The Electrical Circuitry for Formula SAE-Electric 2012

Davip Susanto (10996053)

School of Electrical, Electronic and Computer Engineering

The University of Western Australia

Supervisor: Professor Thomas Bräunl

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Abstract

The Formula SAE-Electric 2012 is a new electric vehicle which is design from scratch by the REV team in preparation to participate in the Formula SAE Series competition.

A new electrical circuitry design has to be developed as existing electrical circuitry on the prototype vehicle is not compliance to the latest rules due to several updated rules. The new electrical circuitry for this vehicle are based around on meeting the design requirements as in accordance to the latest Formula SAE-Electric rules and ensuring the functionality of the system and the safety concern of the vehicle are maintained in the years ahead. Most of the electrical components were sourced from the market and these were combined to form a complete and working electrical circuit. This revolves around the management functions of the electric drive train.

Acknowledgements

First of all I would like to thank Professor Thomas Bräunl, for giving me the opportunity to work on such an interesting and hands-on project. Without him and his effort over the last few years, this project would simply not be possible.

I would also like to thank the entire REV team for their determination and support in particularly Matthew and Alex for their extensive knowledge and experience.

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1. Introduction

1.1 Clean Energy

Fossil fuels contribute a significant percentage of global energy consumption and play an important role in our daily life as they are used in powering vehicles, generating electricity, etc. [1]. As with any non-renewable resource; the continued consumption of fossil fuel has increased prices considerably over the last decade [1]. In addition, fossil fuels contribute significantly to greenhouse gas emissions as well as pollution. All the above makes the use of renewable energy attractive and has prompted, scientists and researchers to start looking towards an alternative energy sources and other technological innovations to reduce the carbon footprint.

Technology innovation such as Electric Vehicle (EV) and installation of renewable energy namely solar and wind farm have become prominent to the public. Government's incentives for clean energy that are currently in place help to accelerate this [2].

These incentives help driving companies towards cleaner and more environmentally sustainable business practice and consumers to reconsider their carbon footprint in part of their everyday lives.

1.2 REV project

The Renewable Energy Vehicle (REV) project at the University of Western Australia (UWA) is a research program run by a team compromising of academics staffs and students from different engineering disciplines collaborating together to design and develop environmentally sustainable technologies for future transportation.

Since it's inception in 2008; the REV project has successfully converted a number of combustion engine vehicles into fully electric vehicles. The first vehicle attempted was a 2008 Hyundai Getz (codename REV Eco), a commuter car fit for everyday use as shown in Figure 1. The second car shown in the Figure 2 was a 2002 Lotus Elise (codename REV Racer) which aimed to demonstrate that the race car's performance would not be affected from its conversion.

Figure 1 REV Eco [3].

The REV team has also undertaken the development of two Formula SAE Electric race cars. The first prototype was built in 2009/10, based on the UWA Motorsport 2001 chassis and was successfully converted into electric vehicle. The prototype was no longer compatible with the latest standards due to several updated rules but it provides good opportunity to attempt an electric drive system without having to design and construct an entirely new vehicle. The second Formula SAE-Electric is currently being developed by the team with the sole purpose of competing in the Formula SAE competition held in Melbourne at the end of this year.

Figure 2 REV Racer [3].

1.3 Formula SAE competition

Formula SAE competition is an International competition run 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 including Australia. This competition challenges university students to design, construct and race Formula style vehicles and provide students with an opportunity to learn in a simulated working environment that incorporates with real-world situations. The competition also imposes strict design guidelines for both the mechanical and electrical components of the vehicle. The competition itself compromises of static events where students present details of the design, cost and manufacturing processes and dynamic events that test the vehicles acceleration, braking, handling and its safety. The following figure shows the several countries that participate in the Formula SAE Australasia competition.

Figure 3 Formula SAE Australasia.

