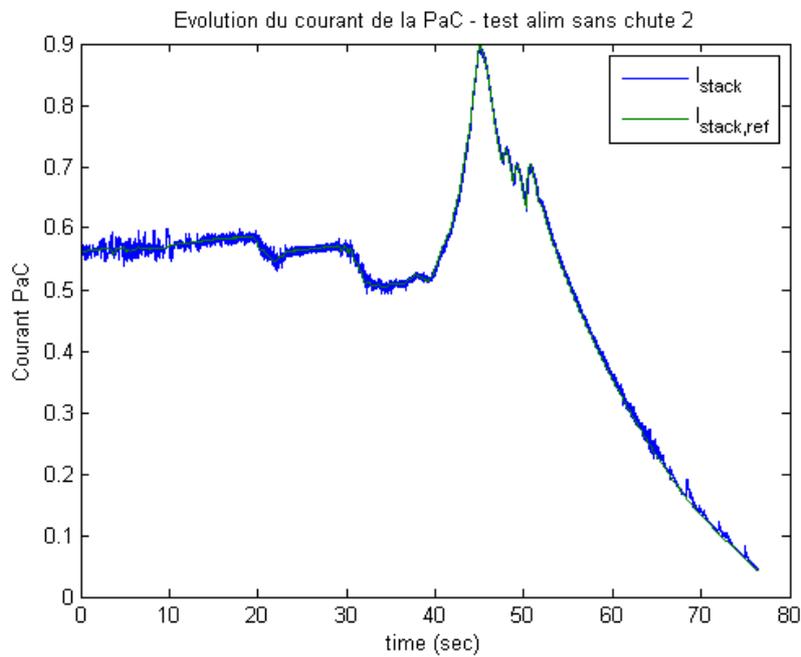


Figure 29: FC current

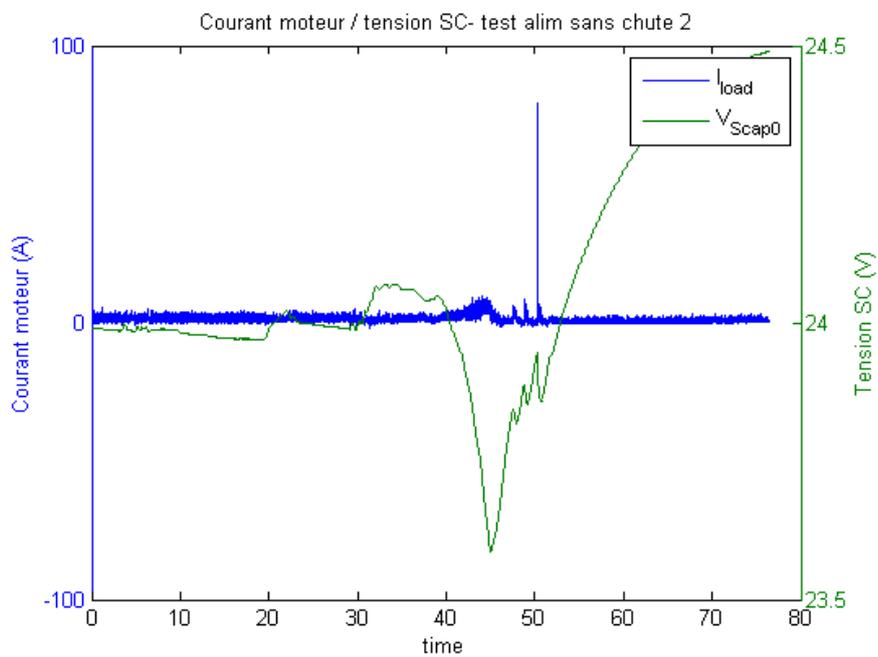


Figure 30: Motor current (blue) and SC voltage (green)

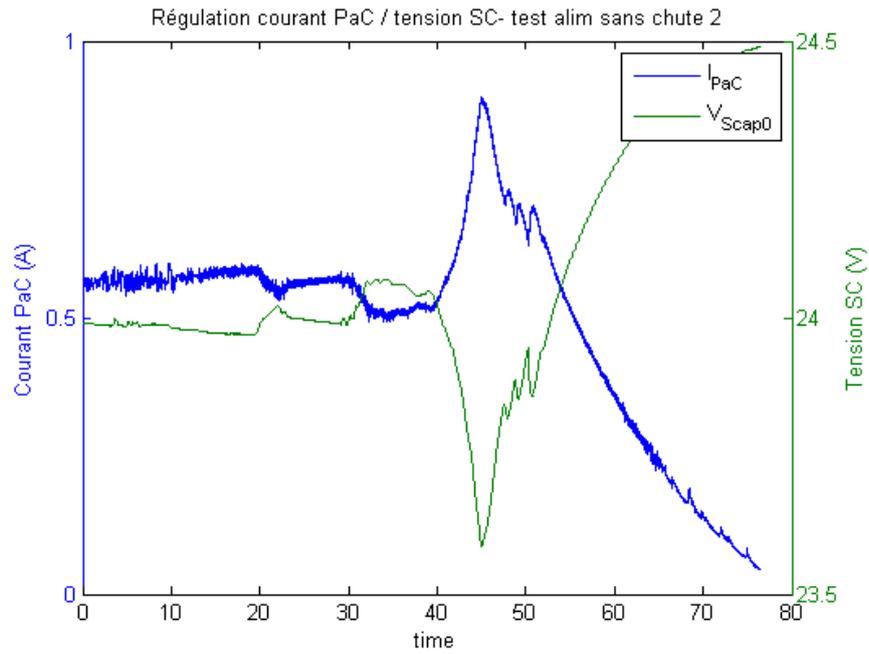


Figure 31: FC current (blue) and SC voltage (green)

Alimentation with resistance and drop

In this test the motor has been replaced by a resistance. The same perturbations happened, so the perturbations source is the FC.

Work done (A2011)

In the second part of this report all the work done during this semester (A2011) is explained.

8 Goal

During this semester several goals have been established. The nature of these goals is quite different and that makes those goals complicated to achieve but also interesting. Here are all the goals that must be accomplished:

- Improve the control system. In this goal the board in charge of the car commandment and energy management must be replaced. Until now a MicroAutoBox module has been used, which is a huge module and big energy consumer, so a microcontroller has to be used instead.
- The previous used control laws are not good enough to manage the energy between the fuel cell and the supercapacitors, so these laws have to be improved. To do this a static modelling of the fuel cell has to be done in order to be able to use a fuzzy controller in a proper way.
- Electromagnetic interferences were determined previously as the source of some problems in the car, so they have to be found, try to reduce those interferences and protect the electromagnetic sensitive parts.
- The car had some mechanical problems, actually it hadn't a transmission joint and the brake didn't worked properly, so a solution must be found.
- The car components were not arranged in the best way, because they used a lot of volume. A better arrangement must be realised in order to reduce the used volume and also to reduce the electromagnetic interferences and other problems like excessive heating of some component.
- During the previous semester an energy car state was needed to know the available energy to drive the car.

9 Energy supplying system

Apparently, some mechanical and energy calculations made in the previous reports are not correct, maybe because the components were not the same, maybe because some values were not correctly estimated or both.

The car has a nominal power of 2.700 W. This power can't be maintained because the supercapacitors rapidly discharge and the can provide 80 A just for one second, so this power it lasts for few milliseconds. In continuous mode the supercapacitors can give 20 A, so the continuous nominal power is 900 W. This power isn't also maintained for a long time, because the supercapacitors also discharge but not as fast as when they provide 80 A, so this power will last for a longer time. The only power that can be maintained for a long time is the fuel cell power, 300 W, while hydrogen tank is full.

10 Mechanical performance

10.1 Transmission

The previous semester the motor transmission broke while testing the car. To buy a new one the motor characteristics must be known.

$$\text{Rotation speed} = V \cdot K_V = 30 \cdot 305 = 9.159 \text{ rpm} \quad (\text{eq. 18})$$

$$\text{Maximum torque} = 2 \text{ Nm (P2011)}$$

Misalignment >1 mm

These are the characteristics while accelerating, but the maximum torque occurs while braking and is not 2 Nm. The next calculation is made considering a 32 km/h speed, that the car doesn't skid and that a full brake is made in 1,11 seconds. The 32 km/h are calculated in chapter 3 and the 1,11 seconds brake has been determined empirically measuring the time used to stop completely running at maximum speed but without load, so this is the minimum time the motor needs to stop. This helps us to know the maximum torque value:

$$a = \frac{32-0 \text{ km/h}}{1,11 \text{ s}} * \frac{1 \text{ h}}{3,6 \text{ km}} = 8,008 \text{ m/s}^2 \quad (\text{eq. 19})$$

$$m = 16 \text{ kg}$$

$$R = 0,0612 \text{ m}$$

$$F = m \cdot a = 128,128 \text{ Nm} \quad (\text{eq. 20})$$

$$T = R \cdot F = 7,84 \text{ Nm} \quad (\text{eq. 21})$$

A joint piece has been searched and the Michaud Chailly's A5-29-06-06-2 has been bought because of its diameter, its maximum torque and its high rotation speed [7].

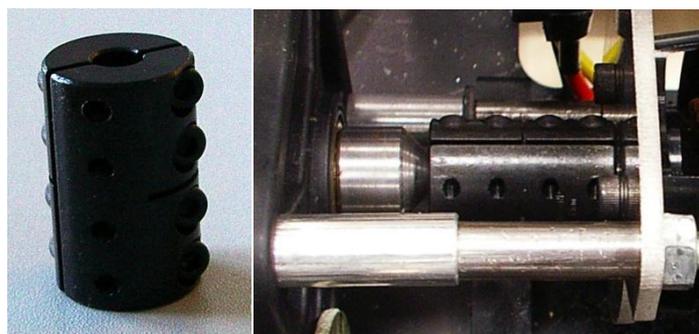


Figure 32: Joint alone on the left and joint placed in the motor shaft

The tolerated misalignment of the joint it was lower than the existing one. To solve that problem some adjustments has been made in the motor fixing piece. Some holes have made bigger, this way the axe can be aligned first and then the fixing piece is tighten in the best place to ensure a good axe alignment.

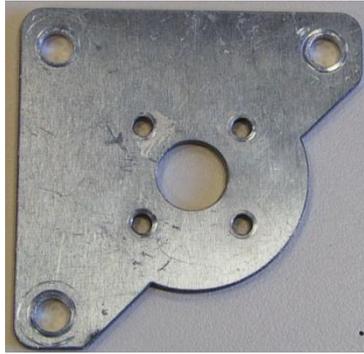


Figure 33: Fixing piece. The three middle size holes are bigger than before

To place the joint the best way, the screws that hold the fixing piece that holds the motor have to be shortened and verify that all of them have exactly the same length. If this doesn't happen the joint will suffer great bend stress because of angular misalignment and can break easily. If the screws are not shortened, the axes will be too far each other and the joint will suffer a great torsion stress and the holding surface will be insufficient, so the joint can slide easily. The problem is that the transmission axle is quite short, so the space between axes will be higher than expected and the joint will be well tightened to prevent from sliding.

10.2 Brake

The car has two different brakes: a built in motor brake and a disk brake. The built in motor brake is magnetic, because a magnetic field is applied to the rotor and the rotor stops. The disk brake is a spinning disk linked to a gear and to stop the disk a metal surface is forced against the disk by a rod.

Each brake alone is useless or not as useful enough because the car doesn't stop as fast as is needed. The magnetic brake can't bear big torques because if the brake is pushed rapidly the rotor wires mess up. The disk brake can be very effective, but is activated by a thin rod that is deformed when braking, so the disk brake can't exert all the torque it could do.

A combination of both brakes has been applied because of its easy realisation and effectiveness.

11 Fuel cell

The core of this project is without any doubt the hydrogen fuel cell. The hydrogen is an excellent energy carrier that provides energy in a clean and environmental friendly way by using it in a fuel cell. In this section the fuel cell operation and all the aspects considered in the project are explained.

11.1 Why a fuel cell?

A fuel cell is a device that provides electricity from hydrogen and oxygen and the main advantage is that this energy conversion only produces electricity and water. The oxygen can be easily obtained from the air but the hydrogen is more difficult to obtain. Anyway the usefulness of a fuel cell is obvious because of its zero pollutant production and its acceptable relation between weight, volume, stored energy and power of the whole system. This means that neither the weight nor the volume are too much and that the stored energy and given power are high enough to be useful. Moreover produces electricity, the more useful energy.

