Modelling and Simulation of an Electric Formula Student Racing Car

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Abstract—The Formula Student competition is a student competition where teams compete against each other in a real world engineering environment. The team of the Technical University of Lisbon decided to go forward in the design of an Electric Formula Racing Car for the Formula Student competitions. This paper proposes a Formula Student Racing Car with an electric power train. The main goal is to compare it’s performance with the previous, Formula Student gas engine car designed and manufactured by the team, in terms of autonomy, performance and efficiency. At the same time, it is intended to develop a simulating tool that can predict the performance and autonomy of the formula

Keywords – electric vehicle; formula racing; batteries; PM machine, formula electric competition

I. INTRODUCTION

Formula race cars are designed for maximum racing performance within specific restrictions; formula competitions involve both driving and engineering. For example, in the “Formula Student Germany” competition organized by the VDI (Verein Deutscher Ingenieure) the Association of German Engineers [1], for college students. Students build a single seat formula racecar with which they can compete against teams from all over the world.

The competition is not won solely by the team with the fastest car, but rather by the team with the best overall package of construction, performance, and financial and sales planning. Formula Student challenges the team members to go the extra step in their education by incorporating into it intensive experience in building and manufacturing as well as considering the economic aspects of the automotive industry.

Teams take on the assumption that they are a manufacturer developing a prototype to be evaluated for production. The target audience is the non-professional Weekend-Racer, for which the racecar must show very good driving characteristics such as acceleration, braking and handling. It should be offered at a very reasonable cost and be reliable and dependable. Additionally, the car’s market value increases through other factors such as aesthetics, comfort and the use of readily available, standard purchase components. The challenge the teams face is to compose a complete package consisting of a well constructed racecar and a sales plan that best matches these given criteria. The decision is made by a jury of experts from the motorsport, automotive and supplier industries. The jury will judge every team’s car and sales plan based on construction, cost planning and sales presentation.

The rest of the judging will be done out on the track, where the students demonstrate in a number of performance tests how well their self-built racecars fare in their true environment. A key restriction is that all the air entering the engine must pass through a 20 mm diameter orifice in a restrictor plate [2]. This serves the purpose of limiting the maximum power, keeping speeds to reasonable levels, and of challenging teams to maximize performance within this constraint. Another one is that there is no minimum weight set by the rules.

So weight is a major concern in all the design process, because less weight means less energy to move the vehicle. In this paper we explore the potential of electric propulsion for a formula competition. The car that was modeled and simulated is identical with the last car but has an electrical power train.

The main goal of the paper is to compare the performance and the autonomy that is expected for this kind of vehicle under racing conditions. It is important to realize that a Formula SAE car is not intended to be operated at top speed, only in the acceleration event. In this paper, make an overview of the state of the art (Section II), discuss the selection of the electric configuration to most fully realize these advantages (Section III), describe the model implemented in MATLAB/Simulink with the electric power train. (Section IV), report the results from the simulations (Section V) and propose future improvements (Section VI).

II. STATE OF THE ART

The electric propulsion is the heart of an Electric Vehicle EV. It consists of the motor drive, transmission device and wheels. In fact, the motor drive, comprising of the electrical motor, power converter and electronic controller, is the core of an EV propulsion system. The major requirements of the EV motor drive are summarized as follows:

• high instant power and high power density
- Very wide speed range including constant-torque and constant-power regions.
- Fast torque response
- High efficiency over wide speed and torque ranges
- High efficiency for regenerative braking
- Reasonable cost

The choice of electric propulsion systems for EV’s mainly depends on three factors: driver expectation, vehicle constraint and energy source. The driver expectation is defined by a driving profile which includes the acceleration, maximum speed, braking and range. The vehicle constraint depends on the vehicle type, vehicle weight and payload. The energy source relates with batteries and fuel cells, capacitors and flywheels. Thus, the process of identifying the preferred features and packaging options for electric propulsion has to be carried out at the system level. The interactions between subsystems and those likely impacts of system trade-offs must be examined.

