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PROGETTO DEL SISTEMA DI ACCUMULO ENERGETICO PER UNA VETTURA ELETTRICA DI FORMULA SAE

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Contents

Abstract

This thesis analyses and explains the design work-flow used to create the battery pack of the new Formula SAE electric vehicle of the University of Pisa. The project starts with Formula SAE rules analysis in order to understand how they reflect on the design, what is the traction system general shape they require and what devices have to be included inside of it, then a state of the art analysis is performed with the purpose of realise how other Formula SAE vehicles are designed. As soon as necessary devices are categorised, commercial solutions available on the market are examined and selected, trying to obtain the best trade off between costs and performance and then the attention is focused on the battery pack mechanical layout, that is a pretty innovative part of this thesis: to get Formula SAE requirements about serial production of designed vehicles, a PCB is used to manage signal connections between BMS slave boards.

At the end of the text simulations are performed to check and evaluate battery behaviour during an endurance event. Each cell has been carefully modelled by an equivalent circuit and electric simulations of an entire race are executed to check the real performance of the battery providing power and energy to the vehicle. Thermal simulations by finite element analysis software are implemented to check temperature trends inside the battery and carefully control that the safe operating temperature of Lithium batteries is never exceeded , and in case, find the simplest and reliable cooling techniques guaranteeing sufficient performances.

Introduction

Contemporary societies are growing up, and they will be growing faster than now over the next years. At the same time, the need for mobility will also increase. In fact, in the next 50 years, the global population will increase from 7 billion to 10 billion and the number of vehicles will increase from 700 million to 2.5 billion. [1] If all these vehicles are propelled by internal combustion engine, pollution and the lack of oil will be the greatest problems over the next years. According to the International Energy Outlook, the transportation sector is going to increase it's oil consumption up to 55% by 2030 [1], so a revolution in this area will become fundamental. The bet is in the electric mobility, which has reached the attention of researchers and which, mostly supported by technical development, seems to be the most promising technology for future mobility.

This thesis analyses all perspectives related to the design and realisation of the battery pack for the new Formula SAE electric car of the University of Pisa, and it can be outlined on this way: part one gives a general introduction to electric vehicles; first of all a general definition of an electric vehicle is given, and then the three main types of electric vehicles such as fuel cell (FCVs), hybrid (HEVs) and battery electric vehicles (BEVs) are introduced. According to the purpose of this thesis, the analysis of FCVs and HEVs is fairly general; only a global description of their main concepts is presented, and further reviews can be found in [1] and [3]. Later, the main subsystems building up a battery electric vehicle are analysed: starting from the propulsion subsystem a fairly general analysis of electric motors is done and then the energy source block is exposed, but due to the purpose of this text only batteries are explained. A detailed overview of each battery type is done, and then the main aspects relating to battery management systems such as battery protection, state of charge estimation and cell balancing are introduced. At the end of part one an important aspect related to the battery pack such as thermal management is studied exposing state of the art solutions for air, liquid and phase change material cooling.

The second part of this text covers the battery pack design. Lots of constraints are involved in the project, such as technical limitations, Formula SAE rules and financial problems, so, at the beginning, limiting the project space by introducing boundary conditions is fundamental, thus an overview of the whole SAE electrical rules is done. As soon as technical requirements are understood and the general shape of the electric system required by rules is highlighted the attention is focused on the battery pack design. The first design step is an introductory analysis of other Formula SAE electric vehicles created by top teams, with the purpose of understand typical order of magnitude about important project parameters such as power, voltage and energy. Computer simulations are then performed to refine these requirements and fit them on the new vehicle; then, according to results, market analysis is performed to find commercial solutions for each device building up the traction system. The analysis is then conducted exploiting details about connections between different devices, analysing how they should be made, and detailing necessary connectors. At the end of part two, as soon as devices are selected and connected each other, the attention is focused on the battery pack mechanical design and two different layout are analysed: the first one which is pretty a traditional solution is not deeply explained and it is exposed as an example, whereas the second one is deeply explained by three dimensional drawings. This is an innovative mechanical layout, and it may become fundamental if serial productions of the battery pack is performed, as it is simulated by Formula SAE events. Physical problems involved on mechanical layout, such as how cells are electrically connected each other, how battery management system is connect to each cell, and how signal wires connecting close BMS boards are arranged, are deeply explained.

The third part of this thesis explains simulations performed in order to verify electric and thermal behaviour of the battery pack during a typical Formula SAE race. Design validation is a fundamental part of each design, and in case cells are not physically available and real tests can not be performed, reliable models, as used, are necessary. From an electric point of view, each cell has been modelled by an equivalent circuit, and electric simulations are performed to check the electric operation of the whole battery pack during an endurance event, trying to understand the maximum mechanical power allowed to complete the race. Due to power levels, thermal problems can not be neglected especially if Lithium cells are used, and in order to understand how temperature varies inside the battery pack during a race and properly design a cooling system, finite element analysis is done by Comsol simulator. This is another innovative part of this thesis because thermal characterisation of cells are widely available in literature, but cells behaviour inside the battery pack is different due to neighbouring cells effects. A simplified model has been created using finite element software to evaluate thermal behaviour of cells inside the battery pack in order to design the most economic and affordable cooling solution. As soon as a prospective cooling system has been identified, CFD analysis has been executed to provide reliable results using a physically accurate model.

Part I

Electric Vehicles

Contrary to popular belief electric vehicles are not born recently, but their origin dates back to the 19 th century. In fact the first electric cars were developed in 1834 and their evolution grew until the last decade of the 19 th century, when a number of company produced EVs in America, Great Britain and France [1]. During the same years, the combustion engine was born, and both the technologies lived together; neither surmounted the other one essentially because both had some weaknesses: EVs were slow and had short operating time, whereas internal combustion vehicles had start-up problems. Thanks to the invention of the electric starter motor [2], combustion vehicles outdo electric ones, mostly because the short operating time of battery electric vehicles had not been improved too.

Modern electric vehicles are completely different compared to their ancestors which were mainly simple electric driven cars. In fact, today EVs are complex systems, which interacts with their surrounding more than a traditional car. So, giving a complete definition of EVs is difficult, essentially because a modern EV is not just a car, but it is a complex system whose design involves automobile engineering, electrical engineering, electronic engineering and chemical engineering. Generally speaking, according to most of researchers, a modern EV is a vehicle which involves with electric propulsion. With this broad definition in mind, EVs may include battery electric vehicles (BEVs), hybrid electric vehicles (HEVs) and fuel cell electric vehicles (FCEVs) [1].

As the name suggests, a Battery Electric Vehicle is a vehicle that utilises chemical energy stored in rechargeable battery packs and motive power provided by electric motors and motor controllers instead of burning petrol or diesel in an internal combustion engine. This definition is rather strict: in fact it is possible to find vehicles with more complex energy storage devices, e.g., batteries and super-capacitors. Performances and ranges of a Battery Electric Vehicle differs considerably from conventional Diesel and petrol ones. In fact, the range of a BEV and its performances depend firstly on the type and size of battery used and secondly on the weight of the vehicle. Battery chemistry allow a wide variation in energy and power density, from traditional Lead-acid batteries to modern Lithium-Ion packs, and different operating time can be obtained. BEVs are becoming commercial solutions, although their high initial cost, short driving range and long charging time show the limitation of battery-powered vehicles, which are mainly suitable for short range applications, typically commuting ones.

Giving a definition to an emerging technology is not easy and HEVs are an example of this problem: in fact, as proposed by Technical Committee 69 (Electric Road Vehicles) of the International Electrotechnical Commission, an HEV is a vehicle in which propulsion energy is available from two or more kinds of sources, and at least one of them can deliver electrical energy [1]. Based on this general definition, there are many types of HEVs, such as gasoline ICE and battery ones, diesel ICE and battery, battery and FC, and battery flanked by capacitors. However, the last definition is not well accepted from consumer. In fact it is thought to an hybrid vehicle as a vehicle propelled by an internal combustion engine (ICE) and an electric motor (EM). So, according to this definition, it is common to define an hybrid vehicle as a vehicle which uses more than one energy sources, typically two, one of them is a traditional fuel (typically diesel or petrol), and the second one is electric. Hybrid electric vehicles can be an interesting trade off which might be useful to improve the typical operating range of a BEV and reduce pollutants emissions. As a matter of fact, HEVs were developed to overcome the disadvantages of both the ICE vehicles and the "pure" BEVs, thanks to the traditional engine that converts energy from on-board gasoline or diesel to mechanical energy, which is used to drive the on board electric motor or to drive the wheels together with the electric motor. So, the on board electric motor serves as a device to optimise the efficiency of an ICE [3], as well as recover energy during breaking or coasting of the vehicle, and it can uses the power produced by the ICE to charge the batteries. Hybrid vehicles have certain limitations, e.g., increased cost due to the introduction of electric motor, energy storage system and power converters and they have also safety concerns due to the introduction of high voltage in vehicle system.

Fuel cell vehicles use fuel cells to generate electricity typically from hydrogen (but also other fuels could be used) which can be used to drive the vehicle or can be stored in a storage device, typically batteries or ultracapacitors. The main advantage of an hydrogen fueled vehicle is its eco-sustainability. As a matter of fact, if hydrogen is used as a fuel, a fuel cell does not produce pollutants, and its byproduct is simply water. FCVs have long-term potential for future vehicle, although they have issues such as high costs of cells and technical issues in hydrogen storage [3] [4].

The basic configuration of an electric vehicle is shown in figure 1, [1] whereas the three main types of EVs are compared each other in figure 2 [3]. In next chapters the three main subsystems included inside an electric vehicle are analysed.

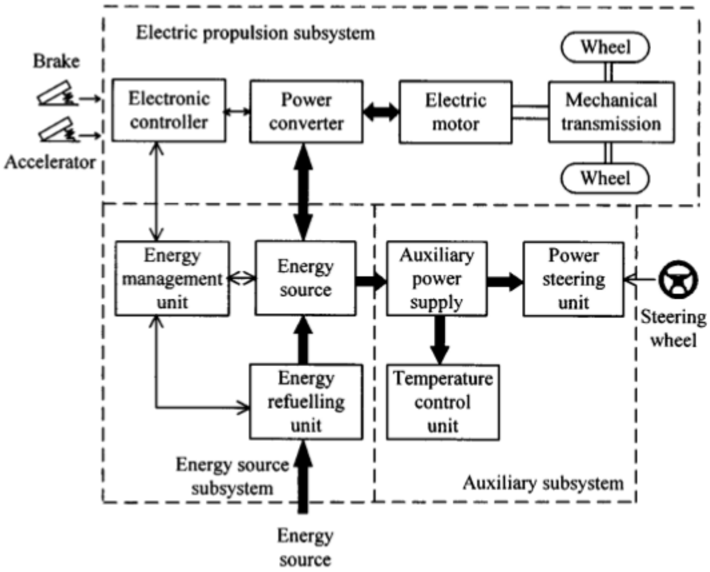

Figure 1: EV composition

Types of EVs	Battery EVs	Hybrid EVs	Fuel Cell EVs
Propulsion	• Electric motor drives	• Electric motor drives • Internal combustion engines	• Electric motor drives
Energy system	• Battery • Ultracapacitor	• Battery • Ultracapacitor • ICE generating unit	• Fuel cells • Need battery / ultracapacitor to enhance power density for starting.
Energy source & infrastructure	• Electric grid charging facilities	• Gasoline stations • Electric grid charging facilities (for Plug In Hybrid)	• Hydrogen • Hydrogen production and transportation infrastructure
Characteristics	• Zero emission • High energy efficiency • Independence on crude oils • Relatively short range • High initial cost • Commercially available	• Very low emission • Higher fuel economy as compared with ICE vehicles • Long driving range • Dependence on crude oil (for non Plug In Hybrid) • Higher cost as compared with ICE vehicles • The increase in fuel economy and reduce in emission depending on the power level of motor and battery as well as driving cycle. • Commercially available	• Zero emission or ultra low emission • High energy efficiency • Independence on crude oil (if not using gasoline to produce hydrogen) • Satisfied driving range • High cost • Under development
Major issues	• Battery and battery management • Charging facilities • Cost	• Multiple energy sources control, optimization and management. • Battery sizing and management	• Fuel cell cost, cycle life and reliability • Hydrogen infrastructure

Figure 2: Characteristics of BEVs, HEVs, and FCEVs

Chapter 1

Electric Propulsion System

Propulsion system inside a vehicle manages the operations to transfer driver decisions' to the engine. It is a complex system which involves different components and has strong interactions with other subsystem, e.g., energy sources. The blocks included in the propulsion system are outlined below:

- Electronic Controller: it is the interface between the driver and the engine, and it is mainly based on control signals transduced by accelerator and brake pedals. As a matter of fact, based on this inputs, the electronic controller provides proper controls to switch on and off the electronic devices used to regulate power flows between the electric motor and the energy sources. It is also possible to find commercial products which include both controller and power converter in a monolithic solution.

- Power Converter: it is the bock which manages power conversion between the motor and the energy sources. As figure 1 suggests, it has a bidirectional channel from/to the motor and from/to the energy sources, because EVs use regenerative braking to generate energy during braking phases, and recharge batteries.

- Electric Motor: it is the main part of the traction system, and it provides the driving force to the vehicle as in traditional cars, but in addiction, in EVs it is used to regenerate energy during braking.

1.1 Electric motor

The major requirements for an electric motor for traction purpose are summarised below:

- High instant power and high power density

- High torque at low speeds for starting and climbing, as well as high power at high speed for cruising.

- 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
- High reliability and robustness for various vehicle operating conditions
- Reasonable cost

Traditionally, DC motors have ever been prominent in electric propulsion because their torque-speed characteristics suits traction requirements well and their speed control techniques are simple. However, DC motors have a commutator; hence, it requires regular maintenance. Recently, technological developments have pushed commutator less motors to a new era, leading with the advantages of higher efficiency, higher power density, lower operating cost, more reliability, and lower maintenance over DC motors. Induction Motors (IMs) are a widely accepted and diffused motor type for EV propulsion because they are mature, highly reliable, and free from maintenance. Alternatively, permanent magnet (PM) brushless motors are also promising because they do not require maintenance and also use permanent magnet, thus high efficiency and power density can be achieved.

1.2 Motor Controller

A motor controller must supervise the operation of an electric motor, providing energy to move the rotor, or giving a path for current produced during regenerative braking. If voltage and current levels of a motor controller are plotted on a Cartesian coordinate system, 4 different operating area can be outlined: on the first quadrant the motor act in forward operation, that is the energy flows from batteries to the electric motor, whereas on the second quadrant, that is the braking one, the motor act as a generator, sending back the energy to the batteries. On the third quadrant the controller provides energy to the motor to rotate in reverse way, whereas on the fourth one the energy flows from the motor, which rotates in reverse directions, to the batteries.

The electronic components used to supply and control DC motors are called Chopper and they are mainly used in step up or step down configurations, both is single, double and four quadrants operation. In contrast, to supply AC motors Inverters are traditionally used especially in multi level configurations including PWM control. Due to the purpose of this text which is mainly focused on battery design, electric motors are not deeply analysed. Additional information about them, including state of the art solutions related to their control can be found in [5], [6], [7], [8], [9].

Chapter 2

Energy Source System

Energy source subsystem has to manage energy reserves of the vehicles, and it can be divided into 2 sections: energy sources and energy management unit. Energy sources include devices used to physically provide energy to the vehicle, whereas energy management unit involves all the electronic circuitry necessary to maintain the energy source into its safe operating area, improving its life cycle avoiding potentially dangerous situations.

2.1 Energy sources

The energy source is the physical device used to produce electric energy and different sources can be used such as fuel cell, battery or ultra-capacitors.

A fuel cell is an electrochemical device that converts the free-energy of an electrochemical reaction into electric energy. In contrast to a battery, a fuel cell generates electrical energy rather than stores it and continues to do it as long as a fuel supply is maintained. Its advantageous features are quiet operation, zero or very low emissions and rapid refuelling. According to the purpose of this text which concerns the design of a BEV, fuell cells are not further examined.

Ultra-capacitors stores energy by physically separating positive and negative charges which are stored on two parallel plates divided by an insulator. Since there are no chemical variations on the electrodes, ultra-capacitors have a long cycle life but low energy density [10]. In contrast, the power density of an UC is considerably higher than that of the battery; in fact ultra-capacitors can be used as assistant energy storage devices for EVs: in urban driving, there are many stop and go situations, and the total power required is relatively low, thus UCs are very appropriate in capturing electricity from regenerative braking and quickly delivering power for acceleration or battery recharging, due to their fast charge and discharge rates.

2.1.1 Battery parameters

A battery is a device that converts the chemical energy contained in its active materials directly into electric energy by means of an electrochemical oxidation-reduction (redox) reaction. In the case of a secondary battery, it is recharged by a reversal of the process.

Desired characteristics of batteries used for electric vehicles are:

- High specific energy and energy density to provide adequate vehicle driving range
- High power density to provide acceleration
- Long cycle life with little maintenance
- Low cost
- Capability of accepting high power repetitive charges from regenerative braking.

Battery is formed by series or parallel connections of cells, and it is used to provide energy to loads, which are the electric motor and the auxiliary systems in an EV. According to the chemistry of each cell, different voltage can be obtained, and series connections are typically used to get the high voltage necessary to supply an electric motor, whereas parallel connections are used to improve provided current and available energy. The most important parameter used to describe and categorise a battery is the available charge, which is usually expressed in Ah at constant temperature and discharge current by cell producers. For example, if a 12 Ah cell is used, it can provide 12 A at constant current and temperature for one hour; 12 is called the C rate of the battery, and it is used to describe charging and discharging currents as multiples and sub-multiples of itself. Battery capacity is not a constant value, thus if a 12 Ah battery is discharged by a 4C current it does not provide 48 A of current for a quarter of hour, because battery capacity change with variations in temperature and discharging current [11]. Typically for lithium batteries which are the state of the art solution for EVs, the higher the discharging current, the lower the related capacity, whereas the lower the temperature the lower the capacity, as shown in figure 2.2 and 2.1 respectively.

During operating phases a battery is discharged, thus its residual charge is highlighted by a normalised indicator called State of Charge (SoC), the equivalent of a fuel gauge in traditional cars, which is conventionally 1 for a fully charged battery and 0 for a fully discharged battery. SoC influences the electric behaviour of a battery, and relationships between the voltage and the SoC of a cell, at constant discharge current and temperature, is shown in figure 2.3. Another indicator called Depth of Discharge (DoD) represents

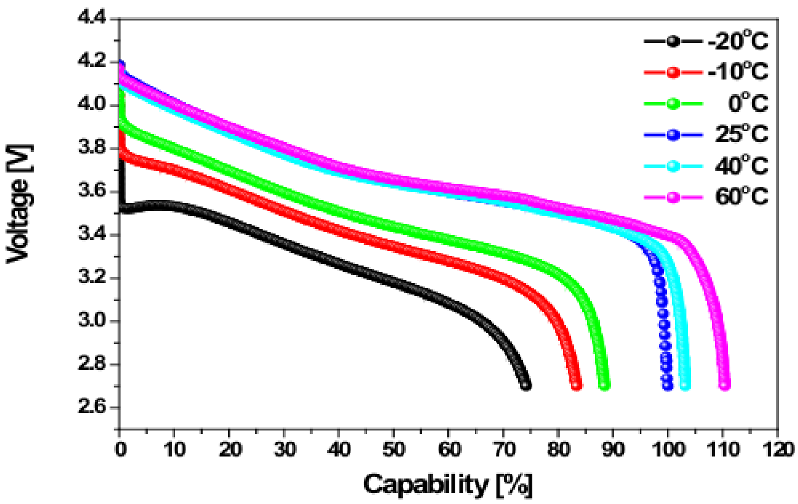

Figure 2.1: Voltage vs. nominal capacity at vary temperature and constant current

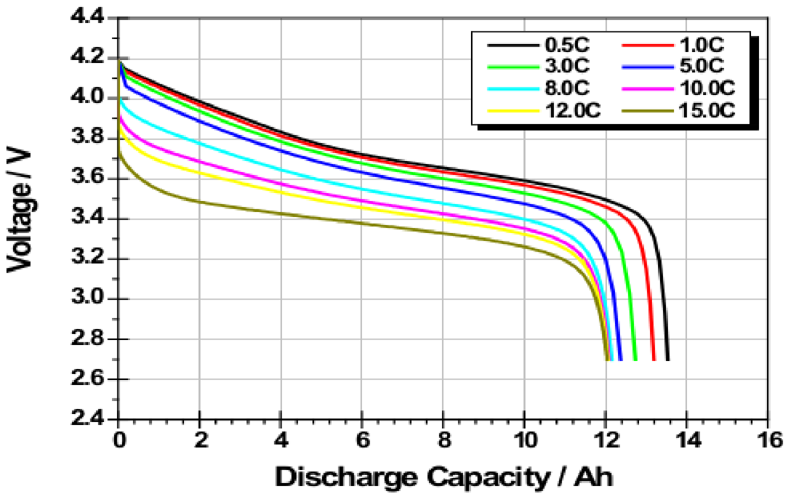

Figure 2.2: Voltage vs. capacity at vary C rates and constant temperature

the quantity of energy used, thus it can be thought as the complement of SoC.

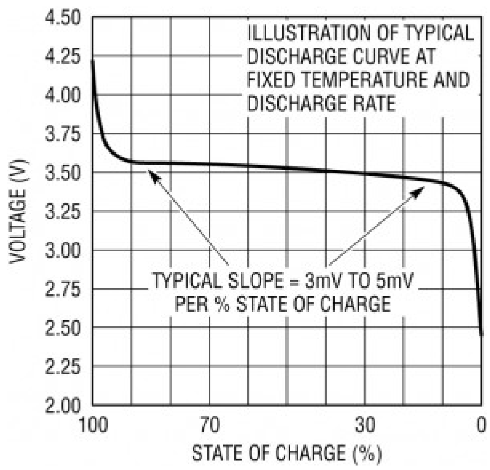

Figure 2.3: Voltage vs. SoC at constant C rates and temperature

Secondary batteries are the main energy sources of a BEV, and the most important types used for electric traction are Lead-Acid, Nickel-Metal Hydride and Lithium ones.

2.1.2 Batteries for electric vehicles

Lead-Acid Batteries Lead-acid batteries are the most commercially mature rechargeable battery technology, with over 20 years of industry usage and they are most commonly used in automobiles as starting lightning and ignition. Lead-acid batteries have about 800 life cycles but their lifetime varies greatly based off of usage, discharge rate, and number of deep discharge cycles. The OCV of a Lead-Acid battery is about 2,1 V [13] on a fully charged cell, and lead to 1,7 V on a discharged one. They also have very low energy density (about $\frac{35\,\mathrm{Wh}}{\mathrm{kg}}$) [12] compared to other battery technologies, whereas their main advantage is their low cost.

During charging, hydrogen is produced at the negative electrode thus if the battery is overcharged it suffer of water loss. This is mitigated in utility scale installations through the use of Valve-Regulated Lead-Acid (VRLA) batteries, which automatically allows recombination of gas.

Nickel-Metal Hydride (NiMH) Batteries NiMH batteries have been the chemistry of choice for EV and HEV applications during the nineties and the early noughties due to their relatively high energy density (about $\frac{70\,\mathrm{Wh}}{\mathrm{kg}}$) [12], proven safety, wide operation temperature ranges, and long life. The best operation performance is achieved when discharged at 20% to 50%

of the rated capacity whereas if repeatedly discharged at high load currents, their life is reduced to about 200 or 300 cycles.

The significant disadvantages of NiMH batteries are the high rate of self-discharge and their memory effect; in fact NiMH batteries typically lose 20% of their charge on the first day and 4% per day of storage after that and in addiction the energy stored into a cell is reduced if the cell is recharged before it has been completely discharged. This memory effect is inherited from Ni-Cd batteries of which NiMH are successors, and it occurs due to the modification of the crystal structure of nickel hydroxide.

A fully charged cell supplies an average voltage of 1,25 V [14], down to about 1,1 V at completely discharged cell. When overcharged, NiMH batteries use excess energy to split and recombine water, thus they are maintenance free. However, if batteries are charged at excessively high charge rate, hydrogen buildup can cause cell rupture, whereas if a battery is over-discharged, it can be reverse-polarised, leading to its destruction.

Lithium Batteries The main categories of Lithium Batteries used in automotive applications are Lithium ion (Li-ion) and Lithium Polymer (LiPo) that can be thought as an evolution of Li-ion ones.

Li-ion Batteries Lithium-ion battery technology has been first commercialised in 1991 by Sony Corporations and its typical applications include portable equipment, laptops, cameras, mobile telephones, and portable tools. Due to its high energy density, Li-ion is the main technology used for batteries in contemporary EVs, and their cost is actually about 800 $\frac{€}{\mathrm{kWh}}$.

The nominal open circuit voltage of a Li-ion battery is 3,6 V reaching 4,2 V at fully charged stage and about 2,8 V at fully discharged stage. Advantages of Lithium-ion batteries include high energy and power density (about 170 $\frac{\mathrm{Wh}}{\mathrm{kg}}$ and 360 $\frac{\mathrm{W}}{\mathrm{kg}}$ respectively) [12], even if they depend mainly on the chemistry used for their cathode, no memory effect, long calendar life and medium self-discharge rate. Li-ion cell can be used with higher current levels than other cells, but some problems have to be solved: to ensure safe operation, it is mandatory to use a battery management system to at least provide over-voltage and under-voltage protections, which act to avoid the voltage to go out of the safe operating range. It is also important to provide over-temperature protection, to ensure the temperature is lower than 60 degrees, which is the maximum allowed temperature of Lithium batteries to avoid chemical damaging.

Different cathode materials are used for Li-ion batteries, and the most interesting for electric vehicle is the $LiFePO_4$ which is mainly used for safety purpose; in fact, in case of misuse, they reduce fire and explosion risks. $LiFePO_4$ batteries suffers from low energy density (about 100 $\frac{\mathrm{Wh}}{\mathrm{kg}}$) [15] compared to Lithium Polymer ones, whereas their power density is higher than Polymer ones (about 300 $\frac{\mathrm{W}}{\mathrm{kg}}$). Their nominal voltage is 3,2 V and it is fairly constant during the operation, reaching 2,8 V at fully discharged and 3,6 V at fully charged stage. They also dispose of about 2000 life cycle at 100% of DOD, whereas their price is relatively high, up to 1200 $\frac{€}{\mathrm{kWh}}$.

LiPo Batteries Lithium Polymer batteries are an evolution of Li-ion ones, based on the way the electrolyte is stored inside the cell. Their open circuit voltage range start from 2,7 V at fully discharged state to 4,2 V at fully charged state, with an average voltage conventionally chosen to be 3,7 V. Their main advantages are high power and energy density compared to other Lithium battery (about 200 $\frac{\mathrm{Wh}}{\mathrm{kg}}$ and 900 $\frac{\mathrm{W}}{\mathrm{kg}}$ respectively) which show the possibility of substitute Li-ion technology on future electric vehicles, both to provide wide operating range and peak power. Therefore, this kind of batteries suffers of security risks as Li-ion ones, thus their temperature and voltage have to be checked by a battery management system.

The main disadvantage of this kind of cell is its relative high cost, which vary from 1000 up to 1600 $\frac{€}{\mathrm{kWh}}$.

2.1.3 Battery models

Future technologies related to electric vehicles are the most promising alternatives to traditional cars but these new technologies will heavily depend on battery packs, thus it is extremely important to develop accurate battery models that can conveniently be used with simulators of on board power electronic systems. Researchers around the world have developed a wide variety of models with different degrees of complexity. Electrochemical models, mainly used to optimise the physical design aspects of batteries, characterise the fundamental mechanisms of power generation and relate battery design parameters with macroscopic (e.g., battery voltage and current) and microscopic (e.g., concentration distribution) information. However, they are complex and time consuming because they involve systems of coupled time-variant spatial partial differential equations requiring days of simulation time to be solved, complex numerical algorithms, and battery-specific information that is difficult to obtain, due to the proprietary nature of this technology [16]. Mathematical models, mostly too abstract to embody any practical meaning but still useful to system designers, adopt empirical equations or mathematical methods like stochastic approaches to predict system level behaviour, such as battery run-time, efficiency, or capacity. However, they cannot offer any I–V information that is important to circuit simulation and optimisation.

Electrical models are electrical equivalent models created by a combination of voltage sources, resistors, and capacitors for co-design and co-simulation with other electrical circuits and systems. For electrical and electronic engineers, electrical models are more intuitive, useful, and easy to handle, especially when they are used in circuit simulators. Most of these electrical models fall under three basic categories: Thevenin, impedance, and run-time based models, as shown in figure 2.4. In automotive applications, mixed solutions composed of Thevenin and run-time based model are typically used.

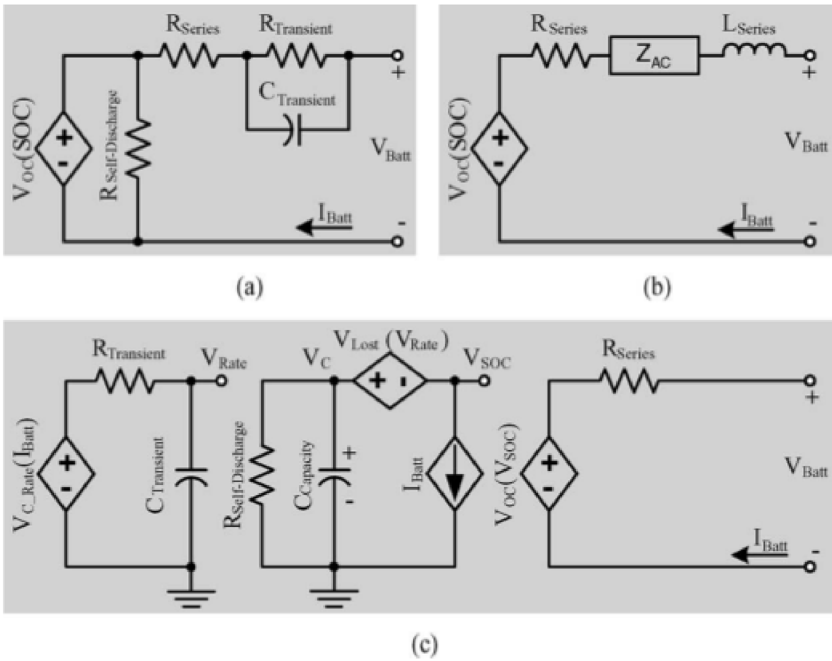

Figure 2.4: (a) Thevenin, (b) impedence and (c) runtime based electrical models

Thevenin model The easiest model consists of an ideal battery with an open circuit voltage E and a constant equivalent internal series resistance. This model does not take into account the varying characteristic of the internal impedance with state of charge, electrolyte concentration and sulfate formation. Another disadvantage is that this model can not reproduce the transient response of the battery which is extremely important whenever the load dynamically require a variable amplitude current. In addition, the voltage E can not be considered constant because its value reduces as long as the battery discharges. This simplified model is only applicable in some circuit simulations where the energy drawn out of the battery is assumed to be unlimited or where the state of charge is of little importance. Clearly, for electric vehicle applications, this model is not appropriate.

