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# FORMULA ZERO: Development and Kart's Competition Driven by PEM Fuel Cell

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## 1 Introduction

Formula Zero (FZ) is a new category of racing for zero emission vehicles and hydrogen fuel cell (FC) that defends an ecological and fun future. The competition is an ideal platform for the development of new technologies and to attract the attention of the general public [1].

In a motor sport competition every team have to follow rules in order to ensure a fair competition. In the Formula Zero championship, there are many rules [2], for the different aspects of the race but here the most relevant technical ones are marked:

- **Vehicle general characteristics.** Fuel cell powered hybrid electric drive train, single seat, no roof, no suspension, four wheels, steering ensured by at least two wheels, propelled by at least two wheels. The maximum weight is 275kg without driver and the minimum 150Kg. If the driver weights less than 75kg, ballast must be added to the vehicle to rise 75Kg. Dimensions (Maximum): length 230cm, Width 150cm, Height 75cm, Wheelbase110cm min 160 cm max, ground clearance 35mm min.
- **Fuel cell.** Vehicles must be powered by one Hydrogenics HyPM HD 8 Fuel Cell Power Module. Exhaust water must be collected in a container on-board the vehicle.
- **Energy storage**. The collection of all components witch store energy recoverable to participate in the propulsion of the vehicle, except for the hydrogen cylinder provided by the organizer, is considered The Energy Storage System (ESS). The maximum usable energy storage capacity of the ESS is 250.00 Joules.
- **Propulsion and motors**. Only electric motors may be used. Propulsion of the vehicle must be made through the wheels. The vehicle must be fitted with a reverse mode.
- **Brakes**. A Hydraulic braking system (the primary braking system) operated by pedal is mandatory. The primary braking system must be a dual-circuit system, with a front and a rear circuit. Any kinetic energy recovery system may not be activated by any means other the brake and/or the accelerator pedal.
- **Electrical equipment**. The fuel cell has to be started without connecting an external energy source. Batteries or capacitors not included in EES must be fused to limit power output to 600W. Battery types other than those listed below are prohibited: Nickel-iron, Nickel-Zinc, Nickel-Metal -Hydride, Lithium-Ion and Lithium-Metal-polymer. Capacitors others than the following types are prohibited: Glycol Ether, Lactone, Amide, Aliphatic carboxylic acids, Ammonia based... Electrical potential of more than 120V DC or 71V AC RMS referred to system ground is prohibited.

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Electrical potential of more than 50V between system ground and the chassis or body of the vehicle is prohibited.

- **Hydrogen feed system**. The hydrogen feed system must be routed such that accumulation of hydrogen in enclosed or semi-enclosed areas is minimized in the event of a leak. Hydrogen cylinders other than those supplied by the organizers are prohibited. Those are 200 bar pressurized deposit. The manual shut-off valve must be accessible by the driver while seated in the cockpit.

### 1.1 How does the kart?

The complete system converts hydrogen energy into mechanical energy and thus gets the movement of wheels (fig. 1).

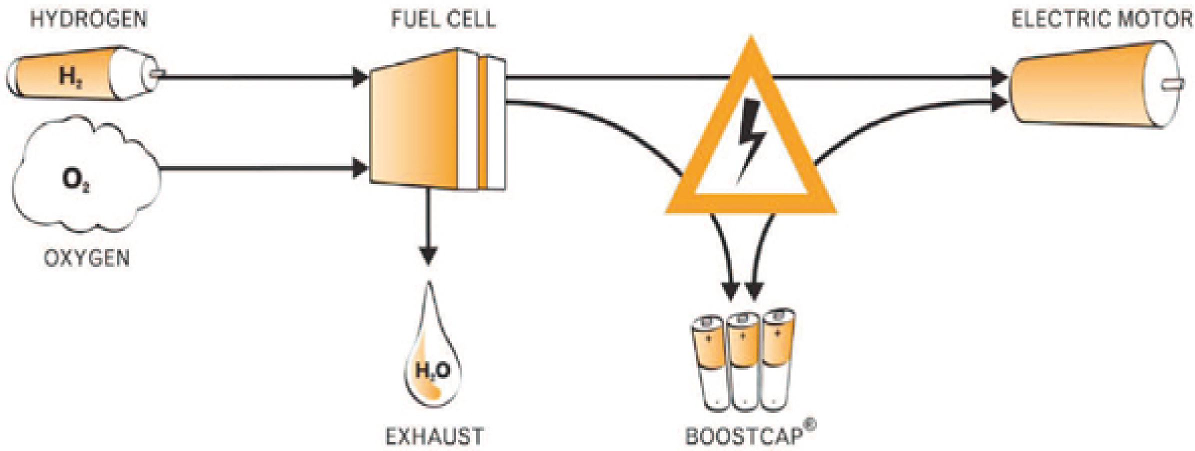


**Figure 1: Basics.**

The fuel cell converts hydrogen and oxygen into electricity and water and the management control system storage the electricity in capacitors or use it directly for propulsion. When the kart requires more power than the one from the fuel cell, energy from capacitors is added to this to get the peak power needed. Besides, electric motors act as brakes, to recover breaking energy in electrical energy way (fig. 2).