A. Electric Motors

1) General Considerations

Traditionally, DC motors have ever been prominent in electric propulsion because their torque-speed characteristics well suited traction requirements and their speed controls are simple. However DC motors have commutators hence it requires regular maintenance. Recently, technological developments have pushed commutatorless motors to a new era, leading to take the advantages of higher efficiency, higher power density, lower operating cost, more reliable and maintenance-free over DC motors. As high reliability and maintenance-free operation are prime considerations for electric propulsion in EVs, commutatorless motors are becoming attractive. Induction motors are a widely accepted commutatorless motor type for EV propulsion because of their mature, high reliability and free from maintenance. Alternatively, permanent magnet (PM) motors are also promising because they use PM to produce the magnetic field, hence higher efficiency and higher power density can be achieved. Switched reluctance (SR) motors also have potential because their simple and robust construction.

2) Vector controlled induction motor drives

Today induction motor drive is one of the most mature technologies among various commutatorless motor drives [3]. Figure 1 shows the characteristics of induction motor drives. In order to improve the dynamic performance of induction motor drives for EV propulsion, vector control is preferred. Although vector control may offer wide speed range up to (3-4) times of base speed, but the efficiency at high speed range may suffer.

![Figure 1. Characteristics of induction motor drive](image)

3) PM motor drives

Among those modern motor drives, Permanent magnet motor drive [3] are most capable of competing with induction motor drives for electric propulsion. Their advantages are summarized below:

- Since the magnetic field is excited by high-energy PMs, the overall weight and volume can be significantly reduced for a given output power, leading to higher power density.
- Because of the absence of rotor copper losses, their efficiency is inherently higher than that of induction motors.
- Since the heat mainly arises in the stator, it can be more efficiently dissipated to surroundings.
- Since PM excitation suffers from no risk of manufacturing defects, overheating or mechanical damage, their reliability is inherently higher.
- Because of lower electromechanical time constant of the rotor, the rotor acceleration at a given input power can be increased

In order to increase the speed range and improve the efficiency of PM motor, the conduction angle of the power converter can be controlled at above the base speed. Figure 2 shows the torque-speed characteristic of a PM brushless motor with conduction angle control. The speed range may reach (3-4) times of base speed. However, at very high speed range the efficiency may drop, the PM may suffer from demagnetization.
Figure 2. Torque – Speed characteristics of a PM motor drive

There are various configurations of PM motors. Depending on the arrangement of the PM, basically they can be classified as surface magnet mounted or buried magnet mounted. The surface magnet designs may use fewer magnets, while the buried magnet designs may achieve higher air gap flux density. The commonly used PM is Neodymium-iron boron (Nd-Fe-B). Another configuration is so called permanent magnet hybrid motor, where the air gap magnetic field is obtained through the combination of PM and field winding. In the broader term, PM hybrid motor may also include the motor whose configuration utilize the combination of PM motor and reluctance motor. PM hybrid motors offer wider speed range and higher overall efficiency but more complex construction.

B. Energy Source

1) General Considerations

The EV energy source has been identified to be the major obstacle of EV Commercialization. Thus, the present and foreseeable future most important EV development issue is on how to develop various EV energy sources. Those development criteria are summarized as follows:

- High specific energy (kWh/kg) and energy density (kWh/liter).
- High specific power (kWh/kg) and power density (kW/liter).
- Fast charging and deep discharging capabilities.
- Long cycle and service lives.
- Minimum self discharging rate and high charging efficiency.
- Safety and cost effectiveness.
- Maintenance free.
- Environmental sound and recyclable.