1.4 Aim

The aim of this project is to design the electrical circuitry of the Formula SAE-Electric 2012 in compliance with the latest Formula SAE-Electric rules. A new electrical circuitry design has to be developed as existing electrical circuitry on the prototype vehicle is not compliance to the latest rules due to several updated rules. Most of the electrical components were sourced from the market and these were combined to form a complete and working electrical circuit. Adjustments were also made on some of the sourced components in order to meet the requirements.

The final point that is particularly critical is the team’s extremely limited budget of $20,000 plus a $5,000 credit at Altronics (local electronics supplier) therefore many design decisions will be cost driven and hence has to be designed with much simplicity. The team’s lack of experience and numbers (consists of 5 mechanical engineering students and 4 electrical students) caused delay in getting design, construction, and implementation to be completed on time. These difficulties have already been realised in the previous year when the original target of competing in the Formula SAE competition had to be pushback due to resources and manpower. The current targets are for the vehicle to be finished by end of November 2012 and the vehicle ready for the competition in Melbourne. It is important to recognise that the team is developing a new vehicle from scratch without any team member or supervisor being previously involved in Formula SAE competition.

2. Literature Review

2.1 Formula SAE Standards and Regulations

A set of rules have been issued by the Formula SAE Rules Committee that detail all of the requirements for Electric Vehicle (EV) in order to enter a Formula SAE competition. Due to its recent expansion to include Electric Vehicle into the competition, there are variations in the standards and regulations from year to year. The standards and regulations reviewed are based on the 2013 Formula SAE Rules which the committee is considering implementing for electric vehicle this year. The majority of the rules pertain to safety. Failing to meet these set of rules will result in consequences ranging from deduction of event points to restriction on vehicle use which the team wants to avoid if possible. The standard is available to the public and can be downloaded at the Formula SAE website [4]. The regulations that impact on the electrical design of the vehicle are summarised below [4] :

- The tractive system or High Voltage (HV) (defined as any voltage greater than 40VDC) must be completely isolated from chassis.
- The border between the tractive system and Low Voltage (LV) system (defined as any voltage below 40VDC) system must be completely galvanically isolated.
- The LV system must be grounded to chassis.
- Each accumulator container must contain at least one fuse and at least two contactors.
- A HV warning sticker must be applied on each accumulator container.
- The contactors must open both poles of the accumulator.
- Each accumulator cell must be monitored by a Battery Management system (BMS) to keep the voltage of each cell within its safe operating voltage range.
- The BMS must continuously measure the temperatures of critical points of the accumulator.
- Tractive system and LV circuits must be physically segregated such that they are not run through same conduit.
- Two tractive system measuring points (TSMP) must be installed and connected to the positive and negative motor controller lines [4].
- LV system ground measuring point must be installed and connected to chassis.
- Each TSMP must be secured with a current limiting resistor of 5kΩ.

- There must be a High Voltage Disconnect (HVD) that is able to disconnect at least one pole of the tractive system accumulator [4].
- Pre-charge circuit must be implemented and it must not be able to pre-charge the immediate circuit, if the shutdown circuit is open [4].
- Tractive System Active Light (TSAL) must be installed and is active whenever the voltage outside the accumulator container exceeds 40VDC [4].
- The shutdown circuit directly carries the current driving the AIRs as shown in Figure 4.
- All electrical system (both low and high voltage) must be appropriately fused.
- Prior to the event team must submit clearly structured documentation of their entire electrical system called Electrical Safety Form (ESF) [4].