11.2 How does it work?

The fuel cell used in this project is a proton exchange membrane⁵ type. This means that there's a membrane called electrolyte that only allows the protons to go through it. When a hydrogen atom, made from one proton and one electron, meets with this membrane the hydrogen atom is divided because this way the proton goes through the membrane and the electron is conducted to the other side of the membrane over a wire producing electricity. This process can be clearly seen in the next picture:

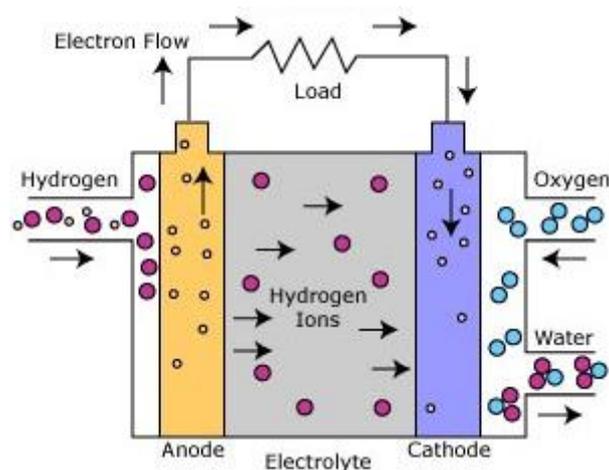


Figure 34: PEM operation

⁵ Also called PEM

This is the basic principle of the majority of fuel cells, but to make this happen in an efficient and effective way more components have to be used.

When the hydrogen enters into a fuel cell it goes through several layers. Each layer is explained in the same order than the hydrogen goes through the stack⁶: [8]

Bipolar plate

The first layer the hydrogen finds is the bipolar plate or also called flow fields plate. In the bipolar plate the hydrogen flow field and the oxidant flow field can be found in each side of the plate. Its purposes are:

- Keep away the hydrogen of one cell from the oxygen of another cell.
- Drive the hydrogen flow and the oxygen flow with their respective fields.
- Conduct the current from one cell to the next one.

When the fuel cell stack is made the bipolar plate is the barrier between two cells. Actually the bipolar plate is usually the only layer of the fuel cell that can be seen without disassembling the stack.



Figure 35: Horizon's fuel cell.

The FC of figure 35 is very similar to the one used in this project, because it is made by the same company, but is smaller. In this last figure the stack of different fuel cells can be distinguished. The external part of each fuel cell is the bipolar plate. The holes that can be seen are the oxidant fields of these bipolar plates.

Backing layer

After the bipolar plate the hydrogen goes through the backing layer. This layer is in charge of distributing uniformly the hydrogen to the anode and also conducts some electrons from the anode to the cathode. The backing layer is usually made with a conductor and porous material.

⁶ Stack: Several individual fuel cells placed in series or parallel circuits to increase the voltage and current output

Anode

After the backing layer the hydrogen meets the anode. In the anode the hydrogen is also dispersed equally and some materials called catalyst helps the hydrogen proton to split from the electron to produce electricity and let the proton go through the PEM. The catalyst is always next to the PEM, so sometimes is considered as another layer.

PEM

Continuing the hydrogen way the core of the fuel cell is found. In the proton exchange membrane the electrons are blocked and forced to take another way, generating electricity, while the hydrogen protons (also called hydrogen ions) goes through it. This is the only function of this layer, but is the more important one.

Cathode

When the protons leave the PEM encounter the cathode. In the cathode the split proton and electron find each other again but now they also find an oxygen atom from the air. When those three particles find each other water is produced with its reaction heat. To accelerate that reaction another catalyst is found in the cathode and like in the anode also facing the PEM.

Backing layer

Another backing layer is found after the cathode to ensure an effective diffusion of the water to permit its fast evacuation.

Bipolar plate

To finish with, the created water is driven to another bipolar plate. In this plate the water is collected to the exit pipe.

Here it is a very good representation of what is just explained:

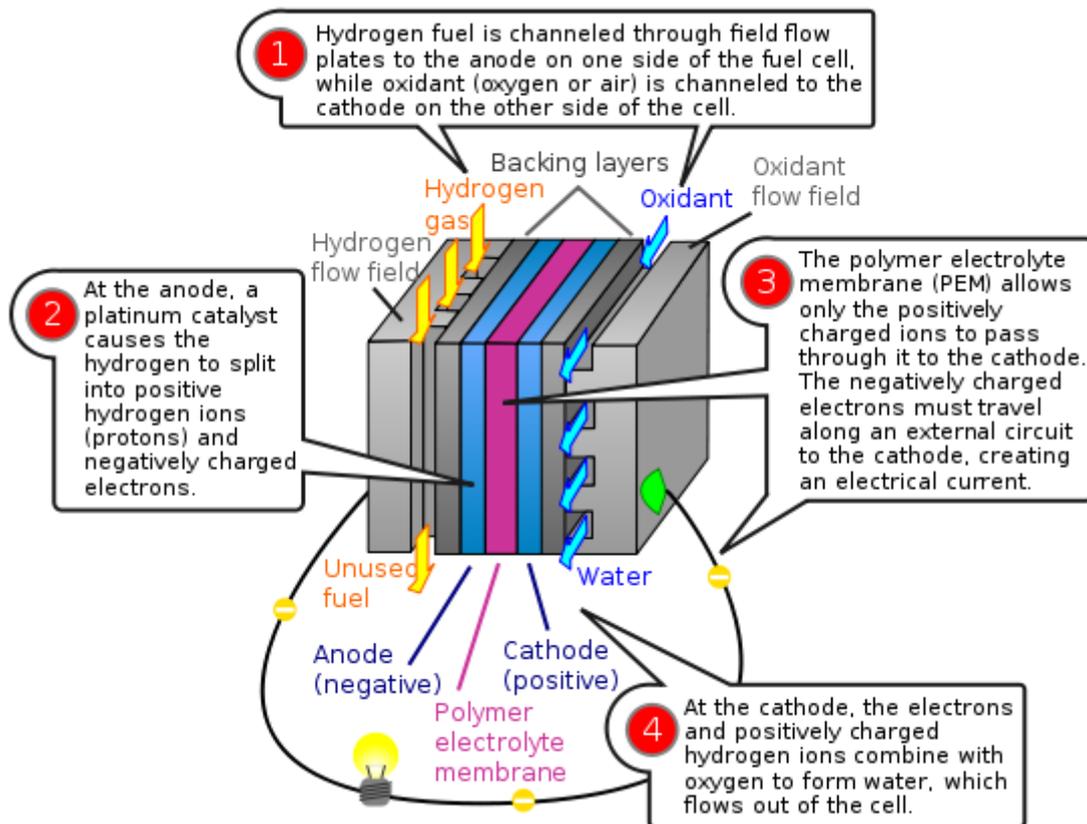


Figure 36: Substances flows, layers and processes in a PEMFC

11.3 Fuel cell heating

As previously explained when the hydrogen goes through the membrane and meets with oxygen atoms and electrons, water is created. This reaction is exothermic, so for each mole of water produced 241.82 kJ of heat will be generated [9]. The next graph is made by knowing the average consumption of hydrogen and the given heat power due to water formation for each electrical power need:

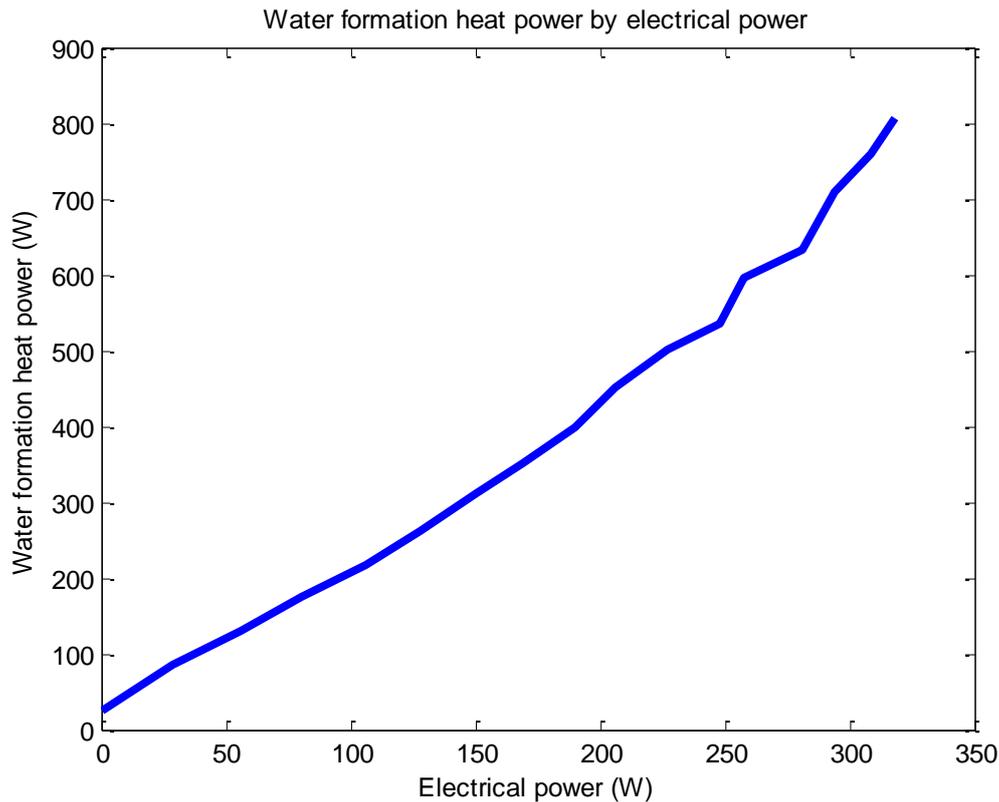


Figure 37: Heat power generated by the water formation in the fuel cell.

Can be easily deduced that figure 37 is highly related with efficiency. The higher the slope is the lower the efficiency is because less useful energy (electricity) is created.

The fuel cell has a temperature sensor that helps to control the fans rotation speed to decrease the temperature of the stack. So the more power needed more stack temperature, faster fan rotation speed, more energy used in cooling and less fuel cell efficiency. That fact make's it obvious that a high fuel cell power demand has to be avoided if the effectiveness of the energy conversion is wanted to be achieved.

The fuel cell controller checks the stack temperature, so if the stack temperature reaches the 65 °C the fuel cell turns off for fuel cell protection. Moreover if the ambient temperature is higher than 45 °C the fuel cell won't start also for fuel cell protection. The problem resides in find a good operating point that makes the fuel cell operate in a good efficiency point and doesn't heat too much to maintain as more as possible that efficiency.

A curious phenomenon occurs when the power supplied by the FC drops too fast and the FC is warm. When this happens the fans spin faster when theoretically they must spin slower because less water is produced due to the hydrogen lower consumption, but that doesn't happens. Instead of that the fans spin faster to avoid that the water contained in the air condensates on the FC layers surface. In the appendix there's a better explanation of that phenomenon [10].

Because of the explained reasons the demanded fuel cell power will be not too high and the demanded power decreasing won't be abrupt.

11.4 Other technological aspects

As always reality is more difficult, so a real fuel cell is more than some different layers together. In this project to work with a fuel cell hydrogen is needed. As said in chapter 6 a pressure regulation valve is used to adjust the tank pressure to the fuel cell operating pressure. Apart from that the polymeric membrane used in the fuel cell needs to be humidified.

Some fuel cells use a hydrogen humidifier before the fuel cell input, but this increases the number of used components and the weight of the hydrogen system. The used FC is self-humidified, so no humidifier is needed. Instead of an humidifier the FC has a SCU⁷. This unit makes a short circuit in the stack every 10 seconds during 100 ms. With this short circuit enough water is produced inside the FC to humidify the membrane and keep it in good conditions for good performance.

Due to this required membrane humidification rejuvenation is needed in case of long term storage. If the FC is not used for a long period of time, more than 4 weeks, and its performance goes down 50% of the power rated at 43,2 V, the FC must be rejuvenated. This is made by injecting distilled water in the hydrogen input port to fill the whole FC. This water is kept inside the FC for 2 minutes and then the water is purged. This process has been performed before doing the FC performance test to ensure a good fuel cell conditions.

⁷ SCU: Short Circuit Unit

12 Energy management

The main aim of this project is to achieve a good energy management between the fuel cell and the supercapacitors. They are connected in series which means that the FC supplies energy to the SC and the SC supplies energy to the motor.

In this chapter all the considered issues are explained and justified.

12.1 Car autonomy

Hydrogen autonomy

The current project uses a hydrogen tank that contains 75 sL of hydrogen. Fortunately the tank doesn't have 75 L of volume because the hydrogen is compressed at 17 bar. 75 sL of hydrogen means that the hydrogen inside the tank it takes 75 liters at 0 °C and at 101,3 kPa (1 atm). Actually the hydrogen is not only compressed, in fact is absorbed into a crystal structure of a metal hydride. That absorption makes this type of storage suitable for lots of usual conditions: between 1 and 10 bar and between 25°C and 120°C.

So in the studied case the autonomy of the car with its tank is 18 minutes at least.