Rather than based on one energy source, the use of multiple energy sources, so-called hybridization of energy sources, can eliminate the compromise between the specific energy and specific power. For the hybridization of two energy sources, one is selected for high specific energy, while the other for high specific power. For examples, there are the battery & battery hybrid, battery & ultra capacitor hybrid, battery & ultrahigh-speed flywheel hybrid (flywheel is still in the research stage, major issues include safety, complexity and weight), and fuel cell & battery hybrid. In fact, the HEV is a special case, of this hybridization, namely the gasoline is of high specific energy for the long driving range while the battery is of high specific power for assisting fast acceleration and providing emission-free operation. Figure 3 shows the characteristics of various EV energy sources.

Figure 3. Characteristics of various EV energy sources

2) Batteries

The working conditions of batteries in EV and Hybrid Electric Vehicle HEV are quite different with that in other applications. Therefore the performance requirements of EV batteries should be fully understood. Table 1 shows the key parameters of EV batteries as compared with the goal figures by the United States Advanced Battery Consortium (USABC). At present, the viable EV batteries include the valve-regulated lead-acid (VRLA), nickel-cadmium (Ni-Cd), nickel-zinc (Ni-Zn), nickel-metal hydride (Ni-MH), zinc/air (Zn/Air), aluminium/air (Al/Air), sodium/sulphur (Na/S), sodium/nickel chloride (Na/NiCl2), lithium-polymer (Li-Polymer) and lithium-ion (Li-Ion) types.
Detailed chemistries of the aforementioned batteries can be found in relevant battery handbooks [4]. It should be noted that these parameters are only for indicative purposes since the data may have wide variations among different battery manufacturers. Even for the same manufacturer, different models of the same battery may also have significant variations because of different tradeoffs among the specific energy, specific power and cycle life. Moreover, these data always change with the advancement of battery technology.

In order to meet the California mandate of on zero-emission vehicles, the development of EV batteries has to be continued and accelerated. It is noted that those batteries with near-term high potentiality are the VRLA, Ni-Cd and Ni-MH. Since the features of the Ni-MH are superior to those of the Ni-Cd except maturity, the Ni-Cd is being superseded by the Ni-MH. Actually, some manufacturers used to produce the Ni-Cd for EV applications have redirected their efforts to the Ni-MH. Thus, in near term, the VRLA is still popular due to its maturity and cost-effectiveness, whereas the Ni-MH is attractive because of its good performances.

On the other hand, those batteries with mid-term high potentiality include the Ni-Zn, Zn/Air, Na/NiCl2, Li-Polymer and Li-Ion. The Li-Ion has been identified by many battery manufacturers to be the most promising mid-term EV battery. The Zn/Air may also be promising because of its excellent specific energy and fast mechanical refueling. However, this mechanically rechargeable battery cannot accept energy resulting from regenerative braking. Since the major drawback of the Ni-Zn, namely short cycle life, is being alleviated in recent development, it may have the potential to compete with the Ni-MH in mid term.

The Li-Polymer has demonstrated to exhibit good performances for EV applications. It is promising in mid term provided that more battery manufacturers are involved to accelerate its research and development.

It should be noted that, in addition to the required performance of the batteries, the battery management system is also prime important to ensure the charging and discharging of batteries are in proper conditions. The replacement and recycling of batteries must also be taken care.