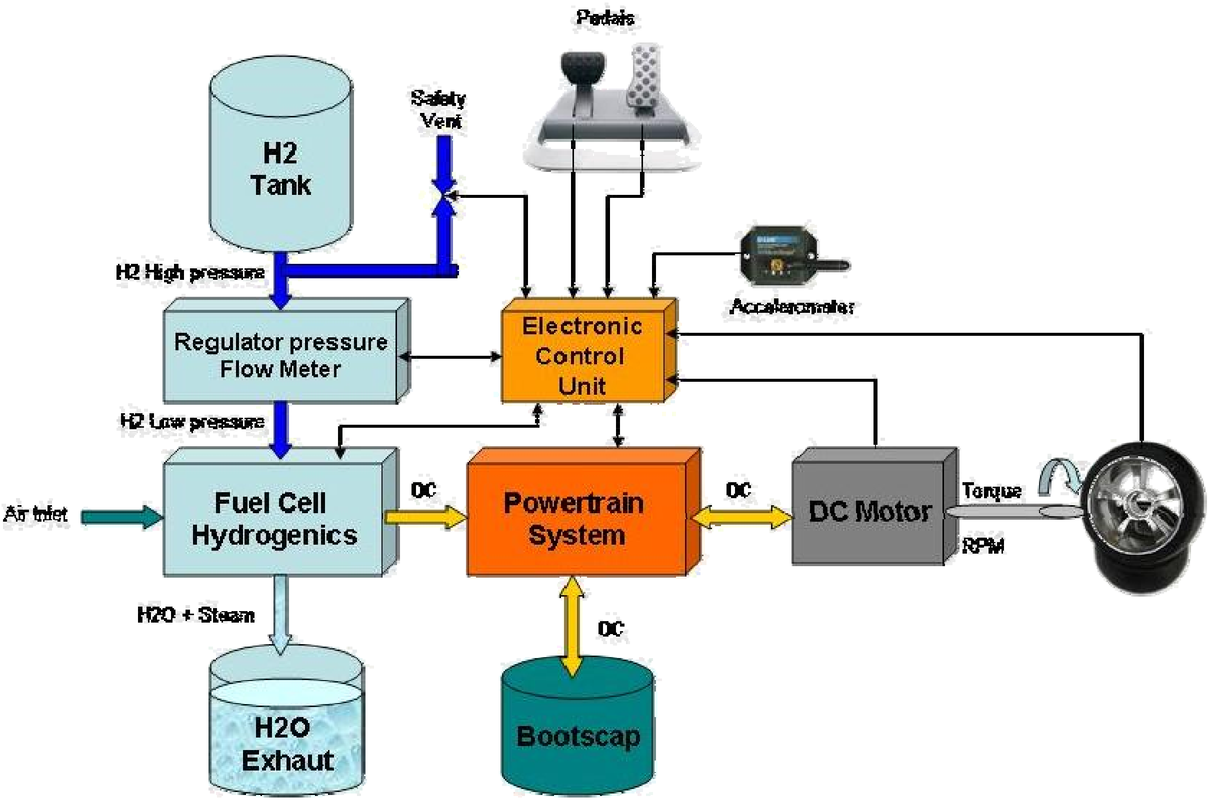


**Figure 2: System diagram.**

Meanwhile, water produced is discharged into the air, as the only waste. After 6 minutes on racing, it has been produced only 0.3 l of water.

Mainly are 3 systems which comprise the go- kart (fig. 3):

- **System of hydrogen:** $H_2$ gas cylinder, $H_2$ safety features fuel cell.
- **Electronic System:** main control, telemetry, data visualization on the steering wheel, capacitors, electric motors.
- **Mechanical System:** chassis, dual rear traction independent, distribution weight central steering wheel, brake.

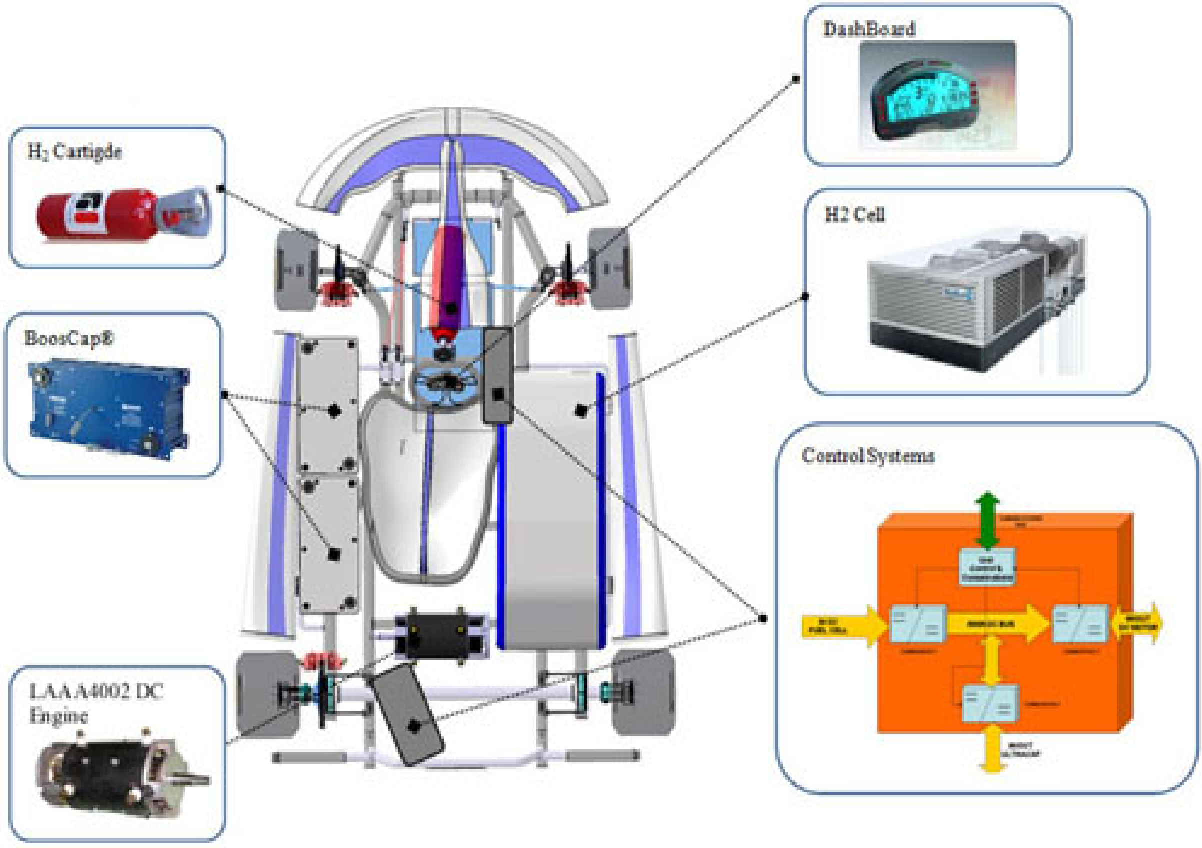


**Figure 3: Kart systems.**

### 1.2 Go-karts built

The first stage (fig. 4) was design and built a prototype kart with a stack of 1.2 kW from Ballard Systems.