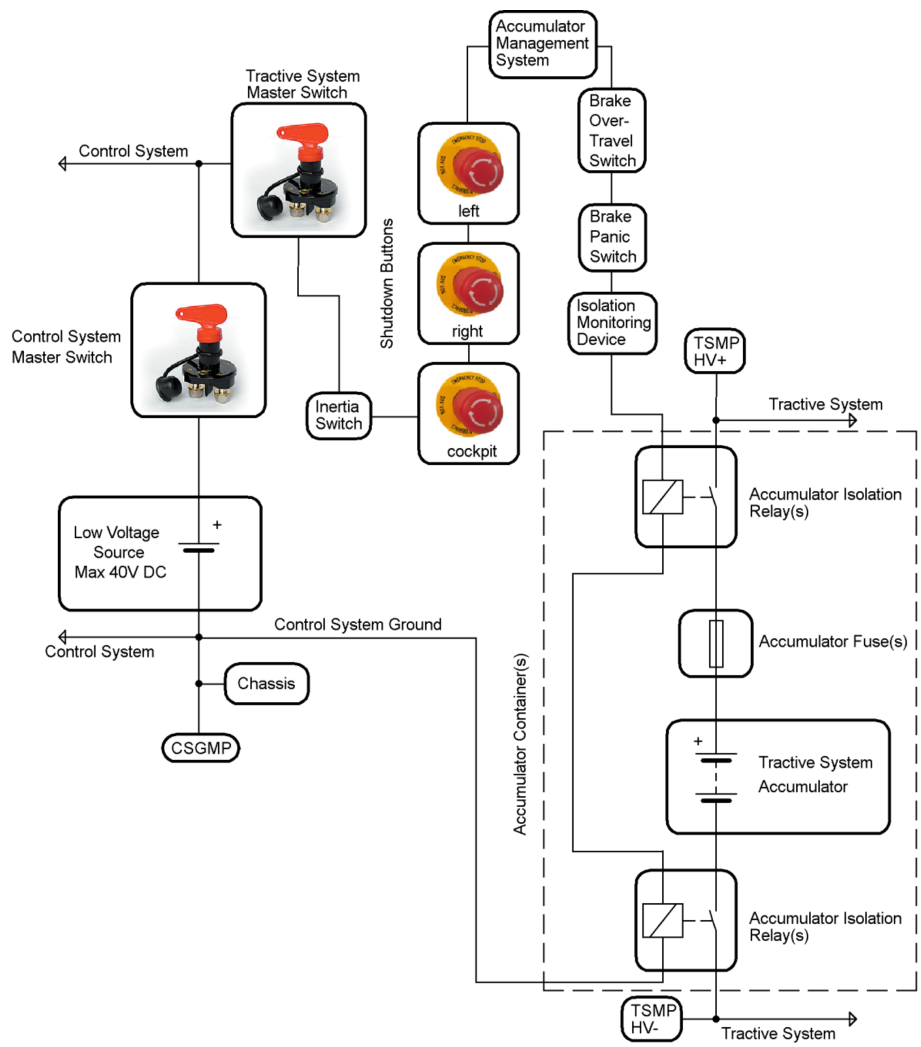


Figure 4 An overview of the shutdown circuit [4].

2.2 Formula SAE-Electric prototype

The Formula SAE-Electric prototype was first developed in 2009/10, based on the UWA Motorsport 2001 chassis. It aimed to convert from an internal combustion engine vehicle to an electric vehicle. Since the chassis was built back in 2001, it was no longer compatible with the latest FSAE standards. This prototype was developed in order to attempt an electric drive system without having to construct an entirely new vehicle. It was never meant to be developed for entering the competition but rather as a test vehicle for future development of the next generation Formula SAE-Electric car. This is also due to lack of experiences with Formula SAE competition as a team.

The conversion primarily consisted of removing the original internal combustion engine and replacing it with two 48V, 5-15kW brushless DC motor. These motors are powered by a traction pack that consists of 15 units of 3.2V, 90Ah Lithium Iron Phosphate ($LiFePO_4$) batteries from Thunder Sky [5], giving a total energy storage capacity of approximately 4.32kWh. Each traction cell is installed with a Battery Management System (BMS) module and monitored by the BMS master from EV-Power based on analog BMS technology [6]. The need of BMS in an electric vehicle will also be reviewed in the latter part.

The following diagram shows the physical layout of electrical components in the prototype vehicle.