### TABLE I. KEY PARAMETERS OF EV BATTERIES

<table>
<thead>
<tr>
<th></th>
<th>Specific energy (Wh/kg)</th>
<th>Energy density (Wh/l)</th>
<th>Specific power (W/kg)</th>
<th>Cycle life (Cycles)</th>
<th>Projected cost (US$/kW h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>VRLA</td>
<td>30-45</td>
<td>60-90</td>
<td>200-300</td>
<td>400-600</td>
<td>150</td>
</tr>
<tr>
<td>Ni-Cd</td>
<td>40-60</td>
<td>80-110</td>
<td>150-350</td>
<td>600-1200</td>
<td>300</td>
</tr>
<tr>
<td>Ni-MH</td>
<td>60-70</td>
<td>130-170</td>
<td>150-300</td>
<td>600-1200</td>
<td>200-350</td>
</tr>
<tr>
<td>Zn/Air</td>
<td>230</td>
<td>269</td>
<td>105</td>
<td>N.A</td>
<td>90-120</td>
</tr>
<tr>
<td>Li-Polymer</td>
<td>155</td>
<td>220</td>
<td>315</td>
<td>600</td>
<td>N.A</td>
</tr>
<tr>
<td>Li-Ion</td>
<td>90-130</td>
<td>140-200</td>
<td>250-450</td>
<td>800-1200</td>
<td>&gt;200</td>
</tr>
<tr>
<td>USABC</td>
<td>200</td>
<td>300</td>
<td>400</td>
<td>1000</td>
<td>&lt;100</td>
</tr>
</tbody>
</table>

3) Ultra-capacitors

Because of frequent start/stop operation of EVs, the discharge profile of the battery is highly variable. The average power required from the battery is relatively low while the peak power of relatively short duration required for acceleration or hill climbing is much higher. The ratio of the peak power to the average power can be as high as 16:1 for a high-performance EV. In fact, the amount of energy involved in the acceleration and deceleration transients is roughly 2/3 of the total amount of energy over the entire vehicle mission in the urban driving. Therefore, based on present battery technology, the design of batteries has to carry out the tradeoffs among the specific energy, specific power and cycle life.

The difficulty of simultaneously obtaining high values of specific energy, specific power and cycle life has lead to some suggestions that EVs may best be powered by a pair of energy sources. The main energy source, usually a battery, is optimized for the range, while the auxiliary source for acceleration and hill climbing. This auxiliary source can be recharged from the main source during less demanding driving or regenerative braking. An auxiliary energy source which has received wide attention is the ultra-capacitor.

In the foreseeable development of the ultra-capacitor, it cannot be used as a sole energy source for EVs because of its exceptionally low specific energy. Nevertheless, there are a number of advantages that can be resulted from using the ultra capacitor as an auxiliary energy source. The promising application is the so-called battery & ultra capacitor hybrid energy system for EVs. Hence, the specific energy and specific power requirements of the EV battery can be decoupled, thus affording an opportunity to design the battery that is optimized for the specific energy and cycle life with little attention being paid to the specific power.

Due to the load leveling effect of the ultra capacitor, the high-current discharge from the battery is minimized so that the available energy, endurance and life of the battery can be significantly increased. Moreover, compared to the battery, the ultra capacitor can provide much faster and more efficient energy recovery during regenerative braking of EVs. Therefore, as a combined effect of load leveling and efficient energy recovery, the vehicle range can be greatly extended. Notice that system integration and optimization should be made to coordinate the battery, ultra capacitor, electric motor and power converter.
The power converter and corresponding controller should take care both the electric motor and ultra capacitor. According to the goals set by the US Department of Energy for the inclusion of ultra capacitors in EVs, the near-term specific energy and specific power should be better than 5 Wh/kg and 500 W/kg, respectively, while the advanced performance values should be over 15 Wh/kg and 1600 W/kg. So far, none of the available ultra capacitors can fully satisfy these goals. Nevertheless, research and development of ultra capacitors for EV applications are actively engaged by some companies.

III. ELECTRIC COMPONENTS

The electric racing car that is intended to be designed needs to have good qualities in terms of acceleration, handling, efficiency and most important of all, needs to store enough energy to finish the endurance event. Our main design decisions were based on cost, availability and simplicity of the components used. Future iterations on the design could include optimization of components for this application and self-made development of some of the modules that take part on the electrical propulsion system.