H2 volume	75	sL	Given FC power	300	W
Molar volume	22,4	litter/mole	FC efficiency	40%	
Molar mass	$2,016 \cdot 10^{-3}$	kg/mole	FC used power	750	W
H2 mass	$6,75 \cdot 10^{-3}$	kg	Autonomy	1080	seconds
LHV	$120 \cdot 10^6$	MJ/kg		18	minutes
Stored energy	$81 \cdot 10^4$	J			

$$75 \text{ sl} \cdot \frac{1 \text{ mole}}{22,4 \text{ sl}} \cdot \frac{2,016 \cdot 10^{-3} \text{ kg}}{1 \text{ mole}} \cdot \frac{120 \cdot 10^6 \text{ J}}{1 \text{ kg}} \cdot \frac{1 \text{ s}}{750 \text{ J}} \cdot \frac{1 \text{ min}}{60 \text{ s}} = 18 \text{ min} \quad (\text{eq. 22})$$

And why the autonomy is just 18 minutes? Because of hydrogen's low energy density, around 0,01005 MJ/L while gasoline's is 34,2 MJ/L. On the other hand hydrogen has a high specific energy (LHV⁸), around 120 MJ/kg while gasoline has 44,4 MJ/kg. That difference can be explained by the low hydrogen density: 0,08376 kg/m³. Once again one of the greatest problems of hydrogen is encountered, the low density of hydrogen.

⁸ LHV (Low Heating Value): Energy given by the combustion of 1 kg of that substance considering that the water produced is in vapour state.



Figure 38: 75 sL metal hydride hydrogen tank

Supercapacitors autonomy

Supercapacitors autonomy is more difficult to know. When the SC discharge its voltage decreases but its current doesn't, so SC supplied power is voltage dependant and decreasing. Actually when the SC discharge the current can increase, decrease or maintain its value, that depends on the load type and load demands.

The SC maximum power, 2.400 W, is higher than motor's maximum power, 1.650 W, but fortunately SC can only supply 2.400 W for one second. In continuous mode SC can supply up to 600 W (at 30 V) and that power decreases while operating until 300 W are reached (at 15 V).

To make an understanding comparison of its autonomy the same demanded power by the FC is considered in this case. Knowing that the useful stored energy in SC at 30 V is 9.788 J and that the demanded power is 300 W the SC autonomy is:

$$\text{Useful stored energy: } \frac{1}{2} \cdot C \cdot (V_f^2 - V_o^2) = \frac{1}{2} \cdot 29 \cdot (30^2 - 15^2) = 9.788 \text{ J} \quad (\text{eq. 23})$$

$$\text{Autonomy operating at 300 W: } 9.788 \text{ J} \cdot \frac{1 \text{ s}}{300 \text{ J}} = 32,63 \text{ s}$$

It is clearly demonstrated that the FC is the main energy carrier (810.000 J) and the SC are the main power suppliers (600 W).

Driving cycle

Apparently the overall autonomy is excessively low, about 20 minutes, but that's not true. What is previously said is the minimum autonomy if all the available power is supplied, but that won't happen when the car will be driven. To make an accurate estimate of the autonomy a driving cycle is needed to know all the power and energy needed.

The current European driving cycle has been searched but hasn't been found for free [11]. The urban driving cycle used in the report A2009 has been used. This cycle doesn't match with the cycle used by a remote control car, but if the urban cycle is used a comparison to a common car (small family car) can be made.

In the driving cycle the maximum speed is 50 km/h. The car of this project can't reach this speed as previously explained, so an adjustment of the cycle speed

will be done. The maximum speed will be the steady state speed of the car and all the speeds will be reduced proportionally.

$$\text{speed proportion} = \frac{\text{steady state car speed}}{\text{maximum cycle speed}} = \frac{32 \text{ km/h}}{50 \text{ km/h}} = 0,64 \quad (\text{eq. 24})$$

The speed values of the cycle will be multiplied by 0,64 to make the adjustment. A table with the time value and the speeds of the cycle are attached in the appendix.

With the driving cycle the energy needed to make an urban travel can be found and check if it's possible. With the equation 12 in the section 3.2 of this report the energy used to accomplish the cycle is 22,5 kJ approximately, very low considering the 810 kJ stored in the hydrogen tank. To find the 22,5 kJ is considered that the power used for each speed value of the cycle lasts for one second.

Overall autonomy

If the speed cycle is assumed as representative enough of the average speed cycle described by the car, then it can be said that the average autonomy is about 2,47 h. Unfortunately this cycle is not representative enough of the real speed cycle of this car, so its autonomy will be lower, but if the cycle test is done the autonomy will be approximately 2,47 h.

12.2 Fuel cell efficiency

The optimal operation range of the FC must be found empirically. By knowing that range and SC requirements a proper energy management can be done to be more efficient.

A hydrogen meter has been connected between hydrogen source and FC, an active load has been connected to the FC terminals. Some multimeters have been also connected to know the FC given power and the FC controller demanded power:

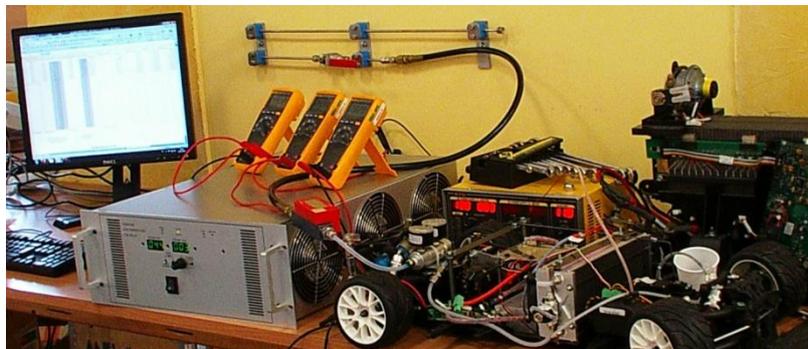


Figure 39: Fuel cell static modelling

This assembly has given very important and useful information about the FC. In the appendix there's the resulting table. These are the results obtained:

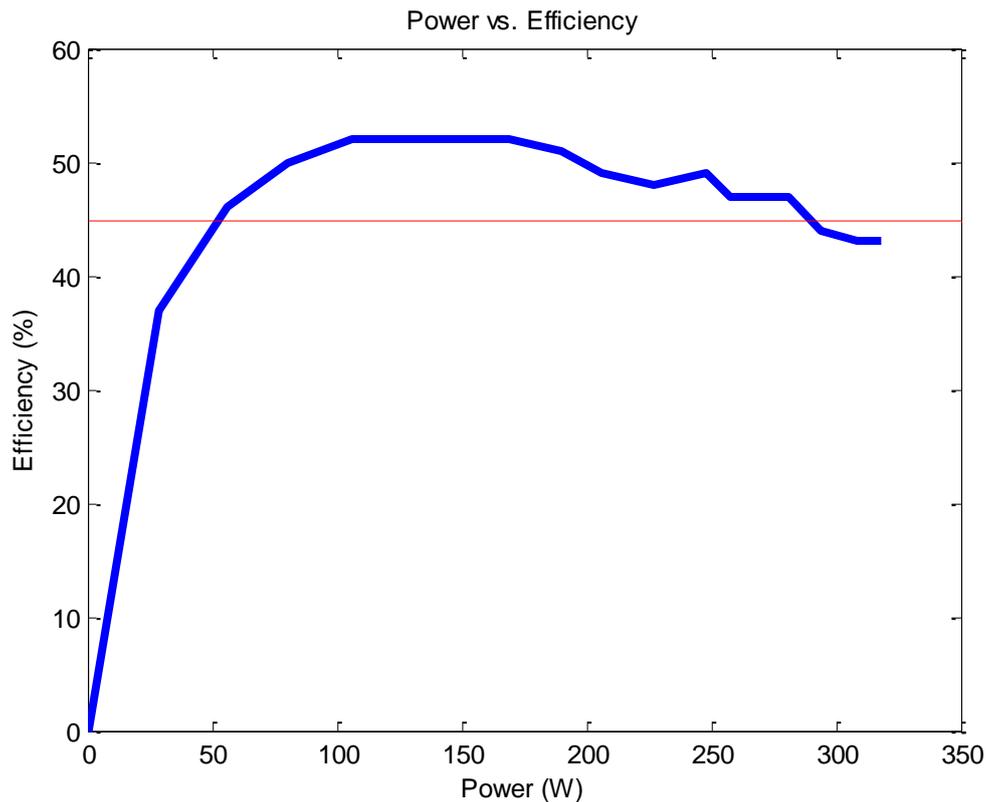


Figure 40: Fuel cell efficiency with its mean efficiency (44,8%)

With this graph is decided to operate the fuel cell between 105 W (2 A) and 169 W (3,5 A) as much as possible because this is the region with the best efficiency. If a lot of power is needed, the fuel cell can provide up to 278 W (6,54 A) with a quite good efficiency, but fast and frequent power changes will be avoided.

12.3 Energy management guideline

The FC delivered power can't stop suddenly because water can be condensed in it. If water condenses in the FC it can be irreparably damaged. Knowing this and knowing also the more efficient operating points the next points will be considered while doing the energy management program:

- Keep the FC supplied energy as stable as possible.
- When decreasing the FC power supply, do it slowly.
- The best FC operating region is between 105 W and 169 W.
- If a lot of power is needed the maximum power given will be 278 W ($\eta=44\%$).
- When operating the car the SC have to work between 15 V and 30 V.

13 Control system

To get the desired behaviour of the car a control system is needed. All the electric connections and considered signals are attached in the appendix.

13.1 Remote control signal

The control system also controls the remote control signal to command the ESC⁹ as desired. Not controlling this signal was considered to make the control system easier, but by controlling the command signal a most efficient energy management can be obtained and also more safety will be obtained.

By default the ESC is configured in "Brake off" mode, so when the throttle stick was in the lowest position the motor stopped but didn't brake. If the "Brake on" mode is set, when the throttle stick is in the lowest position the motor behaves like a brake and the car stops quickly. The "Brake on" mode is been set to improve the car safety.

To improve the car safety at its maximum level the throttle signal has been processed. Until now when the throttle stick was in the still position the car accelerated. That happens because the remote controller is used to drive an RC car and also because the motor and the motor controlled used in the car are meant to be used in RC planes as previously said. The car can be perfectly driven without a signal processing, but when doing the processing the safety and the car driving will be improved.

13.2 Control laws improvement

The aim of this project is mainly an efficient energy management, so the control laws will always follow this objective.

In the previous reports the control laws were in a conventional way: modelling the components with their transfer function, entering the desired value of some variable and modifying the output according to the obtained error of the desired value. This way the supercapacitors charging current can be controlled precisely but its voltage cannot be easily controlled at the same time.

To ameliorate the control laws several aspects must be considered. From now on these aspects will be explained as well as the made decisions.

Rotation speed

The motor rotation speed is voltage dependant, so if the voltage decreases because the supercapacitors are discharged and the stored hydrogen is gone, the motor will slow down by itself. This fact must be considered because it makes the

⁹ Electronic Speed Controller

car control more difficult for the driver, because if the voltage is so changeable the car can reach different speeds for the same throttle stick position.

To guarantee the SC durability the motor controller has been programmed to stop the car if the voltage is lower than 15,5 V. This has been made with the motor controller programmer introducing a cutoff voltage of 3,1 V for cell and 5 cells. Before stopping the car the speed will be reduced by the control program and a red LED will be turned on, so the car stop is justified.

Fuzzy controller

As lately explained the control laws had some problems in controlling the SC voltage. Due to its easy application and its effectiveness a fuzzy controller has been put instead. This decision was taken by Mr. Blunier during the summer of 2011.

The fuzzy logic allows us to provide a simple answer for processes which are difficult to model and are easy to understand [12]. It is very useful in this project because the number of inputs and outputs is not high, in fact there's just one input and one output in this project.

What is intended to control with a fuzzy controller is the SC voltage, so the current of the fuel cell will be controlled accordingly with the SC voltage: If the voltage is low the current will be high and vice versa.