In its most basic form, a Thevenin based model, shown in figure 2.4(a), uses a series resistor (R_{Series}) and an RC parallel network ($R_{Transient}$ and $C_{Transient}$) to predict battery response to transient load events at a particular State of Charge. An increase on the number of parallel RC networks can increase the accuracy of predicted battery response, mainly because battery response is formed by more than one time constants, which can be replicated by different RC networks. The $R_{Self-Discharge}$ resistor is used to reply the self discharge tendency of a cell; its value is high and it can be neglected if desired cell has small self discharge rates, or batteries are not stored charged for a long time. Sometimes is possible to model parasitic effects by a voltage source E_P in series with $R_{Self-Discharge}$ resistor.

Impedence based model Impedance-based model, shown in figure 2.4(b), employ the method of electrochemical impedance spectroscopy to obtain an AC equivalent impedance model in frequency domain, and then use a complicated equivalent network (Z_{ac}) to fit the impedance spectra. The fitting process is difficult, complex, and non intuitive. In addition, impedance-based models only work for a fixed SoC and temperature setting, and therefore they cannot predict battery run-time response.

Runtime based model Run-time based model shown in figure 2.4(c), uses a complex circuit network to simulate battery run-time and DC voltage response for a constant discharge current in SPICE-like simulators, but they can not predict transient response for varying load currents accurately.

Mixed model Mixed models combine both the characteristics of Thevenin and run-time models, and an example is shown in figure 2.5. On the left,

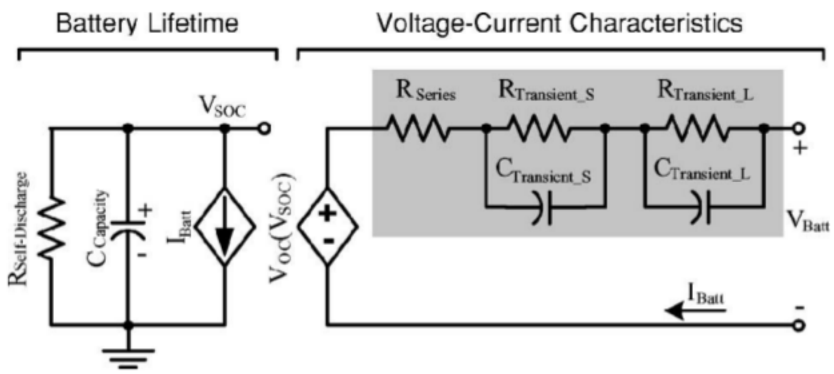

Figure 2.5: Mixed model

a capacitor ($C_{Capacity}$) and a current-controlled current source, inherited from run-time based networks, model the nominal capacity and its run-time behaviour both in charging and discharging phases. The RC network, similar to that in Thevenin based models, simulates the transient response. To bridge SoC to open circuit voltage, a voltage-controlled voltage source is used. This model predicts run-time behaviour, both steady state and transient response and also capture some batteries electrical characteristics such as usable capacity ($C_{Capacity}$), open circuit voltage, and transient response. These characteristics are dependant on temperature, life cycles, age etc. as summarised in figure 2.6. The model works as follows: assuming

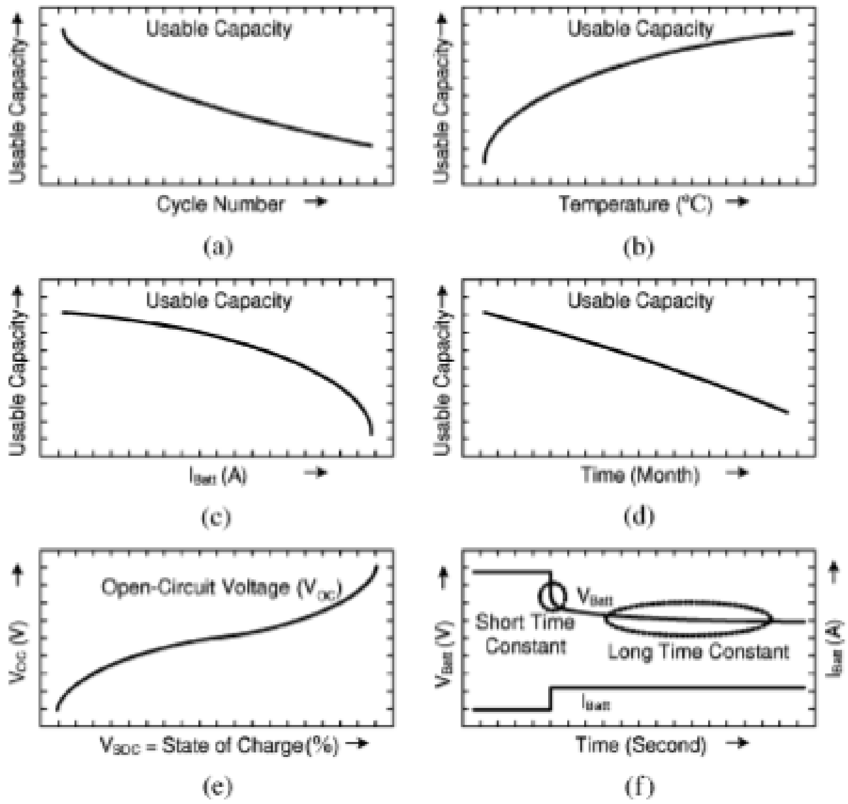

Figure 2.6: Typical battery characteristic curves of usable capacity versus (a) cycle number, (b) temperature, (c) current, and (d) storage time, as well as (e) open- circuit voltage versus SoC and (f) transient response to a step load-current event.

a battery is discharged from an equally charged state to the same end-of-discharge voltage, the extracted energy taken from the equivalent usable capacity, declines as cycle number, discharge current, and/or storage time (self-discharge) increases, and/or as temperature decreases, as shown in figure 2.6(a)–(d). Full-capacity capacitor $C_{Capacity}$ represents the whole charge stored inside the battery by converting nominal battery capacity in Ah to charge in Coulomb, including the dependency between usable capacity and temperature, cycle number, age and provided current. Setting the initial voltage across $C_{Capacity}$ (V_{SoC}) equal to 1 V or 0 V, the battery is initialised to its fully charged (i.e., SoC is 100%) or fully discharged (i.e., SoC is 0%)

state. In other words, V_{SoC} represents the SoC of the battery quantitatively. When the battery is being charged or discharged, current-controlled current source I_{Batt} is used to charge or discharge $C_{Capacity}$ so that the SoC, represented by V_{SoC}, dynamically changes. The nonlinear relation between the open circuit voltage (V_{OC}) and SoC shown in figure 2.6(e) is important to be included in the model, thus voltage-controlled voltage source $V_{OC}(V_{SoC})$ is used.

During a step load current event, the battery voltage responds slowly, as shown in figure 2.6(f). Its response curve usually includes instantaneous and curve-dependant voltage drops and the transient response is characterised by the shaded RC network in figure 2.5. The electrical network consists of series resistor R_{Series} and two RC parallel networks composed of $R_{Transient_S}$, $C_{Transient_S}$, $R_{Transient_L}$, and $C_{Transient_L}$. Series resistor R_{Series} is responsible for the instantaneous voltage drop of the step response. $R_{Transient_S}$, $C_{Transient_S}$, $R_{Transient_L}$, and $C_{Transient_L}$ are responsible for short and long time constants of the step response, shown by the two dotted circles in figure 2.6(f).

Theoretically, the whole parameters included in the model are multi-variable functions of SoC, current, temperature, and cycle number. However, within certain error tolerance, some parameters can be thought to be independent or linear functions of some variables for specific batteries. For example, a low capacity battery in a fairly constant temperature application can ignore temperature effects, and a frequently used battery can ignore self-discharge rates without suffering any significant errors [16].

2.2 Energy Management Unit

The energy management unit, as the name suggests, is the part of the energy subsystem which control the run-time behaviour of energy sources in order to measure important parameters and keep each cell working in safety conditions, inside its safety operating area, avoiding critical situations such as overcharging or undercharging and thermal problems. In case of BEVs supplied by Lithium batteries, e.g, the temperature of each cell has to be kept less than 60°C and its voltage has to be be maintained between a voltage interval which is conventionally chosen to be higher than 2,8 V but lower than 4,2 V, in order to avoid chemical modifications inside the cell. An energy management unit for BEVs which provide only these basic monitoring features is called Battery Monitoring Unit; however providing only monitoring tasks is not adequate for traction purpose where malfunctioning and services interruptions must always be prevented.

Due to the unavoidable miss-match of production systems, cells inside a battery pack are not identical and thus their capacities are different: this is a critical problem, especially in BEVs, because discharging must stop when the cell with lowest capacity is empty (even though other cells are still not empty); this limits the energy taken from the battery [2]. The problem is the same during charging because the energy provided to the battery is stopped as soon as a cell is fully charged, even if the other ones are not completely filled. To avoid these problems, which may become relevant in electric vehicles, and lead to operating range reductions, the Battery Monitoring Unit has to perform battery balancing and charge redistribution and its name becomes Battery Management Unit.

In order to provide a definition, a Battery Management System (BMS) is any electronic system that manages a rechargeable battery (cell or battery pack), protecting it from operating outside its Safe Operating Area, monitoring its state, calculating secondary data and balancing it. A BMS may monitor different parameters in order to check battery status [17], such as:

- Voltage: total voltage, voltages of individual cells, minimum and maximum cell voltage
- Temperature: average temperature and temperatures of individual cell
- State of charge (SoC): to indicate the charge level of the battery
- State of health (SoH), a variously-defined measurement of the overall conditions of the battery
- Current: current in or out of the battery

and it may protect the cell against:

- Overcurrent (may be different in charging and discharging modes)
- Overvoltage (during charging)
- Undervoltage (during discharging), especially important for lead–acid and Li-ion cells
- Overtemperature
- Undertemperature
- Over-pressure
- Ground fault or leakage current detection

The BMS may also control cells temperature through heaters, fans, air conditioning or liquid cooling which may be activated when the temperature overcomes predefined limits.

Additionally, a BMS may calculate values based on the above items, such as:

- Energy [kWh] delivered since last charge or charge cycle
- Charge [Ah] delivered or stored
- Total energy delivered since first use
- Total operating time since first use
- Total number of cycles

The BMS also control battery recharging by redirecting recovered energy (i.e. from regenerative braking) back into the battery pack and it may report calculated or measured data to an external device, using communication links such as:

- Serial communications, e.g., RS-232 or CAN serial communications
- Direct wiring
- Wireless communications

BMS topologies fall in 3 categories:

- Centralized: a single controller is connected to the battery cells through a multitude of wires
- Distributed: a BMS slave board is installed at each cell, with just a single communication wire between the boards and the controller
- Modular: a few controllers, each handing a certain number of cells, with communication between the controllers

Centralised BMS are most economical, least expandable, and are plagued by a multitude of wires. Distributed BMS are the most expensive, simplest to install, and offer the cleanest assembly. Modular BMS offer a compromise of the features and problems of the other two topologies.

2.2.1 SoC estimation

The term State Of Charge (SoC) may be confusing. The main reason for this is that a distinction must be made between the charge inside the battery and the portion of this charge that will actually be available under actual discharge conditions. As previously explained, a significant difference may occur between these two, for example when a battery is discharged at low temperatures. In an attempt to avoid further confusion, the following definitions [19] are used:

- State-of-Charge (SoC): The charge that is present inside the battery which can be expressed in percentage of the maximum possible charge. A practical way to define the battery State of Charge (SoC) is to start from a quantity called extracted charge defined as:

$$Q_e(t) = \int_0^{\tau} I_{cell}\, dt$$

Then, the definition of SoC is:

$$SoC = 1 - \frac{Q_e}{C_n}$$

where C_n is the nominal capacity of the battery.

- Remaining capacity (Cap_{rem}): The available charge under the valid discharge conditions, thus Cap_{rem} is equal to or smaller than SoC, depending on conditions. Cap_{rem} can also be expressed in percentage of the maximum possible charge

State of charge estimation is one of the most important task of Battery Management Systems in hybrid and electric vehicles. Knowing the amount of charge stored in each cell of a battery is indeed crucial for effective battery utilisation that prevents cells from damaging extending their lifetime in particular for lithium batteries, that are less tolerant to overcharging and deep discharging. In addition, State of Charge estimation is the basis for balancing strategies, which lead to a better utilisation of the battery pack extending its lifetime.

State of Charge estimation in a vehicle is a very challenging task because the estimator has to rely on on-board current and voltage measurements, which are typically noisy and inaccurate, but it should also provide reliable estimation in every possible battery operating condition [18]. The calculation may also include additional errors to the estimation process, but a distinction has to be observed: in contrast to BEV applications which involve primarily battery discharge, an HEV application may involve repeated charge-discharge cycles. This distinction is critical: in BEV applications, complete stationary recharge allows the SoC estimation algorithm to be reset to an accurate initial condition; therefore, estimation errors do not accumulate over multiple discharge/recharge cycles. In HEVs instead, batteries are used to improve vehicle efficiency, thus they are never completely discharged: if an error is done, the estimation tends to become inaccurate and unreliable, because the error is never removed, due to the absence of a reset situation.

To perform State of Charge estimation, lots of methods have been realised [19], and they can be divided into the following categories:

- Direct measurement: this method uses physical battery properties, such as voltage and impedance variations during discharging or charging phases.

- Book-keeping systems: Coulomb counting method uses discharging current as the input and integrates battery current over time to calculate the SoC. Book keeping systems use Coulomb counting method with compensations for discharging efficiency, self discharge, capacity losses etc.

- Adaptive systems: these methods can automatically adjust the estimation process for different operating conditions, such as different C rates, temperature etc.

- Hybrid methods: these systems combine the advantages of each SoC estimation method to provide more precise and reliable estimation performance.

In automotive applications model based algorithms are the most promising solutions, mostly because they do not require long training periods as neural networks do, and also provide reliable estimation. In systems that are frequently charged and discharged, such as EVs, Coulomb Counting can be an interesting solution, due to its simplicity.

Direct measurements The direct measurement method is based on a reproducible and pronounced relation between a measured battery variable and the SoC. This battery variable should be electrically measurable in a practical set-up. Examples of variables are battery voltage, battery impedance and voltage relaxation time after application of a current step [19]. Most relations between battery variables depend on the temperature, thus the battery temperature should also be measured and the relation f_T^d between measured battery variables and the SoC, in which d means a generic variable and T the temperature as a parameter, have to be known and stored in the system, allowing indirect measurements. In fact the main advantage of a system based on direct measurement is that it does not have to be continuously connected to the battery. Measurements can be performed as soon as the battery is connected, then the SoC can be directly inferred from the function f_T^d. The main problem is determining the function f_T^d, which should describe the relation between the measured battery variable and SoC under all applicable conditions, including spread in battery behaviour.

Open circuit voltage If the relationship between OCV and SoC is measured and known, thus State of Charge estimation might be achieved by using this characteristics, which can be stored inside a memory; this is useful for lead acid batteries, which have a fairly linear curve, whereas it is more difficult for lithium batteries. In fact, this method have some practical drawbacks: according to previously explained battery models, the open circuit voltage become the electromotive force (EMF) in value, when the current is zero. In practise applications, especially for deeply discharged batteries, the OCV may takes minutes to reach the EMF value. In addiction, the fairly constant drop in voltage, between SoC= 20% and SoC=80% lead to a considerable variation of SoC due to a small variation in voltage, thus this method is not reliable for lithium accumulators.

Book keeping systems Book-keeping is a method for SoC indication that is based on current measurement and integration. This can be denoted as Coulomb counting, which literally means ‘counting the charge flowing into or out of the battery’. The basic idea of Coulomb counting is fairly easy: assuming the initial SoC ($SoC(0)$) is known, SoC evolution can be evaluated by integrating the battery current, as shows in the following equation:

$$SoC(t) = SoC(0) - \frac{1}{C} \int_0^{\tau} I_{cell}\, dt$$

where I_{cell} is the cell current (positive during battery discharge), and C is the nominal cell capacity. This approach, however, is very sensitive to measurement errors, in particular offset and temperature drifting of the current sensor, which may lead to large SoC errors over time, because of the current integration.

The Coulomb counting algorithm requires to be correctly initialised with the initial SoC value, which may not be available, as it happens in HEVs where the battery is never fully charged or discharged, and also offsets and parameters drifts have to be compensated to achive a precise and reliable SoC estimation. Book keeping systems use Coulomb counting method but also include compensations for undesired variations.

Adaptive systems The main problem encountered designing an accurate SoC indication system is the unpredictability of battery behaviour that depends strongly on operating conditions. A possible solution is to add adaptivity to a system based on direct measurement, book-keeping or a combination of them. The basic principle to add adaptivity to an SoC indication system is depicted in figure 2.7. Measured battery variables I_{bat}, T_{bat} and V_{bat} are inputs of the adaptive model, which estimates battery behaviour in the form of output vector Y_m on the basis of these inputs. Adaptivity of the model is based on a comparison of Y_m with observed battery behaviour in the form of vector Y_b, obtaining an error signal $\mathcal{E}$, which is input to an Adaptive Control Unit. The unit updates model informations updating parameter values or even by changing model description. As a result, the model is adapted on the basis of the system to which the battery is connected and the error between estimation and observation is minimised.

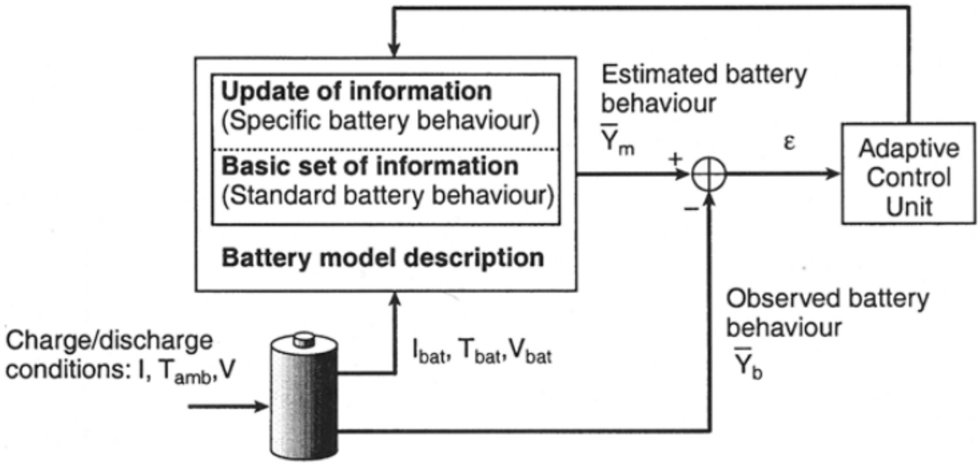

Figure 2.7: Basic principle of an adaptive SoC indication system

Recently, with the development of artificial intelligence, various new adaptive systems based on neural networks for SoC estimation have been developed, but these solutions are mainly research topics, thus they are not explained on this text and can be found in [20].

Hybrid methods The aim of hybrid models is to benefit from the advantages of each method obtaining optimal estimating performance, improving accuracy. The integration of different methods is wide and is not further analysed in this text, however the most important hybrid methods include Coulomb counting and OCV methods to reinforce the SoC estimation by a double measurement, performed during discharging or charging phases by Coulomb counting, and then checked during equilibrium state by the OCV methods. Another important example of hybrid methods is the usage of Karman Filter to correct the initial value of Coulomb counting method, or estimate the SoC in noisy applications [18]. This application is important in automotive applications, where voltage and current signals are mainly noisy and difficult to measure.

2.2.2 Battery charging

The typical structure of an EV batteries charging system results from the combination of AC-DC and DC-DC converters with the respective digital control system [21]. The AC-DC converter is used to rectify the AC voltage from power grid to a DC voltage whereas the DC-DC converter is used to adapt the rectified voltage to a level compatible with the batteries one and also control batteries during charging process. Regardless to battery charger topology, battery charging phase is fundamental for battery life because lots of physical quantities vary while the electric current provided to the battery is converted by chemical reaction, in order to recharge the battery. It is thought that the purpose of a charger is simply to "refill" the charge tank of the battery, whereas there are many other physical aspects involved in charging process such as temperature, over-voltage and over-current which may reduce battery lifetime. Thus, even if the refilling purpose is the most important aspect of battery charging phase, battery voltage, current and temperature have to be carefully controlled. This aspect leads to a carefully choice of battery charging algorithms which are fundamental to prevents premature failure.

The ability of a cell to accept charge is dominated by the electrolyte concentration in the electrode-electrolyte interface region. The surface area of the electrode and the width of electrolyte reservoir determine how fast the newly accumulated charge can "diffuse" into the electrolyte, thus making room for more charge [22]. An equivalent electrical model which can be used to explain the charging process is shown in figure 2.8. The terminal current

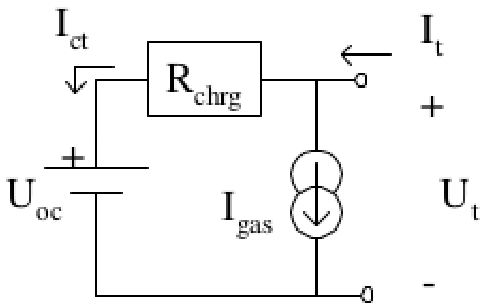

Figure 2.8: Electrical equivalent circuit model of a cell with charging resistance, storage element and gassing current.

I_t is shown entering the cell from the right and it ideally recharges the cell. In real situations, however, parasitic effects occurs, thus the charge Q which enters the electrolyte storage element, U_{oc}, is transported by a smaller current I_{ct}. The difference between I_t and I_{ct} is the parasitic current I_{gas} which model the gas formation during charging phase, whereas the charging resistance R_{chrg} inhibits the charging reaction from taking place. The whole quantities represented in the equivalent circuit are dependent on the SoC; the OCV relationship has been explained in previously chapter whereas the charging resistance and gassing current are fairly constant during most of the charging phase but their value rapidly increase at the end of the charging process. This relationship exploit an important safety problem: at the end of the charging process, gas are usually created inside a fully charged cell, and they may lead to fire and explosion due to overpressure [22]. This safety problem reinforce the need of suitable charging algorithm, to avoid overcharging, overtemperature and cells damage.

Basic Charging Profiles This paragraph discusses the basic charging profiles traditionally used for Lead Acid, NI-Mh and Lithium batteries.

Constant Current Constant Voltage (CC-CV) At the beginning of CC-CV method a constant current equal to, or lower than, the maximum C rate of the cell is applied to the battery under charge until the maximum charge voltage is reached. At that point the charger operating mode turns to constant voltage output, which is maintained across the battery terminals until the charge termination criterion is satisfied, as explained in figure 2.9. Normal charging termination happens when the battery is fully charged. A popular criterion to determine full charge holds that a battery is fully charged when the maximum charging voltage has been reached (thus changing the charge mode to CV), and when the falling value of the charge current (happens after the change to CV) is below a certain fraction (usually 1/30 to 1/10) of the battery maximum charge rate [23]. Another termination approach uses a timeout, stopping the charging after the charger has been in constant voltage mode for two hours, but many other interruption criteria are possible such as cell temperature and gas pressure measurement. Traditionally, at the end of the charging process, if batteries are still under charge, trickle charging is performed, in order to protect cells from overcharging. CC-CV is the most important charging method for Lithium

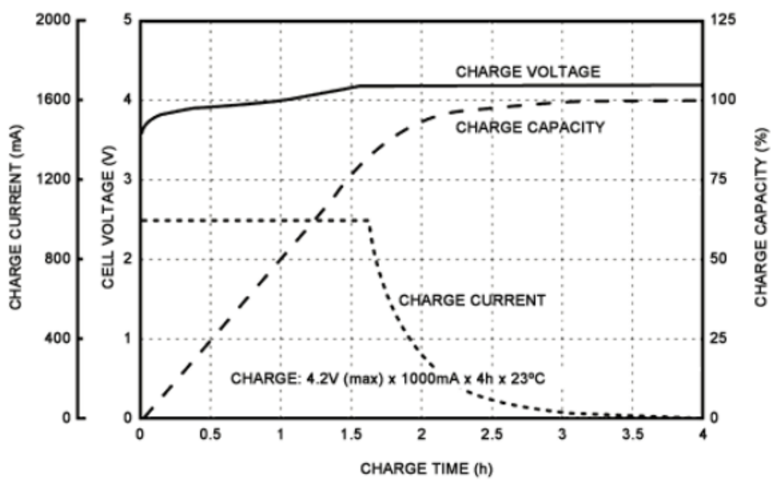

Figure 2.9: Time evolution of CC-CV charge of a Li-on cell.

battery, and in practice it is the mainly used in industrial application.

Pulse trickle charging For batteries which are less thermally stable, or for batteries which are being "fast charged," a pulse type trickle charging is often preferred. In this method, which is often used with VRLA and Ni-MH cells, at the end of the normal constant voltage charging regime, a set of current pulses are applied to the battery and they are usually terminated by a simple timer. The advantage of pulses is that cells inside the battery have time to thermally equalise and the accumulated acid at the electrode-electrolyte interface has a chance to diffuse into the electrolyte.

BMS as charging supervisor Previously explained techniques are traditionally used to control the charging process, as in Lithium batteries where CC-CV is the pretty only accepted method. To obtain a CC-CV charging or any different charging profile, a smart charger, which is mainly a charger with additional electronic logic, is needed. In fact, many chargers have charging profile for a particular type of battery. Experimental results shows that a dedicated charging profile may be the best solutions, but there is also another possibility: the BMS is more able to know when a battery have to be charged (because it knows the voltage of each cell) than the charger (which only knows the total voltage) [24]. Using the BMS to control the charging process and a simple charger with simplified logic could be a reasonable solutions, in order to reduce costs and obtain the same (or even better) performances.

2.3 Battery thermal management

The main goal of batteries inside an electric vehicle is supplying the electric motor and due to unavoidable losses, batteries waste a percentage of the delivered power as heat. Each type of battery has a specific maximum allowed temperature to avoid chemical problems, thus this additional power has to be removed from the battery pack, in order to keep the temperature lower than the maximum temperature level. As a matter of fact, an appropriate thermal management system should be able to keep the temperature between the values to which the battery provide the best performances. This considerations exploit the need to heat the batteries, if the external temperature drops below, for example, 0°C. In fact, as previously explained, batteries' characteristics reduce at low temperature, but due to the purpose of this text, which involves the realisation of the battery pack for a SAE vehicle, whose races take usually place in cold seasons, the heating aspect is not further examined.

Basically there are two main problems caused by temperature. The first one is that during charge and discharge phases temperature must not exceed safety levels decreasing battery performances. Another problem is that the uneven temperature distribution inside the battery pack lead to a localised deterioration. Thereof, temperature uniformity, within a cell and from cell to cell, is important to achieve maximum cycle life of cell, module, and pack. The thermal management system may be passive (i.e., only the ambient environment is used) or active (i.e., a built-in source provides cooling), and it can be also divided into three categories based on medium: air, liquid, phase change material.

2.3.1 Air thermal management

Thinking to use air for battery thermal management may be the simplest approach, and air cooling systems are used due to cost and space limitations. Air cooling may refer to natural or forced convection but according to the experience of commercial electric vehicles it is apparent that air natural convection for battery dissipation is invalid; for example the Toyota Prius supplies forced air from the cabin as thermal management, whereas sport oriented cars like Tesla Roadster need of liquid cooling [25]. In forced convection heat transfer is achieved by directing/blowing air parallel or serial across a battery module or pack.

2.3.2 Liquid thermal management

A battery thermal management system using liquid could be achieved either through discrete tubing around each module or submerging modules in a dielectric fluid for direct contact. A state of the art solutions in liquid cooing is represented by heat pipes. A heat pipe is a heat transfer device that combines the principles of both thermal conductivity and phase transition to efficiently manage heat transfer between two solid interfaces. At the hot interface of a heat pipe a liquid in contact with a thermally conductive solid surface turns into a vapour by absorbing heat from that surface. The vapour then travels along the heat pipe and condenses back into a liquid. The liquid then returns to the hot interface through either capillary action or gravity, and the cycle repeats [26]. Heat pipe are deeply used in battery cooling systems [27] especially in conjunction with sink and air cooling.

2.3.3 PCM thermal management

An ideal thermal management system should be able to maintain the battery pack at an optimum temperature with low volume, weight and cost added [25]. Thermal management systems such as forced air cooling and liquid cooling make the overall system too bulky, complex and expensive due to blowers, fans, pumps, pipes and other accessories, thus solutions using PCM for battery thermal energy management were proposed for electric and hybrid electric vehicle applications. A phase change material (PCM) is a substance with an high heat of fusion which, melting and solidifying at a certain temperature, is capable of storing and releasing large amounts of energy. Heat is absorbed or released when the material changes from solid to liquid and vice-versa. Traditional PCMs, such as paraffin, were taken as the most promising [25] because of large latent heat, nontoxic, not corrosive, stable and low cost. However, pure paraffin suffers from a low thermal conductivity. High thermal conductivity PCM is demand strongly in battery thermal management because if a small volume of the battery has higher temperature than another one, due to an inhomogeneous temperature distribution, heat between the two volumes can be exchanged only by conduction. The main fault in PCM cooling is that if the whole battery pack is submerged in a PCM material, which is solid at temperature lower than its melting point, maintenance inside the battery could become difficult.