**Figure 4: First go-Kart.**

See 1.2 kW prototype data sheet below:

- **Weight:** 150 kg (without driver)
- **Chassis:** Tubular steel special, stretched cold
- **Max.:** 750W, 2200W peaks at 12 seconds
- **Autonomy:** 20 min·bottle-1
- **Speed:** 90 kmh-1

A second stage was to develop 8 kW fuel cell kart with Hydrogenics technology (fig. 5).


**Figure 5: Second go-Kart.**

See 8 kW prototype data sheet below:

- **Weight**: 250 kg (without driver)
- **From 0 km/h to 100 km/h:** in 4.3 seconds
- **Fuel cell:** Hydrogenics HyPM 8, 8.5 kW
- **Power rating:** 26 kW until 45 kW peaks in 20 seconds
- **Autonomy:** 40 min·bottle-1
- **Speed:** 150 km/h

## 2 Development

The aims of this project were to development electronics and hydrogen system, first step separately and second step together.

First step: experiments.

- Ensure that the component are working properly
- Characterize the way of working of every component. To get a better understanding and accuracy of its.
- Find the stability limit working points for each component.

Second step: test.

- Different configurations to observe how all the components interact together.

Third step: verify reality with simulations.

## 2.1 Hydrogen system

The system consists in a hydrogen storage and fuel cell. In it, hydrogen is storage in a cylinder in the form of hydrogen gas to 20 MPa with pressure reduction integrated. Hydrogen system is supported by filters antiparticle, check valves, relief valves, hydrogen sensors and actuators to cut off the supply of hydrogen when needed.

The Fuel Cell used in the system is a HyPM HD 8 from Hydrogenics manufacturer.

There is not possibility of using another one because of the race rules.

It is a low temperature Polymer Electrolyte Membrane Fuel cell with a power of 8.5kW. This power is supplied between 49 and 79 Volts DC (fig. 6).

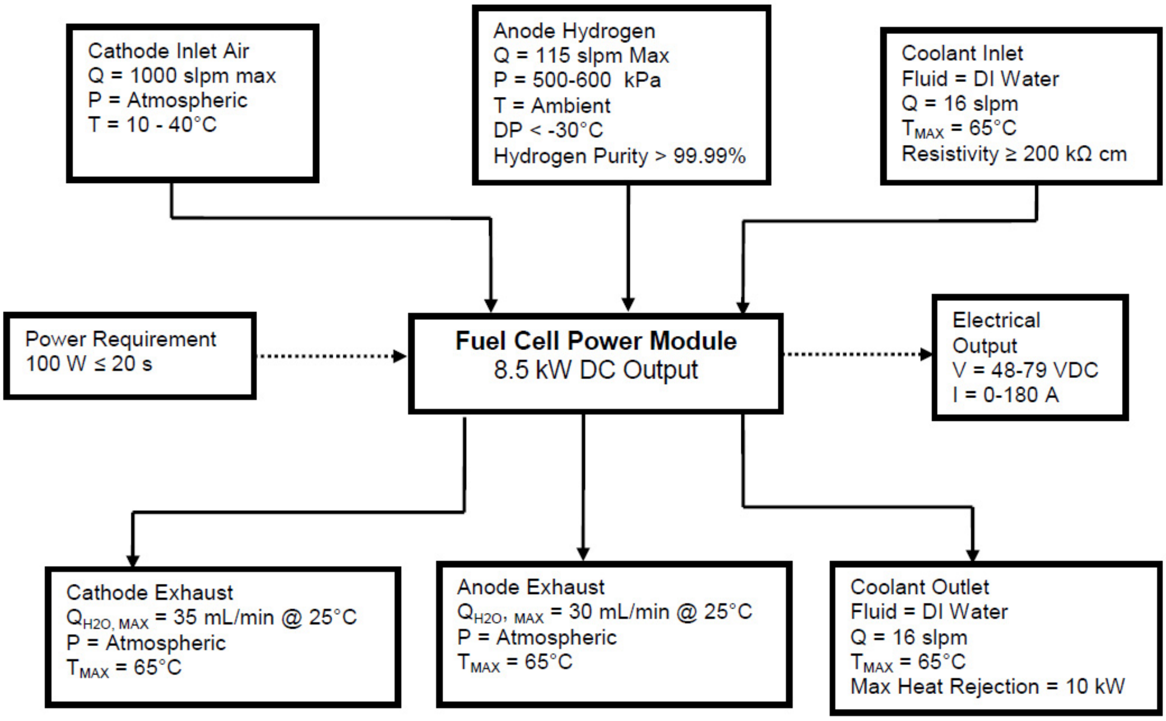


**Figure 6: HyPM Technical data.**

The Fuel cell is characterized by the manufacturer in the data sheet. But it is necessary to know the real limits of the manufactures control system, because the fuel cell is forced to the limit during the race. For these reasons characterizing experiments are done. The main objectives of the experiment are:

- Check the correct operation of the fuel cell
- Know the fuel cell real polarization curve
- Find the fuel cell operation limits.
- Verify how fast the fuel cell dynamic is.

In the first part of the experiment, the fuel cell is directly connected to an Electronic Load. This is a variable load controlled with a laptop. It can simulate current and impedance variable loads. For this experiment a current versus time load is implemented in. It has to be low rate ramp to ensure that the fuel cell is always working in steady state. At the same time the electronic load is monitoring in the laptop the voltage and current measurements each 0.1 seconds. This way we obtain the polarization curve (fig. 7).