Actually the same model used in the previous semesters have been used and reproduced in the best way in the new control board. The fuzzy controller has been also added. From the energy management guideline the rules for the fuzzy controller have been done. The approximate behaviour of the fuzzy controller will be the next one:

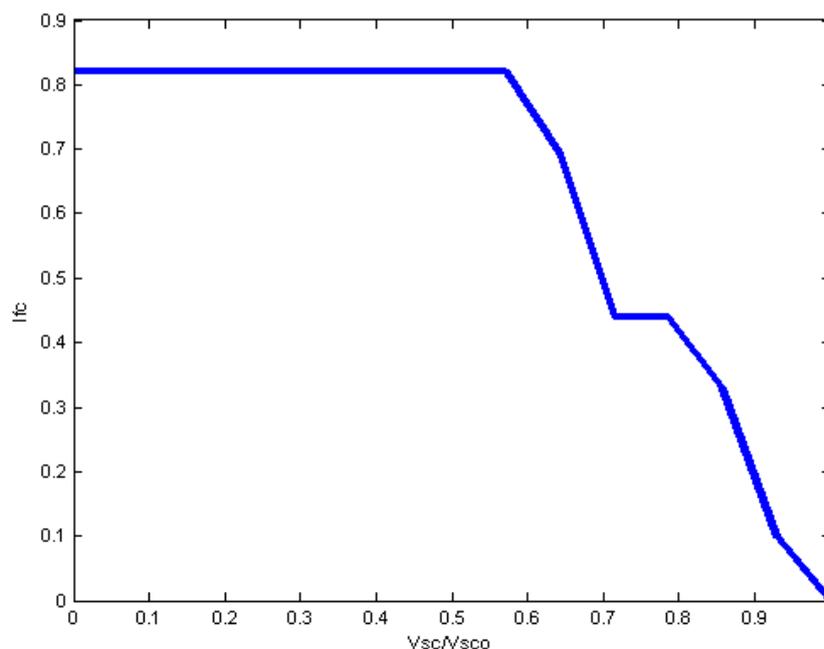


Figure 41: Fuzzy controller surface

As can be seen in the figure the controller will modify the fuel cell current according to the SC charge. The first horizontal line on the left corresponds to a 6,54 A current (278 W) and the second one corresponds to a 3,5 A current (169 W). Between 0,8 and 1 of the V_{sc}/V_{sco} a progressive decrease is done.

Error and boundaries

With the fuzzy controller alone the car can't be correctly controlled, so some boundaries in the variables values and an error handling have been implemented.

When the supercapacitors are almost charged, the FC current will be cut off when V_{sc}/V_{sco} reaches 0,95 (28,5 V). This boundary is established to avoid SC's overcharging. On the other hand, when the SC are discharged the car speed will decrease.

The error calculation allows checking if the measured fuel cell current is equal to the desired fuel cell current. If error is not zero the PWM signal is modified according to the error value.

13.3 Buck

Mr. Larioumlil has made a buck to adapt the FC voltage, between 36 and 69 V, to the SC voltage, between 15 and 30 V. This board has also voltage and current sensors which measures different voltages and currents values. Is the intermediary between the FC and the SC.

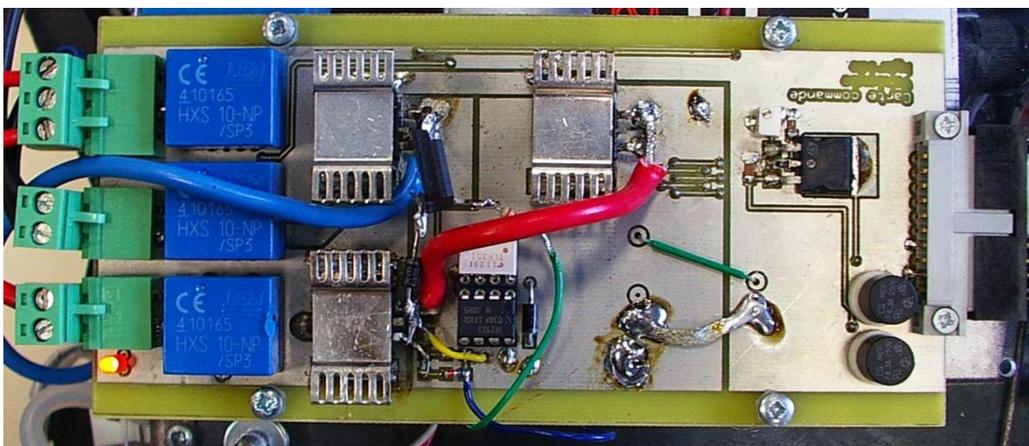


Figure 42: Buck

1. + motor controller
 2. Nothing. Previously:
- motor controller
 3. + SC
 4. Inductance
 5. Inductance
 6. + FC
 7. Nothing. Previously:
- FC
- Blue wire: Ground connection

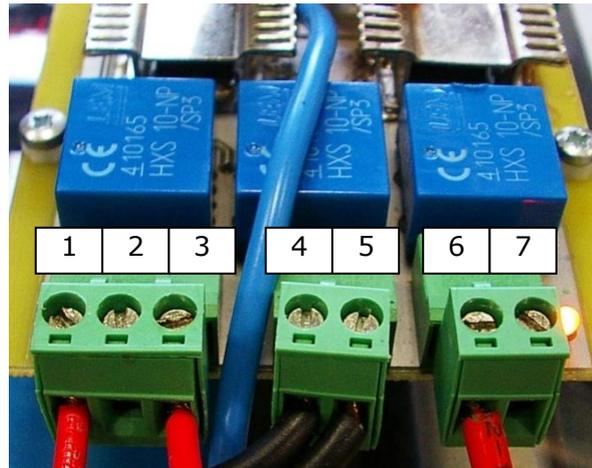


Figure 43: Power board side with its connections

This board has had a lot of problems while creating it. Finally it has been finished eight days before delivering this report. Mr. Larioumlil has tested and said it worked, but when adapting the buck for the car a lot of problems have been encountered.

This board works as follows: One side of the board is in charge of measuring voltages and currents of some components and the other side of the board is in charge of sending this measurements and receiving the PWM signal. The PWM signal sets the voltage of the SC, so the wider the duty cycle is the higher the SC voltage will be. A copy of the final buck scheme is attached in the appendix.

Plenty of modifications and tests have been done with the help of Mr. Larioumlil. At the beginning the buck didn't charged the SC fast enough because it didn't always react accordingly to the PWM duty cycle. After some modifications the charging process is fast enough.

The actual problem is electromagnetic incompatibility. When increasing the PWM signal width more current is delivered by the FC. When this current reach the 400 mA interferences are detected in the sent remote control signal, so the car doesn't reacts as desired because the signal is modified by the interferences. When increasing the current over 400 mA more interferences are detected and the received and sent signals get more distorted.

When the interferences modifies the RC signal means that the Arduino board is affected. Interferences also modify the received signals from the buck. That means that the same buck cause interferences to itself.

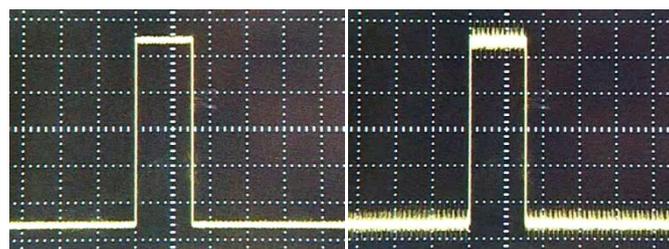


Figure 44: RC PWM signal. Left: Good; Right: Distorted

The measurement interferences are important but they are not as critical as signal distortion. When measuring if the value is not correct the error value is low and lasts for a short period of time, but when the RC signal is distorted the result lasts for longer time and besides the error value is big. This usually causes a fast and undesired response of the car by accelerating. That's why the car cannot be driven safely when the charging current is greater than 400 mA, because the car response will be unpredictable and the car crash can occur easily.

All these interferences make a complete validation impossible, because obtained values are not real and don't correspond to reality.

The day of delivering this report a final modification is done. With this modification everything changed and apparently works perfect. A complete validation of the board can't be realised because of no available time.

13.4 Control board

The latest used board in this project was MicroAutoBox, an embedded DSP board from dSPACE. This board is too big, too heavy and demands a lot of energy, so it had to be changed.

The control board must command the car thanks to fuzzy logic. Besides, the control board must show the energy car state to know what can be done by the car, because if the SC are discharged a complete acceleration is forbidden.

The control board must also be able to read the input PWM signal from the receiver and make some calculations from that information. To read the incoming PWM the microprocessor frequency must be much higher than PWM frequency and the PWM amplitude must be lower or equal to the allowable input pin voltage. Tests have been made and the PWM signal characteristics are the following ones:

- Amplitude= 3 V
- Frequency= 71,43 Hz (period = 14 ms)
- Pulse width= Acceleration dependant
 - Acceleration 0% (brake): 1,1 ms
 - Acceleration 50% (half throttle): 1,5 ms
 - Acceleration 100% (full throttle): 1,9 ms



Figure 45: RC PWM signal measurement

Note: The throttle signal can be higher. The test was made with the emitter trimmed in the lowest level to allow braking in the lowest throttle stick position, so wider pulses can be emitted and higher speeds can be reached.

The new chosen and bought board is Arduino Duemilanove [13]. Arduino Duemilanove board has more than the required amount of inputs and outputs and the clock speed is 16 MHz. The inputs, the clock frequency, the small size

and the easiness of PC connection and Simulink® program transfer and use makes this board a perfect one for the project [14].

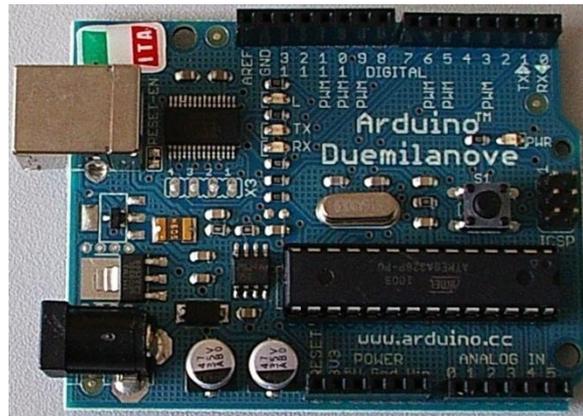


Figure 46: Arduino Duemilanove board

It also bears a connection up to 20 V power source thanks to its voltage regulator.

13.5 Arduino board

This part of the project has been done with the help of two UTBM students: Adietou Cisse and Régis Zajdi.

Lots of tests have been done with the Arduino Duemilanove's board. First of all was tested with its own software, available for free in its website, and after Simulink® was used. To use the Arduino board with Simulink® several days passed, two weeks approximately. Then model used in previous semesters was adapted to the Arduino board and a lots of tests happened. After all the tests done the impossibility of PWM signals generation was found.

With Simulink® the compiled programs can reach just a 1 kHz frequency. In this project a 20 kHz PWM have to be done to control the buck, so the Simulink® software can't be used. That forced the team to work with the Arduino IDE¹⁰. This IDE has the great advantage that gives a complete control of the board and is not difficult to use. The used programming language is similar to C++ but easier. The software has also all the tools needed to communicate with the board, from uploading the compiled programs to send and receive messages from the board via serial port. This last feature is a great help for debugging.

13.5.1 Functions

The final uploaded program has been divided in 5 different parts, which corresponds to 5 different tabs in the IDE project file, explained next:

¹⁰ IDE: Integrated Development Environment

Energy management

In the energy management tab all the control equations have been written as well as an error handling code.

First the currents and voltages values are read and adjusted from the microcontroller number range, from 0 to 1023, to the range of each variable. Second the voltage of the SC decides the value of the FC current. Third the buck duty cycle is calculated and modified if the error between the sent FC current and the measured FC current are too different.

A problem with the current values reading has been encountered. The buck signal for currents almost doesn't change. To measure the current variation the microcontroller has to be able to read variations of 1 mV, but it doesn't. This is why the current variables can't be read and this program cannot be verified completely.

This is the most important code in the program and is attached in the appendix. The commented parts of the code are those parts which couldn't be verified.

PWM

It processes the PWM signal from the remote control receiver and sends it to the motor controller. This can be done because the motor controller accepts different frequencies: the remote control receiver sends a 71,43 Hz signal and the control board sends a 61 Hz signal. This is because the board has 3 timers:

- Timer 0: 8 bit timer used by the board to do some functions as "micros()".
- Timer 1: 16 bit timer, the more flexible with lots of modes and frequencies.
- Timer 2: 8 bit timer.

The timer 1 is used for the buck command, because it is the only timer that can generate the desired frequency with the desired width. The other timers have only few frequencies available depending on the prescaler and the mode. Fortunately a 61 Hz signal can be done and the motor controller can be driven.

Timer 1 is controlled thanks to a library that calculates the needed parameters, but in the timer 2 the datasheet has been checked several times and their registers have been configured manually.

The Timer 1 output is easily determined by multiplying the duty cycle value by the maximum microcontroller's output value in order to adjust the voltage output for the buck.

For Timer 2 more calculations and verifications are needed. First of all the RC signal has to be measured. To measure the RC signal an interruption is needed. Every time that a voltage change is detected in pin 2 an interruption is executed. This interruption measures the time between the previous interruption and the actual interruption. By doing this two values are obtained: the width of the thin part of the signal and the width of the thick part of the signal.

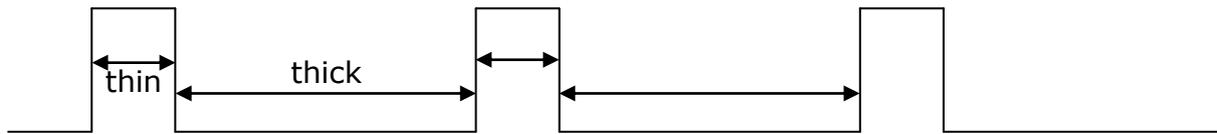


Figure 47: PWM signal with its pulses

When the program uses the measured PWM width this width can correspond to the thin pulse or the thick pulse of the signal. To make the program more simple more code is added to the interruption to return always the same part of the PWM signal, actually the thin pulse.