Part II

Battery Pack Design

As previously explained, the main part of this text involves the realisation of a battery pack for a racing electric vehicle involved in Formula SAE competitions. As soon as a problem that had never been studied and analysed before is presented, design approach have to be clearly understood to produce an high performance, reliable and low cost solution, respecting strict time dead-line. Typically design methodology firstly require to understand boundary conditions limiting the project, such as rules, costs and time limitations, and then if the project has been analysed and resolved before by other people, it is also important to understand who it has been done. The same design methodology is used during this thesis. In fact, before starting the battery design from scratch, boundary conditions limiting the project space are evaluated. This is done firstly analysing what Formula SAE rules, which must always be fulfil by an FSAE vehicle, impose, and then evaluating design solutions used by other Formula SAE teams involved in electric competitions in order to understand, keep and evolve their choices. In this chapter in fact, battery design is performed starting from general vehicle requirements, moving then to electric configuration and connections and exposing, at the end of the part, a mechanical layout for the entire battery pack. As explained in next section by rules, battery design is tightly coupled with other mandatory components and then their choice, based on a trade off between costs and performances are also explained. All other components which are not related with the battery are not further explained.

2.4 FSAE rules

Formula SAE is an international competition supported by the Society of Automotive Engineers since 1978 with combustion engine vehicles and has recently expanded to include electric vehicle. The competition is held every year at many locations around the world and challenges university students to design, construct and race Formula style vehicles providing an opportunity to learn in a simulated working environment that incorporates with real-world situations. The competition itself compromises of static events where students present details of the design, cost and manufacturing processes and dynamic events that test vehicles acceleration, braking, handling and safety.

The aim of this thesis is to design the battery pack of the new Formula SAE car of the "E-Team Squadra Corse" of the University of Pisa in compliance with the latest Formula SAE rules. In fact the competition imposes strict design guidelines included on the "FSAE rules" book which is the collection of all the technical specifications that must be always fulfil by a SAE vehicle. According to the purpose of this text SAE rules are evaluated in order to extract the general shape of the electric circuitry inside the car, how rules reflect to the battery project and also understand how it should be connected with the other electric and electronic subsystems. The most important electrical rules involved on battery pack design are summarised and commented in this section, whereas other electrical ones which are not connected with battery design are not explained on this text.

2.4.1 Definitions

The uppermost aspect that can be observed in Formula SAE rules is safety. This is also an important foundation of SAE competitions in general, and it reflects in electrical rules with strict definitions on voltage levels: in fact whenever a circuit has a potential difference greater than 40 V DC or 25 V AC RMS it is defined as part of the High Voltage or traction system, whereas Low voltage is defined as any voltage below and including 40 V DC or 25 V AC RMS. This is the most important electrical classification provided by SAE rules: two distinct voltage level must be managed inside the vehicle and this reflect directly to the circuitry: the traction system (TS) circuit is defined as every part that is electrically connected to motors and accumulators and it is an high voltage system by definition, whereas the grounded low voltage (GLV) system of the car is defined as every electrical part that is not part of the traction system and it is a low voltage system. The differences between low and high voltage systems is also highlighted on their connections: the GLV system must be grounded to the chassis as opposed to the traction one, which must be completely isolated from the chassis and any other conductive parts of the car. As explained later, an electronic circuitry called IMD is used to guarantee it. There must be no connection between the frame of the vehicle (or any other conductive surface that might be inadvertently touched by a crew member or spectator), and any part of any traction system circuits. traction system and GLV circuits must be physically segregated such that they are not run through the same conduit, except for interlock circuit connections. Where both traction system and GLV are present within an enclosure, they must be separated by insulating barriers made of moisture resistant. The maximum voltage allowed on the traction system is not strictly defined by SAE rules, but it is different for each different competitions as summarised in figure 2.10.

2.4.2 Wiring

Wires, terminals and other conductors used on the traction system must be sized appropriately for the continuous traction system current and must be marked with wire gauge, temperature rating and insulation voltage rating. The minimum acceptable temperature rating for traction system cables is 90℃. All traction system wiring running outside of electrical enclosures

Competition	Voltage Level
Formula SAE Electric	300 VDC
Formula SAE Brazil	300 VDC
Formula SAE Australasia	600 VDC
Formula SAE Italy	600 VDC
Formula Student	600 VDC
Formula Student Germany	600 VDC
Student Formula Japan	Refer to SFJ website

Figure 2.10: Maximum allowed voltage for different competition

must either be enclosed in separate orange non-conductive conduit or use an orange shielded cable. Wiring that is not part of the traction system must not use orange wiring.

2.4.3 Battery limitations: types, container and connections

According to rules, there is no limit on motor power, whereas there is a limitation on the energy drawn from the battery that must not exceed 85 kW. Violating these values will lead to disqualification for the entire dynamic event in which the violation occurred, and the energy drawn is checked by judges an energy meter, which is also used to evaluate the amount of energy used at the end of the endurance, in order to assign fuel economy scores. Regenerating energy is allowed and unrestricted but only when the vehicle speed is greater than 5 km/h.

The energy storage devices are also strictly restricted by SAE rules: in fact, all types of accumulators except molten salt and thermal batteries are allowed; e.g., batteries, super-capacitors, etc. are allowed, but fuel cells are prohibited. All cells or super-capacitors which store the traction system energy must be enclosed in an accumulator containers. Even the accumulator container is strictly regulated: in fact if it is made of an electrically conductive material, poles of the accumulator segments and/or cells must be isolated from the inner wall of the container with an insulating material that is rated for the maximum traction system voltage. The accumulator container has also important limitations on the mechanical configuration: all accumulator containers must be rugged and rigidly mounted to the chassis to prevent the containers from loosening during dynamic events or possible accidents. The accumulator segments contained within the accumulator must be also separated by an electrically insulating and for all cell chemistries different from LiFeP04 ones, barriers must also be fire resistant (according to UL94-V0, FAR25 or equivalent). Holes, both internal and external, in the container are only allowed for the wiring-harness, ventilation, cooling or fasteners. One of the most important aspects during battery pack realisation are cells electric connections; rules forbid soldering in the high current path, thus other solutions have to be taken. In order to dimension wire size, maximum currents and temperature have to be analysed as usual, but in addiction rules force that every wire used in an accumulator container, no matter whether it is part of the GLV or traction system, must be rated to the maximum traction system voltage.

2.4.4 Battery related components

Lots of components have to be included in order to realise compliant battery pack: for example in every accumulator container at least two isolation relays, which must open both the accumulator poles must be installed. If these relays are open, no HV have to be present outside the accumulator container, thus they must be of a normally open type.

As explained during first chapter, batteries must be always controlled by an electronic circuitry called BMS in order to keep them inside their safe operating area. Formula SAE rules impose several regulations on batteries and battery management. In fact, the BMS must continuously measure the voltage across every cell, in order to keep cells inside their safety voltage levels, and it must also continuously measure the temperature of critical points inside the accumulator to keep cells below their safety temperature range. In addiction, temperature sensors used by BMS must be directly in contact with cells.

Each battery container must contain at least one fuse and at least two accumulator isolation relays, and maintenance plugs, additional contactors or similar measures have to be taken to allow electrical separation of the internal cell segments such that the separated cell segments contain a maximum static voltage of less than 120 V DC and a maximum energy of 12 MJ. The separation must affect both poles of the segment. This separation method must be used whenever the accumulator containers are opened for maintenance and whenever accumulator segments are removed from the container. The Accumulator Isolation Relays (AIRs) and the main fuse must be separated with an electrically insulated and fireproof material from the rest of the accumulator.

2.4.5 Shutdown Circuit

The shutdown circuit consists of at least 2 master switches, 3 shut-down buttons, brake-over travel switch, insulation monitoring device (IMD), inertia switch, brake system plausibility device, all required interlocks and the battery management system (BMS). If the shutdown circuit is opened/interrupted the traction system must be shutdown by opening all accumulator isolation relays and the voltage on the traction system must drop down under 40V DC or 25V AC RMS in less than five seconds after opening the shutdown circuit. An explanatory schematic of the required shutdown circuit is shown in figure 2.11.

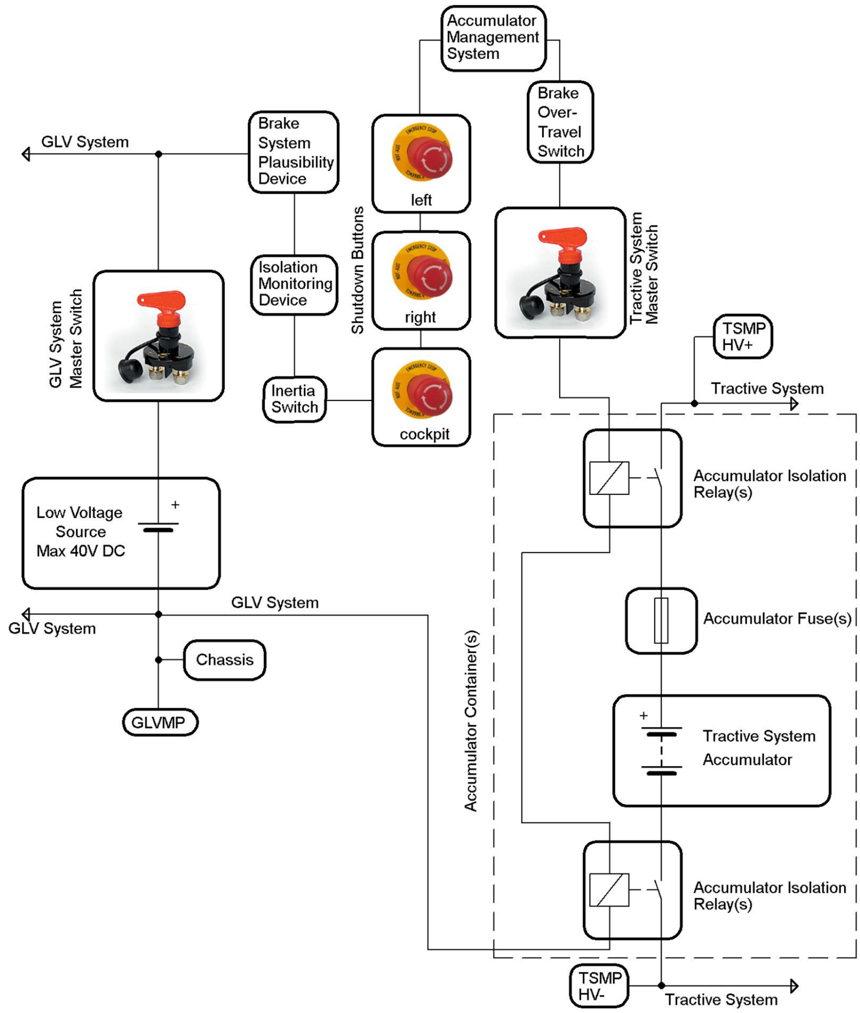

Figure 2.11: Shutdown circuit diagram

2.4.6 High Voltage components

Except for the battery ones, which are included in a dedicated section as previously shown, lots of other devices are fundamentals to the purpose of project compliant high voltage circuitry and are regulated by FSAE rules.

Battery is part of the traction systems, thus an overview of other high voltage devices required by rules to be included inside the traction system is performed.

Two traction system voltage measuring points (TSMP) must be connected to the positive and negative motor controller/inverter supply lines and must be marked HV+ and HV-. TSMP is used by judges during technical inspections, in order to measure the voltage present on the High Voltage circuitry and check if the traction system is shut down properly within the maximum allowed time. Each TSMP must be secured with a current limiting resistor according to the following table, whereas fusing of the TS measuring points is prohibited. A 4mm shrouded banana jacks rated to an appropriate

Maximum TS Voltage	**Resistor Value**
Umax<=200VDC	5kR
200VDC<Umax<=400VDC	10kR
400VDC<Umax<=600VDC	15kR

Figure 2.12: TSMP series resistors values

voltage level have to be used for the TSMP connector.

It must be possible to disconnect at least one pole of the traction system accumulator by quickly removing an unobstructed and directly accessible element, fuse or connector, in case of a stuck accumulator isolation relays for example, thus a device generally called "High Voltage Disconnect" (HVD) must be included. It must be possible to disconnect it without removing any bodywork within 10 seconds in ready to race condition, and the HVD must be positioned above 350 mm from the ground. If a tool is needed to open the HVD this tool must also be attached to the push bar. If no tools are needed to open the HVD, an interlock must activates the shutdown circuit and open the AIRs when the HVD is removed.

Motor controllers in electric vehicles typically have large input capacitance and very low input resistance. As a result, when initially connecting a battery to the motor controllers, there is an inrush in current which may cause several problems to other components such as:

- Damaging the motor controller
- Damaging the battery packs itself which are not rated for the inrush current
- Welding of contactor contacts which cannot be determined by just looking.

A pre charge circuit, which is allowed and regulated by FSAE rules will solves these problems, without limiting the operating current of the traction system. In fact, a circuit that is able to pre charge the intermediate circuit to at least 90% of the accumulator voltage before closing the second AIR must be implemented. This circuit must be disabled by a deactivated shutdown circuit, therefore it must not be able to pre charge the system, if the shutdown circuit is open. If a discharge circuit is needed to guarantee that when the shutdown circuit is open the voltage drop down to a value lower than 40 V DC in less than five seconds, it must be designed to handle the maximum discharge current for at least 15 seconds and it must be wired in a way that it is always active whenever the shutdown circuit is open. Furthermore the discharge circuit must be fail-safe such that it still discharges the intermediate circuit capacitors if the HVD has been opened. Thus, summarising, regulations involved on the electrical design of the vehicle are summarised below:

- The traction system or High Voltage (HV) (defined as any voltage greater than 40 V DC) must be completely isolated from chassis.
- The border between the traction system and Low Voltage (LV) system (defined as any voltage below 40 V DC) system must be completely galvanic isolated.
- The LV system must be grounded to chassis.
- Each accumulator container must contain at least one fuse and at least two contactors.
- Contactors must open both poles of the accumulator.
- Each accumulator cell must be monitored by a Battery Management system (BMS) to keep its voltage within its safe operating voltage range.
- The BMS must continuously measure the temperatures of critical points of the accumulator.
- traction system and LV circuits must be physically segregated such that they are not run through the same conduit.
- Two traction system measuring points (TSMP) must be installed and connected to the positive and negative motor controller lines.
- Each TSMP must be secured with a current limiting resistor.
- There must be a High Voltage Disconnect (HVD) that is able to disconnect at least one pole of the traction system accumulator.
- Pre charge circuit must be implemented and it must not be able to pre charge the immediate circuit, if the shutdown circuit is open.
- The shutdown circuit directly carries the current driving the AIR.

- All electrical system (both low and high voltage) must be appropriately fused.

2.4.7 Rules analysis and considerations

Analysing FSAE rules general requirements on battery and high voltage circuitry are highlighted and with the purpose of realise a rules compliant battery pack, the following devices have to be chosen:

- AIR
- Battery fuse
- Pre charge and discharge circuits
- HVD
- Wires

Other devices which are obligatory according to FSAE rules are not discussed in this thesis, mostly because they are not directly connected to the battery pack, which is indeed the core of the work. As explained later, a state of the art analysis is performed in order to understand how other teams had realised their car, and couple their choices with rules restriction, to limit the boundary of our project. Analysing SAE rules, however, some important electric considerations which lead to the first design choice can be outlined: the maximum allowed voltage is not limited by rules, but each competitions have its own limitations. Traditionally, Italian and German competitions are the reference ones to which our team participate, so 600 V could be the ideal target to become the maximum traction system voltage. In addiction, to obtain the same amount of power, the higher the voltage the lower the current. This is an important feature for the whole traction systems; reducing the current lead to a weight reduction of the whole vehicle, which is an important feature for a racing car. Summarising, the maximum traction system voltage is chosen to be 600 V.

FSAE rules analysis explain another important limitation: the maximum amount of power which can be drawn by the battery is 85 kW, and this limit the maximum current on the traction system. This value, however, is indeed excessive for mechanical reasons: thinking to drawn 85kW from the battery, even if the efficiency of motor, controller and mechanical transmission is not unitary, lead to an available mechanical power too high to be managed and transformed in performance improvement for our vehicle. Inside an electric vehicle, increasing the power lead to weight increase due to additional need of energy which is obtained with additional battery. A carefully choice in power limit is then fundamental, and its calculations is performed later on the text.

2.5 Formula SAE Vehciles analysis

As soon as general requirements are obtained by rules analysis, the maximum traction system voltage is selected, but another important part of preliminary work is understanding if commercial components with required voltage level are available, and in case what should be home-made. It is therefore important the way devices are sized, and in particular understanding the amount of energy needed inside the car is fundamental to battery sizing and choosing. As soon as the amount of energy is chosen, the maximum current will be estimated and then wires, fuses and AIR will be chosen.

The work explained in this thesis had never been done before at the University of Pisa, thus lack of experience about general order of magnitude is relevant. For example, the amount of energy needed to complete an endurance event is unknown, and so the optimal power of electric motor is. In order to fill the gaps and understand energy and power requirements of cars a state of the art analysis is performed. The results of course are not used as they are, but they are only a starting point which must be adapted and validated with other simulations. Formula SAE competitions are student competitions whose primary goal is improve student experience with a realistic working experience, and competition itself is just an excuse to drive students to think, project end experience new ideas. According to this idea, usually winning teams performs small presentations about their cars and explain the way they used to project and realise their vehicle. The analysis thus try to gather data and information to understand the order of magnitude of power, energy and other design parameters.

Formula Student Germany is the most important SAE competitions, and then the overall results of two past editions are analysed in order to understand which are the best team, and then focus the attention on their cars. The overall results of the electric Formula Student Electric competitions 2012 and 2011 are summarised in table 2.13 and 2.14 respectively. It is easy to understand that the best teams are pretty the same and they are the subjects of my survey; figure 2.15 and 2.16 summarise the results. Results evaluated by previously exposed table are interesting: the best team (Delft) uses, for its last vehicle, a voltage level of 600 V which validate the previous choice, and teams which in the past chose a lower voltage, moved to higher voltage during next years. All the teams also chose for their cars LiPo cells, in order to obtain high power and energy density. This is a predictable choice in a racing context, where weight reduction and power improvement are fundamental. Another important aspect of the survey is energy capacity, which is fairly constant from the whole cars, varying in a range of 5 and 7 kWh. These are interesting values which must be indeed especially fit on each car, mostly because the energy capacity is tightly related to vehicle's power and weight. The analysis however covers and expose values used by top teams which are able to produce light cars, using particular details in

Formula Student Germany
Results

FSE Overall Results

Car #	University	Cost [points]	Present. [points]	Design [points]	SkidPad [points]	ACC [points]	AutoX [points]	Endurance [points]	Efficency [points]	Penalties [points]	Overall scores	Overall placing
E1	Delft TU	82,67	70,00	150	67,84	75,00	97,27	303,45	92,38	-5	933,61	1
E33	Zürich ETH	80,09	67,93	145	29,45	60,44	100,00	325,00	66,33		874,24	2
E26	Stuttgart U	65,66	54,63	100	73,95	57,65	70,77	276,76	67,62		767,02	3
E40	Eindhoven TU	79,25	69,02	100	75,00	48,47	42,38	170,89	67,31	-15	637,31	4
E76	Freiberg TU	77,56	62,20	110	64,42		51,96	150,99	81,55		598,67	5
E4	München TU	78,27	53,05	135	38,06	42,33		161,38	88,54		596,63	6
E67	Osnabrück UAS	78,94	63,41	70	45,37		42,66	174,53	23,08		497,99	7
E34	Ingolstadt UAS	55,77	55,85	110	45,18	35,04	27,78	124,08	35,80		489,51	8
E21	Karlsruhe KIT	77,40	73,00	100	66,63	56,20	85,53		10,14	-10	458,90	9
E11	Ravensburg DHBW	77,56	67,07	125	47,07	68,73	62,16				447,59	10
E58	Leuven Group T	56,86	54,63	65	14,03	45,35	13,59	132,66	47,90		430,03	11
E96	Zwickau UAS	79,60	75,00	130	65,44	37,47	27,58				415,09	12
E20	Bayreuth U	75,93	52,93	65	47,71	3,50	24,72	119,90	16,67		406,36	13
E44	Dresden TU	54,50	42,44	90	61,89	30,59	8,29		100,00		387,70	14
E69	Diepholz UAS	74,50	74,00	85	44,32	32,45	11,13				321,40	15
E31	Odense SDU	59,82	34,02	55	26,43	34,79	4,50	106,50	0,07		321,14	16
E100	Siegen U	63,44	63,05	100	38,08	27,45	28,79				320,81	17
E32	München UAS	74,63	62,68	70	39,06	17,41	32,20		12,22		308,21	18
E62	Regensburg UAS	62,02	40,00	100	59,68	16,97	4,50				283,17	19
E12	Köln UAS	49,00	57,32	110	44,87	15,20					276,38	20
E22	Stuttgart DHBW	51,32	55,37	70	35,04	25,91	4,50				242,13	21
E25	Darmstadt TU	74,90	60,12	70		42,40				-10	237,42	22
E64	Kaiserslautern TU	73,94	64,15	65	34,38					-5	232,46	23
E14	Deggendorf UAS	65,38	60,37	90		3,50	12,91		0,00		232,15	24
E65	Wiesbaden UAS	69,56	57,93	90							217,49	25

Figure 2.13: 2012 FS Germany results

Formula Student Germany
Results

FSE Overall Results

Car #	University	Cost [points]	Present. [points]	Design [points]	SkidPad [points]	ACC [points]	AutoX [points]	Endurance [points]	Efficency [points]	Penalties [points]	Overall scores	Overall placing
E85	Delft TU	78,26	74,00	140	58,73	69,51	97,41	325,00	66,00		908,92	1
E33	Zürich ETH	74,64	47,10	150	75,00	74,36	74,03	294,35	63,58		853,05	2
E110	Ravensburg DHBW	76,06	68,71	100	29,74	75,00	78,85	268,06	49,25		745,68	3
E21	München TU	22,57	55,07	100	71,99	72,30	100,00	309,65	0,41		731,98	4
E22	Karlsruhe KIT	63,90	75,00	120	72,16		8,65	295,75	39,78		675,24	5
E40	Eindhoven TU	70,88	68,28	85	38,51	49,65		285,73	0,00		598,05	6
E1	Stuttgart U	69,72	65,63	110	45,03		6,79	275,33	19,85		592,35	7
E96	Zwickau UAS	77,60	69,23	130	73,62	54,67	77,59				482,71	8
E53	Graz TU	78,12	60,99	90				127,25	100,00		456,36	9
E14	Deggendorf UAS	72,84	72,00	85	61,82	42,49	23,60		9,83		367,58	10
E66	Diepholz UAS	74,69	50,96	90	7,71	25,84			50,12		299,32	11
E77	München UAS	72,05	62,54	50	3,50	47,31	4,50	25,00	0,00		264,89	12
E50	Lisboa IST	64,70	71,00	85	22,00	3,50	4,50				250,70	13
E12	Köln UAS	25,50	59,45	75	51,21	3,50	19,49			-5	229,15	14
E44	Dresden TU	61,52	73,00	90		3,50					228,02	15
E11	Bayreuth U	65,97	59,19	85							210,16	16
E107	Siegen U	70,04	44,78	85							199,82	17
E65	Wiesbaden UAS	67,61	49,41	55				25,00	0,00		197,03	18
E13	Karlsruhe UAS	71,72	70,00	40							181,72	19
E62	Regensburg UAS	57,74	38,60	75							171,35	20
E67	Osnabrück UAS	56,11	40,92	70							167,03	21
E97	Landshut UAS	52,00	42,55	60	3,50	4,33	4,50				166,88	22
E71	Stockholm KTH	50,59	55,93	55						-5	156,52	23
E23	Clausthal TU	48,89	53,79	30							132,68	24
E26	Hannover U	25,36	55,33	50							130,69	25

Figure 2.14: 2011 FS Germany results

Name	Weight	Motor Power	Battery Type	Capacity	Voltage
Delft 2012	148 kg	Pn=99kW Pm= 133kW	LiPO 144S2P	4,2 kWh	600V
Delft 2011	177 kg	Pn=28kW (2x14kw) Pm=55kW (2x28kw)	LiPO 96S3P	5,7 kWh	355V
Zwickau 2011	260 kg	Rear= 2x32Kw Front= 2X7Kw	570 cells		400V
Zwickau 2010	240 kg	Rear= 2x30Kw Front=2X6Kw	400 LiPO cells		400V

Figure 2.15: Comparative table

Name	Weight	Motor Power	Battery type	Capacity	Voltage
Dresden 2013	240 kg	Pn=100kw (2x50kw)	288 LiPo 144S2P cells	5,3 kWh	600V
Dresden 2012	227 kg	Pn = 72kw (2X36kw)	330 LiPo 110S3P cells	5,2kWh	450V
Stuttgart 2013-2012	190 kg	Pn= 92kw	LiPo	6,2 kWh	600V
Stuttgart 2012-2011	230 kg	Pm=112kw (2x56kw)	LiPo	6,9kWh	
Zurich 2012	170kg	Pn=80kW (2x40kW)	LiPo		

Figure 2.16: Comparative table

layout, chassis and aerodynamic design; this technology are extremely expensive and unaffordable for our team which must necessary use traditional ones, reflecting on vehicle's weight improvement. Energy requirement has been evaluated with software simulations: as previously explained German competitions is the most important on SAE events and it has been used as a test bench. In fact, the ideal geometric trajectory of Hockeneim circuit has been calculated by Vehicle Engineering students and used as input of a vehicle models: the other electric parameter are the maximum power available at the wheels and the amount of energy regenerated during braking. The first one has been evaluated with parametric sweep analysis whereas the amount of regenerated energy has been calculated as the 20% percentage of the delivered power, which is a pretty standard literally value. The other parameter used inside the model are mechanical, layout and dynamic ones and are not further explained on the text. Results shown the amount of energy needed is about 7 kWh with a delivered maximum power of about 40 kW. The ideal power value is refined, as explained next in this work, in order to complete the whole endurance event, as soon as an accurate electrical battery simulation is performed. Figure 2.17 shows simulation results: the black line expounds the power required to complete a single race, whereas green line shows regenerated power during braking. Maximum power levels both in charge and discharge situations can be set, and orange and red lines expound regenerated and provided power limits respectively. On the bottom side of figure 2.17, energy requirements are explained: on the left side the energy provided by the battery is shown, and on its right side regenerated one is displayed. Their difference is shown in the middle, as "Energia Netta", whereas "Energia Lorda" expound the energy necessary to complete an endurance event, including regeneration e and also an additional safety energy rate of about 20% which is necessary to be inside the battery at the end of the race.

Summarising the boundary conditions analysis performed, it is possible to sum up the following electric choice useful to continue with the battery pack design:

- Maximum Voltage = 600 V
- Amount of energy ≈ 7 kWh
- Maximum power ≈ 40 kW

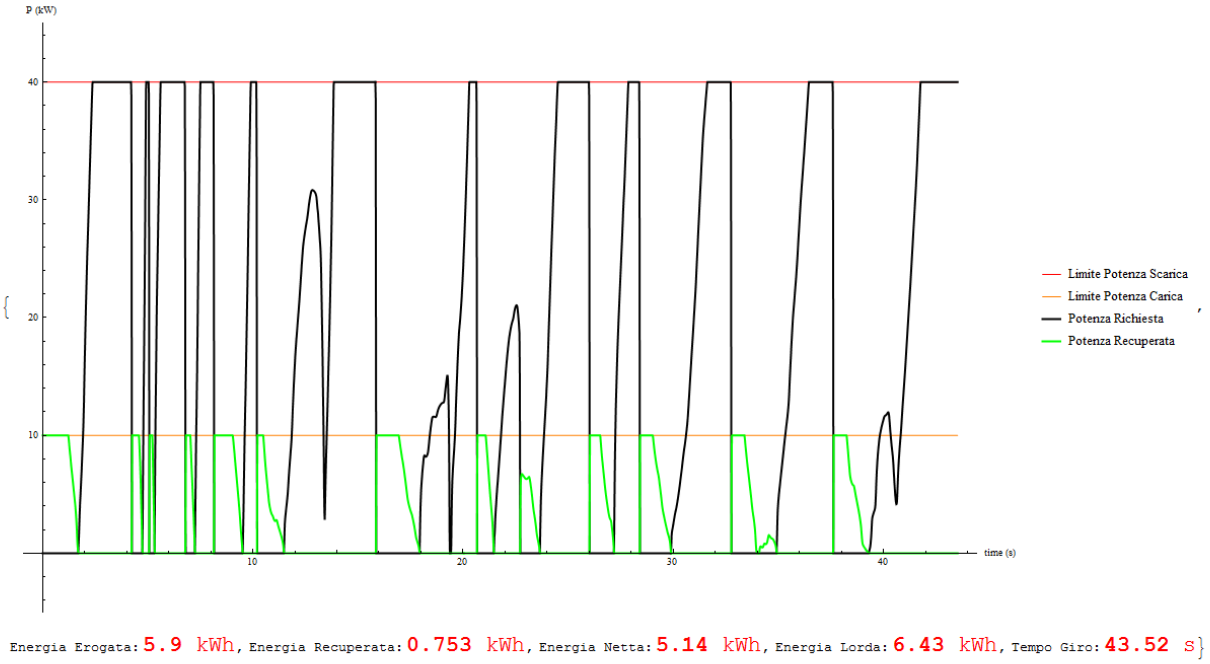

Figure 2.17: Single race simulation results

Chapter 3

Components Selection

At the end of rules and state of the art analysis, components used within the High Voltage circuit and the battery pack are highlighted and also voltage, energy and power levels are fixed, thus essential requirements on device choice are pretty highlighted. In order to get a device, there are typically two opposite solutions: searching on the market for commercial products or developing new ones. Both solutions have advantages and disadvantages: searching for commercial products typically imply higher costs and lower performances compared to the optimization achievable by custom solutions. Developping new products, however, require experience and time. Due to the lack of experience of all team members about electric vehicle, and in order to reduce development time, all the power electric and electronic components are commercial solutions, and on this chapter their selective criterion are explained, starting from vehicle requirements and moving through the whole project space, searching for the optimal solutions in terms of performances, costs, weight and safety.