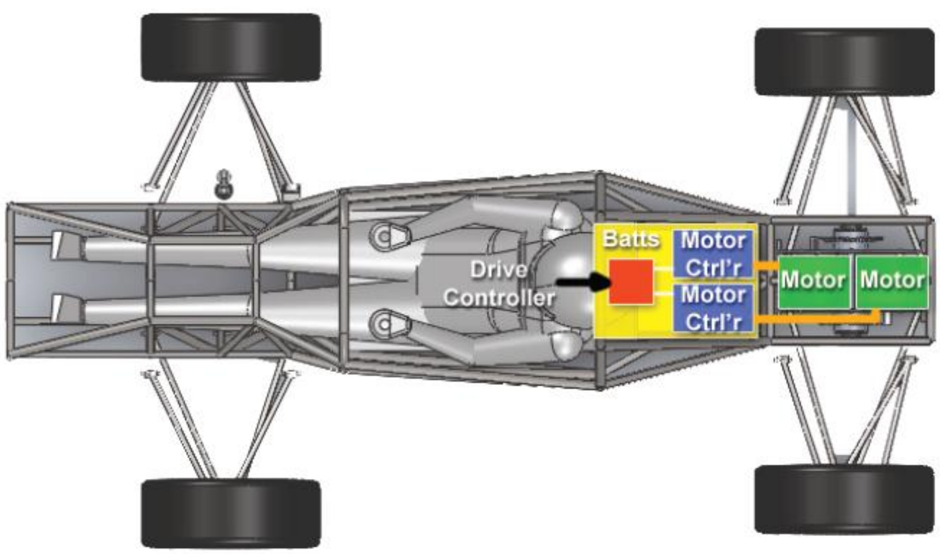


Figure 5 Top view of prototype vehicle showing component locations [7].

The following table summarises the electrical components used in the prototype vehicle

Component	Description
Motor	2x Mars ME0201, 5-15kW Brushless DC Motor
Motor Controllers	2x Kelly KBL72301, 72V 300A BLDC
Batteries	15x ThunderSky LFP090AHA, 3.2V 90Ah $LiFePO_4$ cell (48V 90Ah, 4.32kWh, ~20kW peak)
Battery Management	EV Power BMS MCU mini (Master) 15x EV Power BMS-CM90 (Module)
Contactor	Gigavac GX14
Emergency Stop	Nanfeng ZJK250
Fuse	250A ANN fuse

Table 1 Component summary for the prototype vehicle.

The following figure shows the schematic of electrical system of the prototype vehicle.