After measuring the RC signal this function adjusts the measured signal to the sent signal. If the SC voltage is lower than a specified value, if the throttle stick is pulled the car will move slower and the hydrogen depletion signal is turned on. If the SC voltage increase a little bit more than the recently specified value the car moves according to the throttle stick position and the hydrogen depletion signal is turned off.

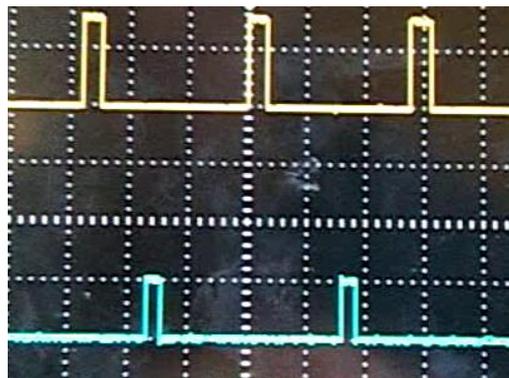


Figure 48: Read signal (yellow) and sent signal (blue)

LED

The LED tab has the code that makes the LEDs to turn on and turn off according to the SC's voltage (U_{bus}). Here it is the correspondence between the LED colour and the U_{bus} value:

- $0 \leq U_{bus} < 20$: Red
- $20 \leq U_{bus} < 25$: Yellow
- $25 \leq U_{bus} \leq 30$: Green

If the FC is running out of hydrogen all the LEDs are turned on. The signal which indicates if the hydrogen is finished or not is sent by the PWM function

Main

Like its name says in this tab the core of the program can be found. The two essential functions: `setup()` and `loop()`. In the `setup()` function the pin use is determined and the timers, serial and SD classes are initialised, and in the `loop()` function there's all the code that have to be executed repeatedly. The `loop()` function is repeated again and again while the `setup()` is executed once.

After the `loop()` function another function is written. Is called "`changeVariable()`" and allows the user to change the value of the desired variable with the keyboard. When the chosen variable is changed some code must be changed in the other functions.

SD

In the last tab a function that writes data into an SD card is written. This function writes the read and sent signals by the Arduino board to permit a later debugging of the program.

To realise this function another board has been bought. This new board can be easily connected with the Arduino Duemilanove board, has an square pads prototyping zone and has also an RTC¹¹ which gives the actual date and time if it's well configured.

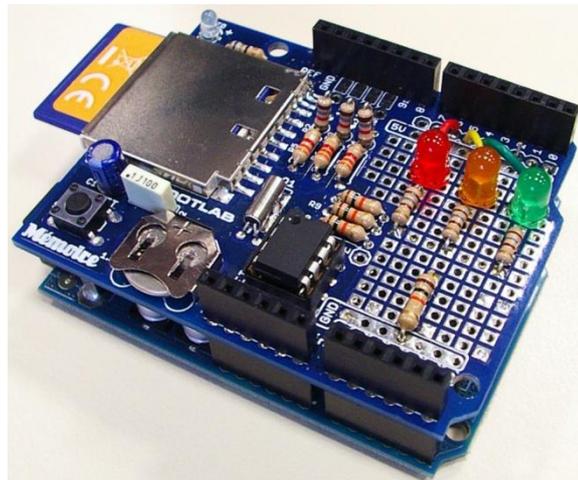


Figure 49: Memory and RTC clock board connected upon the Arduino board

In this board the LEDs have been welded as well as one resistance to decrease interferences. The RTC doesn't works always fine, so sometimes it has to be configured again in order to make the program works. In order to have an stable and safe program execution the RTC functions are not used, so the code is commented and not compiled.

The SD function slows down the program a lot. Without this function the program execution frequency is about 1,9 Hz, and with this program this frequency decreases up to 120 Hz. This makes the SD function quite useless unless a slow

¹¹ RTC: Real-Time Clock

response is not critical. Usually the SD function won't be compiled because a fast program response is needed for the car driving.

Comments

The first two tabs (energy management and PWM) are written by me, the next two tabs (LED and main) are written by all the team and the last tab (SD) is written mainly by Adietou and Régis. In the last tab some help is provided, but the most part of the code is written by them.

Many constant definitions have been made in order to adjust the read and sent signals to reality and to establish the needed boundaries for a good operation of the car.

In this report this issue is quite short and the length of the text doesn't represent the time spent in programming. All the considerations aforementioned have been written into a code by the team, so lots of trials and errors happened and lot of time have been spent thinking about how to write what it has to be done.

The whole program has to be modified when the electromagnetic interferences are solved. Due to the late finishing of the buck board all the problems couldn't be solved.

13.5.2 RC filter

To implement the previously explained idea of processing the throttle signal the PWM width of the remote control had to be read.

Before knowing how to measure PWM signals with interruptions another solution have been done. If the PWM wanted to be read by the board the "analogRead" command was used, but the values obtained were 0's and 1023's with a lower frequency than the real one. A PWM width has an average voltage associated, if the duty cycle is 50% and the highest voltage is 5 V the average voltage is $5\text{ V} * 0,5 = 2,5\text{ V}$. The initial idea was to calculate that average voltage with the board, but later on the idea of the RC filter came up because the board can read the variation of voltage.

The RC filter is an electronic circuit that filters a signal by blocking certain frequencies and passing others. The correct resistance and capacitors were chosen by trials and errors until the desired result was found. The capacitor was a 100 μF polarized one, while the resistance was 1 k Ω . The problem of the resistance was that the read values changed a lot, they are not stable when pulse width remains constant. If the resistance is bigger the acceleration is lower but more stable. Besides sometimes the capacitor remains charged and modifies the measures, so it might be discharged regularly.

Fortunately the PWM width is read using interruptions and none of these problems occurs.

13.5.3 Connections and displays

The Arduino board has several input and output pins, and almost every pin has a signal assigned. The board has also four useful LEDs with different meanings. In the next figure the pins assignment and LED meaning is shown. Note that the arrow determines if the pin is used as input, output or both:

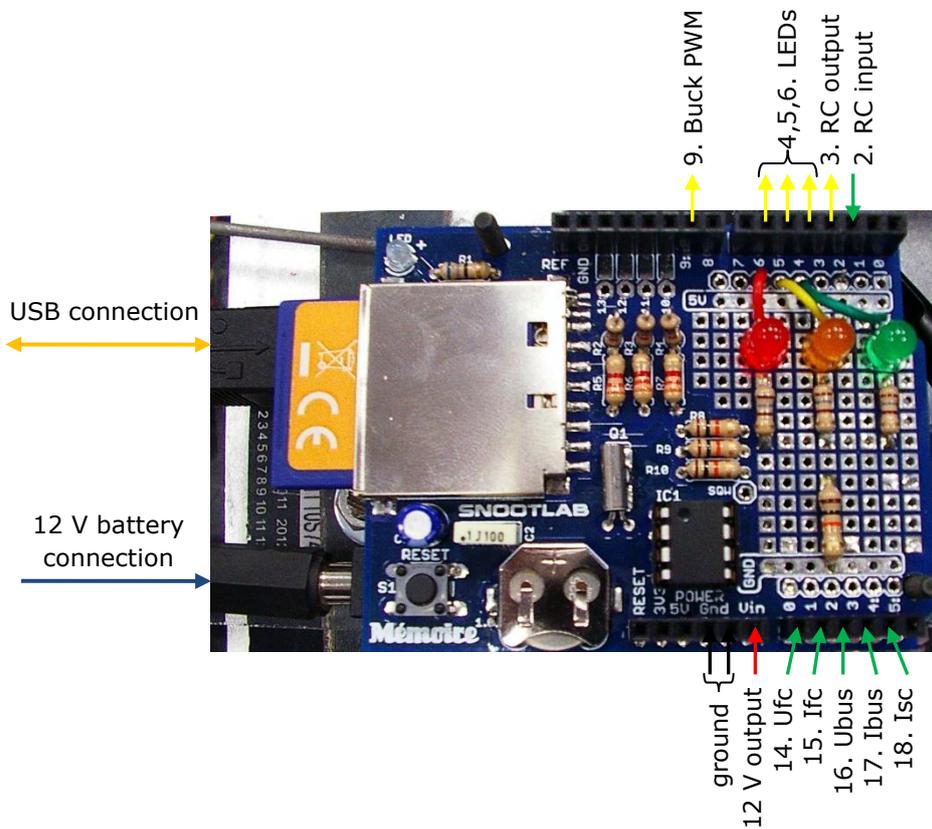


Figure 50: Arduino board with pin assignment, pin mode, LED meaning and other connections

14 Electromagnetic interferences

Electromagnetic fields are anywhere and they usually don't cause any problem, but sometimes they are strong enough to be called "interferences" and to affect some things such as electronic circuits. In this project some interference has been detected and this issue has to be tackled.

14.1 Find electromagnetic fields source

In the car there are a lot of electronic circuits and cables, so many electromagnetic fields sources can be found as many electromagnetic fields victims.

The most suitable sources are boards and cables that work with high intensities, between 5 A and 20 A, and with frequent and fast voltage change (high frequencies). In this case those sources are the motor power supply system components: Motor, motor controller, buck, supercapacitors, fuel cell, fuel cell controller and all that cables that link them.

On the other hand, the most suitable victims are boards and cables that work with lower intensities, less than 100 mA, but also with high frequencies. In this project the victims are: control board, buck and all the cables connected to them.

As can be seen the buck is in both lists. That means that at the same time he is a source and a victim of electromagnetic interferences. That happens because the buck is in charge of changing the FC voltage and to manage the SC power that cause electromagnetic interferences and also is in charge of measuring different currents and voltages with a victim like circuit.

14.2 Reduce the generated electromagnetic fields

Several advices from Mrs. Bouriot helped to improve the electromagnetic compatibility of the car. Next aspects have been considered while redesigning the PCB¹² and the wire placement:

- PCB
 - Guarantee enough space between tracks and mass.
 - Reduce the use of double layer. If it has to be used, the shared surface of each layer must be reduced to prevent a capacitor effect.
 - Limiting the disturbances generated with disturbance suppresser like an RC filter.
 - Avoiding cross-joint (i.e. physically separate two highly incompatible elements)
 - Desensitizing potential victims by using shielding.

¹² PCB = Printed Circuit Board

- Wire placement
 - Spiral wiring to reduce the closed circuit loops. If an electromagnetic field goes through a closed circuit loop a current is induced in the circuit loop and cause many problems.

The advices for the PCB design couldn't be implemented because no PCB has been done. The buck had to be replaced, but finally the existing one has been modified. On the other hand the wiring advices have been applied from the beginning of the component arrangement.

14.3 Protection against electromagnetic fields

Some sensitive wires have been protected from electromagnetic interferences to avoid unexpected and undesired errors and accidents. Other wires haven't been protected because no interference for those wires was expected, but afterwards some interference has been detected.

The boards haven't been protected from interferences because the interferences effect was unknown with the new component arrangement. After testing the operation of the car was realised that the Arduino board must be protected with a metallic box.

15 Components arrangement

The car components are not arranged in the best possible way due to the volume usage and also to the electromagnetic interferences. A better arrangement must be found to solve this problem.

15.1 How to arrange

The car chassis is quite small and opaque, so it will be really difficult to arrange the components to make the chassis can be mounted and without having electromagnetic interferences. If it's opaque the interest of having the chassis on is lower because none of the systems can be seen, so it's not a priority. Besides if the chassis is on, the air needed for the fuel cell operation and for circuit cooling won't be enough.

The best disposition can't be found until all the components are finished, that's why this part of the project have to be done at the end. Anyway, before that some components are already fixed because they are in the best position.

While arranging the components their connections have been considered. An electric diagram with all the components connections can be found in the appendix.

15.2 Electromagnetic interferences

These interferences were one of the worse problems during the last semester, so is the first priority while arranging. The sensitive boards and wires like Arduino board and PWM wires have been placed as far as possible of high current sources and wires.

The buck has been placed with the signal socket near the Arduino board and the Arduino board has been placed near the buck's signal socket.

The ground connection have been done as Mr. Larioumlil said to reduce the electromagnetic interferences as much as possible.

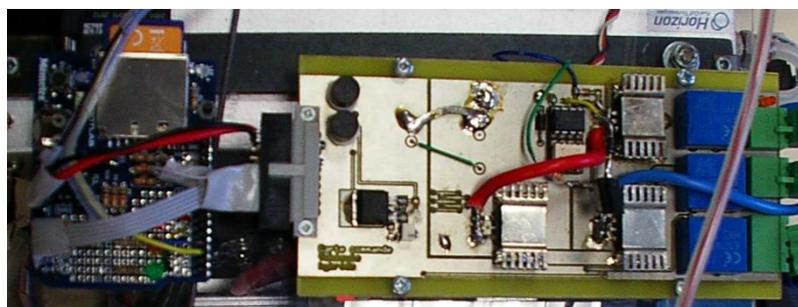


Figure 51: Arduino card (left) and buck board (right)

15.3 Cooling system

When the arrangement has been done, not only the volume and the electromagnetic interferences are considered, but the cooling of some components as well.