3.1 Motor and Motor Controller selection

After rules and comparative analysis, the amount of energy and power are highlited. Energy is fundamental and involves only with battery design, whereas the maximum power provided by the electric motor is a parameter "shared" with dynamic and mechanic layout. From an electronic point of view, the best choice in order to obtain high power and torque density, low weight and high reliability is a brushless motor, even if their control is more complicated than other motor types. The electric motor choice reflects with layout and mechanic engineering, for example on motor numbers: if a single motor is used then a mechanic differential gear must be used, and the vehicle's weight increase. The maximum total power have to be limitated according to simulation results (which satisfy rules) and even if powerful motors are available on the market, such as the Yasa 750H which is able to produce a peak power of 150 kW and a peak torque of 700 Nm with a total weight of 25 kg, in order to reduce the weight of the vehicle, a single motor with differential gear is not used but two motors acting on the rear wheels with fixed reduction gear are chosen. Using two separate motors less powerful than the Yasa one leads to an optimizitation of cost and weight: in fact the total power is significantly lower than the Yasa one, but suffiecient to meet simulation results. Enrmax 200 motors is choos: it is able to provide about 35 kW of continuous power with a singluar weight of 8,7 kg and abot 31 kg including two motor and their related controller. In addiction the total cost of motors and controllers is lower than Yasa one. According to the aim of this thesis, motor choice is not further examined, but the attention moves on the motor controller, which are directly connected to the battery pack. Enrmax motor are sinusoidal brushless motor, thus a generic controller could be used; Enrmax suggest to couple their motor with a Bamocar D3 700 V controller, which has been carefully characterized with Enrmax motor, and whose paramter are available to Enrmax customers. The whole characteristics of the controller are not exposed, but some particular ones are evaluated next during the text. Figure 3.1 and 3.2 shows Enrmax 200 and Bamocar D3.

Figure 3.1: Enrmax 200

Figure 3.2: Bamocar D3

3.2 Cell selection

3.2.1 Physical and electrical requirements

Cell choice is obviously one of the most important aspect involved in battery pack design and lots of characteristics have to be carefully evaluated. First of all, vehicular aspects lead to power improvement and weight reduction, which is pretty easy to understand in a racing vehicle. Contrary to traditional electric vehicles, energy density is not a really important bond on cells choice, because a Formula SAE vehicle is typically involved in short competitions, which last up to half an hour. This lead to highlight the first desired characteristics: cells should be an high power model, instead of an high energy one. In fact, if an energy oriented is chosen, the total weight of the vehicle could be increased, firstly because the higher the energy, the heavier the cell, and also because in order to reach 7 kWh of energy, few cells are needed, reducing the voltage to a value lower than 600 V, which increases wires and motor weights, due to the additional copper. In order to meet these constraints, Lithium chemistry, which is the state of the art solutions in contemporary EVs should be chosen, and in particular LiPo ones, due to their high power density compared with other Lithium batteries.

Cells connection is also an important aspect of battery pack design; it is pretty obvious that series connection improves voltage whereas parallel connection improves current. In the past, when high power batteries with related capacity greater than 10 Ah were not available, parallel connection were used. Parallelling cells is a problem: in fact, a cell can be thought as a voltage generator whose voltage and series equivalent resistance levels depend on its SoC. When two voltage sources are connected in parallel, if voltage levels are not the same, there may be an inrush in current. Different voltage across a cell are directly related to different state of charge levels, and unfortunately, as explained during part one, it is a really frequent situations in practical application, due to the unavoidable mismatch in cells production that leads to different parameters. This may be a critical conditions, as explained in figure 3.3 where an empty cell is connected in parallel to other fully charged cells.

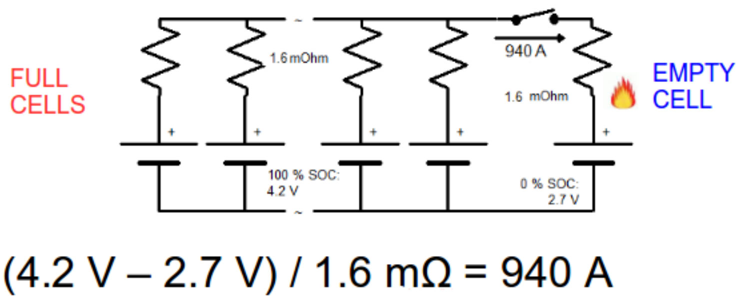

Figure 3.3: Inrush in current due to different voltage levels

The inrush in current produces two negative aspects: it may damage the cell if the current amplitude is higher than its safety limits, and secondly there is an amount of energy wasted as heat. Connecting cells in parallel is also possible, but it must be carefully done: first of all parallel connections should be done by cell manufacturer, checking the individual voltage and resistance, in order to reduce the inrush amplitude, and then each group of parallel cells can be connected in series with other cells. During the operation, however, unbalance in cells are inescapable, and balancing techniques have to be used. In conclusion, series connection is always preferred if possible, and it is the way cells are connected on this text.

If Lithium chemistry and series connection are used, the amount of cells is definitively fixed; in fact, if the maximum voltage is 600 V and the maximum cell voltage is 4,2 V the amount of cells n could be easily calculated as:

$$n = \frac{600}{4,2}$$

the result is 142 cells, but this value will be fit as soon as cell capacity is chosen.

To understand the amount of current flowing through the battery, and then choose cell capacity, output power, traction system voltage and battery chemistry have to be considered. In fact, if Lithium chemistry is used, in order to obtain 40 kW of mechanic power with an average efficiency of motor and controller of about 10% as the producer suggests, about 45 kW of power is drawn from the battery. This power requirements leads to a

Model	Nominal Capacity	Continuous C Rate	Pulse C Rate	Dimensions	Weight
Kokam SLPB70205130P	12Ah	15	20	220x132x7,5 mm	340g
Kokam SLPB60205130H	13Ah	8	15	220x132x7,3 mm	332g
Tenergy 9759156	10Ah	7	10	157x59,5x9,8 mm	210g
Eig F104	14Ah	5	10	222x129x7,1 mm	383g

Table 3.1: List of potential cells and related characteristics

spread in current values: in nominal conditions, using 142 series connected cells with a nominal voltage of 3,7 V the flowing current amplitude is:

$$i = \frac{45000}{3,7 \cdot 142} = 85,65\text{A}$$

and with similar calculation, the highest current value is

$$i = \frac{45000}{2,8 \cdot 142} = 113,17\text{A}$$

and the lower value is

$$i = \frac{45000}{4,2 \cdot 142} = 75,45\text{A}$$

which correspond to a fully discharged and fully charged battery pack respectively. Calculated current values are useful to understand the shape of the desired cell. In fact, summarising, the potential cell could be a LiPo one and in order to obtain the required energy of 7 kWh with a total voltage of 600 V, cell capacity should be

$$C_n = \frac{7000}{600} = 11,67\text{Ah}$$

with at least a C rate of 11. At the end of these calculations both physical and electric target requirements are obtained, and they are used to find on the market a cell that meets required characteristics.

3.2.2 Market Analysis

This section explain the way the ideal cell identified during last section is fitted into a real one. Various configurations are examined and discussed, in order to find the best trade off between performances and cost, which is always a strong bond in all the engineering projects, especially in an innovative one. Analysing market solutions to find the ideal cell is quite difficult because producers have a wide portfolio which may not include target capacity or current ratings. Table 3.1 summarize research results, showing only prospective cells. Other producers such as A123, Minamoto and Yok have been examined, but their cells do not fit our capacity rating, thus they are not summarised in table 3.1.

Observing results shown in table above, Eig cell's capacity is a little bit too high than the target value of about 11 Ah, whereas Tenergy one show

Model	Maximum Voltage	Cells number	Continuous Current	Pulse current	Total weight
Kokam 12Ah	583V	138	180A	240A	46.9Kg
Kokam 13Ah	538V	128	104A	195A	42.5kg
Eig 14Ah	500V	119	70A	140A	45.6kg

Table 3.2: Potential battery pack and related characteristics

lower capacity value than the desired one. In fact if Eig is used, in order to reach the required energy value of 7 kWh, about 120 cells are needed and the maximum total voltage is about 500 V, whereas using Tenergy one, is not possible to meet the energy target with a voltage limit of 600 V using only series connection. Thus, only Kokam and Eig cells can be used. The first Kokam cell (SLPB70205130P) seems a pretty ideal solution; in fact its nominal capacity is very similar to the target value and it also shows high C rates, which easily allows to meet previously calculated current limits of 75 A and 113 A during the best and worst case respectively. The second Kokam cell (SLPB60205130H) shows a capacity higher than the target value which reflects into the voltage level. In fact, keeping the total energy constant (the energy is related to the total weight, thus its value should not be higher than the needed one) , with 13 Ah capacity, the total voltage is 538V obtained by 128 cells. The voltage level is close to the ideal one, then Kokam SLPB60205130H should be a prospective cell. Summarising, three prospective battery pack are designed, keeping total energy constant to 7 kWh value, using Kokam and Eig cells in table 3.1 and the results are shown in table 3.2.

The first battery pack better approximates the ideal electric characteristics: even if the real voltage is 583 V and the real current during the worst case is:

$$i = \frac{45000}{2,8 \cdot 138} = 116,46\text{A}$$

it can easily provide the required current, thanks to the high C rate. The second battery built by Kokam 13 Ah cells could be a good solutions, but in this case, the real current flowing during the worst case is:

$$i = \frac{45000}{2,8 \cdot 128} = 125,56\text{A}$$

which is higher than the desired continuous current. Analysing the third solutions, current requirements increase: in fact during the worst case the flowing one is:

$$i = \frac{45000}{2,8 \cdot 119} = 135,05\text{A}$$

that is a really high value, close to Eig maximum pulse current and then automatically lead to discharge Eig cell.

In conclusion, Kokam SLPB70205130P is selected thanks to its high C rate which allow to provide current, limiting stress to the cell. In fact, due to the racing application, the battery pack is typically susceptible to fast and heavy discharges during short period of time (about half an hour), creating electrical stress cells: if stress is reduced cell life cycle increases. This solution has the drawback of higher weight compared to the other one, which is always not attractive in racing application. The alternative battery pack solution using Kokam SLPB60205130H, even if lighter than the previously explained one, improve the electric stress to the cell and then is not selected. The choice of improving life time, even if creating an heavier battery pack is preferred because batteries are the most expansive parts of an electric vehicle, and then they must be used for at least two or three years. Choosing the lighter battery pack could be an alternatively solution, which leads to a reduction in weight of about 7 kg, but it is not performed due to the limited percentage weight reduction referred to the total estimated weight of the vehicle, which is about 270 or 280 kg. Figure 3.4 shows Kokam SLPB70205130P cells.

Figure 3.4: Kokam SLPB70205130P cell

3.3 AIR selection

As rules explain, each battery pack must be protected by two normally open relays. Due to voltage and current ratings, contactors are used. In fact, a contactor is basically a relay which is capable of carrying large amount of current. A number of objectives for finding suitable battery contactor are

Model	Maximum Voltage	Continuous Current	Electric Life (cycles)	Coil Power	Weight	Cost
Tyco EV200	900V	500A	4800	1,7W	430g	193$
Tyco EVC135	Up to 900V	135A	2700	3W	190g	110$
Gigavac GX11	750V	150A	15600	8W	460g	193$
Gigavac GX14	750V	350A	77000	3W	500g	179$

Table 3.3: Potential contactor and related characteristics

set: the most important one, and it is pretty obvious, its related to electric characteristics that must fit with the traction system one; in addiction the way the low voltage inductor is activated is examined: in fact the low voltage circuitry inside the vehicle is chosen to be a 12 V system, thus the contactor must be controlled by a 12 V coil. The presence of an economizer, which is a device used to reduce the amount of current necessary to keep energised the low voltage coil when the contactor is closed, is also a desirable characteristic. Other characteristics such as maximum break or make current, voltage contact insulation, electric life etc. are also carefully examined.

In order to find the best compromise between electric, mechanic and economic characteristics, some of the most important electric producers such as Tyco and Gigavac which provide especially Ev designed contactors are examined, and the result are shown in table 3.3, which only shows normally open contactors with 12 V primary coil. Analysing table 3.3 the best choice could be the Tyco EVC135, which shows proper voltage and current limits and it is also the lightest and cheapest solutions examined. Unfortunately, in order to reach the 600 V requirement, Tyco approval should be asked by submitting a formal proposal to their technical division and wait for their approval. This increase project complexity and costs, thus in order to simplify the job and reduce costs, this solution is not further examined. Looking to remaining contactors in table 3.3, Gigavac ones are not ideal solutions because are heavier and show worse electric characteristics in terms of voltage, current and power compared to the Tyco EV200, which is indeed the chosen device, thanks to its high electric quality, low power consumption and cost, which is equivalent to the other ones.

As soon as Tyco EV200 is chosen, its electric characteristics are deeply analysed, in order to confirm the choice. In fact the AIR must protect the whole traction system, than it must be a reliable and affordable component to avoid damaging to the battery pack or the traction system and then relevant economical losses. As previously explained Tyco EV200 is able to continuously carry up to 500 A (both in make or break operation) with a maximum break current of 2000 A. In addiction, the maximum make current to avoid welding current is 650 A which is significantly lower than the expected current rating, thus welding effects between wires and contactor terminal are avoided, even during fast transitions. The maximum allowed voltage between terminals before an electric arc set off is 2200 V an also to reduce arc detrimental effect on contacts, which inevitably reduce their life time, magnetic blow outs are used. Contact resistance of about 0.2 mΩ lead to a voltage drop out of 25 mV if 125 A are carried: this is a negligible value compared to other voltage levels inside the traction system. It is therefore important to notice that all the additional characteristics exposed about Tyco EV200 are quite always better than the other contactors ones. Figure 3.5 shows Tyco EV200 contactor.

Figure 3.5: Tyco EV200 view

3.4 traction system wire selection

Choosing the correct wire for a battery electric vehicle is fundamental because wires must carry a huge current that leads to reach high temperature. As previously explained, FSAE rules require traction system wires are orange (this is a standard colour for traction system wires in EVs) with a minimum temperature rating of 90℃ and correctly sized for the continuous current flowing into the system. If a normal operating condition is considered, then the continuous current is

$$I = \frac{\mathrm{P_{req}}}{\mathrm{V_{nom}}} = \frac{45000}{138 \cdot 3,7} = 88,13\mathrm{A}$$

but if a worst situation is analysed, that is if full power is required to a discharged battery pack, than the current become:

$$I = \frac{\mathrm{P_{req}}}{\mathrm{V_{nom}}} = \frac{45000}{138 \cdot 2,8} = 116,45\mathrm{A}$$

The last calculated current is the reference one used in wire sizing.

In order to correctly size wires, that is mainly choose the correct wire section according to current, maximum allowed temperature, and operating conditions, from an electric point of view, two parameters are used:

- Maximum allowed temperature

- Maximum voltage drop

The maximum voltage drop is pretty used if wires directly supply motors that may provide deeply voltage drops due to their relevant inductance, or in case long wires have to be used. In this project wires directly supply the motor controller instead of motors, and wires length are less than one metre, then maximum voltage drop method is not used. The maximum allowed temperature method, which is used in this text, provide the ideal diameter of wires when wire material, maximum current and temperature are chosen. In fact, is pretty obvious that when current flows in wires, an amount of power is wasted as heat increasing wires temperature. When thermal transients are finished and stationary situation is reached, the amount of power wasted as heat on wires must be equal to the heat exchanged with the surrounding. In mathematical expression:

$$P_t = R \cdot I^2 = P_{exch} = \lambda \cdot A \cdot \Delta T_{max}$$

with:

- R=conductor resistance
- I=DC or RMS value of current flowing through the wire
- λ= global thermal transmission coefficient, including convective and radiation exchange
- ΔT_{Max}= maximum allowed temperature difference between wire and surrounding ambient
- A= thermal exchange area between wire and surrounding ambient

On the last expression, designers can act modifying a few parameters such as conductor resistance and ΔT_{Max}, whereas I and λ are fixed by operating conditions. In order to modify conductor resistance, if the same wire shape is used, typically two different materials such as copper and aluminium can be chosen. Copper is pretty a traditional solution, whereas aluminium can be an interesting alternative in order to reduce wire weight: in fact it is quite lighter than copper, showing a density of about 2.6 $\frac{\mathrm{kg}}{\mathrm{dm}^3}$, about a quarter of the copper one which is 8.9 $\frac{\mathrm{kg}}{\mathrm{dm}^3}$. Unfortunately aluminium is also less conductive than copper, with a resistivity of about 2,75 $\cdot 10^{-8}\Omega m$, higher than the copper one (1,7 $\cdot 10^{-8}\Omega m$). It is evident that using aluminium wires a little reduction in weight is possible, but also dimension and costs increase, thus in this project traditional copper is chosen.

The ideal diameter of wire can be calculated expounding power balance shown before, as:

$$d = \sqrt[3]{\frac{4\rho I^2}{\pi^2 \lambda \Delta T_{Max}}}$$

which lead, if a traditional circular copper conductor is chosen, with a typical value for λ of 15 $\frac{\mathrm{W}}{\mathrm{K}\cdot\mathrm{m}^2}$ and $\Delta T_{Max} = 30$ [28] to an ideal diameter d=6,2 mm and a cross sectional area of 30,5 mm^2. This area correspond to an AWG 2 wire size, that in fact, according to table conversion, carries about 115 A at 75°C with PVC insulator and copper conductor. The maximum area corresponding to AWG 2 wires is 33 mm^2, which is really close to the value calculated before; thus AWG 1 wire is selected. In order to commercially found an appropriate wire corresponding to desired characteristics, some producers solutions is investigated: Tecnofuture SRL is recognised to be a prospective producer and its H05V2V2-F wire is an interesting solution, providing desired temperature and electric characteristics. In order to improve temperature limits choosing wires designed to sustain higher temperature and then higher current than the chosen one, different insulator material are used: just to give an example, Coroplast 9-2611 that has been especially designed for electric vehicle power train, uses Silicone insulator and then is able to reach up to 180°C, allowing higher ΔT_{Max} and higher current. Due to its high cost (about 22$ metre) it is not the choice for this project.

3.5 HVD selection

A High voltage disconnect (HVD) is necessary for electric race cars like Formula SAE-Electric ones as required by rules. The HVD must be able to disconnect at least one pole of the traction system, providing insulation between the battery pack and traction system and protection for users working during downtime situations or rescue operation after an incident, thus to achieve this it must be manually activated. Analysing market finding suitable solutions for the project has been incredibly difficult: lots of devices do not meet our voltage or current levels, or in case they meet them, they are typically expensive and heavy solutions like big circuit breaker. The only one, but reliable and perfectly compliant with rules and electric requirements device found is the TE AMP 800, which is an especially designed solution for battery connection inside EVs, with 1000 V and 250 A limits in voltage and current respectively. The only possible drawback is that TE AMP 800 works only with a limited range of wires area, from 16 up to 50 mm^2. Fortunately, this is not a problem, because selected wires are included within the range. Figure 3.6 shows TE AMP 800.

3.6 Fuse selection

The main purpose of a fuse is battery protection during a short circuit situation, with secondary protection for controller or motor failure. There are many different types of fuses available on the market, from Slow Acting

Figure 3.6: TE AMP 800 view

to Very Fast Acting fuse, making selection somewhat daunting. Bamocar, which is the the motor controller producer suggests to include a 250 A fuse in series connection with battery pack, in order to protect a single electric motor. In fact, the maximum allowed current for Enrmax motor is 240 A, so a 250 A fuse is suggested. The main fuse task however, as previously explained, is providing protection to the battery pack. Thanks to the high C rates of Kokam SLPB70205130P cells, up to 240 A of current can be provided by cells without damaging, so this must be the maximum current allowed to be delivered by battery, and also the fuse melting current.

Market analysis performed in order to find desired fuse shown lack of devices combining good electric characteristics, light design and affordable price. The analysis is performed searching for fast act fuses, which reduces the amount of time needed to melt, and then the stress to the battery pack. The selected model is the Cooper Bussmann PVS-R-125 one, a 600 V, 125 A fast acting fuse. Its melting time characteristics that is used to choose the fuse current rating, is shown in figure 3.7: the melting plot for 125A fuse model is not shown, but it can be easily extrapolated by 100 A and 200 A ones and the melting time for over-current situations (about 300 A) is about 12 seconds, reducing up to 3 second for 500 A current, avoiding potential risks for battery pack. The 125 A rating is not limiting for normal battery operations because the highest current value flowing through the traction system in absence of fault or short circuit is:

$$i = \frac{45000}{2,8 \cdot 138} = 116,45\text{A}$$

a value lower than the fuse current rating. It is also important to realise

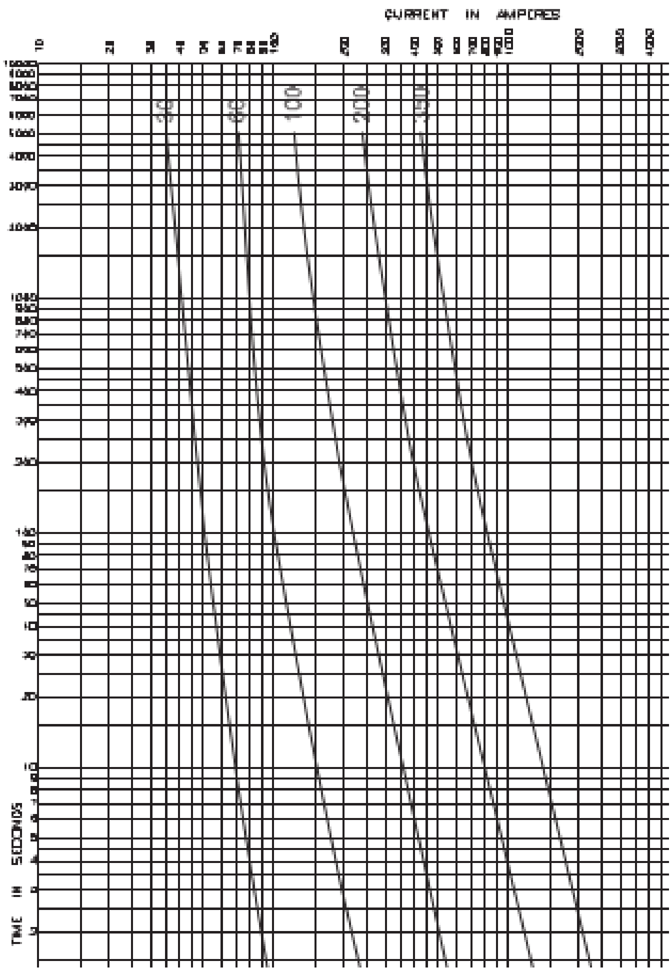

Figure 3.7: Melting time characteristics at various current rating

that the selected fuse also gives protection to the motor, because its current limit is 240 A which is the same of the battery pack, thus the same current limitations can be used. Figure 3.8 shown Bussmann PVS-R-125 fuse.

3.7 Battery charger selection

Charger is required to recharge the battery pack once its available energy is near depletion due to usage. A number of objectives for finding suitable battery charger for the vehicle are set. Firstly, the charger must be suitable for charging the accumulator packs of 600 V and it must also be able to provide desired current to the battery pack, which is limited to 12 Ah (1C) as Kokam suggests, even if lower C rates are typically used during slow

Figure 3.8: Bussmann PVS-R-125 fuse

charging. In addiction weight is not considered as the charger will not be mounted inboard as this will add an additional weight to the vehicle and could affect its performance. Meeting these mandatory requirements is not difficult so a set of secondary ones is also used in choosing the most suitable charger and they are as follow:

- Programmable: A charger with a fully programmable charging profile for complete control of the output voltage and current could be the ideal solutions, because the typical CC-CV charging profile is adapted and fitted to selected cells.

- Control input: Charger could be controlled through a dedicated input such that it can stop from charging when the battery is fully charged. Finding a charger with a standard interface (RS 232 or CAN) allows to connect it with the BMS, ensuring full cell protection.

- Price: chargers are typically expensive devices, with prices up to a few thousand Euro for the most "intelligent" ones. As explained later, the most "intelligent" the charger, the higher the price.

- Efficiency: The higher the efficiency, the faster the charging and also the lower energy is wasted as heat, reducing fan requirements.

Finding commercial solutions fitting desired requirements is not really difficult; some interesting charger such as Brusa NLG5 and Elekto Automatik BCI8000 are found: they are both completely programmable solutions able to set and act specified CC-CV profiles, fitted on the desired cell. The electric characteristics are fully compliant, with voltage ranges up to 700 V and power size between 1,5 and up to 15 kW of power and also they both have RS232 and CAN interfaces. Their drawback is cost: in fact their prices are higher than 2500 $. In order to find the best compromise between performances and costs, another solution is possible: as explained at the end of part 1, choosing a smart intelligent charger inside a vehicle where a BMS is also available could lead to an excessive amount of "intelligence" inside the car. In fact, if a battery management system is available, there is no need to dispose of custom charging profile fitted on the particular kind of cell: a simple CC-CV charger, without the possibility of making custom profile, connected with the BMS is also an interesting solutions, at a reduced price. According to BMS producer, fully charging a Lithium battery pack with a CC-CV (Constant Current / Constant Voltage) charger and a BMS requires three stages:

- Full charge: charger is fully on (full current: CC), until a cell reaches its maximum voltage
- Balance: charger goes off and on (full current: CC), while BMS balances cells, until all reach 100% SoC
- Top off: charger stays on (full voltage: CV), while the current is reduced exponentially down to 0

Figure 3.9 shows charging stage, where HLIM is a digital dedicated signal provided by the BMS, in order to highlights if a single cell reach its fully charged voltage. Finding reliable dumb charger fitting on desired electric levels is not really easy; in fact lots of products are available at lower voltage level, but few solutions reaches 600 V of voltage. FSAE rules also require during charging activity the whole battery pack is supervised by the BMS in order to avoid potentially dangerous situations. In order to do this, the battery charger must also provide a 12 V output used to supply the BMS and a relay connected in series with the AC line, which is used by the BMS to directly interrupt charging process and allow balancing process. Figure 3.10 explain this.

Ennebi elettronica, a specialised solar system producer has been contacted and selected as a prospective partner: they traditionally works on solar energy systems, and fortunately, the desired voltage level fits perfectly with a standard solar system one. This allow them to provide us a dumb charger, which is basically an AC-DC converter with output current control at a reduced price compared to the smart charger previously explained, thus it is the selected charging device. In order to power the low voltage system of the car, including cooling fans, low voltage relay, electronic control board, safety light etc, a 12 V source must be available inside the vehicle. This lead to another problem; in an EV there is no electric generator connected to the

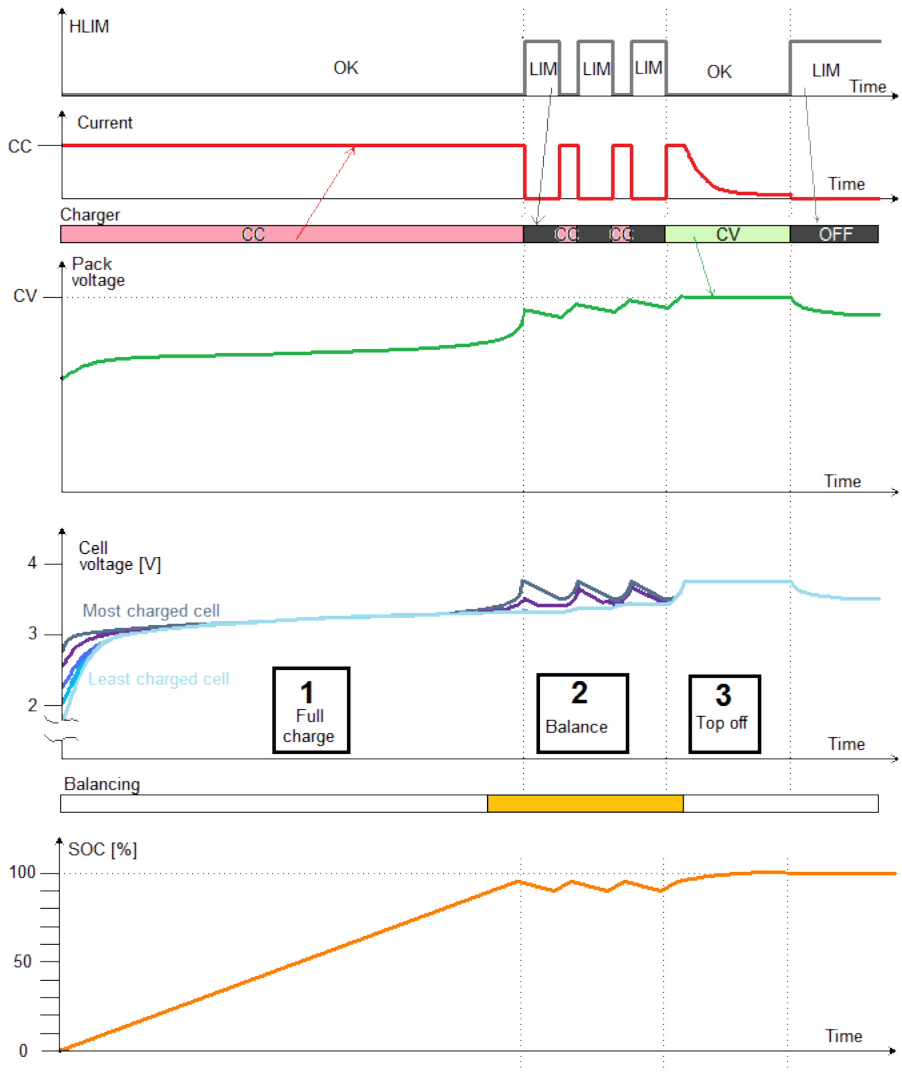

Figure 3.9: Charging phases with constant CC-CV charger and BMS

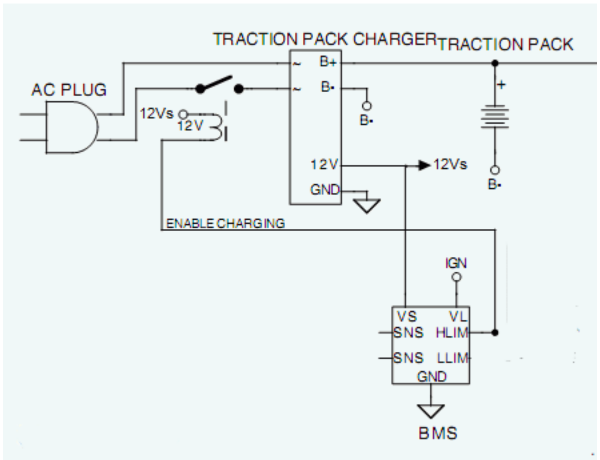

Figure 3.10: Charger-BMS connection during charging phase

crankshaft as in traditional cars, thus there is no way to refill a traditional 12 V Lead-Acid battery. To overcome this problem a fairly easy solution is used: the low voltage battery is recharged by a step down DC-DC converter (600 V to 12 V) connected to the main battery charger. The connection between converter and battery is managed by a NC serially serially connected and open as soon as the charging process is terminated and the 12 V battery supply the whole low voltage systems.