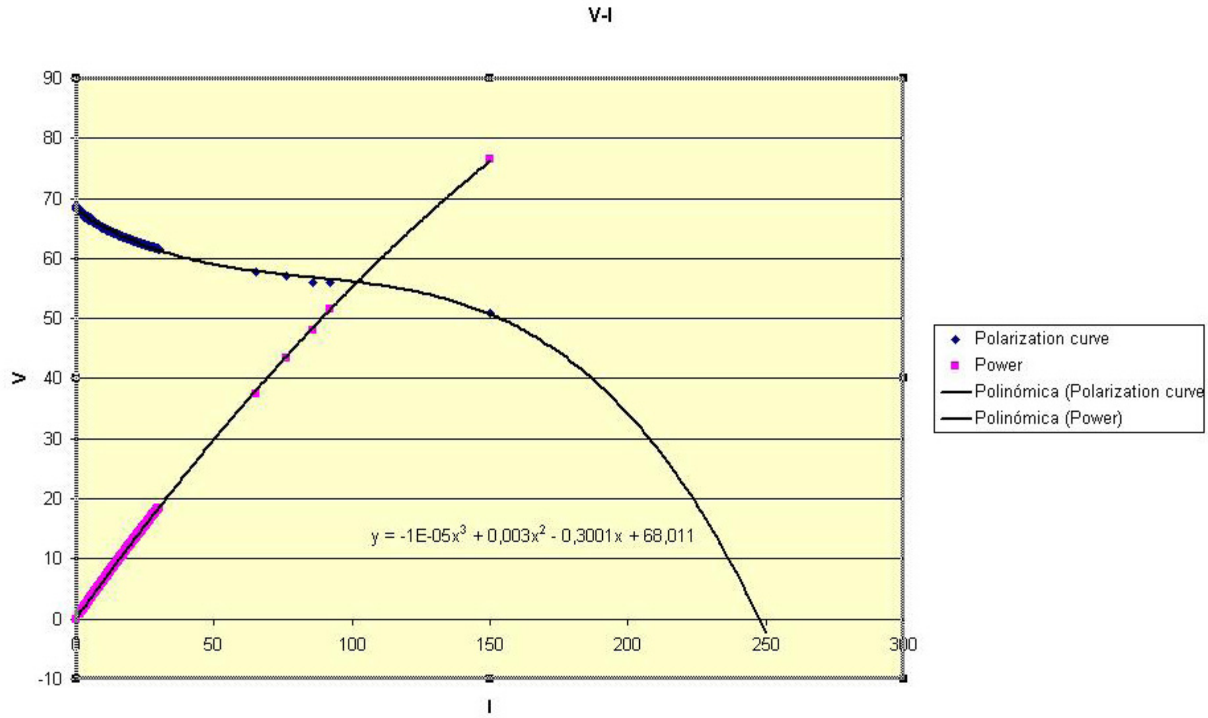


**Figure 7: HyPM polarization curve.**

The polarization curve is:

$$V = -10^{-5} \cdot I^3 + 0.003 \cdot I^2 + 0.3001 \cdot I + 68.011$$

The aim of the second experiment is to study the dynamic limits of the fuel cell.

The fuel cell is tested with different current ramps rates. The maximum current rate supported is assumed to be the maximum fuel cell rate. First step is to apply to the FC the maximum step allowed by the electronic load used before. Next graph shows the FC behavior with 30A (fig. 8).

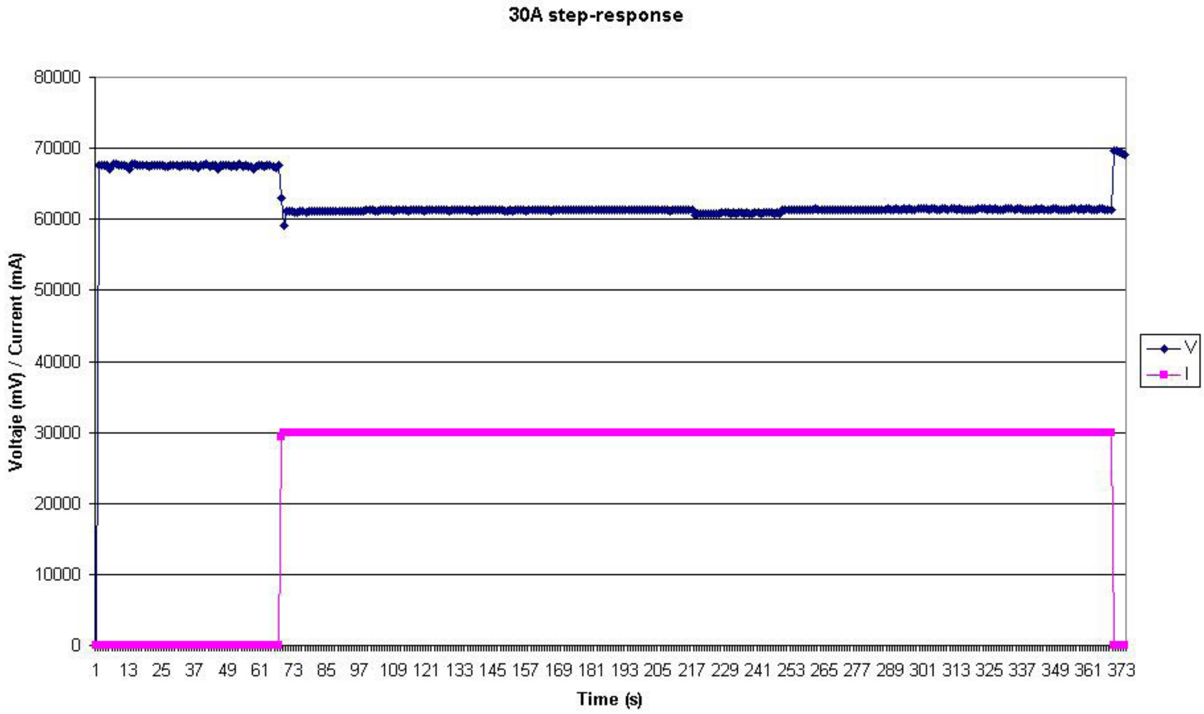


**Figure 8: HyPM behavior with 30A.**

## 2.2 Electric system

The electric system is composed by DC-DC converter, capacitors, a regulator for each electric motor and a central control unit.

The first part of the power system is a single DC / DC converters with a switching technology, which seeks the maximum energy from the fuel cell as long as possible to be supplied to the wheels or to be stored at the storage system.