The two main aspects of the car that will be discussed are the type of motor to use and what kind of battery technology to use. So, let’s start with the motor. As one can see in table 2 the Induction machine and the Permanent Magnet PM motor are very close. Although, nowadays in the auto industry the PM motors are more used for hybrid vehicles and the induction machines are used in electric vehicles like Tesla Roadster [5], it will be used an PM machine because of it’s higher efficiency, easier controllability and higher power density.

| TABLE II. COMPARISON DIFFERENT MACHINES |
|-----------------|-----------------|-----------------|
|                | DC Motor | AC-Induction | PM Motor |
| Power           | 2        | 3.5           | 4.5      |
| Efficiency      | 2        | 3.5           | 4.5      |
| Controllability | 5        | 3.5           | 4        |
| Reliability     | 3        | 5             | 4        |
| Maturity        | 5        | 4             | 4        |
| Cost            | 5        | 4             | 4        |
| Total           | 22       | 23.5          | 25       |

The motor drive system chosen is a LMC D127 [6], which has a rated power of 25.12 kW continuous and 50.76 kW of peak, a maximum torque of 152 Nm, and weights 22 kg. This weight is almost three times less than the weight of the gas engine. The motor drive chosen is supplied by 144 V and has a rated current of 200 A. The peak of current is 400 A for one minute. This motor allows the use of a single gear ratio, chosen as 4:1.

With this gear ratio the car can reach 85 km/h of top speed, it is still something that needs to be proved in the race track but the average speed in any FSAE track is defined as 50 km/h in the rules. It seems a good compromise between top speed and torque.

Regarding batteries, the technology used was lithium iron phosphate LiFePO4 [7], although it high cost there was no other option available since the other batteries technologies like: nickel-metal hydrogen Ni-MH; nickel cadmium NiCad or Lead Acid would need to have a lot of cells since it’s energy density is smaller than the first ones as well it’s lower specific power. That would make the car heavy and with small acceleration capabilities. Although the high cost of the LiFePO4 battery, this technology is the safest in the universe of lithium technology and has a longer cycle life. It’s necessary between 1500 to 2000 cycles of deep discharge until the user starts to note some losses in the total capacity of the battery.

The lithium iron has at least 5.5 years until it losses 20 % of it’s total capacity, averaging 1 cycle of charge per day. So the best, solution in order to have a safe storage system, with enough energy to finish the endurance run of 22 km regarding to weight and speed is using lithium iron cells. Connecting 160 cells one can get a total of 7.2 kWh of stored energy. Each cell has the capacity to discharge a current of 50 A continuously and 140 A during a short period time of 18 s. The maximum charge current is 30 A.

The controller in this drive system provides optional regenerative braking, since it has a 2 quadrant converter [8]. With this controller we manage the voltage that is supplied to the motor in order to control the current that is fed to the motor. The controller reads the current reference signal and compares it with the current that it’s on the armature circuit. Depending on this difference, the controller supplies a voltage that makes the armature current follow the reference value. When the driver brakes when he approaches to a corner, the voltage across the motor is 0 V and the semiconductors in the converter commutate in order to allow the current to flow from the armature circuit to the storage system allowing the recovery of energy. The semiconductors used are IGBT since, are the only ones that can handle the currents and voltages present in this propulsion system. The MOSFET are quicker to commutate but can not handle this kind of currents and voltages.

The complete vehicle including a driver of 70 kg is estimated to weight 330 kg. This is heavier than a typical FSAE (Formula Society of Automotive Engineers) car, but we nonetheless expected a competitive performance. In figure 4 one can see the back section of an electric formula student. This car is the electric vehicle of Hertfordshire that competed last July in Silverstone, where it won the Class 1A. In the figure is notorious the simplicity of the drive train as well a great amount of volume occupied by the batteries in the place where usually goes the internal combustion engine ICE.
IV. THEORETICAL MODEL

The model implemented is composed by five main systems. Two of them correspond to the previous ones discussed on section II. The five subsystems are: the mechanical system, the storage system and the two quadrant 2Q dc-dc converter, the controller and the electric motor. In the mechanical system is calculated the tractive effort necessary to move the race car through a road profile of ever changing speeds.