The low voltage consumption is estimated to be about 130 W thus the DC-DC converter power is about 150 W. Test activities will be done as soon as the car is physically realised to explain if partially energy refilling are necessary during endurance events, so the serially connected relay have to be closed again by the low voltage systems. Figure 3.11 explain the low voltage charging connections, highlighting the GLMS switch, the manual switch included to start the low voltage system.

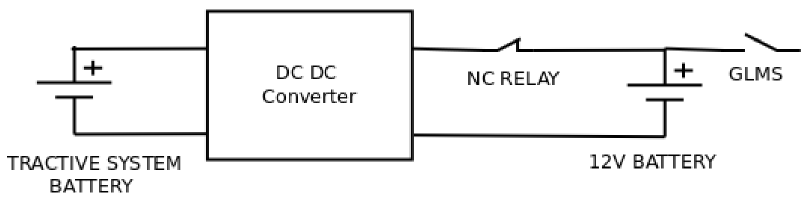

Figure 3.11: Main battery and DC DC converter connection

3.8 Pre charge and discharge circuits

When initially connecting a battery to a load with capacitive input, there is an inrush of current as the load capacitance is charged up to the battery voltage. Using large batteries with low source resistances, the inrush in current can easily peak 1000 A. Formula SAE rules require to create a pre charge circuit able to pre charge the traction system to at least 90% of the traction system voltage before closing the main AIR. A discharge circuit is not obligatory, but FSAE rules require that if the shutdown buttons are open, the voltage across the traction system must drop to under 40 V DC or 25 V AC RMS in less than five seconds after opening the shutdown circuit.

According to motor controller datasheet, the input capacitance of a single controller is 400 μF, whereas the DC link between battery and controller has a total capacitance of about 275 μF. In this project two motor are supplied in parallel, thus a total capacitance of 1200 μF is present. In order to reach at least 90% of the total traction system voltage in a reasonable time of 5 second, the time constant τ of the equivalent RC network is about 1 second, thus the resistor value is 833 Ω. The pre charge resistor needs to dissipate as much energy as the energy stored in the input capacitors, so with a total capacitance of 1200 μF and a voltage level of approximately 600 V at the end of the pre charge, the total energy stored inside the capacitor is:

$$E = \frac{\mathrm{C} \cdot \mathrm{V}^2}{2} = 216\mathrm{J}$$

which is equivalent, if the charging time is 5 second, to an average power of 43,2 W. At the very beginning of charging process, however, the instantaneous power dissipated by the resistance is higher than the previously calculated value: the capacitance can be thought to act as a short-circuit and the instantaneous power dissipated by the resistance is:

$$P = \frac{\mathrm{V}^2}{\mathrm{R}} = 432\mathrm{W}$$

So, during pre charge phase, the resistance is stressed by an sudden, high, power.

In order to find commercial power resistance fitting electric and power requirements, lots of devices are evaluated, and the Ohmite L50J800E is selected. In fact, it is a 50 W 800 Ω resistor, which is able to bear power 10 times higher the nominal power rating for 5 second. In order to simplify the whole project, due to the chosen pre charging time, it is also possible to reuse the same component both for charging and discharging circuits. Pre charge and discharge circuit also require an auxiliary relay that needs to be rated for the full battery voltage, because when the system is off, the full battery voltage appears across its contacts. The relay needs to be able to handle the peak of the inrush current; but, since the average current is low, and the breaking current is nearly zero, the current rating of the relay is not critical. In this project the maximum inrush of current, which happens as previously explain at the beginning of the pre charging phase, is 0,75A. A suitable commercial relay is the Meder LI12-1A85 one, a 1 A, 1000 V DC

PCB mount relay, with a current limit of about 2,5 A and a 12 V primary coil, that is perfect to fit inside the low voltage system. Figure 3.12 and 3.13 show pre charge relay and resistor respectively.

Figure 3.12: Precharge resistor

Figure 3.13: Precharge relay

3.9 BMS selection

Finding a suitable and reliable battery management system is pretty one of the most important tasks during battery pack project. In fact, batteries are one of the most expansive component inside an electric vehicle, thus their operating life must be properly checked and supervised by a reliable electronic circuit. The most important characteristics required to a BMS are:

- Voltage monitoring of each cell, to prevent undervoltage or overvoltage situations
- Temeperature monitoring of a cell or groups of cells
- Cell balancing, typically passive one
- Cell parameter (SoC, SoH, internal resistance) calculation
- Distributed architecture, to the purpose of reducing wires and connection obtaining tidy systems
- Communication between BMS and other devices inside the car via serial bus, typically CAN or RS232

Finding commercial solutions for battery management system up to 600 V and 7 kWh of power is not very difficult and interesting devices are made by Orion, Elithion, Elektromotus and Kokam. All examined products fit electrically to the project, thus selection is based on different criteria: Kokam systems are custom made solutions especially designed by Kokam engineers and their cost is about four times higher than commercial solutions, thus Kokam battery management systems are not selected and further examined. Orion BMS is an interesting solution: the system is a distributed one including passive cell balancing, voltage fault protection, digitally communication etc. as explained in figure 3.14. Its cost is aligned with traditionally mar-

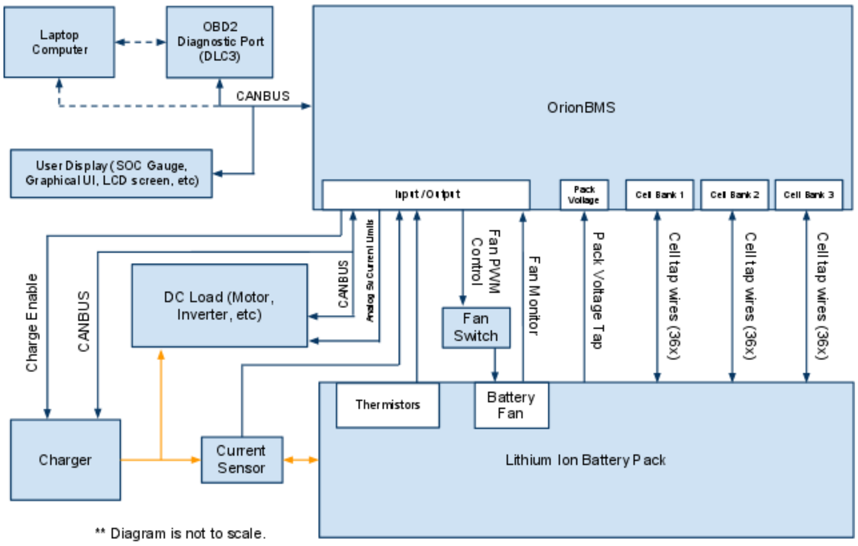

Figure 3.14: Orion BMS overview

ket ones, but it is not selected due to an important drawback: in order to measure cells temperature, on a basic configuration, it uses 4 thermistor measuring the average temperature inside the battery pack. FSAE rules require the temperature of at least 30% of cells inside the pack is measured, thus additional sensors have to be used. In fact it is possible to include external auxiliary thermistor, even if the whole circuit is more complicated than the basic one, and also costs increase. Other systems perform all measurements without additional component at lower costs, thus Orion BMS is not selected. Elektromotus BMS is another interesting solution that perfectly meets all desired requirements at affordable price, thus it could be the selected device. Elithion, a leader company on battery management systems produces two different BMS models, named Lithiumate Lite and Lithiumate Pro. The first one is a basic and economic BMS model which can not be used in this project, because it works only with prismatic cells, and Kokam cells are pouch ones. Lithiumate Pro is an expensive systems, whose main features are:

- Plug and play installation
- Distributed (a cell board is mounted on each cell: measures voltage and temperature, balances the cell)
- Minimum number of wires in HV pack, single wire to adjacent cell boards
- Up to 256 cells (about 900 V), in up to 16 banks, and up to 16 strings in parallel
- Supports all cell form factors: prismatic, small large cylindrical, pouch
- Protects cells from over current, under/over voltage, under/over temperature
- Dissipative (passive) balancing
- Ensure control of each cell voltage and temperature
- CAN and RS232 communications
- Fully configurable
- Cable mount Hall Effect current sensor
- Contactor, fan and pre charge relay drivers
- Optical isolation between pack and low voltage circuit
- Graphics User Interface

This system is an ideal solutions that of course meets all desired characteristics and include some extra facilities such as logic drivers for relay, fan and contactor and also a GUI which allows to easily control the whole system. The most important drawback of Lithiumate Pro is cost; in fact it is the most expansive solutions examined, so it could not be selected. Fortunately, due to sponsorship, the total cost required by Elithion become the lowest between all the examined systems, thus battery management system choice become easy to do; Lithiumate Pro combine highest performance and lowest cost and it is the selected system. The basic Lithiumate Pro system consists of a controller, cell boards and current sensor as explained in figure 3.15. Detailed connection are explained in next chapter. Figure 3.16 and 3.17 show Lithiumate Pro controller and pouch cell board respectively.

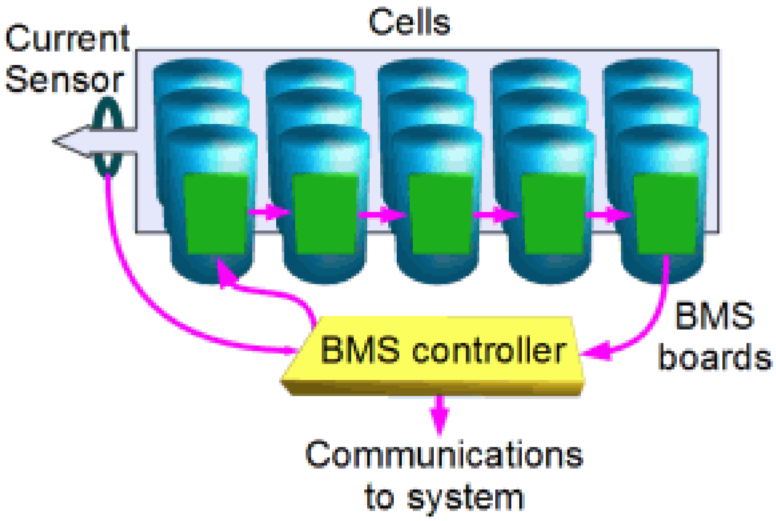

Figure 3.15: Lithiumate BMS overview

Figure 3.16: Lithiumate Pro controller

Figure 3.17: Pouch cell board

3.10 Components connections

In order to realise the battery pack for a Formula SAE vehicle, lots of different components have to be selected an connected each other. Component selection has been previously explained, whereas how components are connected each other is explained in details during this chapter. Low voltage connections, that are of course necessary to properly supply traction system components are not examined.

3.10.1 Battery connections

Battery pack external connections are pretty easy to understand: two power connectors have to be included in order to provide voltage to the traction system. FSAE rules require that each connector inside the traction system circuit must include an interlock to avoid undesired disconnections. Lots of connectors are available on the market; for example Bamocar motor controller uses Pfisterer P1 connectors: they have high electric and thermal rating (1250 V DC up to 400 A and 150 ℃ as maximum allowed temperature) that seems a little bit over sized for the designed battery. However, power connectors are expensive components; prices for high quality ones are really high, about 40€ both for plugs and socket. In order to reduce costs buying a large amount of connectors, Pfisterer P1 connectors, which include a safety interlock as FSAE rules require, are used even for the battery pack. Figure 3.18 shows Pfistere P1 plug and socket.

3.10.2 BMS connections

BMS controller manages high voltage connections through opto-isolated devices, and low voltage ones related to cell monitoring. Even if low voltage connections are not related to traction system, BMS ones are explained in order to understand how controller works. In figure 3.16 the controller is shown; lots of connectors are available, and on the upper side of it, bank connections, which are the ones used to check cells parameter are shown. Lithiumate Pro BMS can handle battery packs with up to 256 cells in series, but for technical reasons, and for reliability, the BMS views the battery pack as composed of a number of groups, called "banks". This does not mean that the pack itself is physically divided in sections: it only regards the way the BMS sees the pack. A Bank is a set of cells wired in series that communicates with the controller through its own communication cable. So, if the pack is divided into 3 banks, there are 3 cables between the BMS controller bank output and each of those banks. While it is convenient to divide a pack into banks of equal number of cells in series, that is not necessary, and indeed is not always possible. When choosing the number of cells per bank, two opposing criteria must be considered: for reliability it

Figure 3.18: Pfisterer P1 plug and socket

is preferred to use many banks: if one bank fail to communicate, the other ones can be used to guess the state of the broken bank. On the other hand, for convenience, it is preferred to use few banks: fewer banks require fewer cables, and the assembly time and the cost are lower. As a rule of thumb, more than 8 banks should be used. All cells inside a bank are serially connected each other by 2 signal wires as in a daisy chain connection, then the first and the last cells are connected to the controller. In fact, for N cells in series 1 positive end cell board, N-2 mid bank cell boards and 1 negative end cell board are needed. This refers to communication signals, but each board also has two connectors used to monitor battery behaviour. Figure 3.19 explain how 4 cells are checked by four slave boards before series connection is performed: signals ends are named C- and C+, whereas electrical terminations are named B- and B+. Green areas are N cell boards, light blue lines are the N-1 communication wires, dark blue lines are the N+1 terminal taps and yellow areas are spacers. Figure 3.20 shows how cells board are connected to folded cells. Another important BMS connection

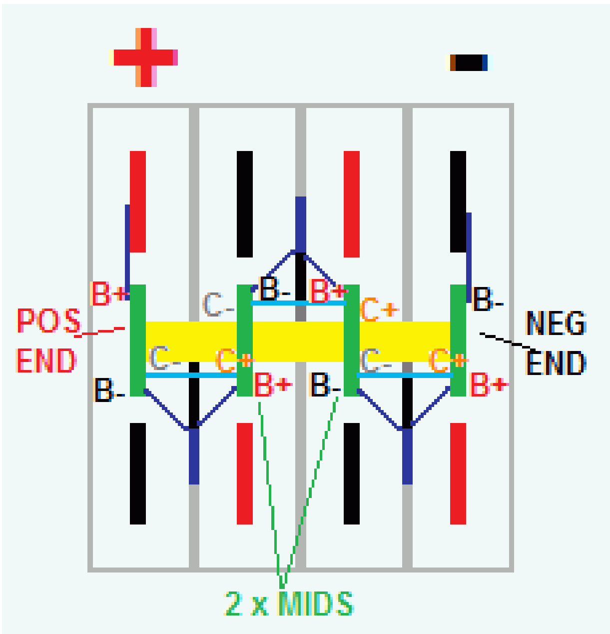

Figure 3.19: Top view of cell stacks, before cells tabs are folded to form series connection.

related to the battery pack regards how currents are measured. Inside an electric vehicle there are mainly two current to be measured: the charging and discharging ones. In order to properly measure both the currents, two current sensors are needed: due to levels available on this project, a 20 A and a 200 A sensors are used. Both of them are Hall effect sensors produced by Tamura, and Elithion suggests the way they have to be connected to

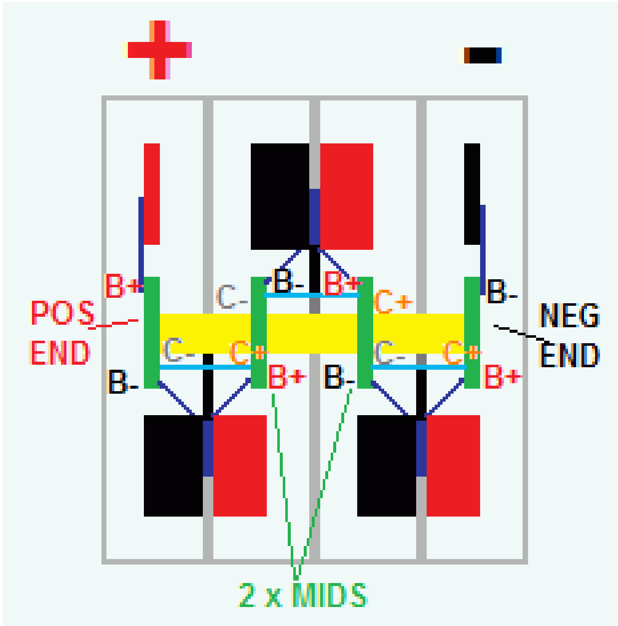

Figure 3.20: Top view of cell stacks, after cells tabs are folded to form series connection.

the controller. First of all, current sensor input are placed in front of the BMS controller, and are named "EXT CURR SNSR". How sensor output are connected to the controller through a shielded cable is shown in figure 3.21 If two current sensors are needed, it is impossible to connect both o

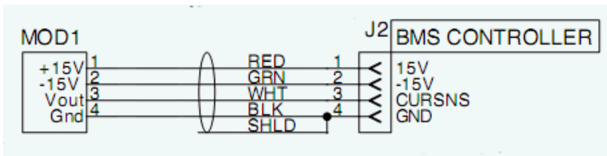

Figure 3.21: Current sensor connections to the BMS controller.

them to the specific socket, thus a general purpose input have to be used. Figure 3.22 explain the connection. Other important BMS features related to the battery pack involves fans, contactors and pre charge relays. All these components are directly managed by the BMS via two open drain dedicated connectors, which can provide up to 5 A of output current.

3.10.3 TSMP, AIR, precharge and discharge circuits connections

Other components previously chosen do not require particular connector except for the BMS; for example the AIR electric high power ends are me-

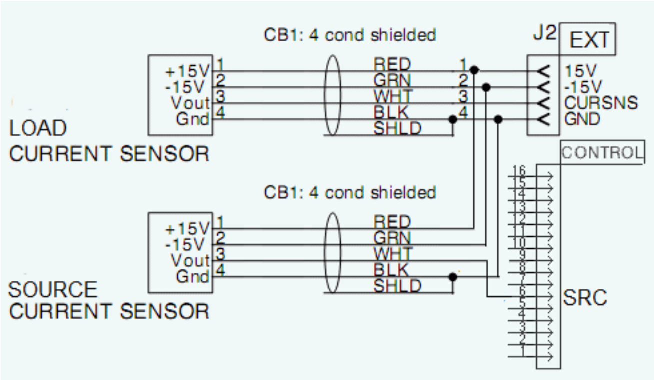

Figure 3.22: Two current sensors connections to the BMS controller.

chanically connected to the high voltage wires by screw and nut, which are also used to fasten its external frame to the battery pack case. In particular M8 screws are used as suggested by Tyco.

As rules suggests other safety devices have to be included into the traction system such as pre charge and discharge circuits, fuses and TSMP. As explained during last section, these circuits are mainly composed of relays, fuses and resistors, thus they do not have mechanically prepared connection to the frame. In order to safely fasten components, simple PCB are used, and their electrical connections to high voltage wires is achieved by M8 screws and nuts, which are also used to safely fasten boards to the battery pack frame. In order to mechanically connect high voltage wires up to 35 mm^2 in area with desired voltage and current, Phoenix MKDSP 25 can be used, as they are rated up to 1000 V and 125 A in current. Airs and PCB are physically arranged in front of the cells, with a separation barrier between components and cells as explained later during next chapter. Just to provide a global view of connections between components included inside the traction system, an electric plot is shown in figure 3.23

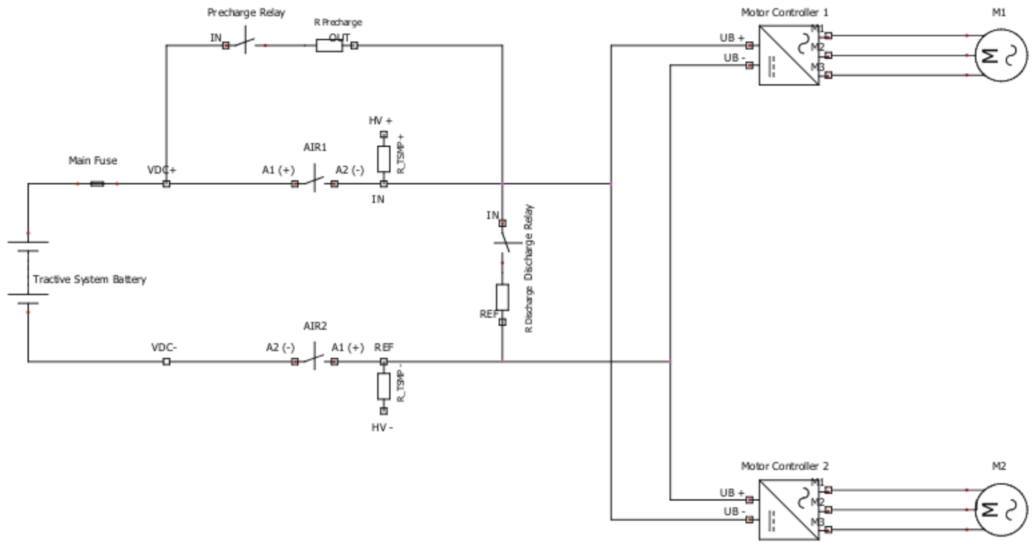

Figure 3.23: Electric schematic of the whole traction system

Chapter 4

Battery pack mechanical design

As soon as components are selected and connections involving the battery pack are explained, the next important step is to analyse how cells are connected each other to realise a rules compliant battery pack. In this chapter two different structures are examined: the first one which is a standard solution if pouch cells are used is not deeply explained, whereas the second one, that has been completely designed from scratch, is deeply explained by three-dimensional CAD drawings. Creating battery pack do not only refer to serially connect cells but other practical problems have to be examined: for example how BMS cell boards are positioned inside the module to properly check cell behaviour and also the way cells are electrically connected each other are important tasks during mechanical design. Due to the amount of electric current flowing through cells tabs, electric connection is a fundamental aspect of battery pack design: for example, if one tab connection is not perfect a parasitic resistance of 5 mΩ may be obtained and if 100 A flows through the contact, a drop out of 0,5 V across each cell is achieved, thus the electric behaviour of each cells is irreparably compromised.

4.1 Single segment traditional layout

As explained during previous chapter, 138 cells have to be serially connected in order to fulfil electric requirements and FSAE rules also require each module contains a maximum static voltage of 120 V DC and a maximum energy of 12 MJ. Just to obtain a symmetrical structure and observe FSAE rules, 6 segments composed of 23 cells are created: the maximum voltage of each module is about 100 V, and the energy stored is 4,32 MJ, thus they are perfectly rules compliant. The general shape of the battery pack is pretty highlighted: 6 segments have to be included and serially connected inside a container. The easiest way to obtain series connections is to arrange cells with alternating polarity, so that the '+' terminal of one cell is adjacent to the '-' terminal of next cell. This method is used in both the battery pack examined during this chapter.

Using pouch cells, the easiest and traditional way to create a battery segment is explained in figure 4.1: cells are arranged with alternating polarity and connected each other by short metal bar between close cells, tightened by a long bar to obtain good electric connections. A thin plastic insulator is placed between adjacent cells to avoid undesired electric connections and BMS cells boards are included between each cell, as explained in figure 4.2 This solution guarantees good electric connection and allow to obtain tidy

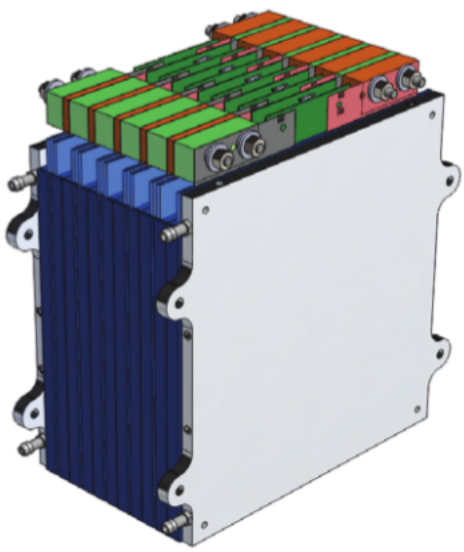

Figure 4.1: Traditional arrangement of pouch cells

battery pack, thus it may be used during this work. Unfortunately, this solutions is afflicted by two drawbacks: first of all it is difficult to perform maintenance operations; if a single cell is broken and has to be replaced, the metal bar have to be removed and all the cells become free because electric connections are removed. In addiction this solution may become a little bit too expansive if it is used in huge volume productions. In fact connections between cells board and tabs have to be manually made adding wires on each cell board and then welding them on each tabs. Every FSAE team during competitions have to simulate an industrial production of its vehicle, thus during a new design an important aspect is reducing costs, for example creating symmetrical and repetitive structure whose costs can be reduced by serial production. It is important to realise that FSAE competitions are not only composed of racing activities, but an important part of total scores achieved by each team is obtained by project and cost analysis. In order to

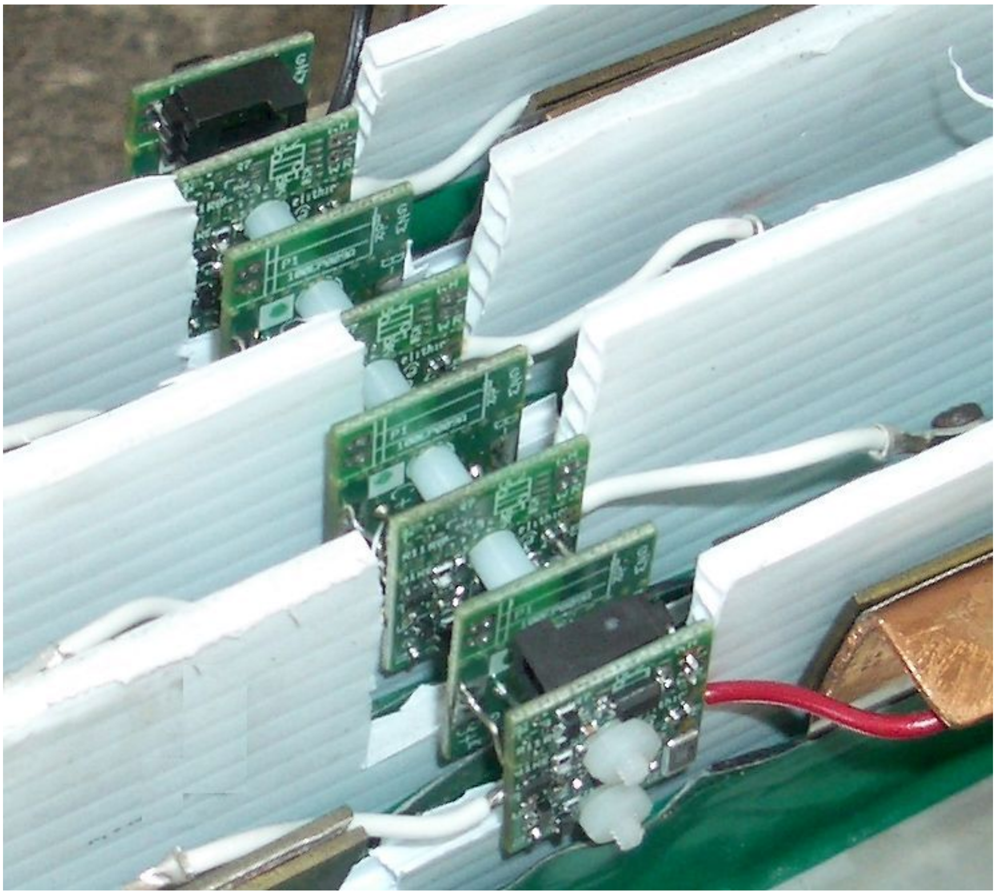

Figure 4.2: Detailed view of cell boards between tabs

create an alternative solutions, overcoming drawbacks previously explained, another arrangement is created.