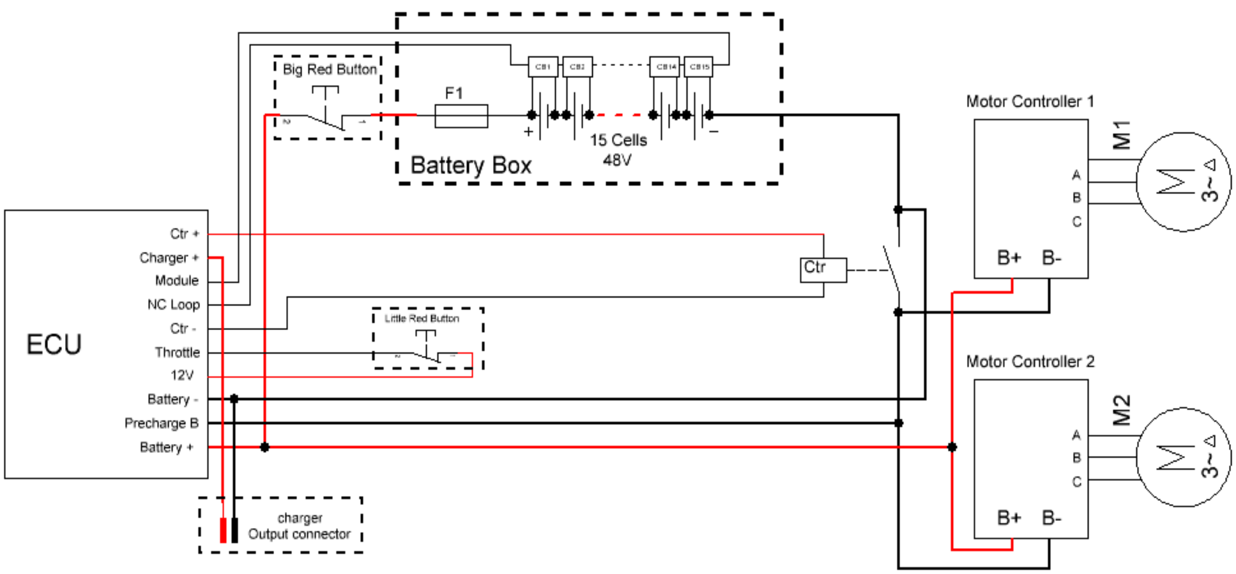


Figure 6 The schematic of the electrical system of the prototype vehicle.

The tractive system (motors and motor controllers) is powered in two stages. The first stage is lifting the ‘Big Red Button’[1] (shown in the figure above next to the Battery Box). This will close the circuit between the battery packs and Electronic Control Unit (ECU). The DC/DC converter which is inside the Electronic Control Unit (ECU) will then convert the battery pack voltage to power the 12V systems such as the BMS master. The second stage is lifting the ‘Little Red Button’ that is located in the dash. This button is also use for drivers in the case of

[1] *The ‘Big Red Button’ : A high voltage disconnect switch*

emergency situation by pushing it down. By lifting this, the coil of the contactor (or high voltage relay) labeled as ‘Ctr’ in the figure which powered by the 12V system will then energise and close its contact. This will close the circuit between the battery packs and the traction system and the tractive system is no and the vehicle can now be drivable waiting from the input from the accelerator pedal. Inside the ECU, it also consists of precharge circuit and charger relay. The purpose of precharge circuit is to precharge the motor controller when vehicle is first initially on (when lifting the ‘Little Red Button’). On the other hand, the charger relay is use for disconnecting the charger output when the battery pack is fully charged. In the case of emergency situation or low battery packs, the connection between battery pack to the motor is opened. The conversion was successful and the vehicle is running.

2.2.1 Issues with Formula SAE-Electric prototype

As with any project, the development of the prototype vehicle also had its fair share of problems. First of which was the electrical design is based on 2010 Formula SAE rules. Due to several changes in the latest rules, the previous electrical design could not be used in the next generation of “Formula SAE-Electric vehicle”. One of the changes in the rules that impacted most on the electrical design of the new Formula SAE is the definition of High-Voltage [8]. It was defined as any circuit carries more than 60VDC but in the latest rules this is dropped to 40VDC. This means that as accordance to 2010 rules the whole electrical system is classified as a Low-Voltage while with the latest rules the whole system is classified as a combination of Low Voltage system and High Voltage system. For High Voltage system, there are an additional set of rules that are needed to be met but are not covered and explored in the prototype vehicle.

The final issue with the prototype vehicle is that the vehicle did not have a battery meter that will indicate battery level discharge status. Without this, impending disconnect is not known and the driver/user would continue to drive until the vehicle stops abruptly.

2.3 Formula SAE-Electric 2011/12

Since the prototype vehicle could never be used at competition, it was necessary to develop and build a whole new vehicle that is compliant with all the latest Formula SAE rules. The vehicle is developed with the intention of competing in the Formula SAE competition. The design commenced in 2011 and it is still currently ongoing by the REV team. This review will only cover some of the relevant developments left out by previous years REV team. The structure of the vehicle has been designed with major improvement on its predecessor such that the chassis is more compact and there are more spaces for larger battery packs, which would offer more range and power. The battery packs are situated at either side of the driver for optimal weight distribution thereby enhancing stability. Another major improvement is that use of quad in-wheel hub motor(s). These motors are powered by 51.2V accumulators packs with total energy capacity of approximately 6.5kW. Each of these motor is rated from 5kW to 15kW (peak).