### 2.2.1 Capacitors

The race rules limits the energy that can be stored in batteries and super capacitors. As the target in this car is to increase power and reduce the weight, supercapacitors are the best solution. The use of Maxwell capacitors was decided because those are one of the most power full capacitors in the market and its technology is accepted by the race rules. The energy that can be stored on is limited to 250.00 Joules. Each capacitor has a capacity of 3000 Farads and it can support 2,7volts. The number of capacitor was calculated not to store more energy than the maximum allowed. To get the voltage necessary for the motors the capacitors was connected in parallel (equ. 1).

$$\frac{1}{C_{tot}} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} \ldots$$

Equation 1

Where $C_{tot}$ is the total capacitance of all the capacitor´s connection and $C_i$ is the capacitance of each capacitor. The energy stored is calculated in the equation 2.

$$E = \frac{1}{2}CV^2$$

Equation 2

To install 30 capacitors and operate it at 72 volts was decided, so the maximum energy stored is 259 200 Joules. But the capacitance will be decreasing with use so forthe race the rules will be followed. The maximum voltage allowed by the capacitorsis 81 volts so it is a safe system because the operating voltage is far from the limits.

An ideal capacitor is connected to a parallel resistance that represents the auto discharge of the capacitor. It is also connected to a series resistance that represents the instantaneous decrease in the voltage when a current is demanded to the capacitors.

Two experiments are done to determine the value of each resistance.

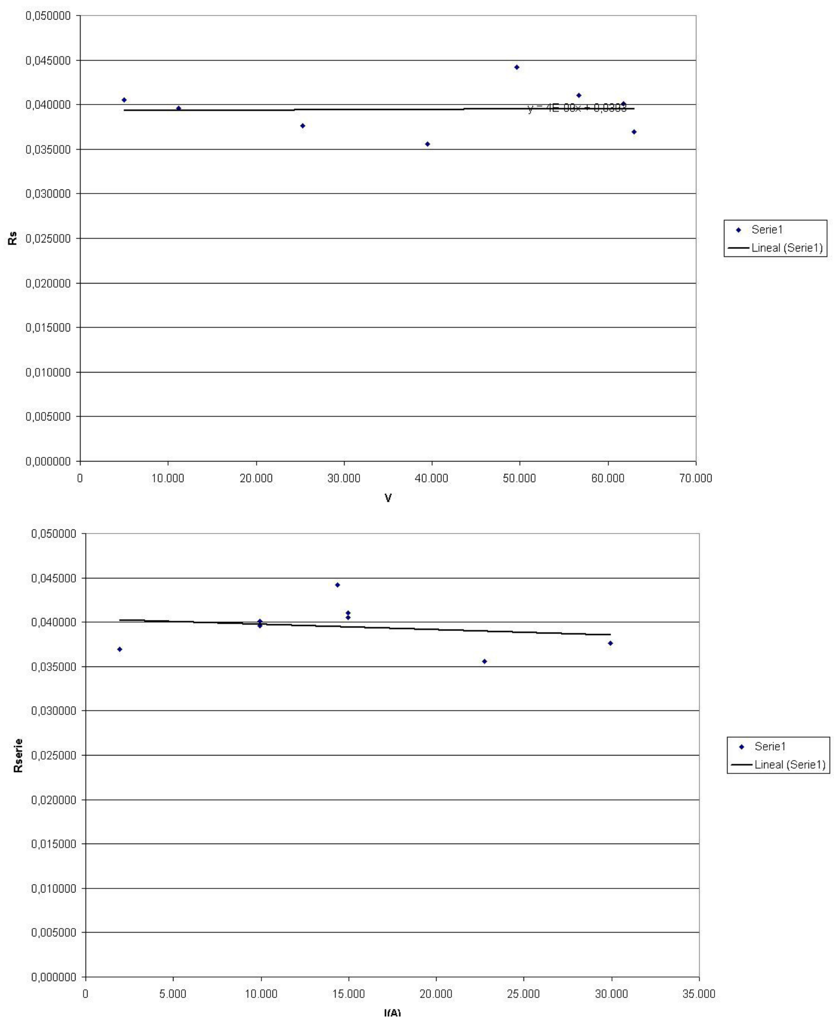


**Figure 9: Capacitor series resistance.**

The real capacitors are connected to the electronic variable load. The load generates different steps of current demand from zero to different values of current. Measuring the voltage difference before and after the step and knowing the current demanded the instantaneous resistance can be measured (fig.9).

As a conclusion the series resistance of the capacitor is assumed as constant every situation and equal to 0'04 ohms. The measure of the parallel resistance is done by discharging the capacitor alone. The experiment consists on charging the capacitor to a voltage, leave it alone and measure the voltage from time to time. Applying the RC discharge formula [3] and approximation of the parallel resistance can be obtained (equ. 3).

$$\frac{t}{R_p} = ln(V_0) - ln(V_c)$$

Equation 3

Where $V_0$ is the initial voltage, $V_c$ is the instantaneous voltage t is the time in second from $V_0$ to $V_c$ and $R_p$ the parallel resistance.

The resistance obtained variates a lot depending of which point of the discharge is took. But it is always a big value greater than 1000 ohms.

This resistance is not really important in a motor sport go-kart because the time of discharge is quite bigger compared with the race times (3-5 min approximately). Therefore a infinite parallel resistance can be assumed

### 2.2.2 Motors and Controllers

The motor is a permanent magnet DC machine, because of the high power weight ratio of permanent magnet machines. In every mobile application the weight is a significant factor, as less weight of the car as less energy needed to accelerate the car. The motors (in case of full power demand) have to transmit to the car the power from the fuel cell and the capacitor together:

- The maximum peak power of the fuel cell is 8,5 kW.
- The capacitors can supply until 3500 amperes in a peak. But then the capacitors are discharged in less than one second. Let’s assume that at least 15 seconds of capacitor power is needed. If the capacitors are fully discharged in 15 seconds it gives a power of 18kW.

So the maximum power demanded by the motors has to be 26,5kW. The car has two motors, one for each rear wheel. Each motor has a nominal power of 7,22 kW but it’s can be operated at twice its power for a period no longer than 10 minutes.

As the formula zero races are less than 10 minutes it can be assumed that each motor has 14,44kW nominal power. Therefore the dispensable mechanical power in the wheels is 28,88kW.

### 2.2.3 DC/DC converter (Step Up)

For the voltage control of the capacitors an DC/DC converter connected to the fuel cell is necessary. It has two deferent functions:

- Control the voltage on the capacitor terminals. To control the capacitor it supply or store energy when needed.
- Ensure that the current from the fuel cell is lower than it maximum. So the fuel cell doesn´t stops and works in a properly working point.