4.2 Single segment innovative layout

Even on this new mechanical design, cells inside a segment are arranged with alternating polarity to simplify series connections, but the way cells are electrically connected is completely different: cells are organised close to each other, and a thin layer of holed plastic material is used as a separation between cells and the electronic circuitry positioned above. Tabs of each cell are then slightly folded to obtain a symmetrical structure (it is important to notice that selected cells are not symmetrical, because tabs are not positioned on the middle of the cell, but at the end of it) and serially connected with the near tab by a short metal bar. In addiction, to reinforce electric connections, the short metal bar may be screwed directly to tabs. Metal bars have to sustain the whole electric current flowing through the battery thus it is important to check if safety current level density are overcame. For example, if the bar is made of copper whose safety current density could be approximately thought to be $6\frac{\mathrm{A}}{\mathrm{mm}^2}$ in order to avoid overheating, thanks to its huge area (about $4000\,\mathrm{mm}^2$), a short bar is perfectly able to sustain 117 A of current. In figure 4.3 the holed plastic layer is shown, whereas figure 4.4 shown the metal bar used to push down and connect two near tabs. As

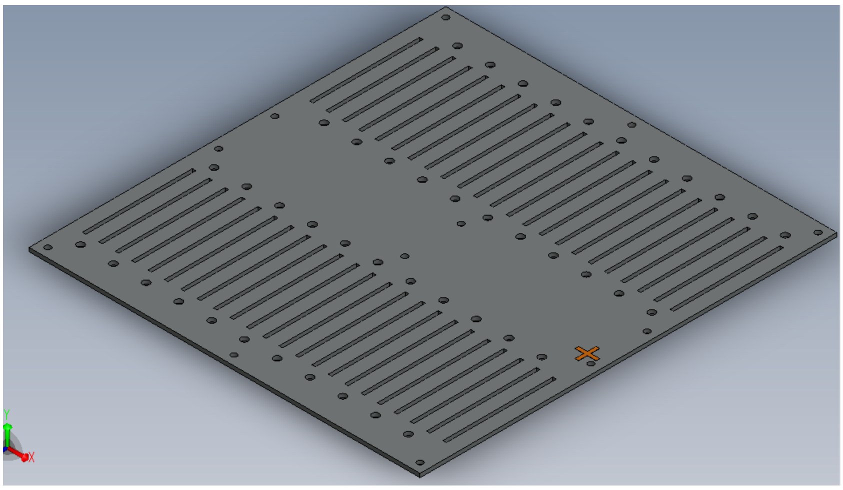

Figure 4.3: Separation layer between cells and electronic circuitary

soon as all tabs are electrically connected, BMS cell boards have to be included inside the container. The easiest way to do this is to put them on the middle of the plastic layer, creating a sequence of cell boards, as explained in figure 4.5. This mechanical design ensure good electric contact and also

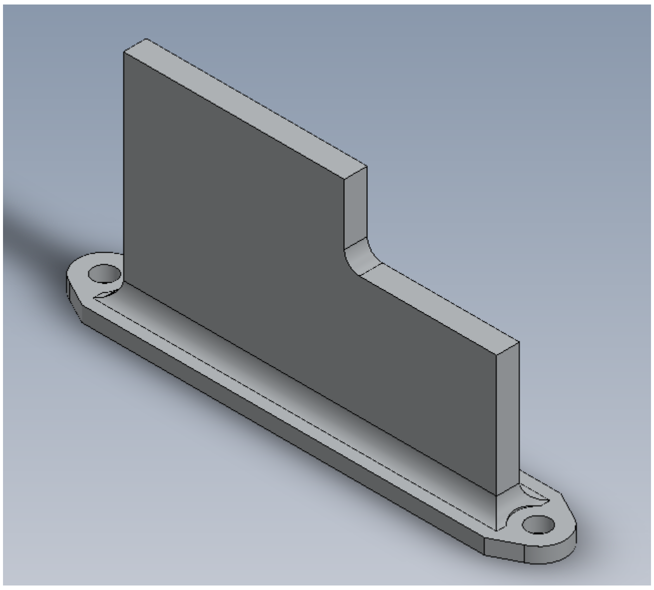

Figure 4.4: Metal bar used as electric connector.

allow to replace broken cells because the long bar moving through cells array is replaced by single short metal bar, which can be removed in case a cell brake, and the cell can be easily replaced removing it from the bottom side of the pack. The most important drawback of this arrangement is tab bending which may lead to mechanical stress due to limited tabs thickness which is about 0,3 mm. As an alternative, cells connections can be easily obtained by a single metal bar which is not used to push down two near tabs, but is interjected between two tabs and screwed at the end of them. This solution increases costs; in fact due to the asymmetric design of tabs in each cell, two different metal connections have to be used for near and far tabs. As explained at the beginning of this chapter, the higher the cost, the less score is achieved during cost analysis event: this is the most important motivation leading to tab bending; if tabs are folded, a symmetric design is achieved and a single metal connection can be used, reducing costs. Regardless to cells connections, this mechanical design has another drawback: lots of wires are used to connect cell boards to related tabs, obtaining an untidy design. In FSAE competitions during "static events" design solutions are also analysed and discussed by judges and the more innovative and organised they are, the higher score is obtained. In order to create innovative and tidy solutions avoiding to use strewn wires, different connections for cell boards are studied.

The main idea is using short metal bar as electric connections for cell boards, managing signal connections by a PCB. As previously explained, creating symmetric and repetitive structures allows costs reductions in huge

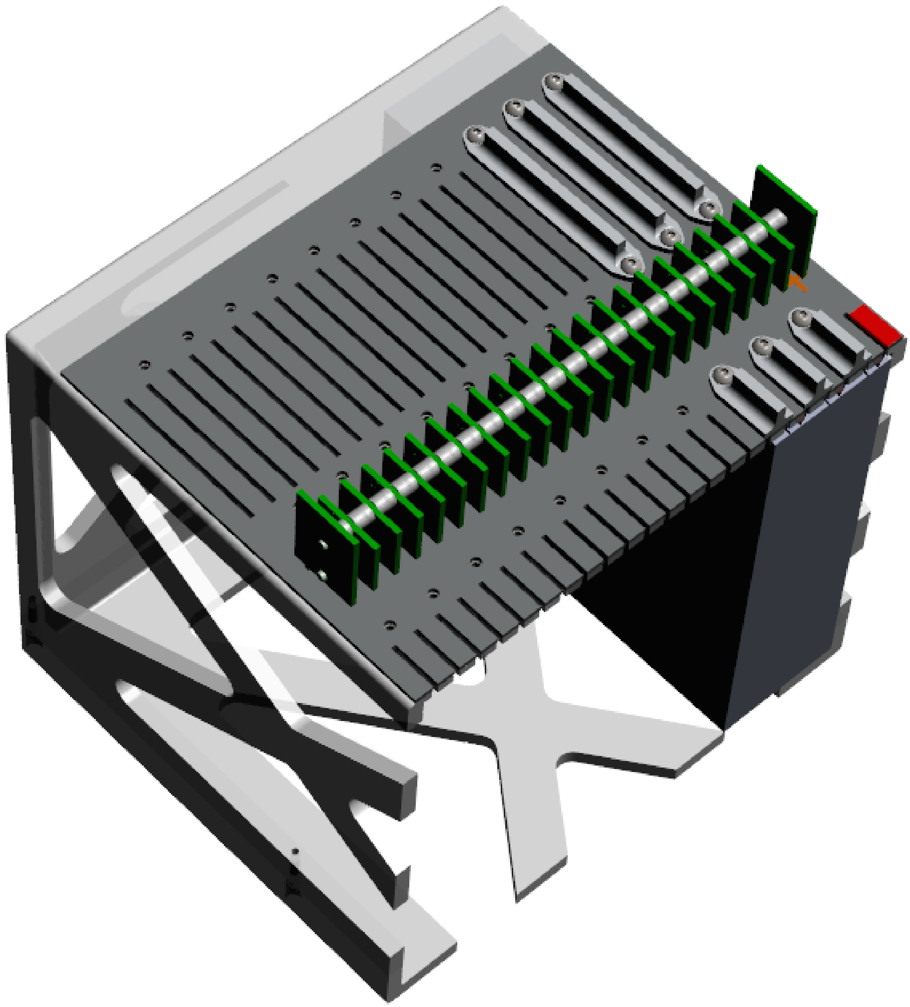

Figure 4.5: Top view including cell boards

volume productions (the same Formula SAE tries to simulate) and also achieve higher score during cost events, thus a PCB is used to connect metal bar to cell boards. The advantages of a PCB are pretty evident: as soon as a board is created to manage signal connections between board and copper traces, costs related to link each cell board to a tab by wires are avoided.

On the PCB bottom side electric connections are managed and symmetrically arranged to the middle of the board where cell boards are included. The bottom view of the board is shown in figure 4.6 whereas a more detailed view which emphasize how cell boards are connected to copper traces is shown in figure 4.7 and 4.8. As explained in figure 4.8 thanks to the

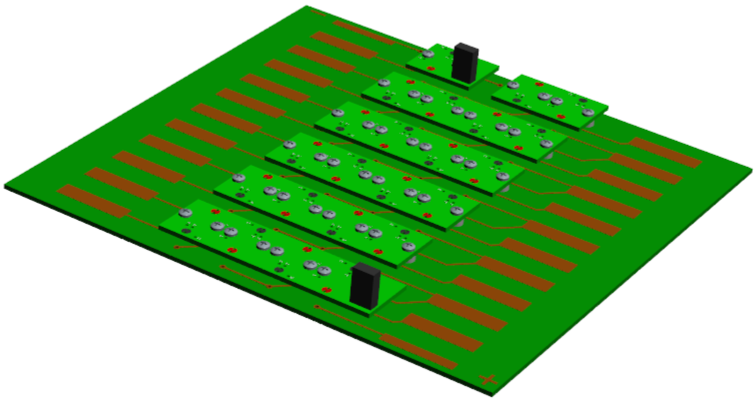

Figure 4.6: PCB bottom view including cell boards

alternating arrangement, electrical terminations of each board are always precisely oriented to the predetermined via, then welding process can be automatized reducing costs. On the upper side of the PCB a plastic threaded bar is located to mechanically screw cells, as shown in figure 4.9. Using a PCB as explained during this new mechanical design is possible to reduce costs, even if further reduction are possible. In fact, as explained in figure 4.9 electric connections between cells and copper traces have to be manually realised, whereas if cell boards are turned, their electric connections can be electrically managed by another PCB. Daughter boards can be used to locally manage connections between cells, and a motherboard may be used to connect copper traces to daughter boards. If this layout is used, no spare wire are present and no human actions are required, thus a complete serial production is possible.

As soon as two mechanical designs are explained, it is difficult to choose what could become the ideal one for the project: traditional design guarantees good electric connections and preserves cells from mechanical stress,

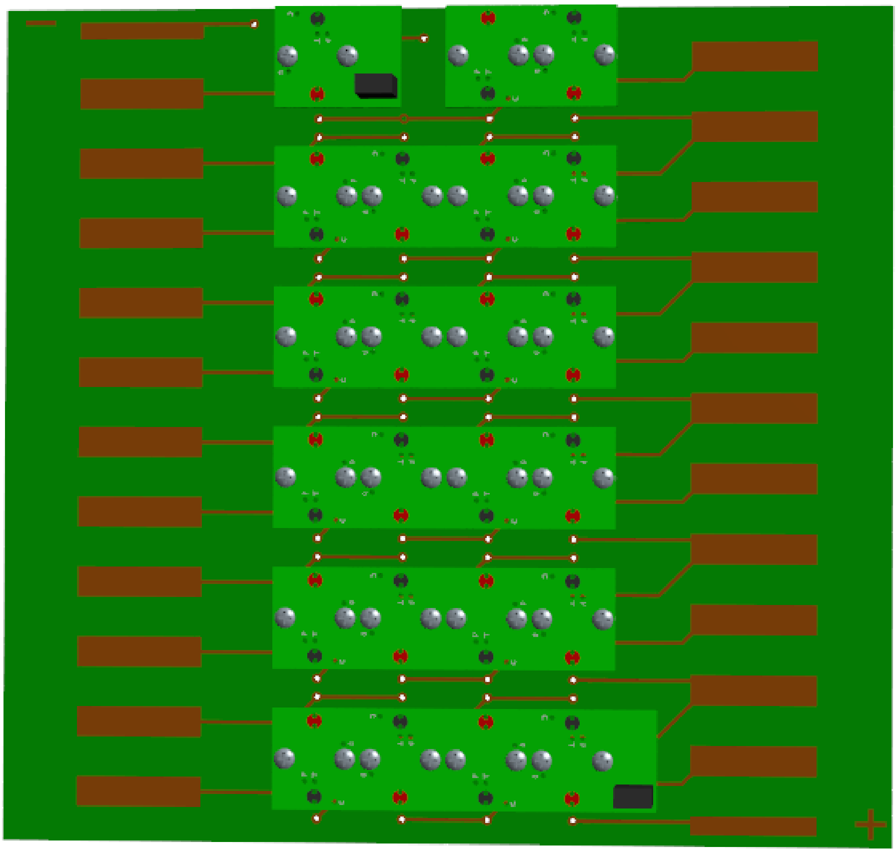

Figure 4.7: Bottom view detailing cell boards connections

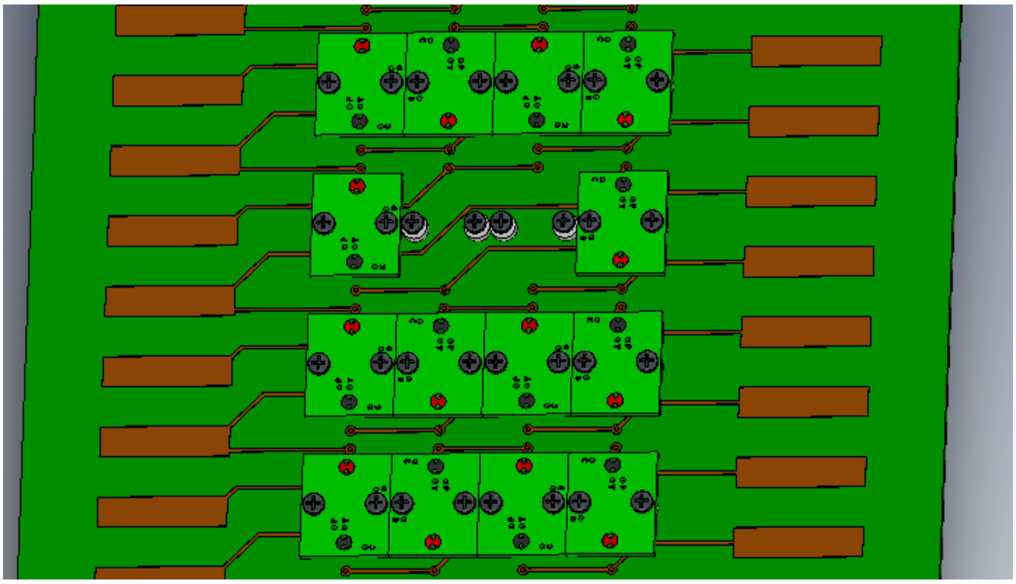

Figure 4.8: Bottom view without 2 cells showing how cells are connected to tracks

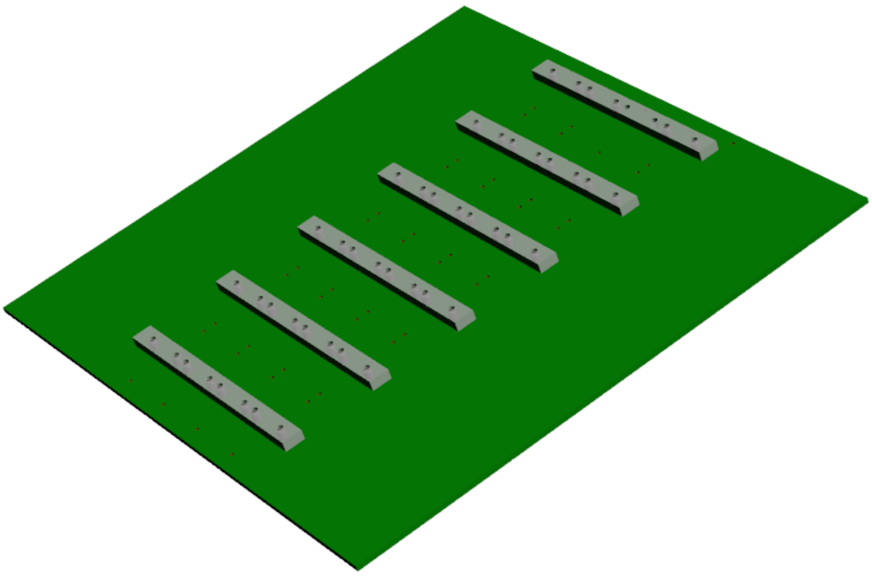

Figure 4.9: PCB upper view

whereas it may become too much expensive to be used in serial productions as Formula SAE require. The new design, which reduces production costs creating tidy systems, has a mechanical drawback: as previously explained, tabs on each cell have to be bended creating mechanical stress on them. Practical experience could suggest the best design: as soon as cells are bought and are available for tests, practical experiments can be performed in order to evaluate if mechanical stress created by bending is extremely damaging for tabs. If tests confirm excessive mechanical problems on tabs, the first solutions have to be performed, whereas if stress is not damaging, the new mechanical design is chosen. Another solution is also possible, combining both traditional and innovative layouts: a short metal bar with an L shape may be used to serially connect cells and a long bar can be used to tighten connected cells. Thanks to the L shape, short bar connect cells to the upper PCB. Both solutions are fused and a third one; power connections are managed as in traditional layout but thanks to the L shape, small metal bar are also used to connect cells to the upper PCB that manage cell board connections. If the third solution is used, serial production is even more possible and costs are further reduced.

4.3 Battery pack layout

All the segments building up the new mechanical design have been individually explained and in figure 4.10 and 4.11 cross sectional views of a segment is shown, while in figure 4.12 an isometric view is presented. The main battery accumulator is then composed of six segments serially connected and included inside a battery pack container which is shown in figure 4.13: all the segments are included inside the main box whereas electric and electronic circuitry connected with the battery pack are put into the triangular prism located above the box. Prism positioning is indeed variable according to the electric power train arrangement inside the vehicle: it may be possible to locate it upright with electric motors and their relative controller on its back as explained in figure 4.14 or it may be possible to lye the battery pack under the seat and arrange motor controllers over it, locating electric motor on the back as shown in figure 4.15.

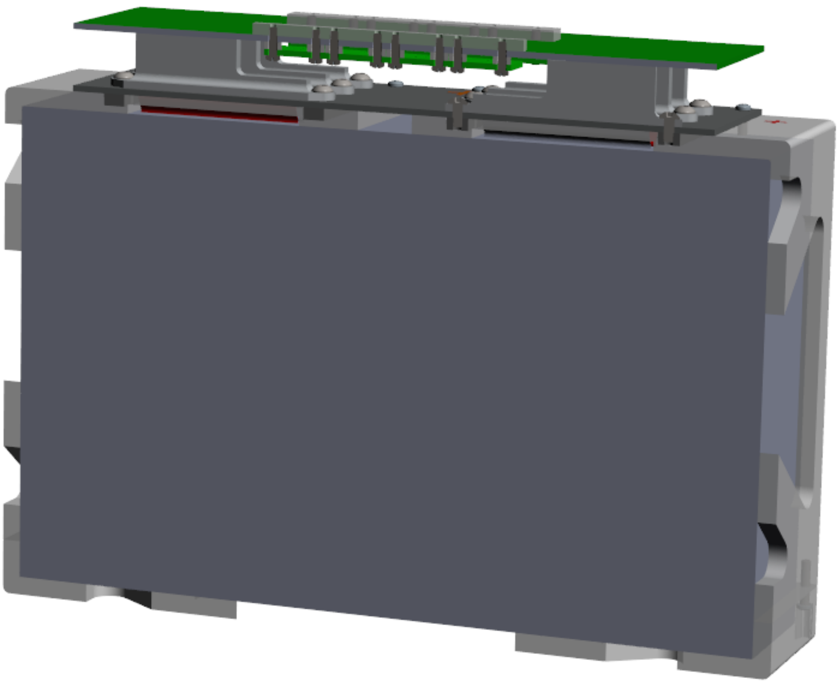

Figure 4.10: Cross sectional view of a segment

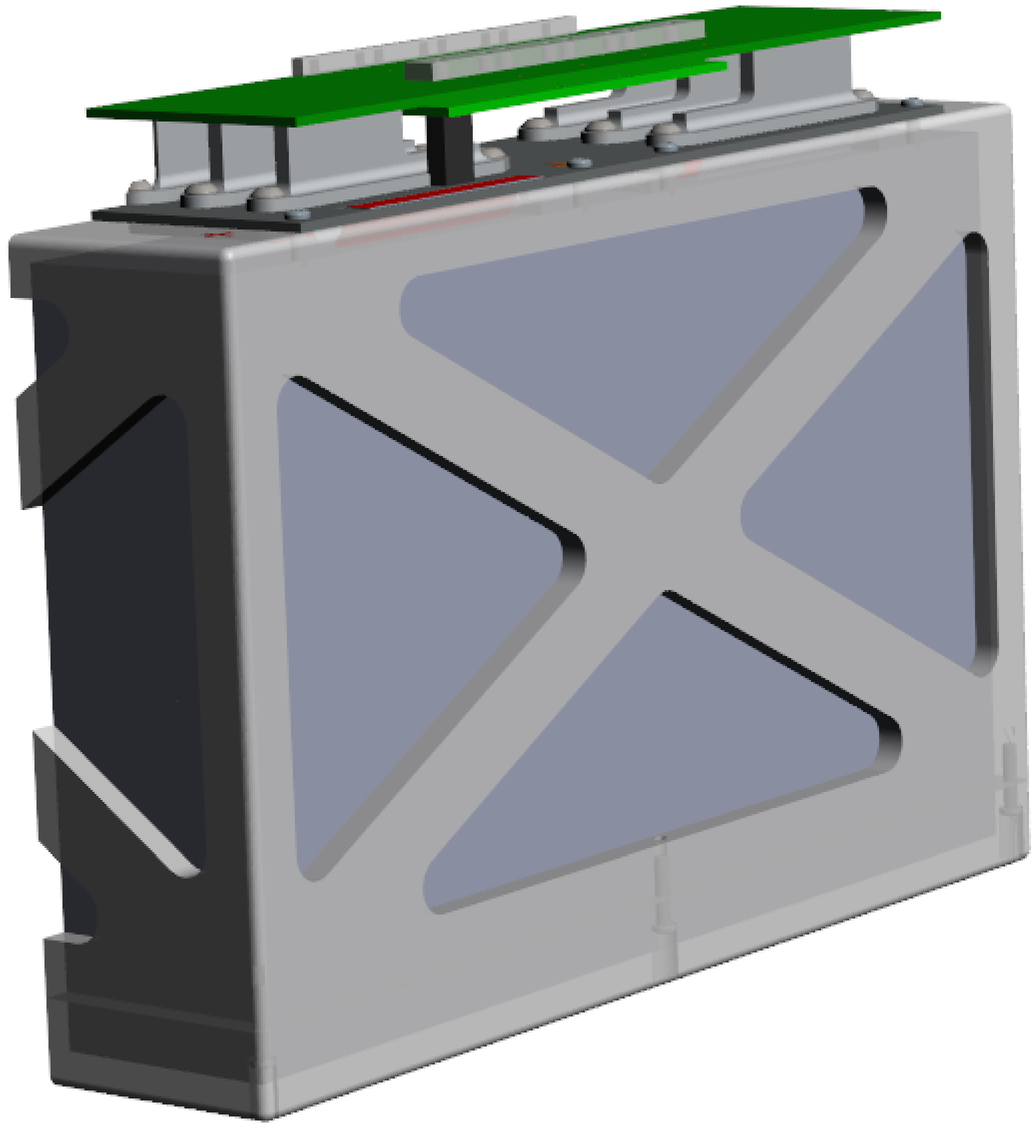

Figure 4.11: Cross sectional view of a segment

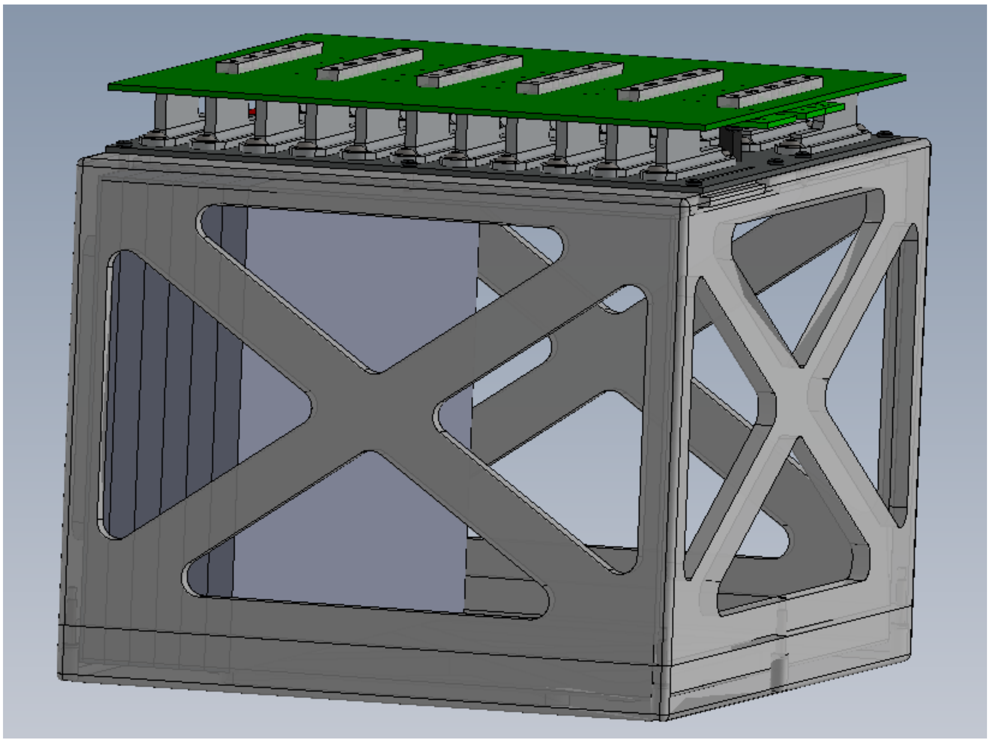

Figure 4.12: Isometric view of a segment

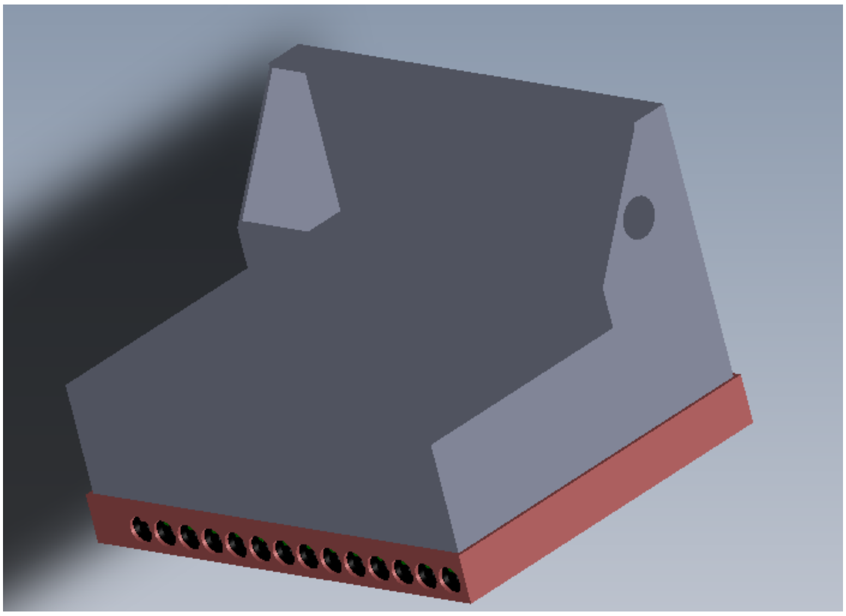

Figure 4.13: Battery pack accumulator view

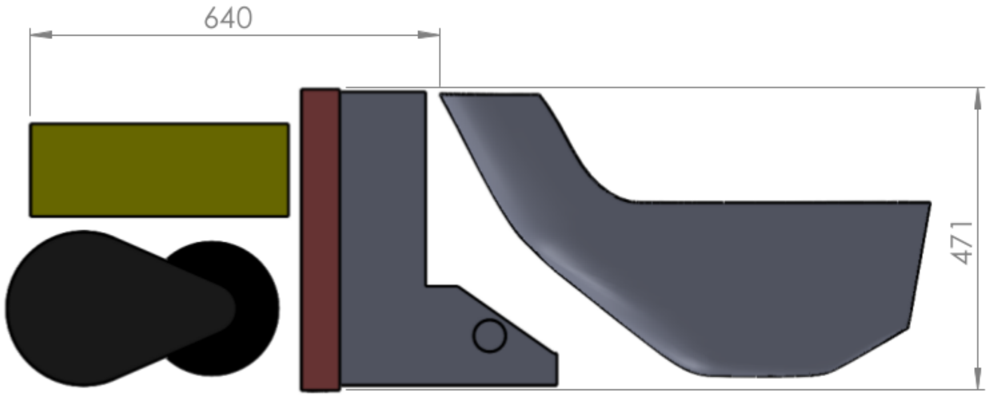

Figure 4.14: Possible power train positioning

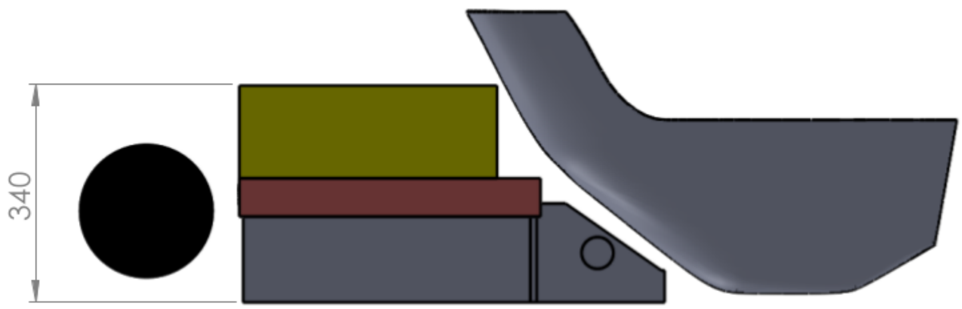

Figure 4.15: Possible power train positioning

Part III

Simulations and Validations

At the end of a project validating performed choices by practical measurements on real devices is extremely important. In case there is no possibility to validate the whole design by practical experiences, simulations become the most important way to control design quality. In this project two kind of simulations are performed: first of all electric simulations are used to check battery behaviour during an endurance event, for example understanding the maximum power that should be delivered to the wheels in order to complete an entire race without damaging cells, and also suggests alternative solutions to reduce power consumptions, such as dynamic power reduction. Another fundamental aspect involved in battery pack design is cooling: even if batteries energetic efficiency is traditionally high (about 90%), a huge amount of energy is wasted as heat, leading to cells over-temperature, which may become detrimental. Three dimensional FEA analysis is performed in order to understand good cooling methods, and then as soon as an efficient method is found, thermal simulations is refined by CFD analysis.

Chapter 5

Electric Simulations

5.1 Cell model and simulation setup

In order to evaluate the electric behaviour of the whole battery pack, modelling activities are performed to create reliable electric models of the single cell. Thevenin model with two time constants, as shown in figure 5.1, is used in order to precisely represent transient response of the battery.