The following diagram shows the physical layout of electrical components in the next generation Formula SAE-Electric.

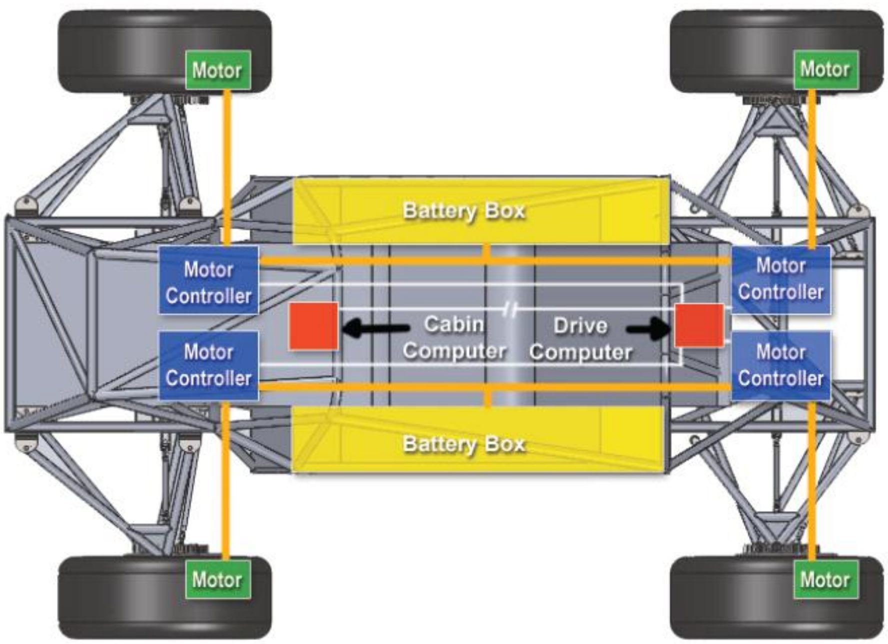


Figure 7 Top views of next generation Formula SAE-Electric showing component locations [7].

The following table summarises some of the electrical components used in the Formula SAE-Electric vehicle.

Component	Description
Motor	4x Turnigy CA120-70, 5-15kW Brushless DC Motor
Motor Controllers	4x Kelly KBL72301, 72V 300A BLDC
Batteries	640x K2 26650EV, 3.2V 3.2Ah $LiFePO_4$ cell (51.2V 128Ah, 6.5kWh, ~60kW peak)

Table 2 Summary of the components used in the vehi

The accumulator packs used in the vehicle are made of 640 cells of 3.2V, 3.2Ah Lithium Iron Phosphate ($LiFePO_4$) batteries from K2 Energy [9]. Each of the accumulator pack shown in the Figure 8 is arranged in 8 in series and 40 parallel (8s40p) and has a pack voltage of 25.6V and total capacity of 128Ah each. The two accumulator packs are connected in series to form a 51.2V circuit that power the tractive system of the vehicle.

Figure 8 One of the accumulator packs with BMS modules installed.

It was found that different manufacturers had different performance outputs (i.e. discharge rate, life span etc...) for the same type of battery ($LiFePO_4$). This could be attributed to the QA/QC methods employed by them during manufacture and hence it is recommended that battery testing of different makes be performed; e.g. whether it is capable of handling the continuous currents drew by the motors without damaging the battery from over temperature over extended period of time and the maximum charging currents it can handle up to.

Previous battery testing had been performed on an individual cell by a former REV student, Mr. Ian Hooper who analyzed the impact of varying the C-ratings during charging and discharging [10]. C-rating is defined as a measure of the rate at which the battery is discharged/charged relative to its capacity. From the test results, the cell is able to maintain the temperature under 60°C during discharging at 3C and 5C. The charging performance of the cell is found to be underperformed at 1C [10]. However, it is found to be acceptable at 0.5C having satisfied the C-rating as stated in the battery cell data sheet [9].