An ideal voltage control has to allow the maximum variation in the voltage, so most of the energy stored in the capacitors is used. The capacitor voltages are limited by the motor controller; it can admit an input voltage from 25 volts to 96V. The optimal device for this task is a step up and down so the output voltage can be lower and greater than the fuel cell one (fuel cell voltage 49-79V).

The step up is tested to ensure that all the internal devices are working properly and its limits.

First it is tested without current limitation, to just simply check how it controls the output voltage. The reference (signal that controls the output voltage) is decreased until the output voltage is not decreasing any more. Then the maximum voltage difference between input and output is get. As it is a step up, it is suppose that the output voltage is always greater than the input. But in the reality it allows to decrease the voltage a bit from the input that is the value obtained in this experiment. On the table 1 the input voltage is 35 but the outlet voltage can be decreased until 34,3.

**Table 1**

| Working Point | Vref | Vbat | Iin | Vout | Iout |
|---|---|---|---|---|---|
| 1 | -4,76 | 34 | 33,5 | 70 | 15 |
| 2 | -3,42 | 34,86 | 23,6 | 50 | 15 |
| 3 | -2,45 | 35 | 17,1 | 36 | 15 |
| 4 | -2,38 | 35 | 16,7 | 35,1 | 15 |
| 5 | -1,62 | 35 | 16,2 | 34,3 | 15 |

The second experiment is setup to check the way of working of the current limitation.

The firs fact checked is that the current limitation is lost if the step up has less voltage at output than at input. In the real car it can happens if the capacitors are too much discharged. That is a situation that have to be avoided, because in this case the FC demand is not controlled, therefore there is risk of fuel cell stop.

For the next part of the experiment the current demand is fixed to 9A and the input current limitation set up to 13A. Then reference is increased until the output voltage is not increasing any more. It is the upper limit, where the input current is in the limit, so the output voltage can´t increase due to a energy balance. The input energy is in the maximum allowed so the output energy (voltage) can´t increase.

Then the reference is decreases until the voltage is in the minimum, like in the first part of the experiment. This part of the experiment is done to check the voltage range with current limitation and how it affects to the lower voltage limit (table 2).

**Table 2**

| Working point | Ref (Lim, current) | Vref (Voltage) | Vbat | Iin | Vout | Iout (A) |
|---|---|---|---|---|---|---|
| 6 | 56ohm (max Vout) | -3 | 34,95 | 13 | 44,2 | 9 |
| 7 | 56ohm | -2,72 | 35,06 | 12 | 40 | 9 |
| 8 | 56ohm | -2,59 | 35,03 | 11,3 | 38 | 9 |
| 9 | 56ohm | -2,45 | 35,05 | 10,7 | 36 | 9 |
| 10 | 56ohm | -2,38 | 35,05 | 10,5 | 35 | 9 |
| 11 | 56ohm (min Vout) | -2 | 35,06 | 10,2 | 34,2 | 9 |

## 2.3 Electronic system

The fuel cell status is sent via CAN bus so it can be monitored. The same CAN bus is used to receive orders (switch on, switch of …). It also gives the Current Draw Allowed (CDA) [4] that indicates the maximum current that the fuel cell can supply in the next time step. If the current demand is lower than the CDA the manufacture ensure that the fuel cell is working properly.

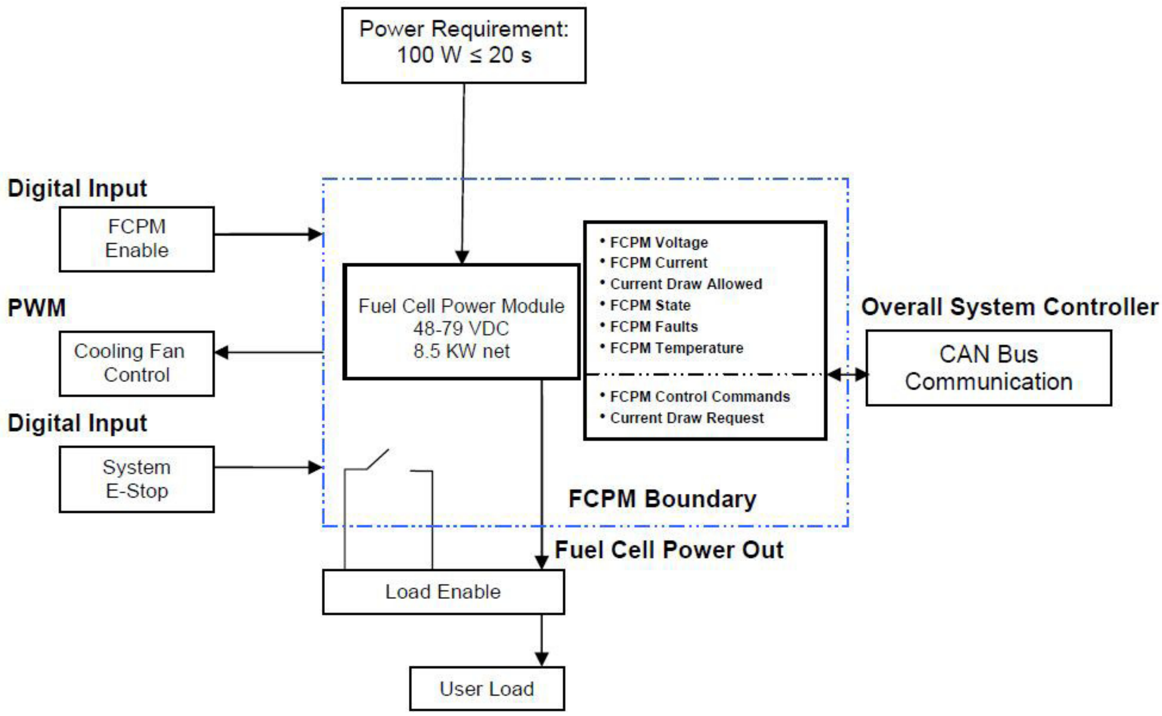


**Figure 10: HyPM communication.**

The kart system also has a telemetry system. This system send (in real-time) data from every parts of kart, collected in data acquisition system based on an Arduino microchip, to a external computer, in this allow to study the behavior of the kart and all its subsystems for further development of improvements (fig. 11).