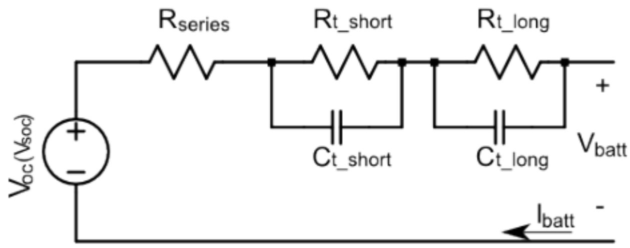

Figure 5.1: Cell electric model

The main difficulty during modelling activities is obtaining cell parameters by laboratory measurements, which cannot be performed in this case, due to two different problems: first of all cells are unavailable then, of course, they cannot be characterised. The second problem is pretty a practical one: in order to characterise selected cells at high discharge rates, high current levels (more than 200 A) have to be managed and this is possible only with tools and machinery which are not available at the electronic department of the University of Pisa. Fortunately, within the department characterisation of small capacity Lithium Polymer high power cells produced by Kokam has been performed in the past, and then results are available. Cell parameters mainly depends on chemisrty and energy rating and it is possible to extrapolate parameters for cell with different capacity starting from measured ones. In fact, for example, it is reasonable to suppose a 12 Ah cell as the union of 6 cells with a capacity of 2 Ah if they are made of the same chemistry, thus it is possible to suppose that equivalent resistance value are reduced on high capacity cells, whereas time constants are kept constants, thus capacitance value increases. So, starting from measured value [30] parameters are extrapolated and collected on table 5.2. As soon as parameter

SOC [%]	OCV [V]	Rseries [Ω]	Rt_long [Ω]	Ct_long [F]	Rt_short [Ω]	Ct_short [F]
1	3,28014	0,01231125	0,0030955	35877,704	0,00558213	1368,993
10,5	3,50153	0,00641638	0,00175988	65514,628	0,00315538	3207,505
20	3,60816	0,00503163	0,002401	69501,577	0,00168075	8247,2206
29,5	3,71862	0,00378913	0,00243513	57404,453	0,00212988	5788,6381
39	3,76704	0,00246263	0,00212488	71765,844	0,001497	7899,6478
48,5	3,78043	0,00233863	0,00174063	69325,34	0,001196	8908,7806
58	3,81951	0,002515	0,00118013	258070,74	0,00172988	12443,811
67,5	3,86597	0,00237938	0,00096475	109086,67	0,001349	9021,4026
77	3,94544	0,00247	0,001507	94887,091	0,0021465	6812,3484
86,5	4,0457	0,00232538	0,00179475	42223,702	0,0019985	6978,7636
96	4,145290	0,0024185	0,00128575	72426,626	0,00175738	4961,5133

Figure 5.2: Cell model parameters

are obtained, other decisions are necessary in order to perform electric simulation. First of all, using electric model an electric simulator such as Spice should be thought to be the ideal solution. This is not true mainly for two reasons: the first one rely on the way parameters are available; table are not easy to be included in Spice like simulator, and the second one rely on the particular type of simulations needed. In fact, as explained later, arbitrary current profile dependant on vehicle parameters have to be used to perform endurance simulations, thus an object oriented, multi domain simulator is preferred. In specific, Dymola software, which is very used in automotive environment is chosen, due to the possibility of connect electric domain (for example the battery one) with mechanical or dynamic ones.

The electric cell model created by Dymola software is shown in figure 5.3 and it is pretty easy to understand; variable resistance, capacitance and voltage source depending on the SoC are used to represent the schematic shown in figure 5.1. SOC calculation using simple coulomb conunting technique is performed by another module called BMS, which is also responsible of over-voltage and under-voltage detection by a digital error signal called "Charge-Error".

In order to simulate and check the electrical behaviour of the battery pack during an entire formula SAE event, simulations with custom load current is performed. To obtain desired current profiles, first of all, the ideal path, based on geometric calculation of Hockeneim Formula SAE circuit is performed, and then it is used as input of a dynamic model of the E^2T1, the new Formula SAE car of the University of Pisa, whose battery pack is studied during this thesis. The model is customised by lots of mechanical and dynamic variable, and in addiction other parameters such as

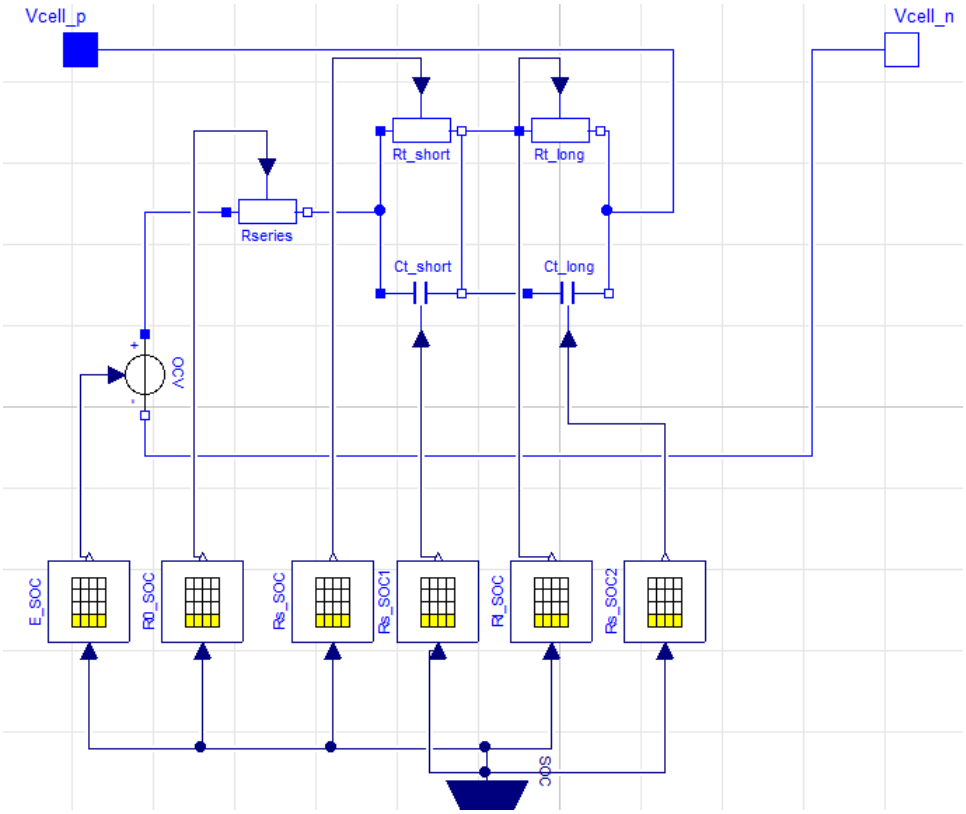

Figure 5.3: Dymola model of a single cell

the maximum power delivered to the wheels and the amount of power regenerated during regenerative braking can be selected in order to simulate various hypothetical situations. Calculation have been performed by other team members obtaining a table representing the instant power delivered to the wheels during the race, and these value are used to simulate battery behaviour. In fact, if mechanical power provided to the wheel is known, it is easy to reconstruct the electric power drawn from the battery if the efficiency of electric motor and inverter is generally about 90%, according to Enstroj. Then, if the electric power drawn from the battery is known, in order to obtain the current extracted by the battery, it is possible, on first approximation, to suppose the battery voltage is constant. This hypothesis is supported by the slight OCV dependency to the SoC, so if the voltage provided by each cell is supposed to be 3,7 V, which is an average value for Lithium chemistry, it is possible to obtain a good approximation of the time dependant current provided by the battery during a race. These current values are gathered into a table which is used as a current load to the cell model. The experimental setup is composed of cell model, BMS and current generator, as shown in figure 5.4.

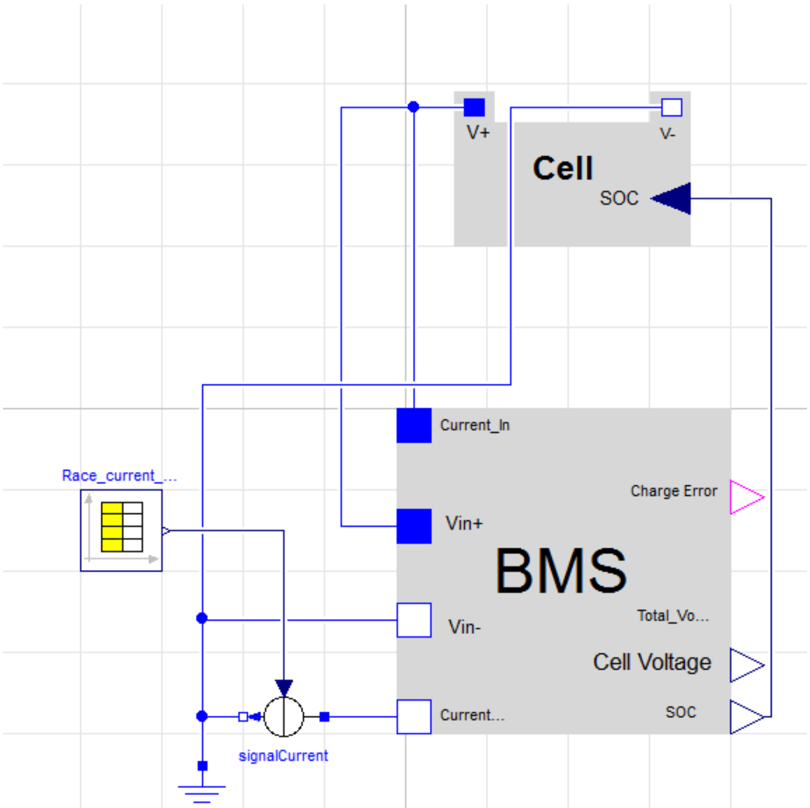

Figure 5.4: Experimental setup

5.2 Performed simulations

The first simulation is performed to verify if the maximum amount of mechanical power delivered to the wheels (about 45 kW) that has been estimated at the beginning of the text, is greater than real battery capabilities. With a maximum mechanical power of 45 kW, assuming to regenerate 10 kW during each braking (the value is about 22% of delivered power, thus it is pretty a standard value), simulations are performed and results are not as desired: at the end of the race the amount of energy available inside the battery is less than estimated one. Figure 5.5 shows the simulated SoC through which it is possible to realise that, at the end of the race, the amount of energy is lower than 20%, a safety value which should not be passed, in order to protect Lithium cells. Even if 45 kW of mechanical power could be a value a little bit higher than the real one, because it is obtained supposing the driver is able to drive following the ideal geometric shape, it could not be possible to complete an entire race in real situations, thus the power to the wheels have to be reduced. Other simulations are then performed with

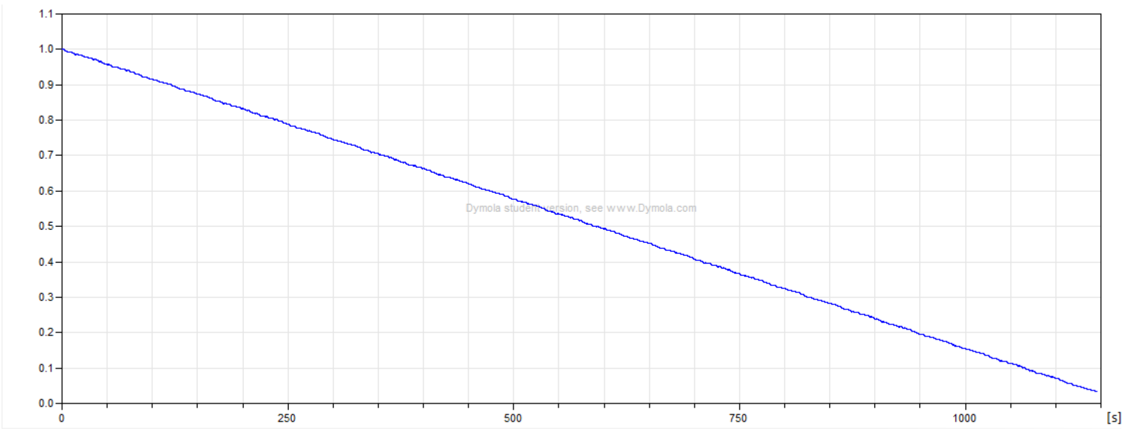

Figure 5.5: SoC simulation with a maximum power limit of 45kW available at the wheels

reduced power limits: the first one is performed supposing to be able to provide 40 kW of mechanical power to the wheels, and the SOC slightly changes, as shown in figure 5.6. At the end of the race, the available energy is a little bit lower than 20%; it may be possible the real driver uses a little bit less energy than the ideal one, thus the energy could be sufficient to complete the whole race but it is not cautious to rely on this suppositions. Another simulations, with a mechanical power limit of 35 kW is performed and results are pretty interesting: as shown in figure 5.7 the SOC at the end of the race is higher than 20% and cell voltage during the race varies as shown in figure 5.8. No potential damaging situations such as over-voltage

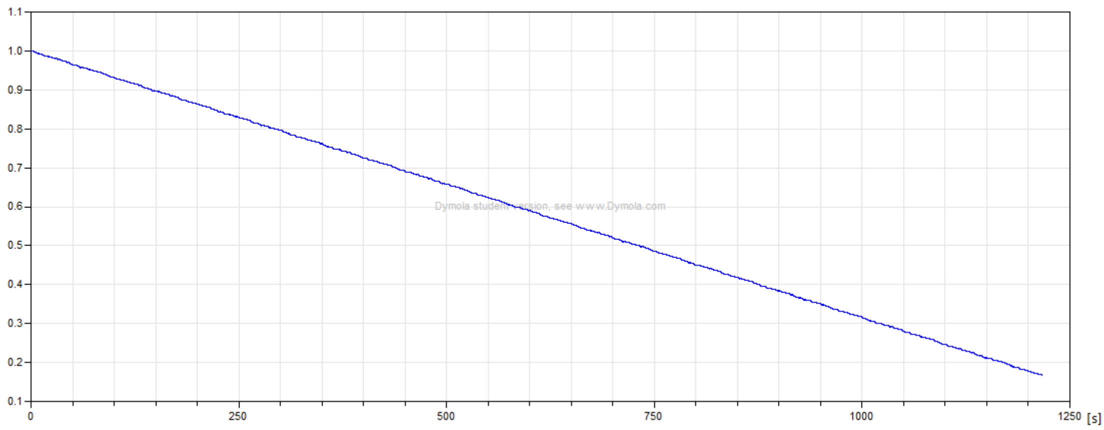

Figure 5.6: SoC simulation with a maximum power limit of 40kW available at the wheels

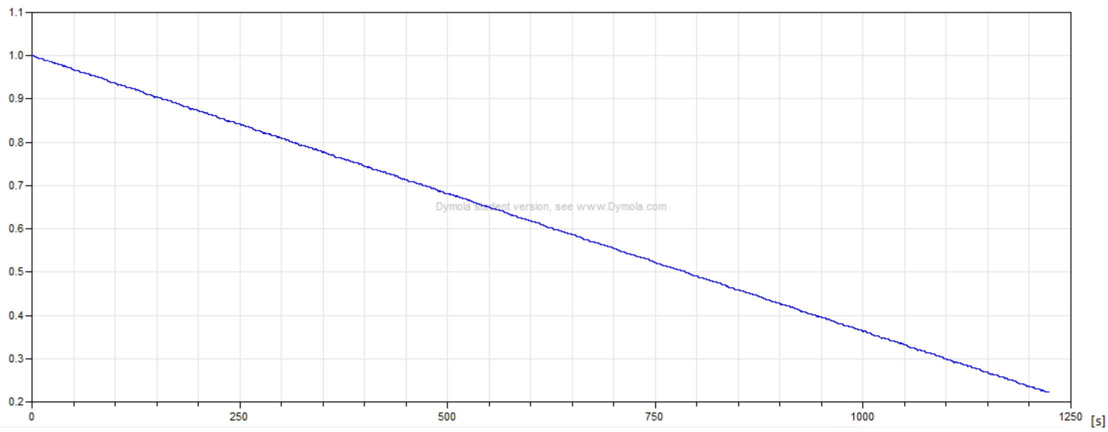

Figure 5.7: SoC simulation with a maximum power limit of 35kW available at the wheels

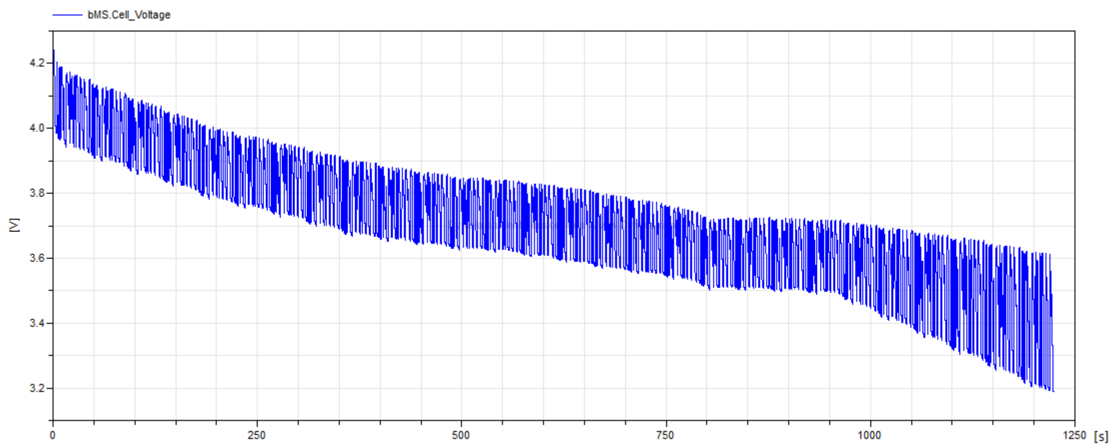

Figure 5.8: Cell voltage variations during a race supposing a maximum power limit of 35 kW available at the wheels

(cell voltage higher than 4,2 V) or under-voltage (cell voltage lower than 2,8 V) are highlighted, thus the real power to be provided to the wheels is thought to be a value within 35 and 40 kW.

As soon as the maximum mechanic power provided to the wheels is highlighted, electric simulations are refined. In fact the hypothesis performed before through which it is supposed the voltage of each cell is constant to a value of 3,7 V is correct only if the SoC is about 50%, whereas at the beginning of the simulation cell voltage is higher than 3,7 V (because the SoC is higher than 50%) and current is lower than calculated value. In contrast, at the end of the simulation, cell voltage is lower than 3,7 V then current may be higher than obtained value and under-voltage may occur. In order to refine simulations and achieve reliable simulations, Dymola model has been complicated: the power drawn from the battery is used as a simulation input, and it is divided by the actual measured voltage across electric endings of the battery pack, in order to let the software calculate the current flowing out from the battery depending on the measured voltage. Refined simulations are performed with a mechanical power of 35 kW, which is thought to be the maximum allowed value in order to complete the endurance event. SoC and cell voltage are highlighted and shown in figure 5.9 and 5.10 respectively and it is possible to realise that performing more realistic simulation, the SoC at the end of the race is slightly lower than the previously calculated value, assuming the voltage is constant. Fortunately, SoC value is 0,2 at the end of the endurance event, thus it must be possible to complete the race, even because a real driver could use less power than the ideal simulated driver.

Just to understand differences between current calculated supposing a constant voltage and on-line calculated one, a single lap simulation is per-

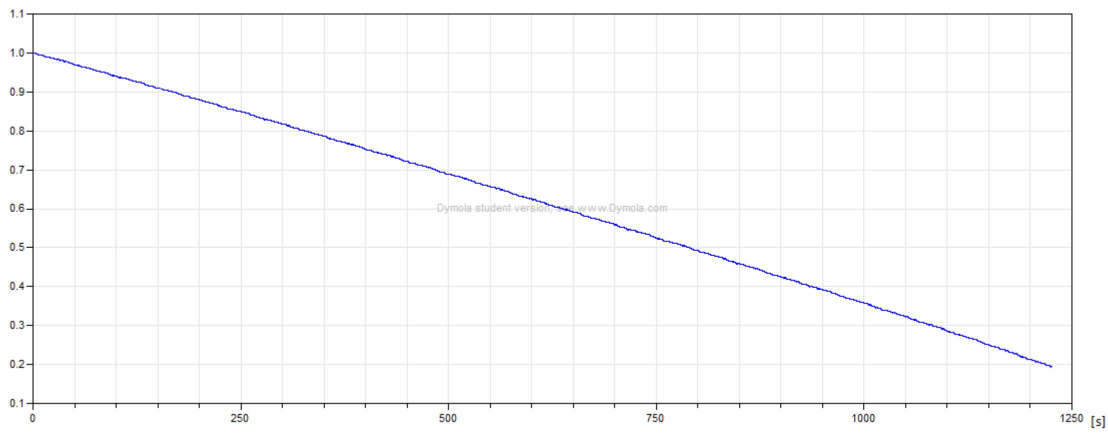

Figure 5.9: SoC simulation supposing a maximum mechanic power limit of 35kW, without constant voltage hypothesis

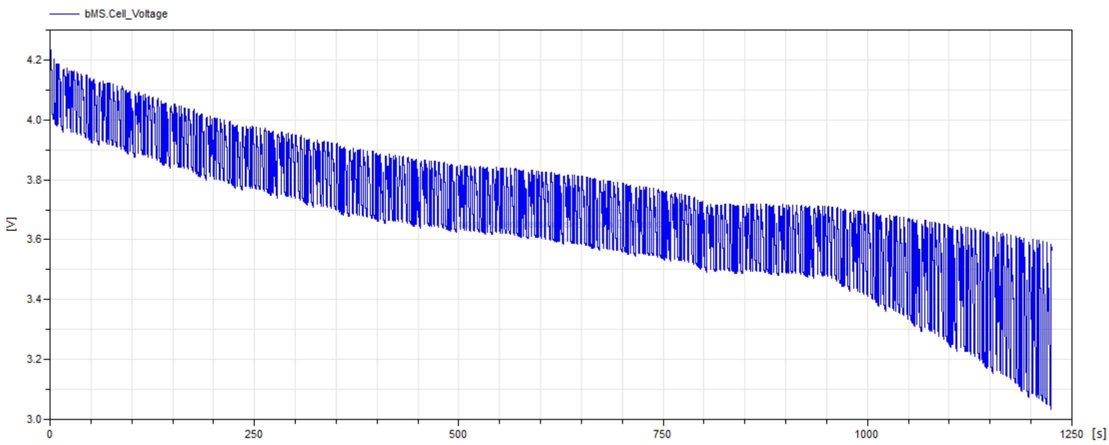

Figure 5.10: Cell voltage variations during a race supposing a maximum mechanic power limit of 35kW, without constant voltage hypothesis

formed supposing two different SoC: if a fully charged battery is used, cell voltage is higher than 3,7 V and the real current flowing out from the battery have to be lower than the value calculated supposing a constant voltage. In contrast, if the battery is discharged the real current have to be higher than the approximated one. Both these considerations are shown in figure 5.11, where a single lap with a unitary SoC value is performed and in figure 5.12 where the SoC is supposed to be 0,3. Blue line refers to refined simulation whereas red line is about constant voltage simulation. Analyzing figure 5.11

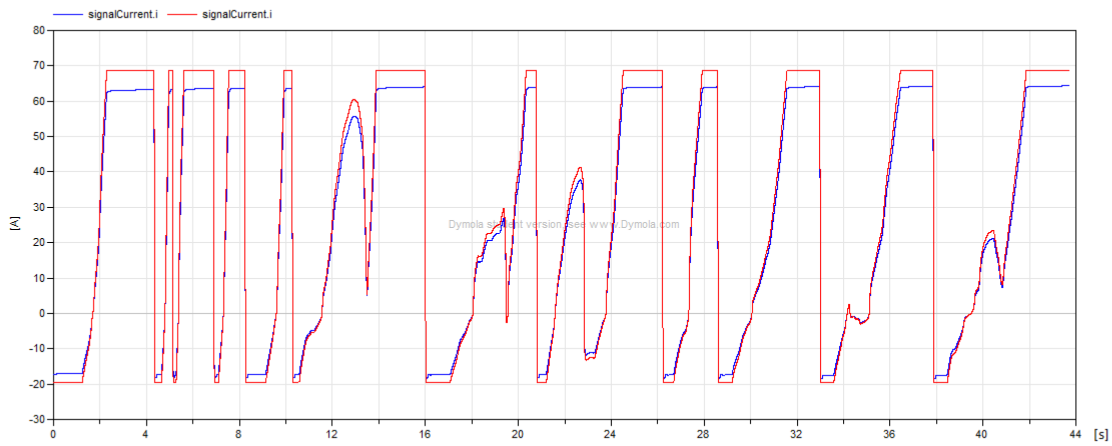

Figure 5.11: Single lap comparison beween simplified and run-time calculated currents, with fully charged battery

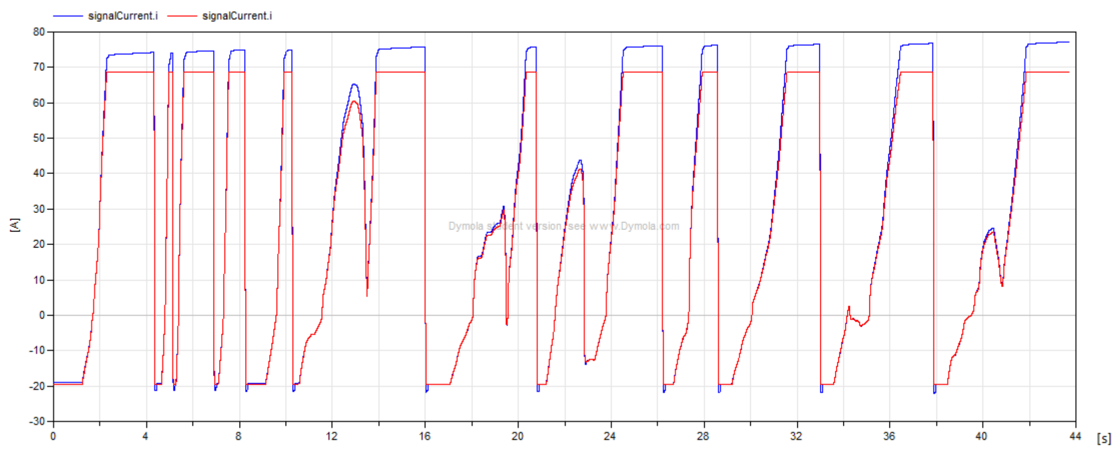

Figure 5.12: Single lap comparison beween simplified and run-time calculated currents, at SoC=0,3

and 5.12 it is possible to confirm suppositions about current level previously done, and also estimate the error performed by constant voltage hypotesis: if a fully charged battery is simulated, the differences between current levels is about 5,5 A which correspond to a relative error of 7,7%, whereas if the SoC is supposed to be 0,3, the absolute error is 7,2 A and the relative one is 10%. These results confirm that in order to perform a first order analysis, supposing the voltage to be constant does not lead to unacceptable errors, compared to model and simulator inaccuracy.

Chapter 6

Thermal Simulations

6.1 Cells thermal parameters

In order to design the battery pack of an electric vehicle, an important aspect involves thermal management. In fact, even if energy efficiency of Lithium cells is in general about 90%, due to the amount of energy provided, a huge quantity of it is wasted as heat, thus thermal behaviour of the battery pack have to be studied to avoid cells damaging. In fact, as explained during part one of this thesis, Lithium chemistry does not allow temperature higher than 60℃ then a reliable and efficient cooling system have to be realised.

The first part of thermal analysis concerns how a cell exchanges heat with the surrounding, thus thermal characterisation have to be performed. However, cells are not available at the moment, thus they cannot be thermally characterised. Luckily, thermal parameter regarding Lithium pouch cells whose dimensions are like selected ones are literature known and pretty standard [29], and are summarised in table 6.1. These values form a param-

Thermal parameter	Typical Range	Value
k $[W/mK]$	0.40 – 0.85	0.66
c_p $[J/kgK]$	650 - 950	795
ρ $[kg/m^3]$	1700 - 2500	2100

Figure 6.1: Thermal parameters of Lithium pouch cells

eter called thermal diffusivity, which measures the ability of a material to conduct thermal energy relative to its ability to store it, whose expression is:

$$\alpha = \frac{k}{\rho \cdot C_p}$$

6.2 Comsol model

In order to obtain thermal characterisation of the whole battery pack finding efficient cooling techniques, the way cells are physically arranged inside the pack is fundamental: as explained during part two of this text, cells are arranged within a battery container and divided into six equal segments. Cells have to be kept as close as possible to each other inside each segment in order to avoid the creation of a thin air layer between them that acts as a thermal insulator, increasing temperature in the middle of the pack. Unfortunately, due to packaging error and battery physical behaviour (each cell has a natural variation in thickness of about 0,5 mm between fully charged and fully discharged states) it is not possible to realise a solid mechanical structure, but a parasitic thin air layer is always present. With the purpose of study three dimensional structures a FEA software called Comsol is used and a simplified model of a battery segment is realised: cells are represented using their real dimensions and are arranged in parallel, with a 0,5 mm air layer between close ones. An isometric view of the model is shown in figure 6.2. "Heat transfer in solids" module included in Comsol simulator is used

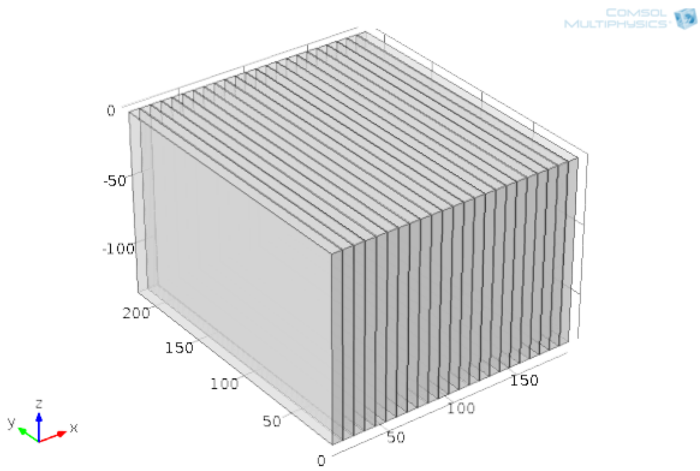

Figure 6.2: Isometric view of the segment model

and boundary conditions are changed according to different simulations. Each cell is thermally characterised with typical values of parameters summarised on table 6.1, whereas power generation varies according to different simulations. This model is used to understand thermal behaviour of the battery pack combining accuracy and computational cost: in fact boundary conditions between solids and fluids are modelled by dimensionless analysis and lumped parameters instead of solve fluid dynamics equations. As soon as simulations are performed, and an efficient cooling technique is designed and CFD simulations are performed to check model accuracy.