The cycles are intended to correspond to realistic driving patterns, in a Formula Student track. To calculate this force we use the equations described in the next section. In the storage system it is intended to have in account how does vary the SOC (State Of Charge) with the voltage cell and the current of discharge drawn from the battery. For that, are used curves where the voltages changes with the SOC, as well with different current discharges.

With this one can predict how will change the SOC in terms of different discharge currents, as one can see form figure 5. The race car will be in a constant transient regime. To get the necessary energy one associate cells in series or parallel, in order to get the total amount of energy necessary, depending on the application. The SOC is described by the equation 1.

\[
SOC = \frac{I_n a - I_{u}}{3600 Q} \times 100
\]  

(1)

Where \(I_n\) is the current necessary to the electric motor; \(a\) is the number of cell packs in parallel; \(I_u\) is the already current used and \(Q\) is the total amount of battery charge. The controller system is implemented with a Proportional Integral PI controller in order to control the supply voltage applied to the PM motor. Reducing the supply voltage the torque falls in proportion. One can see that the supply voltage can be controlled simply and efficiently [9]. Finally the electric motor is modeled in MATLAB/Simulink using a existing model but with some minor changes in order to model a PM machine, for instance the PM constant and all the internal connections that exist because of the independent magnetic circuit, that are removed since it’s a PM machine.

In figure 6 one can see the complete system. As the driving cycle is loaded the mechanical subsystem calculates the mechanical torque that will be the reference to the electric motor as well the reference current to the controller. Following this reference torque, the machine produces an electromagnetic torque which moves the vehicle. The storage system supplies energy to the machine depending on the load that is requested by the driving cycle. The controller compares the reference value with the one that is read from the current that flows in the armature circuit. As the error gets smaller the voltage supplied to the machine is smaller, controlling the machine and supplying the necessary energy instead of being always supplying the maximum voltage.
V. RESULTS

A. Acceleration 75 points /1000[2]

Acceleration is simulated on a 75 m run. The first step in vehicle performance is to modeling an equation for the tractive effort. This is the force propelling the vehicle forward, transmitted to the ground through the drive wheels. The force propelling the vehicle forward, the tractive effort, has to accomplish the following: overcome the rolling resistance; overcome the aerodynamic drag; provide the force needed to overcome the component of the vehicle’s weight acting down the slope; accelerate the vehicle, if the velocity is not constant. The total tractive effort is the sum of all these forces:

\[ F_{te} = F_{rr} + F_{ad} + F_{la} + F_{waal} \]  

(2)

Where: \( F_{rr} \) is the rolling resistance force; \( F_{ad} \) is the aerodynamic drag; \( F_{la} \) is the force required to give linear acceleration; \( F_{waal} \) is the force required to give angular acceleration to the rotating motor [4]. Thus,

\[ F_{te} = \frac{g}{R_{wheel}} T \]  

(3)

Substituting eq. 3 in 2 and developing eq. 2 we have:

\[ \frac{g}{R_{wheel}} T = \mu r r m g + 0.625 A C v^2 + \left( \frac{m v^2}{\eta g r^2} \right) \frac{d v}{d t} \]  

(4)

\[ T = \frac{K U - K^2 \omega}{R a} \]  

(5)

In equation 4, \( G \) is the gear ratio; \( R_{wheel} \) is the radius of the wheel which is 0.25 m; \( \mu r \) is the coefficient of rolling resistance which we used 0.007; \( m \) is the mass of the vehicle; \( g \) is the gravitational acceleration which is 9.8 m/s\(^2\); \( A \) is the frontal area of the formula race car with 0.7 m\(^2\); \( C \) is the drag coefficient and was estimated as 0.36; \( v \) is the speed of the vehicle; \( \eta_g \) is the efficiency of the transmission it’s assumed to be 0.97, since it’s a simple power train. It is considered that the air density is 1.25 kg/m\(^3\).