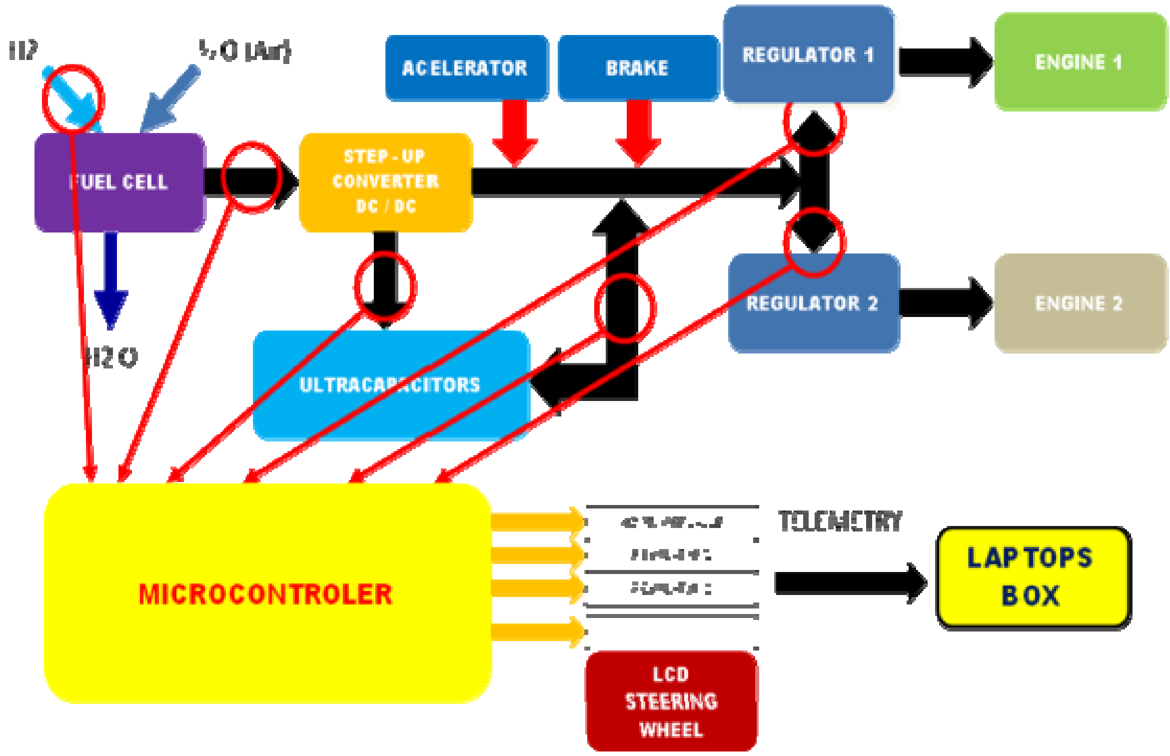


**Figure 11: Electronic system.**

### 2.4 Safety system

The first priority in every car has to be the security. As security criteria the fuel cell switch-off if something goes wrong. Because of this, a life line was designed. It is a single 12VDC wire that ends in the fuel cell, it switches of if this life line circuit is open (fig. 12). Also the super capacitors are disconnected from the system with the same signal. There are deferent security devices that open this circuit in case of danger:

- Crash sensor: It measures the acceleration of the car, if it is greater than a crash value (fixed) it opens the life line.
- Driver out sensor: It detect if there is driver or not using a mechanical device. If the driver isn´t in the car, this sensor opens the drive line. In case of crash, if the driver jump out of the car the life line is also opened.
- ON switch: The pilot has to push this button to switch on the car.
- Emergency stop switch pilot (S1/A): In case of emergency the pilot can pulse this button to open the life line.
- Emergency stop switch team (S1/B): In case of emergency the team can pulse this button to open the life line.

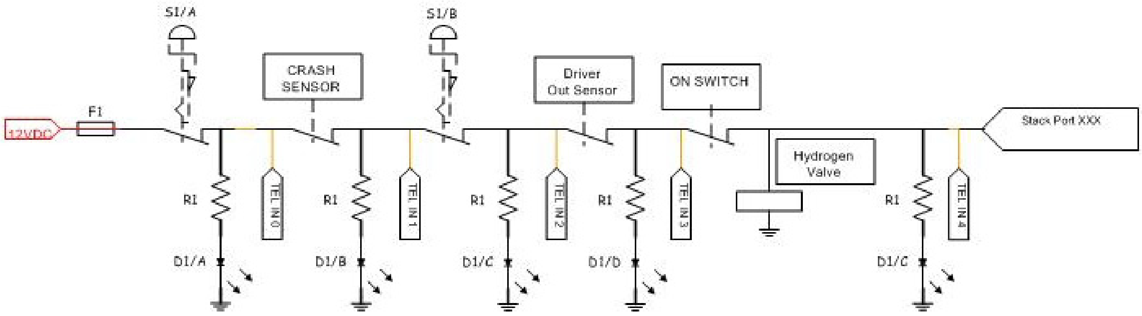


**Figure 12: Life line.**

When current is passing through the life line is also holding open a hydrogen solenoid valve. If one of the security system is activated and it opens the life line, the fuel cell stops and the hydrogen supply is disabled.

## 2.5 Connection

Once all the devices are tested alone. Is time to see how is the way of working all together. The fuel cell connected to the step up input, the capacitors and motor are in parallel at the step up output.

In that configuration the step up is set up to limits the current to 50 A at the start of the experiment, it variates to 160 A in the middle of the experiment. The reference set the output voltage at 70 Volts. The motors are accelerated in order to generate a demand higher than the step-up maximum power (limits by the input 150A).

The graphical result of the experiment can be seen in the figure 13. All the currents and voltages are monitored with current (lend effect) and voltage sensors connected to a data acquisition system.