The table below summaries the approximate C rating and current the accumulator packs could handle during charging and discharging with the assumption that the performance each cell is equivalent to whole accumulator packs.

Specification	C rating	Current
Continuous Discharge	~3.5C	~440A
Pulse Discharge(for 30 seconds)	~8C	~1000A
Charge current	~0.5C	~60A

Table 3 Accumulator packs' C rating and current rating.

This specification is crucial in choosing appropriate electrical components such as fuses and contactors.

2.4 Battery technology and Battery Management System

The final section of the literature review is a review of battery technology and Battery Management system. Battery is one of the main key components in an electric vehicle. It is used for energy storage and for supplying power to the electric drive train of the vehicle. So it is crucial to understand the different types of battery.

Battery technology has been undergoing extensive research and development efforts over the past 30 years and the longest development history of all battery technology is the lead-acid battery particularly ones that are used in industrial EVs such as golf carts and forklifts.

There are many types of rechargeable batteries considered for EV applications. A few examples of the same include:

- Lead acid
- Nickel-cadmium (NiCd)
- Lithium-ion (Li-ion)
- Lithium-polymer (Li-poly) and many others

Among these several types of batteries, Li-ion batteries are found to be the most attractive to many consumers as they have the highest energy density and capable of amazing performance compare to any other batteries. This is clearly shown in the Figure 9.

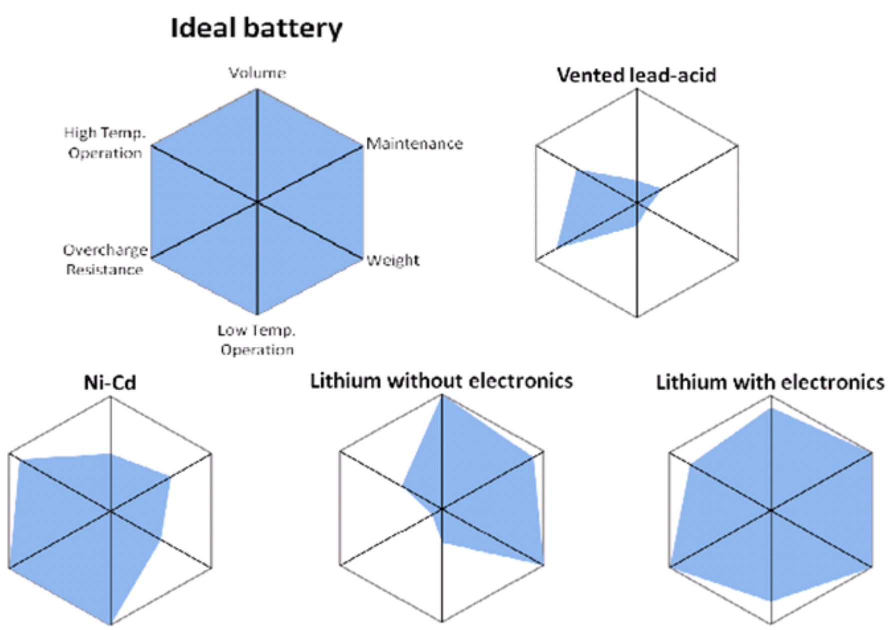


Figure 9 Relative merits of various battery technologies [11].

There are also many various types of chemistries available for Li-ion battery. The nominal voltage, energy, and power density of these cells varies with their chemistry. Some are considered safer and are more appropriate for large traction packs especially Lithium Iron Phosphate ($LiFePO_4$) and Lithium Titanate ($Li_4Ti_5O_{12}$) compared to standard ($LiCoO_2$) Li-Ion cells [12]. Figure 10 compares the different characteristics of several Li-ion chemistries.