The equation 4 holds until the torque begins to fall when, \( \omega = \omega_c \), where \( \omega_c \) is the critical angular speed. After this point the torque is governed by equation 5, where \( K_t \) is the permanent magnets constant, \( R_a \) is the armature resistance and \( U \) is the voltage.

If we substitute this, and the other constants, into equation 4 one have the equation necessary when the torque falls as speed increases. Since in equation 4 almost all terms are constants and the team knows it’s values, from previous testing one can calculate how much time it takes to accomplish the 75 m. In figure 7 we have a graph with the distance over time to accomplish the acceleration run. In 4.6 s the car runs the 75 m, that’s slower than the conventional formula, which has done 3.95 s. The electric car is 14 % slower than the conventional car, although the electric car is 13 % heavier than the conventional. So, we can conclude that the performance in terms of kg/hp in both cars are the same, since drag, rolling friction are the same because the chassis and suspension is the same, the only change occurs in the power train.

![Acceleration run](image-url)

With the results from the previous graph one can compute a vector with the different velocities in the 5 seconds of the acceleration run. This vector can be used as the input file to the MATLAB/Simulink model and compute all the electric variables. In figure 8 one can see how the current varies along the acceleration run. As one can see the maximum current value is 655 A. From the electric machine’s datasheet one knows that the peak current allowed is 400 A for a time interval of ten minutes. In other words, the machine supports 168 kJ of energy in one minute. This means that theoretically the electric car can produce as much torque as one want, since one does not drawn current that in a time interval does not produce as much heat as 168 kJ of energy. The maximum current is also limited by the discharge current of the batteries. The total amount of current that can be drawn from the batteries is 700 A for a period of time of 18 second pulse. For this case it’s drawn 655 A during 3.5 seconds, the total amount of energy produced is 26.3 kJ. It’s important to note that the performance of the conventional formula race car in this event is at the top of its capabilities, as well as the drive cycle demanded to the electric formula race car. In the case of the sprint and endurance event the performance of the conventional car which is imposed as the drive cycle to the electrical car, is not at the maximum capabilities of the first one, due to the fact that it is not the main goal to evaluate the pure performance of the electric car but instead it’s energy requirements.
B. AutoX- Sprint 150 points/ 1000[2]

To this event that is done around a track of 830 m one can calculate the total amount of energy that is consumed along a lap is 878.2 kJ, as one can see in the figure 9. So, per lap, it is consumed 0.244 kWh of energy. The average current drawn of the system per lap is 168.8 A. With this result one can see that the machine per lap is not pushed beyond it’s limit of rated current, which is 200 A. That’s an important result that can guarantee that in the endurance the machine will not be overloaded.

The maximum current drawn from the batteries during the sprint event is 660 A during 0.2 seconds, as one can see in the figure 10. Note that the maximum current is 13.36 C which is 133.6 A per pack. Since it’s five packs the total amount of current is 660 A.

C. Endurance 425 points/ 1000[2]

This is the most important event in the several ones that take place in any competition of formula student. Repeating 28 times the data that one has for the sprint event one can accomplish the 22 km of the endurance run. Thus, as we can see in the figure 10 after 1513 s which is 25 minutes, the electric car finishes the endurance with 6.1 % of it’s total energy. The storage system starts the endurance run with 7.2 kWh of energy and consumes along the 22 km 6.7 kWh. Comparing this result with the one obtained per lap for the Sprint event one can see that in the endurance the amount of energy consumed is superior than the predicted using the data calculated from the sprint event, due to the fact that as the SOC (state of charge) gets lower the current drawn from the storage system needs to be higher, because of the increase in the internal resistance and the lower voltage in the cells of the battery system. That is why the energy used during the endurance is 6.7 kWh instead of the 5.9 kWh predicted.
It’s assumed that both cars, the conventional and electrical, raced in similar track conditions and driving cycle. Assuming that the gas engine formula race car have an efficiency of 20 %, knowing that the car consumed 3.67 l to perform the 22 km and knowing the energy density of the gasoline one can compute it to a kWh result. So the gasoline car used 35.27 kWh of energy, but since the system is assumed to have 20 % of efficiency, only 7.1 kWh was used to move the car. Using this result and comparing it with the amount of energy consumed by the electrical car and knowing that the electrical car is 15 % heavier (30 kg), it consumed less 5.6 % of energy.