One of the components that has to be cooled is the fuel cell like is mentioned in its respective chapter. Other components with cooling needs are two electronic circuits: The motor controller and the buck. This is because they manage currents high enough to generate heat by the joule effect. In those circuits the most heated elements are the packaged elements like the driver, the transistors and integrated circuits. They heat more than other elements because a lot of power is concentrated in a small volume.

The initial idea was to put the boards that heat the most in a vertical position to improve the convection heat transfer, but make real that idea is too difficult. A better and easier solution has been found. The buck is placed on the top of the car and separated enough from other elements to let the air flow around it. The buck is also placed on the front of the car, so is the car elements with more air flow. The motor controller is placed in the air flow that comes from the fuel cell. The fuel cell air is hot, but never hotter than 55°C because that is the maximum temperature the output air can reach. Anyway, the air flow helps the convection heat transfer through the motor controller heat sink. The fuel cell heats up with the time as the motor controller does. The operating time of both elements is not high enough to heat up excessively because the hydrogen tank is small.

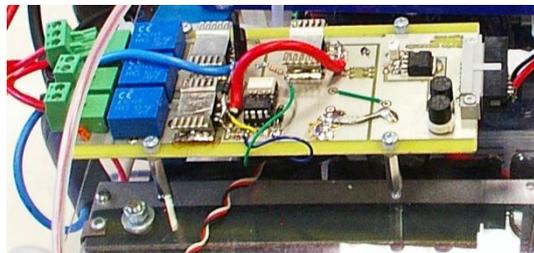


Figure 52: Buck elevation

15.4 Fix and arrange

Another aspect considered while arranging the components has been a good fixation. If the components are not well fixed unexpected and undesired movements can occur damaging some component. The more dangerous thing that can happen is a hydrogen leakage because of a bad fixing. The hydrogen handling components have been revised and protected if possible.

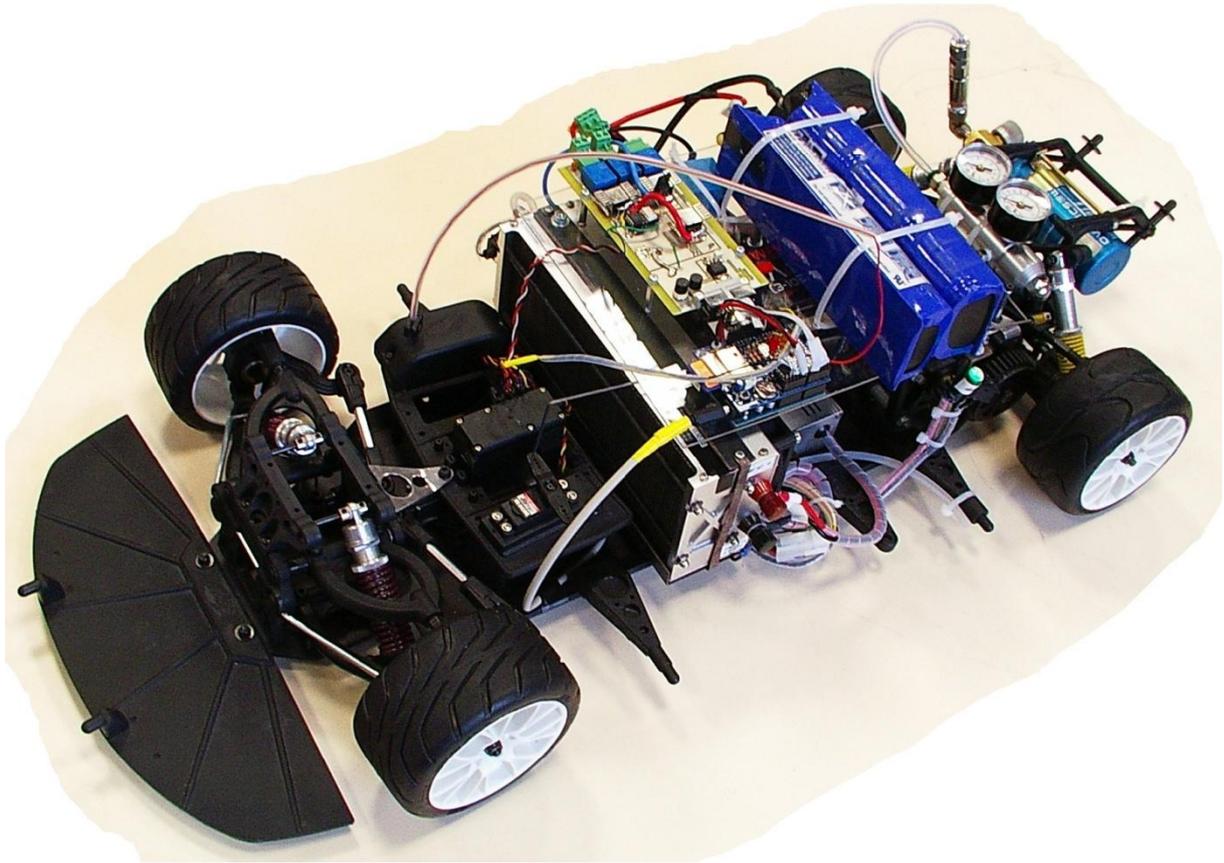


Figure 53: Definitive arrangement

16 To do

In this semester a lot of work has been done, but the car can be improved. Here are some issues to ameliorate:

- Energy recovering while braking: This implies a motor controller change by a new one made from scratch.
- Reverse gear: The actual motor it belongs to a plane, so it hasn't reverse gear. With a new motor controller the reverse gear can be implemented.
- Wheel motor: A wheel motor provides some useful improvements for any car like low center of mass and distributed power consumption.

Conclusion

With this project the problems of car hybridization have been known. Many technological aspects are gathered and a wide view of the problem must be kept in mind, if not the project result is not satisfactory.

Lots of technical aspects about fuel cell, supercapacitors and electronic cards have been learned and a good time has been spent while doing this project, the empirical trials above all. After studying the fuel cells for two years the real experimentation was needed and desired.

The possibility of a fuel cell and supercapacitors hybridization has been demonstrated: with the nowadays technology an hydrogen electric car is possible, is just a matter of time, patience, knowledge and money. This makes a more attractive future for the car manufacturers and for everyone interested in this subject.

Thanks

First of all I have to thanks to many people that made this project possible, without them I wouldn't be able to realise all the work is made.

My most sincere thanks to Mr. Benjamin BLUNIER for his guidance during all the project and his help. Thanks to Mr. Djelalli LARIOUMLIL for the buck realisation and his help in many issues of the laboratory. Thanks to Ms. Adietou CISSE and Mr. Régis ZADJI for his work with the Arduino programming and the research done to reach the achieved goal. Thanks to all the technicians, specially to Mr. Pierre DIEBOLT and Mr. Abdelmajid NAIMI, for their help in the laboratory to make the tests and the car construction possible. Thanks also to Mr. Bouquain with his help in the hydrogen tank refilling and component ordering and thanks to Mr. Alexandre RAVEY in his help with the hydrogen sensor and fuel cell tests.

Appendix

i. Start up process

1. Turn on the transmitter
2. Turn on the power supply card
3. Open the hydrogen valve
4. Turn on the fuel cell
5. Adjust the fuel cell hydrogen input pressure with the tank valve (between 0,45 and 0,55 bar)
6. Wait until the car makes some beeps and an ascending music
7. The car is ready to run so the throttle stick can be moved

ii. Shut down process

1. Shut down the fuel cell
2. Shut down the power supply card
3. Turn off the transmitter
4. Close the hydrogen valve

Just in case that the motor controller doesn't turn off because the supercapacitors are still charged

5. Disconnect the three pin socket from the buck

iii. Water condensation

The water contained in the air condensates when the temperature decreases, and this is explained by psychrometrics.

When the power used by the load drops too fast, the temperature drops as well. When the temperature drops the air that goes through the stack cools as well and starts the condensation of the water contained in the air. For a better understanding of this phenomenon the next chart will help.

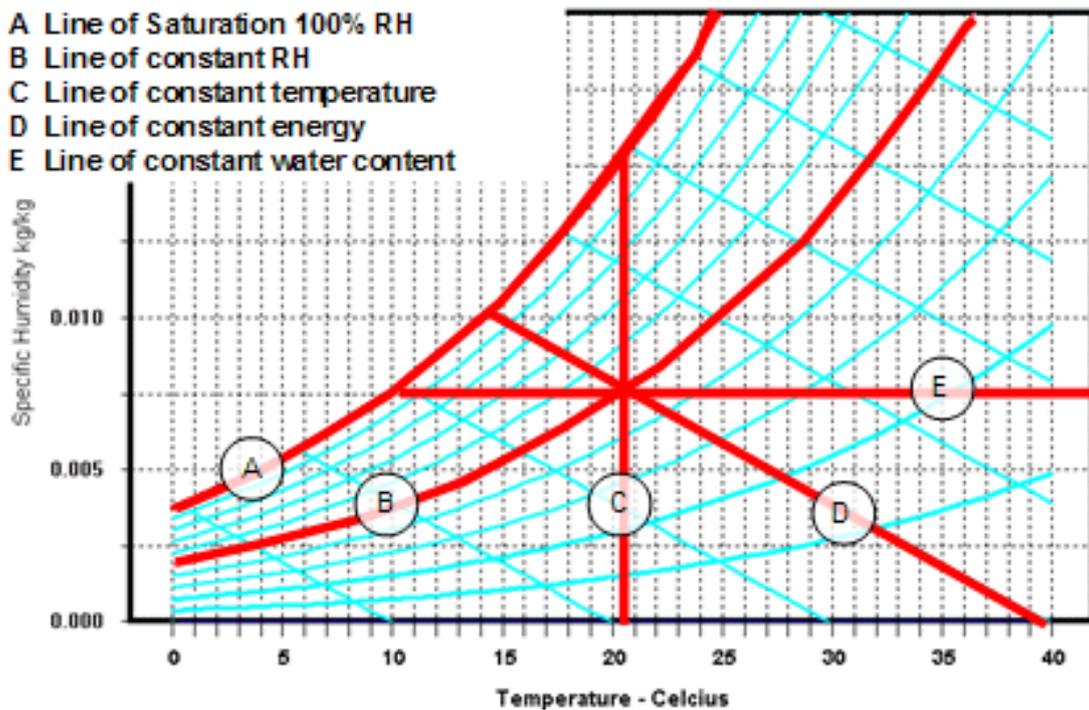


Figure 54: Psychrometric chart

The psychrometric chart shows the water contained in air for each temperature. In the X axe is the temperature ($^{\circ}\text{C}$) and in the Y axe is the water content in air (kg of water for 1 kg of air), also called specific humidity.

When the air temperature and its water content are in the line A, the water in the air starts to condensate. When the FC is turned on the air, which is used for the water formation and for the FC cooling, is on the right side of the line A. When the delivered FC power drops suddenly the layers temperature drops as well but the air still has the same content of water. This makes the air to be on the left side of the line A and condensates on the FC layers surface. If there's some water present in the air FC side, the membrane can lose its properties and decrease its efficiency or even break.

Now the question is: why the air water content remains the same when the FC cools down? That can be easily explained with the temperature distribution in that FC zone as shown in the figure:

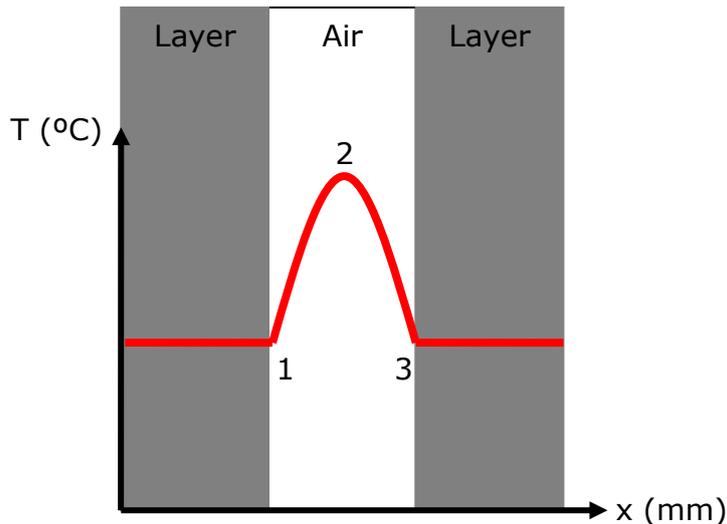


Figure 55: Temperature distribution between layers

The temperature in the layers is almost the same in all its depth because they are made by metal and they are good heat conductors. But air is not a good heat conductor so the air temperature between layers when the FC supplied power drops is the shown in the figure. All the air between the two layers has almost the same water content as much water as the hottest air just in the middle of the layers. If the water content is the same between the layers, in the psychrometric chart (figure 41) the air follows the line E.

iv. Driving cycle

Here it is the table with the time and speed values of the European urban cycle and also with the adjusted speed for the car.