6.3 Performed Simulations

The first simulation performed is a steady state analysis with the purpose of understand the maximum temperature obtained if a constant power is dissipated as heat. The selected value is 8 W for each cell, which is the average value of the time dependant power dissolved as heat during the race by each cell building up the battery pack. Natural convection is selected to be the boundary condition between cells and air, the initial temperature is set to 300 k and in figure 6.3 an isometric view of the model with local temperatures reached at the end of the race is shown. It is therefore easy to

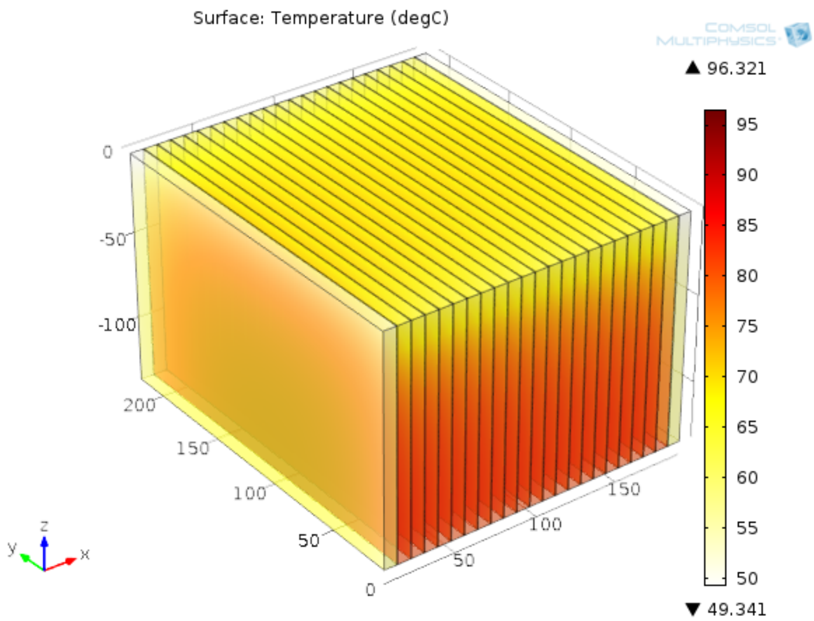

Figure 6.3: Isometric view of the model exploiting temperatures in steady state conditions

understand that cooling techniques are necessary, even if a simple constant power is used, in order to protect Lithium cells.

During next steps, simulations are made more complex and realistic. In fact, according to the electric model shown during previous chapter, each cell wastes an amount of power both during charging and discharging phases which can be expressed as the power dissipated by the series resistance R_{series}. If the current drawn from the battery $i(t)$ is known, the amount of power wasted as heat by each cell can be calculated as :

$$P(t) = R_{series} \cdot i(t)^2$$

. The R_{series} value is selected to be 3 mΩ which is a value a little bit higher than the one that is possible to calculate as the average between SoC=100% and SoC=20% of values shown in table 5.2. This choice has been performed to introduce safety margin during approximated simulations. If the mechanical power is 35 kW, and the efficiency of inverters and electric motors is 90%, a time dependant power generation function is obtained, and an entire race can be simulated. Figure 6.4 shows the time dependant power wasted by each cell during a race. As shown by steady state simulations, an effective

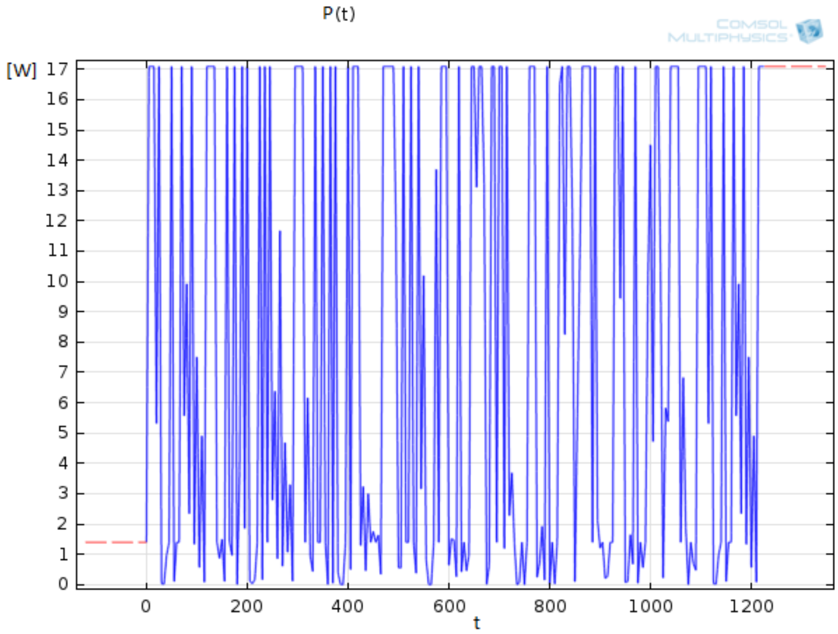

Figure 6.4: Time dependant power wasted as heat by each cell

cooling system have to chosen, and forced air convection seems to be the easiest technique. The most important choice to be taken is air direction; in fact, depending on the way air collide with cells, it can stroke a cell and continue chilling the other ones or it can collide with the first cell becoming useless to chilly other cells. According to cell datasheet shown in figure 6.5, small thins, that seems to be especially included to cool down the cell, are included on the back of it, thus the ideal direction for cooling air flow is thought to be downwards, moving parallel to fin. In order to try performances provided by this cooling technique during an endurance event the time dependant power shown in figure 6.4 is used as stimulus for each cell, whereas boundary conditions are set to replicate the cooling system; both sides of each cell are stroked by air at the speed of 2 $\frac{\text{m}}{\text{s}}$ moving downwards, whereas the thin layer between close cells are modelled as stagnant air. The starting temperature is chosen to be 305 K, in order to simulate races during hot seasons. In order to check spatial gradient without increasing hardware

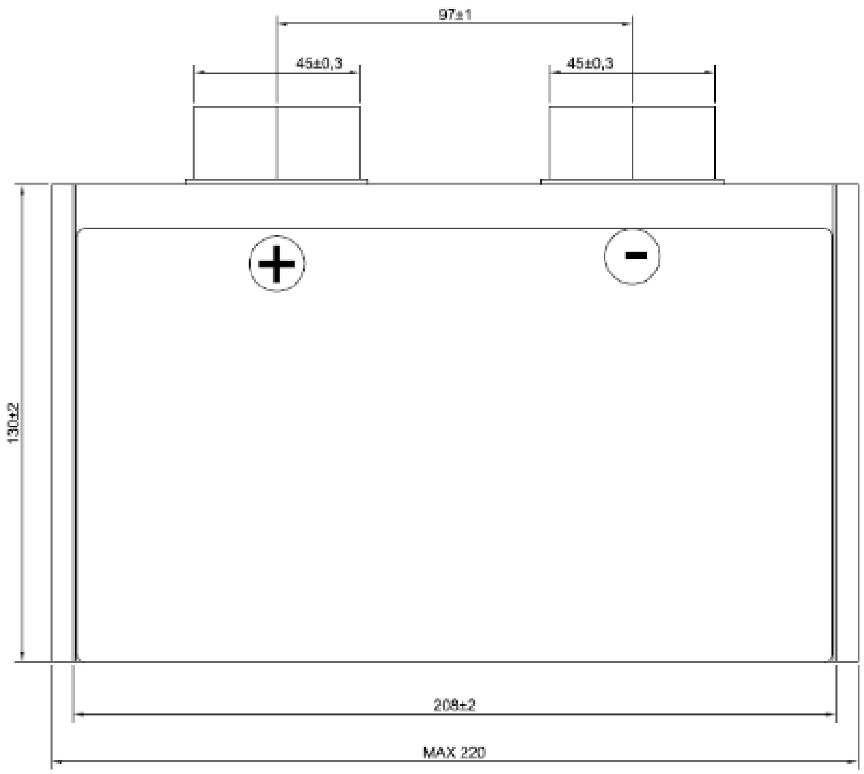

Figure 6.5: Kokam SLPB70205130P two dimensional drawing

requirements and simulation time, three distinctive cells (the leftmost, the rightmost and the central one) are observed during the whole simulation, and their temperature plots are shown in figure 6.6, 6.7 and 6.8 respectively.

Figures 6.6, 6.7 and 6.8 shown important features: the problem is pretty symmetrical and temperatures of the leftmost and the rightmost cells are equal during the race as expected due to homogeneous power generation inside each cell and symmetrical cooling. In addiction the temperature of the central cell is higher than the other one, as expected due to the absence of air flux on cell sides. Steady state temperature is never reached during the race and temperatures plots are pretty monotonic except for a sudden drop after about 1000 seconds, which may result from numerical error. In fact, if residuals calculated by numerical solver during simulations are analysed their values are steady to a value of $3 \cdot 10^{-6}$ except for time values close to 1000 seconds of simulation when an inrush is shown, reaching an error of about $4 \cdot 10^{-4}$ that is one hundred times higher than the other residual. The spatial gradient inside each cell is therefore fundamental in order to understand how temperature increases inside each cell, and highlights potential

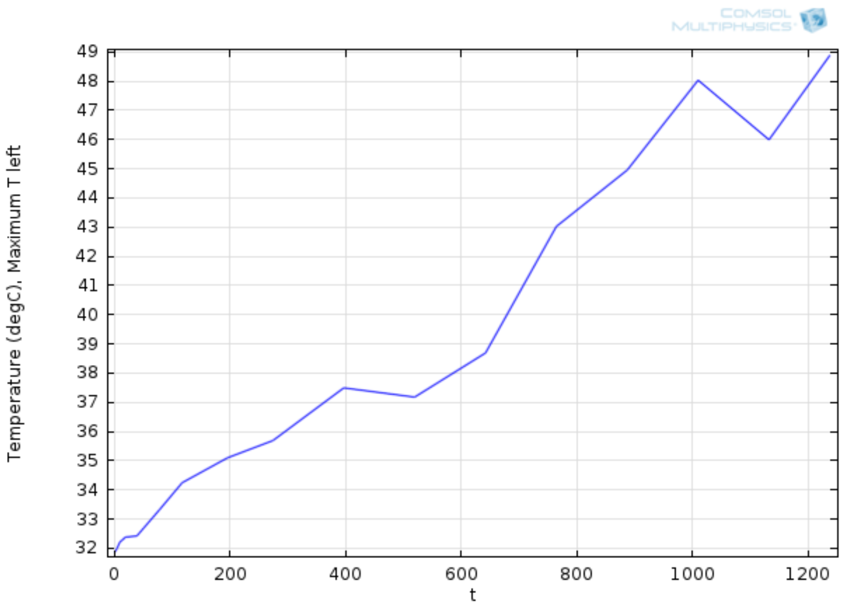

Figure 6.6: Time dependant temperature of the leftmost cell during the race

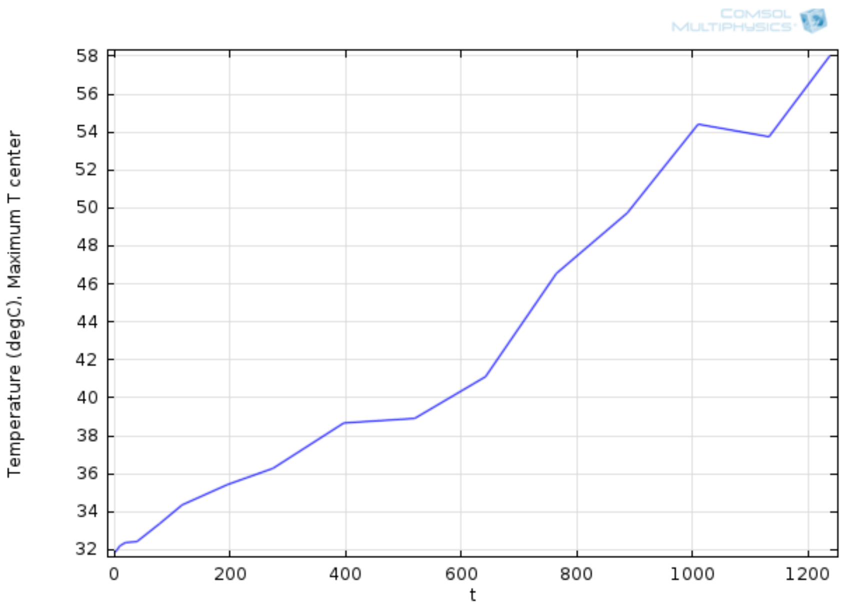

Figure 6.7: Time dependant temperaure of the central cell during the race

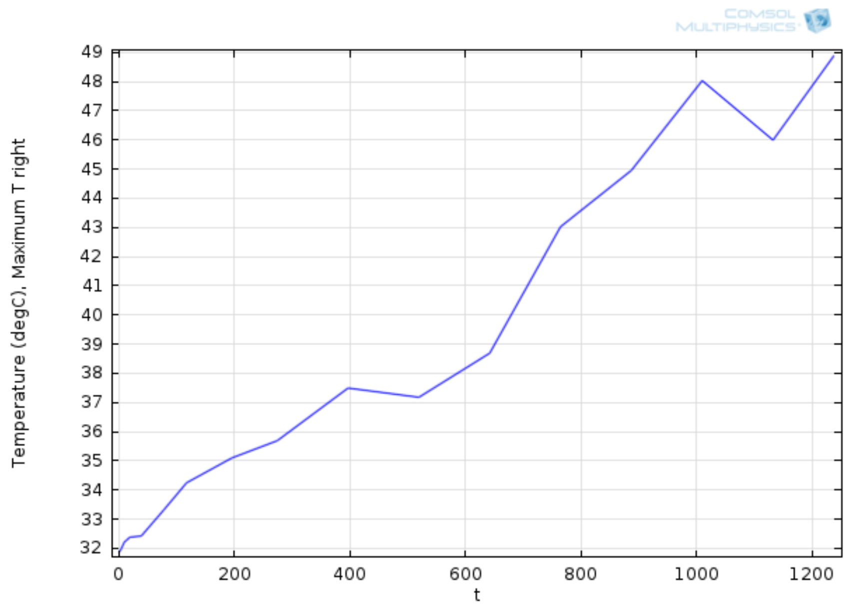

Figure 6.8: Time dependant temperature of the rightmost cell during the race

damaging situations for Lithium cells, thus at the end of simulations, when maximum temperatures are reached, three spatial slices of the leftmost, the central and the rightmost cells are performed and shown in figure 6.9, 6.10 and 6.11 respectively.

The simple model created by Comsol simulator involves heat transfer in solids, and mould solid and fluid interfaces using dimensionless analysis, which is typically used for simple, first order calculations. Even if dimensionless analysis is able to provide rough solutions, thermo fluid dynamics phenomena are too complex to be simply evaluated by a single scalar quantity, thus CFD simulations with Fluent software are performed. The main scope of CFD simulations is to deeply understand interactions between air moving downwards at an average speed of about $2\frac{\mathrm{m}}{\mathrm{s}}$ and cells.

The geometric model used during CFD simulations is pretty the same used on Comsol ones: cells are arranged in parallel with thin undesired air layers between adjacent cells, and a rectangular pipe made of air of about 2 cm in thickness is used to mould convective forced air moving downwards. The temperature obtained at the of the race inside the central cell is shown in figure 6.12, that also provide additional interesting information: the ending temperature is a little bit higher than the value calculated by Comsol simulations and spatial gradient is very similar, except for the high temperature area inside the cell that is smaller than the one obtained by Comsol. This is an interesting result obtained thanks to the improvement in solid and fluids

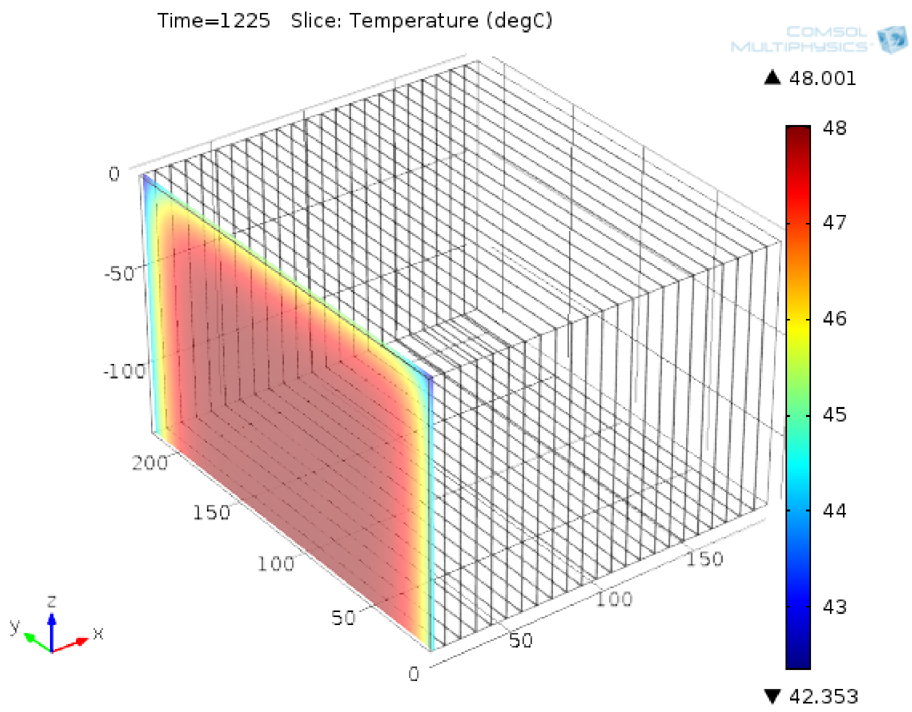

Figure 6.9: Spatial gradient of the leftmost cell at the end of the race

interfaces study provided by CFD simulator. Figure 6.13 shows the area inside the cell where temperature is betwen 334 K and 335 K, which are the highest temperatures reached inside the cell. An interesting characteristics obtained by CFD analysis, that can not be obtained by Comsol simulations is air pressure: in fact according to figure 6.14, the air moving downwards reduces its pressure and become stagnant before reaching the end of the cell, reducing cooling effects. The mechanical layout of the battery pack may help air to stroke the whole cell length; in fact, if the battery is laid as shown in figure 4.15 and holes are open through the body of the vehicle, fresh air is is provided on the upper side of the battery and it is moved down by fans. If in addiction small holes are open on the bottom side of the vehicle, where a low pressure area is established during the race, air may be accelerated and it can reach the bottom of the cell without become stagnant, improving cooling effect.

Analysing figures 6.6, 6.7 and 6.8 and CFD simulation results, it is possible to appreciate temperature reduction obtained thanks to air flow: even if temperatures are close or a little bit higher than Lithium safety range, their reductions highlight that cooling by air with downward direction may become an efficient way to chill the entire segments. Other cooling techniques may refer to improve air speed or create an additional cooling channel for

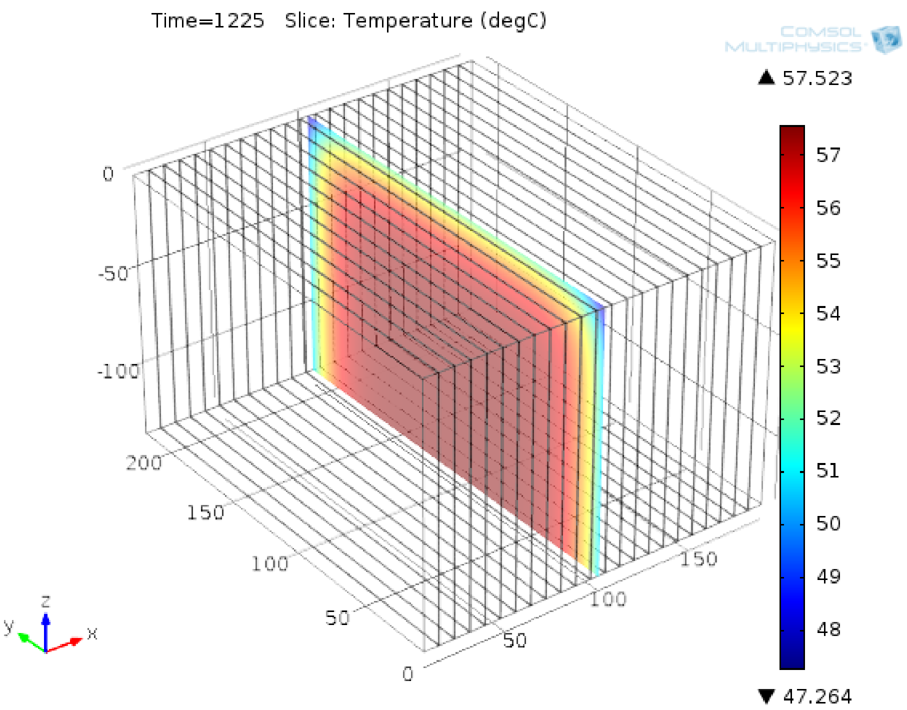

Figure 6.10: Spatial gradient of the central cell at the end of the race

air on the bottom side of each cell. Liquid cooling systems, such as heat pipes can be an interesting solutions but they are not further examined. Even if each segment is chilled by air, an additional cooling system have to be realised in order to cool each segment inside the container. This may be easily obtained by forced air if a gap of about 2 cm is created between close segments, allowing to obtain a laminar air flux between them.

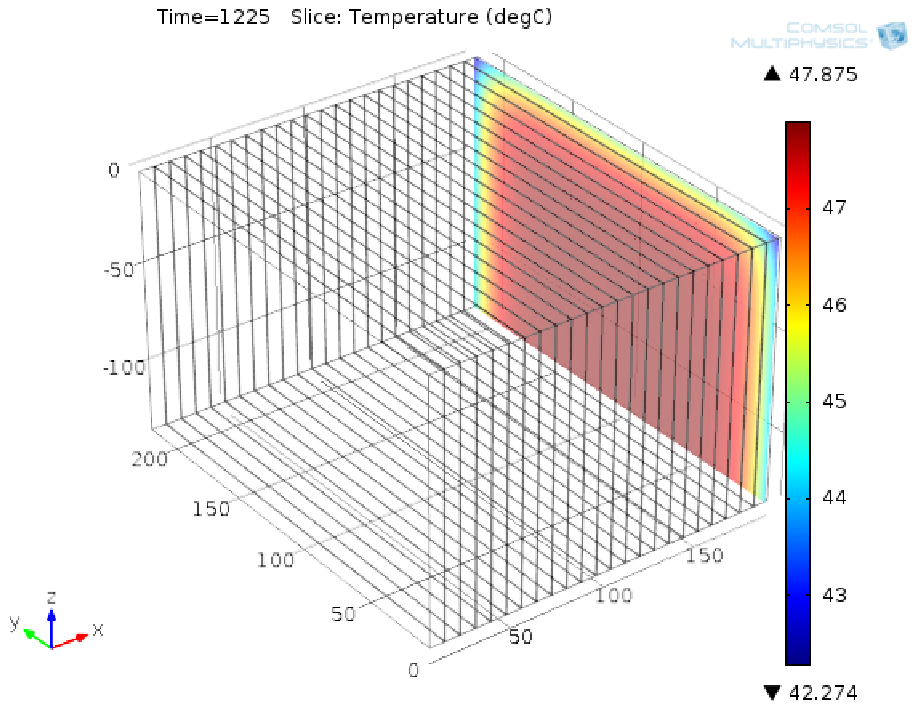

Figure 6.11: Spatial gradient of the rightmost cell at the end of the race

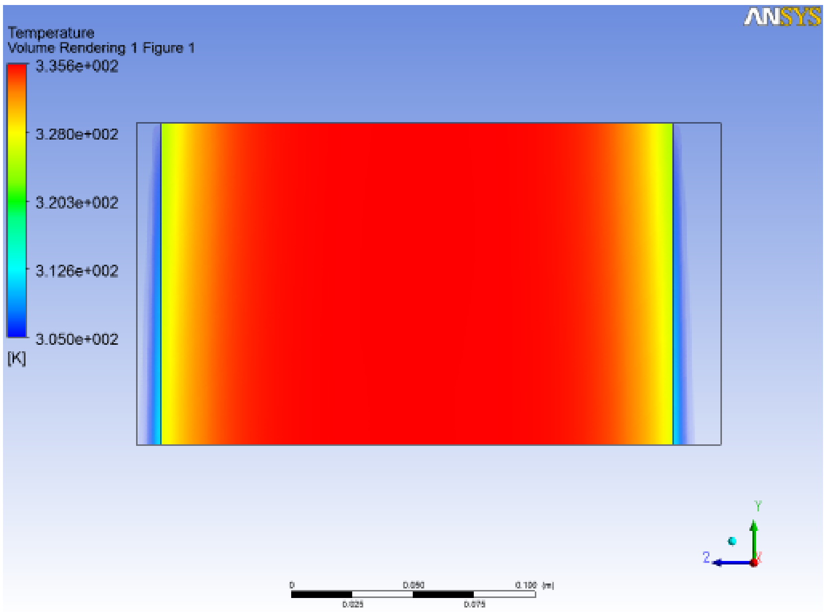

Figure 6.12: Spatial gradient of the cell cell, calculated by CFD analysis, at the end of the race

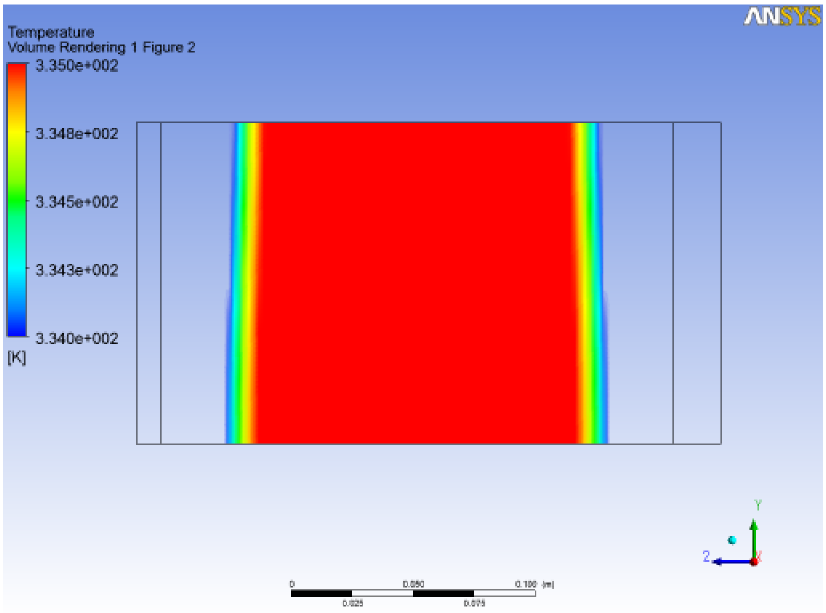

Figure 6.13: Area inside the cell with temperatures between 334 K and 335 K

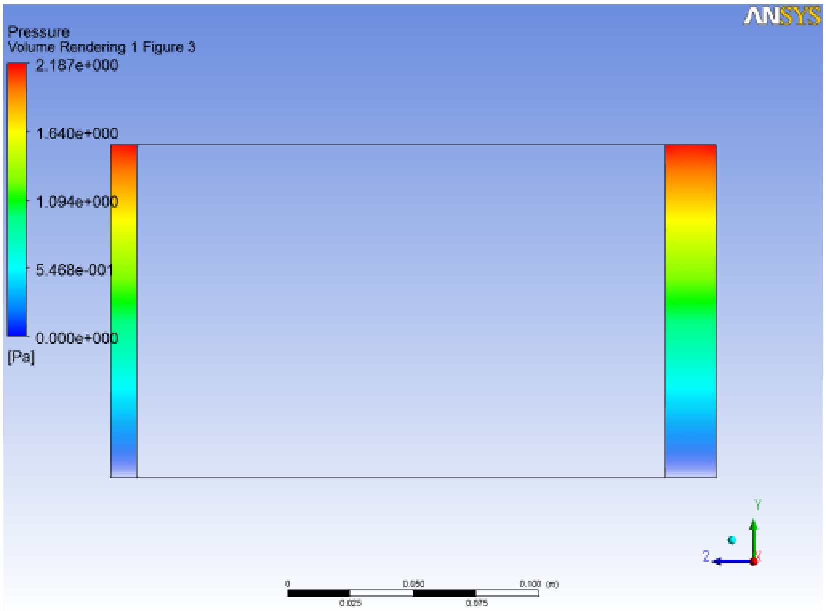

Figure 6.14: Pressure drop on cell side

Conclusions and future work

During this thesis the battery pack of a Formula SAE vehicle has been designed, providing complete and detailed reports about how the battery pack should be realised and connected with other components that are necessary to respect Formula SAE rules. At the beginning of the project, in order to reduce degrees of freedom introducing boundary conditions limiting the design space, FSAE rules are analysed and the general shape of the electric traction system they require has been highlighted. In addiction, necessary devices have been put in evidence, creating a list of components to be included inside the vehicle. As soon as devices are categorised, a state of the art analysis about other Formula SAE vehicles has been performed, with the purpose of understand general order of magnitude for vehicle requirements, such as power and energy, and then computer simulations have been performed to adapt these value to the vehicle under design.

With fixed electric requirements it has been possible to analyse the market in order to find commercial solutions and then the attention has been focused on components interconnections, providing detailed informations about how devices are connected each other both inside the battery and the traction system. The mechanical layout has been explained later, exploiting two different solutions: the first one which is a standard solution using pouch cells is provided as an example, but is not further examined, whereas an innovative layout has been developed in order to create a mechanical arrangement that allows serial industrial production. This solution has been deeply explained by three-dimensional drawings and it is an innovate part of the whole text; if a serial production of the battery pack is necessary, as Formula SAE event requires, costs reduction is made possible by introduced innovations.

As soon as the layout is created, the project of the battery pack may be finished. However, at the end of each design, confirming provided solutions by experimental setup is fundamental, so, during the third part of the text, simulations have been performed. Each cell building up the battery pack has been modelled by an equivalent electric circuit and then the operation of the whole battery pack has been simulated during an entire endurance event, in order to check its behaviour during a realistic situation. Sweep analysis at various power levels has been performed to check the maximum mechanical power allowed at the wheels to complete the endurance event. In addiction, thermal behaviour during an entire race has been simulated by fine element analysis, with the purpose of control the maximum temperature reached inside the battery pack, avoiding potential damaging of Lithium cells. Cooling techniques are necessary and a simple and reliable air method has been simulated to demonstrate that the temperature inside the battery pack may be kept below Lithium safety limits. To refine thermal simulations without using lumped models for fluid dynamic effects, a CFD analysis of the battery pack during an entire event has been performed, and results have been compared to the ones obtained by finite element analysis.

At the end of this thesis, a complete engineering project is provided, including component selections, mechanical layout, and simulations. This work is pretty complete and explain how the battery pack should appear as soon as it is realised. However, due to the high cost of cells it may be wise to check the behaviour of a real battery (or segment of battery), in order to verify simulated results. This is the obvious next work to do, and it must be done as soon as possible, prior to physically realise the real battery pack. When real simulations are performed, the battery pack may be realise and connected with selected devices, and then the global functioning of the traction system can be controlled in a real situations.

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