Although the regenerative braking system is too simple and needs further studies and improvements, it gives an estimation of the total amount of energy that can be recovered in braking. In the model implemented which is represented in figure 12 it is assumed that only 17.1 % of the total amount of energy that the car has before braking is recovered. This is due, to the inefficiencies of the different subsystems. Only 50 % of the kinetic energy of the car can be recovered in braking (rule 3.3.2) [1]; only 45 % is used to regenerative braking, since the brake bias is 45-55 (front, rear); 95 % is the efficiency of the converter; the efficiency of the energy transferred to the batteries is of 80 %.

With the previous assumptions, the energy recovered by regenerative braking during the endurance is 20 % of the total amount of energy consumed. It represents almost 20 kg saved in weight, which means that the car could have almost the same weight as the conventional formula race car. With this save in weight the performance of the car will undoubtedly increase, since the mass to accelerate would be smaller, as the consumed energy.

VI. FUTURE WORK

Although much testing of the prototype vehicle and its components remains to be done, our initial simulations highlight the importance of improvements in several areas.

Implement new PWM control methods to increase efficiency (lowering the losses by the switching of the semiconductors), reliability and extend battery lifetime.

Create a thermal model to simulate the heat produced in the energy storage system and electric motor for a given current.

Optimizing the motor control strategy offers opportunities for performance improvement with few hardware changes. Ensuring that the controller aggressively keeps the motor at its (thermally-limited) peak torque or power is important, to realize its full capability in race events.

The motor control could also be adapted for acceleration events by allowing the driver to establish a high rotor flux in advance of commanding any torque, in order to reduce the time required to increase the torque from zero to maximum.

Strong regenerative braking on only the rear axle upsets the front/rear brake bias and wreaks havoc with the tires' road-to-rubber friction circles, making the car prone to oversteer instability. The optimal solution would be to modify the drive train to couple all four wheels. This could improve acceleration, but would definitely improve handling during “trail-braking” while entering corners [8].

There are also energy efficiency considerations: any race car benefits from better efficiency but electrics can derive additional advantages from efficiency improvements, because these would allow for reduction in size and weight of the
onboard energy storage system. Since the front brakes do more of the work to stop the car, ignoring the front brakes for regenerative braking sacrifices a significant amount of potential regenerative energy capture.

Regenerative braking also reduces the workload on the vehicle's mechanical brakes, lowering the heat dissipation requirements. This reduces the potential for brake fade and could also allow a reduction in the mass of calipers and rotors. In the previous car the brake bias was settled as 70 - 30 % front and rear respectively.

VII. CONCLUSIONS

It was proven that an electric vehicle can offer significant advantages under formula racing rules. An electric power train was modeled and simulated in MATLAB/Simulink and proved to be capable of perform equally as a conventional formula race car, in terms of kg/hp. It was also proved that the electric car is much more efficient than a conventional one.

In figure 13 one can see a complete assembly of the electrical car, with the correct location where will be the energy storage system, motor and controller.

In table III one can see the components that were chosen and its cost.

<table>
<thead>
<tr>
<th>Componentes</th>
<th>Custo (€)</th>
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</table>
| Battery system LifeBATT, LiFePO4 | *1.44 kWh = 2664  $ 
~1782x 5 = 8910 € |
| Controller Alltrax 2 Q, DCX 600 | ~1500 € * |
| Motor LMC 2D127, Lynch Motors | ~3.000 €* |
| Total | 13.410 € |

REFERENCES

[9] G.Terörde, “Electrical drives and control techniques” acco