T: time

S_{ECE} : Speed of the cycle

S_{adj} : Adjusted speed

T	S_{ECE}	S_{adj}
[s]	[m/s]	[m/s]
0	0,00	0,00
1	0,00	0,00
2	0,00	0,00
3	0,00	0,00
4	0,00	0,00
5	0,00	0,00
6	0,00	0,00
7	0,00	0,00
8	0,00	0,00
9	0,00	0,00
10	0,00	0,00
11	0,00	0,00
12	1,04	0,67

13	2,08	1,33
14	3,13	2,00
15	4,17	2,67
16	4,17	2,67
17	4,17	2,67
18	4,17	2,67
19	4,17	2,67
20	4,17	2,67
21	4,17	2,67
22	4,17	2,67
23	4,17	2,67
24	3,47	2,22
25	2,78	1,78
26	1,85	1,18

27	0,93	0,60
28	0,00	0,00
29	0,00	0,00
30	0,00	0,00
31	0,00	0,00
32	0,00	0,00
33	0,00	0,00
34	0,00	0,00
35	0,00	0,00
36	0,00	0,00
37	0,00	0,00
38	0,00	0,00
39	0,00	0,00
40	0,00	0,00

41	0,00	0,00
42	0,00	0,00
43	0,00	0,00
44	0,00	0,00
45	0,00	0,00
46	0,00	0,00
47	0,00	0,00
48	0,00	0,00
49	0,00	0,00
50	0,83	0,53
51	1,67	1,07
52	2,50	1,60
53	3,33	2,13
54	4,17	2,67

55	4,17	2,67	92	3,54	2,27	128	6,64	4,25	164	9,72	6,22
56	4,17	2,67	93	2,78	1,78	129	7,25	4,64	165	9,72	6,22
57	5,11	3,27	94	1,85	1,18	130	7,87	5,04	166	9,72	6,22
58	6,06	3,88	95	0,93	0,60	131	8,49	5,43	167	9,72	6,22
59	7,00	4,48	96	0,00	0,00	132	9,10	5,82	168	9,72	6,22
60	7,94	5,08	97	0,00	0,00	133	9,72	6,22	169	9,72	6,22
61	8,89	5,69	98	0,00	0,00	134	9,72	6,22	170	9,72	6,22
62	8,89	5,69	99	0,00	0,00	135	9,72	6,22	171	9,72	6,22
63	8,89	5,69	100	0,00	0,00	136	10,24	6,55	172	9,72	6,22
64	8,89	5,69	101	0,00	0,00	137	10,76	6,89	173	9,72	6,22
65	8,89	5,69	102	0,00	0,00	138	11,28	7,22	174	9,72	6,22
66	8,89	5,69	103	0,00	0,00	139	11,81	7,56	175	9,72	6,22
67	8,89	5,69	104	0,00	0,00	140	12,33	7,89	176	9,72	6,22
68	8,89	5,69	105	0,00	0,00	141	12,85	8,22	177	9,31	5,96
69	8,89	5,69	106	0,00	0,00	142	13,37	8,56	178	8,89	5,69
70	8,89	5,69	107	0,00	0,00	143	13,89	8,89	179	8,02	5,13
71	8,89	5,69	108	0,00	0,00	144	13,89	8,89	180	7,14	4,57
72	8,89	5,69	109	0,00	0,00	145	13,89	8,89	181	6,27	4,01
73	8,89	5,69	110	0,00	0,00	146	13,89	8,89	182	5,40	3,46
74	8,89	5,69	111	0,00	0,00	147	13,89	8,89	183	4,52	2,89
76	8,89	5,69	112	0,00	0,00	148	13,89	8,89	184	3,65	2,34
77	8,89	5,69	113	0,00	0,00	149	13,89	8,89	185	2,78	1,78
78	8,89	5,69	114	0,00	0,00	150	13,89	8,89	186	1,85	1,18
79	8,89	5,69	115	0,00	0,00	151	13,89	8,89	187	0,93	0,60
80	8,89	5,69	116	0,00	0,00	152	13,89	8,89	188	0,00	0,00
81	8,89	5,69	117	0,00	0,00	153	13,89	8,89	189	0,00	0,00
82	8,89	5,69	118	0,83	0,53	154	13,89	8,89	190	0,00	0,00
83	8,89	5,69	119	1,67	1,07	155	13,89	8,89	191	0,00	0,00
84	8,89	5,69	120	2,50	1,60	156	13,37	8,56	192	0,00	0,00
85	8,89	5,69	121	3,33	2,13	157	12,85	8,22	193	0,00	0,00
86	8,13	5,20	122	4,17	2,67	158	12,33	7,89	194	0,00	0,00
87	7,36	4,71	123	4,17	2,67	159	11,81	7,56	195	0,00	0,00
88	6,60	4,22	124	4,17	2,67	160	11,28	7,22			
89	5,83	3,73	125	4,78	3,06	161	10,76	6,89			
90	5,07	3,24	126	5,40	3,46	162	10,24	6,55			
91	4,31	2,76	127	6,02	3,85	163	9,72	6,22			

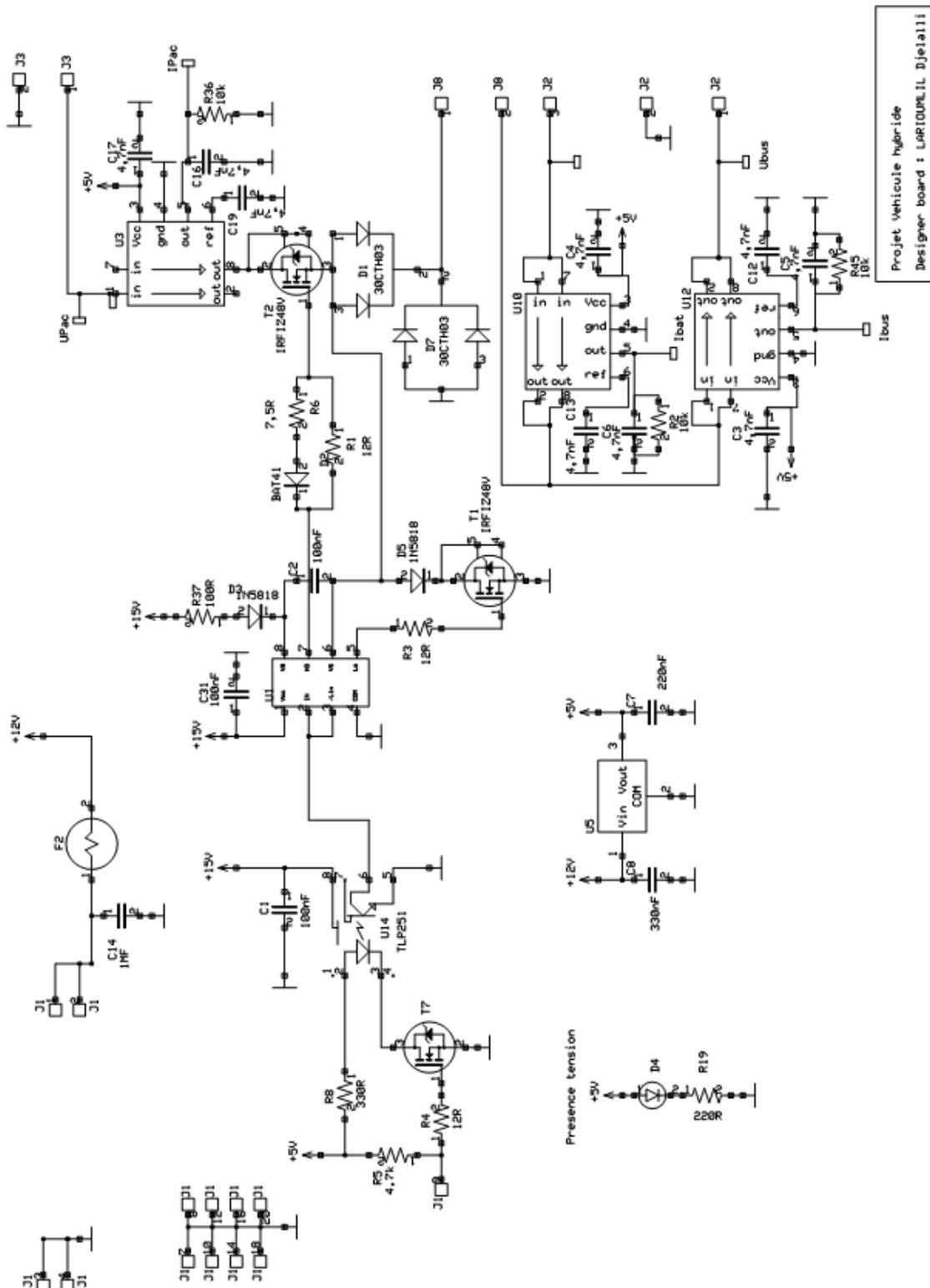
v. Fuel cell test

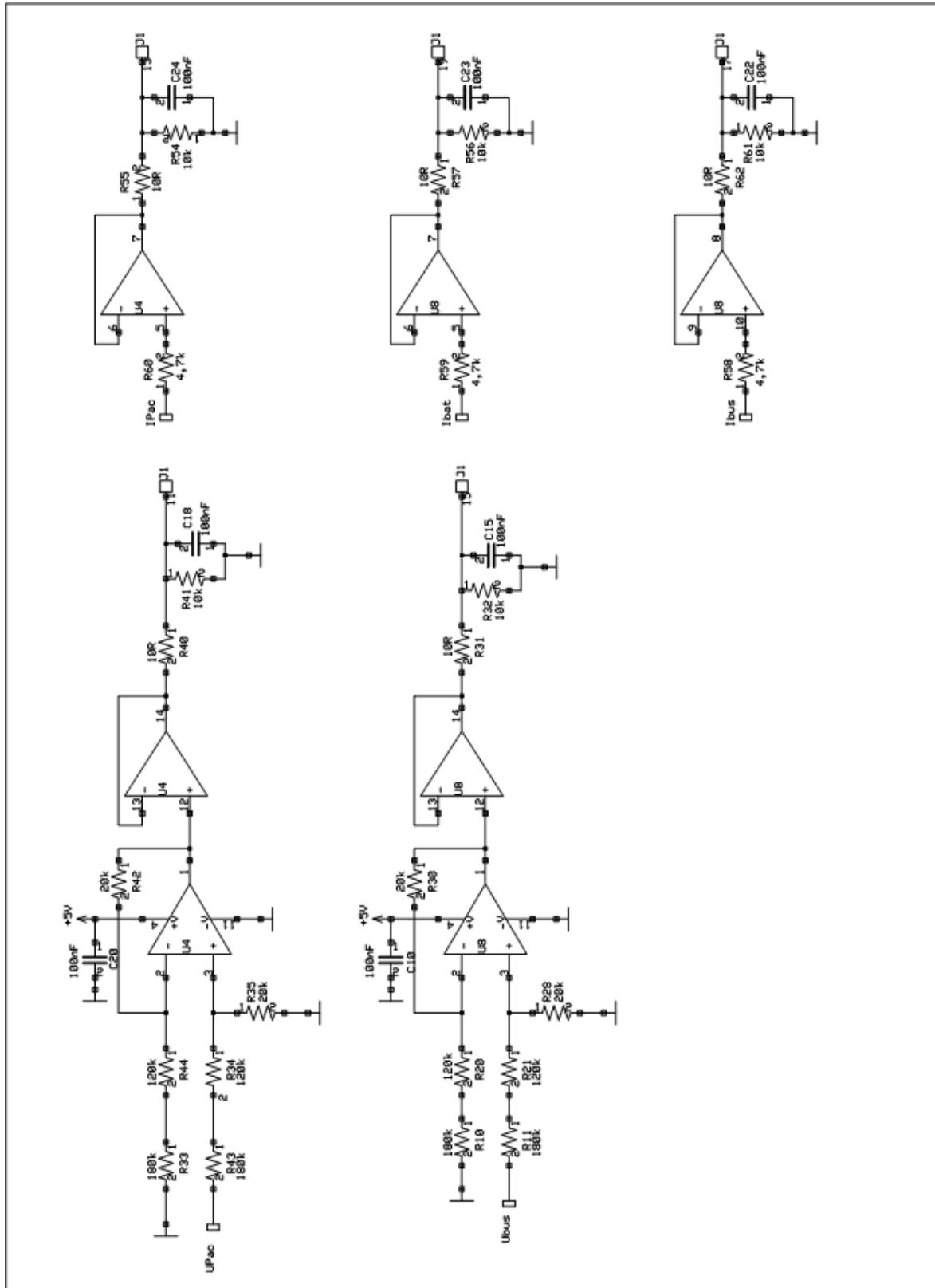
This is the resulting table with the measures done while testing the fuel cell operating.