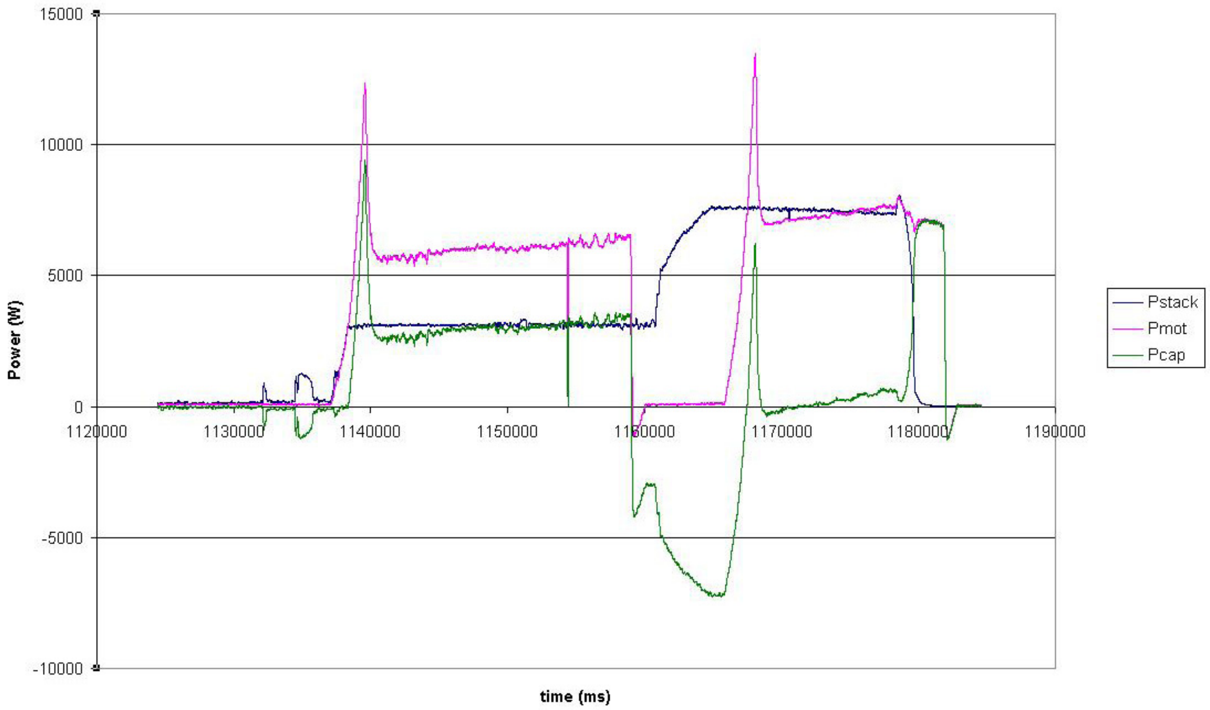


**Figure 13: Power train behavior.**

## 3 Results

The devices have been checked and all of them are working properly. The way of working of each device is obtained. The fuel cell has been approximated by a third order polynomial, because this is the polynomial order that it's better the polarization curve. The maximum current ramp allowed by the fuel cell is 150A in 0,5 seconds. The capacitor parallel resistance is considered infinite, because the auto discharge time is quite long in relation to race time ( in a order of hours and the races are always less than 5 minutes). The step up is the key of the system, depending how is managed the control of the current limitation and voltage reference the system acts in a different way.

The current have to be limited always to ensure that the system can supports any kind of current demanded. Depending of the current limit fixed in the step up and the demand the capacitors supply or store energy. So by the step up the capacitors storage can be controlled. The voltage references fix the maximum voltage value that the capacitor can achieve.

The system way of acting is:

- The step up fixes the limit of fuel cell current.
- The capacitors supply the power difference between fuel cell current and demand.
- If the load is lower than FC production the capacitor is charged until the maximum voltage (limited by voltage reference signal).
- If the load is higher than the FC production the capacitor is discharged.

- When the capacitors voltage becomes lower than the FC voltage the system became unstable because of the step up voltage cross. This voltage cross fix the minimum useful voltage of the capacitors.
- The CDA (Current Draw Allowed) is the value of demand that the fuel cell can supply every instant. The fuel cell communicates it via a BUS CAN wire.
- This value of CDA is used in the circuit test to control the current limit of the step-up. By this way the properly working of the fuel cell is ensured, the fuel cell demand in never higher than CDA. The problem is that these CDA can´t be modeled, because is unknown how the fuel cell calculate this value.

## 4 Conclusions

A Formula Zero car has been designed, simulated and circuit tested. The car is working properly and it follows all the FZ organization rules. All the car devices have been tested.

By the experiments the way of working of all the car elements is known. The fuel cell is completely characterized (dynamic and static working points). The values of the parallel and series resistance of the capacitors are obtained. Also the step-up control limits are now known. The car was working properly in the circuit test. The voltages and currents are behaving as it was planned in the design. This car is a step forward in comparison to the previous car version. Comparing this car with the time results of the last race, our car is the fastest one.

The reason of the configuration selected is simply, it is the faster one. The electrical part of the simulation is really close to the reality because the blocks came directly from the experiments. But the load part is just estimation. So the controllers have to be checked in the real car to be sure that the control is the better one.

Choosing between a system with step up or not, is a trivial decision. As far as the demand supported is quite lower in the system without step up. The capacitor is worse controlled in this case. Also in this configuration the fuel cell is not limited so there is the risk of fuel cell stops.

In this project the feasibility of build a hydrogen motor sport vehicle is demonstrated. The next challenge is to get good results in the next Formula Zero championship. To get this target a good car set up for the concrete circuit have to be done. The correct controller for one race could not be the best one for other races.

Also the knowledge generated at this project will be applied into future projects at Foundation for the Development of New Technologies Hydrogen in Aragon [5].

## References

[1] Web page of the UNIZARTech2 team. http://unizartech2.wordpress.com

[2] Web page of the Formula Zero. http://www.formulazero.nl

[3] An Analog Electronics Companion Basic Circuit Design for Engineers and Scientists Scott Hamilton University of Manchester

[3] Web page of the HYDORGENICS. http://www.hydrogenics.com/

[4] Web page of the Foundation. http://www.hidrogenoaragon.org