V: Voltage	P_{fc} : Fuel cell power	η_{elec} : Electric efficiency = P_{elec}/P_h
I: Current	P_{aux} : Auxiliary power	η_{sys} : System efficiency
V_{aux} : Auxiliary voltage	C_m : Mean consumption	
I_{aux} : Auxiliary current	P_h : Heat power	

V (V)	I (A)	V_{aux} (V)	I_{aux} (A)	P_{fc} (W)	P_{aux} (W)	C_m (l/min)	P_h (W)	η_{elec}	η_{sys}
65	0,000	13,00	0,883	0	11,479	0,15	24,29	0%	-47%
56	0,514	13,00	0,828	29	10,764	0,47	79,29	37%	23%
55	1,017	12,99	0,831	56	10,795	0,73	121,45	46%	37%
53	1,518	13,04	0,827	80	10,784	0,97	162,49	50%	43%
52	2,037	13,02	0,826	105	10,755	1,21	202,98	52%	46%
51	2,500	13,02	0,813	126	10,585	1,46	244,58	52%	47%
49	3,062	13,01	0,827	150	10,759	1,73	289,25	52%	48%
48	3,522	13,01	0,821	169	10,681	1,96	328,06	52%	48%
47	4,044	12,99	0,944	189	12,263	2,22	372,45	51%	47%
46	4,486	12,99	0,931	205	12,094	2,51	421,03	49%	46%
45	5,043	12,96	1,110	227	14,386	2,79	467,38	48%	45%
45	5,505	12,95	1,132	245	14,659	2,98	499,77	49%	46%
43	5,984	12,99	1,280	260	16,627	3,31	555,05	47%	44%
43	6,539	12,97	1,262	278	16,368	3,52	589,67	47%	44%
42	7,000	12,96	1,288	292	16,692	3,94	659,47	44%	42%
41	7,520	12,95	1,318	307	17,068	4,22	706,66	43%	41%
40	7,960	12,95	1,375	320	17,806	4,48	750,21	43%	40%

vi. Buck scheme





vii. Energy management program

```

/// begining of constant definition

// reading pin assignment
const int pinUfc = 14; //pin used to read the fuel cell voltage. Pin 14 is pin 0 of analog in
const int pinIfc = 15; //pin used to read the fuel cell current. Pin 15 is pin 1 of analog in
const int pinUbus = 16; //pin used to read the bus voltage. Pin 16 is pin 2 of analog in
const int pinIbus = 17; //pin used to read the bus current. Pin 17 is pin 3 of analog in
const int pinIsc = 18; //pin used to read the supercapacitors current. Pin 18 is pin 4 of
analog in

// boundaries. All of them are "float" type to obtain more precision while operating, mainly
in divisions.
// real boundaries
const float minUfc = 36;           // minimum fuel cell voltage (V).
const float maxUfc = 60;           // maximum fuel cell voltage (V).
const float maxIfc = 8;            // maximum delivered fuel cell current
const float minUbus = 16;          // minimum bus voltage (V).
const float maxUbus = 30;          // maximum bus voltage (V).
const float maxIbus = 55;          // maximum bus current (A).
const float maxIsc = 55;           // maximum supercapacitors current (A).

// measured boundaries
const float minMeasuredUfc = 0;     // mimimum Ufc measured value
const float maxMeasuredUfc = 810;    // maximum Ufc measured value. 812 -> 60 V
//const float minMeasuredIfc = 000;   // mimimum Ifc measured value. The same as
//                                     reference value because cannot be negative.
const float referenceMeasuredIfc = 511 ; // reference Ifc measured value. This value
//                                     corresponds to a current of 0 A.
//const float maxMeasuredIfc = 000;    // maximum Ifc measured value. Know the value for
//                                     some current and calculate
const float minMeasuredUbus = 0;     // mimimum Ubus measured value.
const float maxMeasuredUbus = 403;    // maximum Ubus measured value
//const float minMeasuredIbus = 000;   // mimimum Ibus measured value.
const float referenceMeasuredIbus = 510; // reference Ibus measured value. This value
//                                     corresponds to a current of 0 A.
//const float maxMeasuredIbus = 000;   // maximum Ibus measured value.
//const float minMeasuredIsc = 000;    // mimimum Isc measured value. This can be
//                                     negative, so it will be the maximum value of
//                                     current while discharging.
const float referenceMeasuredIsc = 515; // reference Isc measured value. This value
//                                     corresponds to a current of 0 A.
//const float maxMeasuredIsc = 000;    // maximum Isc measured value

// other constants
const float Uscdef = 30;             // supercapacitors rated voltage
const float errorThreshold = 0.2;   // minimum error value tolerated
const float proportionTable[] = { 0, 0.6 , 0.71, 0.83, 0.95 };
// proportion values to distinguish between energy management strategies.
const float strategy[] = { 6.539 , 5.505 , 3.5 };
// current needed for each strategy. Values from 0 to maxIfc

/// end of constant definition

/// begining of variable declaration and initialisation

// measured variables
float Ibus = 0;           // bus current
float Ubus = 0;           // bus voltage
float Isc = 0;            // supercapacitors current
float Ufc = 0;           // fuel cell voltage
float Ifc = 0;           // fuel cell current

// other variables
float proportion = 0.0;   // (supercapacitors voltage) / (default voltage) = Ubus/Uscdef
float newIfc = 0;         // new desired current from the fuel cell
float prevIfc = 0;        // previous value of newIfc
float error = 0;          // diference between Ifc and newIfc
float alphaBuck = 0;     /* duty cycle of the PWM signal sent to the buck with Timer1.
                           Value between 0.00 and 1.00. If alphaBuck = 0 then Ifc = 0
                           and if alphaBuck = 1 then Ifc = maxIfc */

/// end of variable declaration and initialisation

```

Fuel cell and supercapacitors remote control car

```
/// function

void energyManagement() {

    // data read. By dividing the measured value by its maximum measured value the value
    // obtained is between 0 and 1, and by multiplying by the maximum value of each variable the real
    // value is obtained.
    Ubus = (float)analogRead(pinUbus) * maxUbus / maxMeasuredUbus;
    Ufc = ((float)analogRead(pinUfc) * maxUfc) / maxMeasuredUfc;

    // The currents can't be measured because the microcontroller is not precise enough and the
    // voltage variation is not high enough
    //Ibus = ((float)analogRead(pinIbus) * maxIbus) / (maxInput - referenceMeasuredIbus);
    //Isc = ((float)analogRead(pinIsc) * ) / (maxInput - referenceMeasuredIsc);
    //Ifc = ((float)analogRead(pinIfc) * ) / (maxInput - referenceMeasuredIfc);

    // calculations and assignments
    proportion = Ubus/Uscdef; // supercapacitors charge calculation

    // needed current calculation
    if (proportionTable[0] <= proportion && proportion < proportionTable[1]) // the
    proportionTable decides which strategy must apply
        newIfc = strategy[0];

    else if (proportionTable[1] <= proportion && proportion < proportionTable[2])
        newIfc = strategy[1];

    else if (proportionTable[2] <= proportion && proportion < proportionTable[3])
        newIfc = strategy[2];

    else if (proportionTable[3] <= proportion && proportion < proportionTable[4]) //
    progressive and proportional decreasing
        newIfc = (((proportionTable[4]-proportionTable[3]) - (proportion -
        proportionTable[3]))/(proportionTable[4]-proportionTable[3])) * strategy[2]; // strategy[2]
    applied if proportion = proportionTable[3] and 0 if proportion = proportionTable[4]

    else newIfc = 0;

    // Buck duty cycle calculation. Value between 0 and 1
    alphaBuck = newIfc / maxIfc;

    /* This code can't be used because of unavailability of current measurement

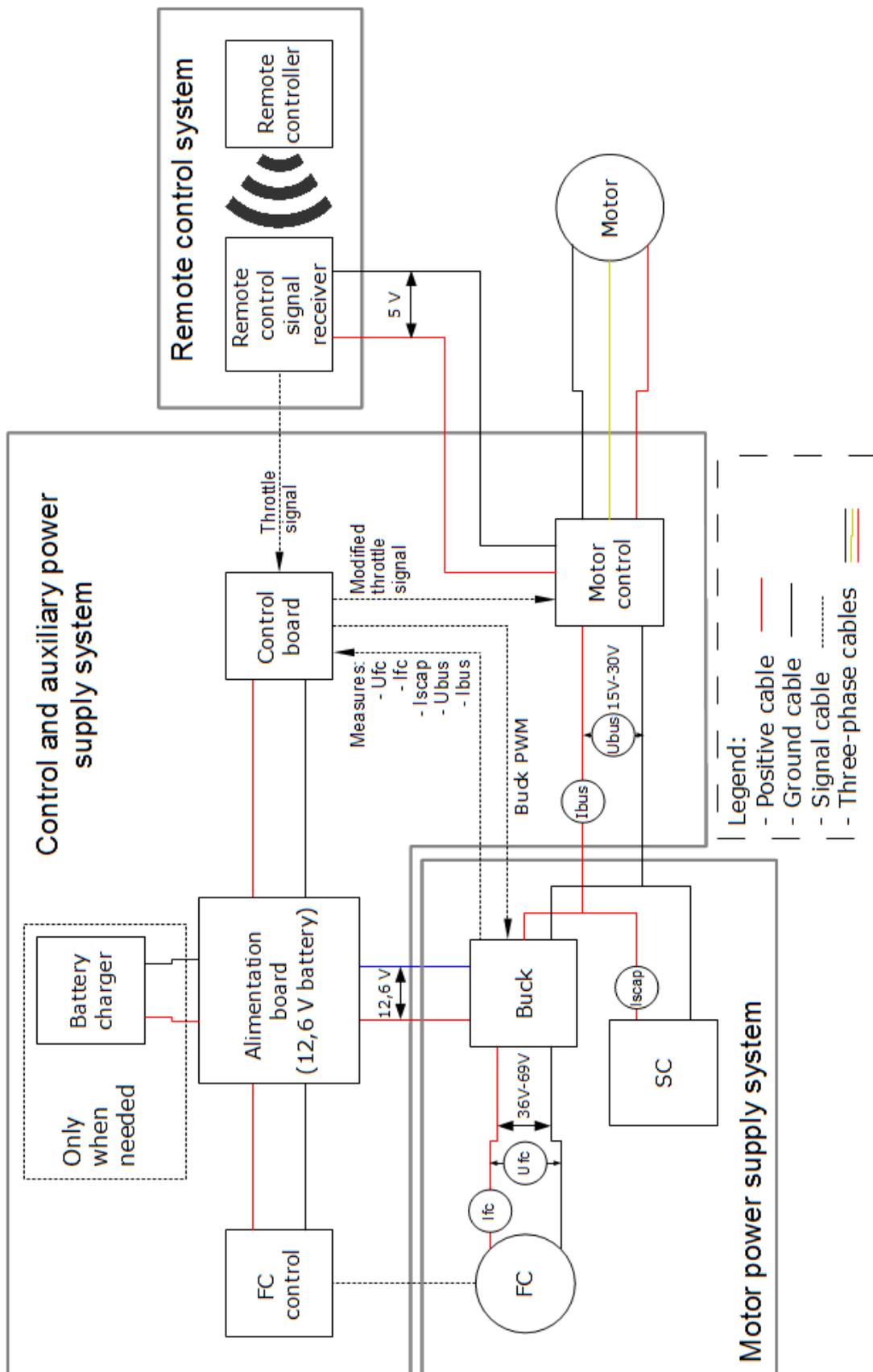
    // stability
    error = Ifc -
    prevIfc; // if the previous newIfc is not equal to the measured Ifc an error handling is needed

    if (error >= errorThreshold)
        alphaBuck = (newIfc + error) / maxIfc; // the signal sent to the buck is modified by the
    error
    else alphaBuck = newIfc/maxIfc;

    prevIfc = newIfc; // latest newIfc replacement

    */
}
```

viii. Electric diagram



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Summary

This project to studies the advantages and disadvantages of a hybrid car that works with fuel cell and supercapacitors and tries also to make it real. By doing this car lots of different kinds of problems have been found. From electromagnetic interferences, to excessive heating and even microcontroller programming, are solved in the best possible way by researching and trying.

To start with all the power needs and technical aspects must be known. Then the components are sized and ordered according to the resulting forces and different needs like the motor fixation. After that the assembly is possible.

By doing the modelling and simulation of the energy components (fuel cell, supercapacitors, etcetera) the best control laws are found and with a suitable board these laws are implemented. With the electronic support brought by an Arduino card all the aspects have been solved.

This report tries to make an approach of all the mentioned technological aspects to all kind of people. Except the mathematical calculations the considerations explained in the whole document are explained from the beginning to allow the reader to understand it all.