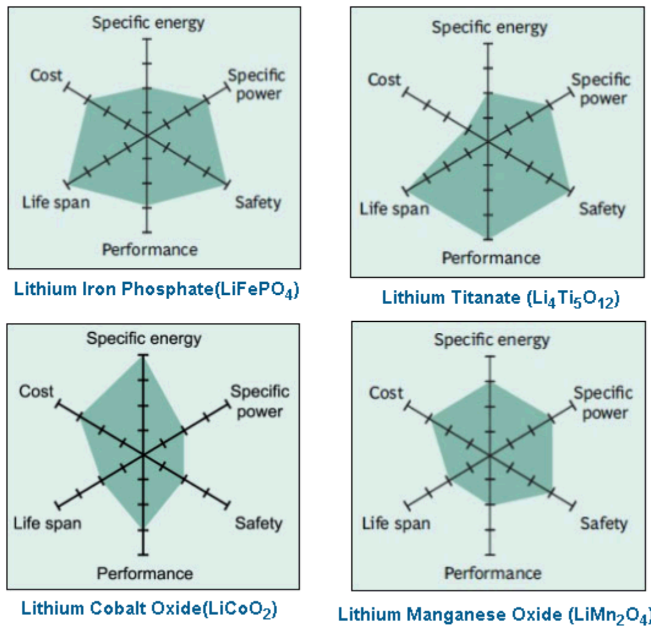


Figure 10 The relative merit of various Li-ion chemistries [13].

With the reference to Figure 10, in term of costs and safety, $LiFePO_4$ battery seems to be the best for cost-effective vehicle as compared to Lithium Titanate due to its high costs. These cells are considered safer because they are immune to thermal runaway.

Li-Ion cells perform magnificently; however if these are operated outside its tight Safe Operating Area (SOA), it could result with consequences ranging from the annoying to the dangerous. In most cases the only effect is simply that the life of the cell is reduced, or that the cells are damaged, with no safety issue [12]. In real-world, large battery packs, with many cells in series, are more prone to be charged and discharged unevenly due to unbalance among cells (e.g. different leakage and resistance). It is therefore that a Battery Management System (BMS) is essential to keep the cell within its SOA and to maximise the pack's performance by balancing the cells. The SOA of a $LiFePO_4$ battery is shown in Figure 11. To keep the cell within its SOA, there must be a way for the BMS to shut down the charger when it is fully charged and shut down the tractive system when it is nearly empty.

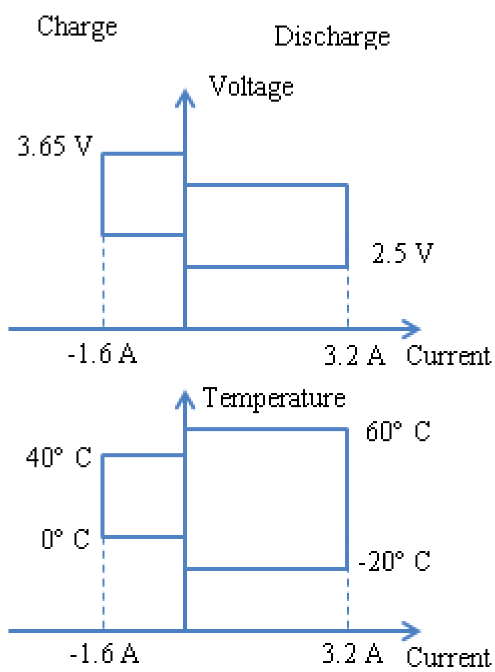


Figure 11 Safe Operating Area of $LiFePO_4$ battery cell.

Since each battery cell needs to be monitored, the topology of the BMS is distributed and usually consists of several modules depending on the number of cells and a master.

The technologies used in the BMS can be catagorised into two classes: analog and digital. The distinction between analog and digital is related to how the information is processed. While all systems requires some form of analog front end, BMSs that process the cell voltage with analog circuitry (an analog comparator, op-amp or something similar) is considered as analog. BMSs that process the cell voltage digitally are considered to be digital.

The capabilities of analog BMSs are also quite limited; however it still could protect and balance the battery. One of which is that analog BMS lacked is the capability to report the individual cell voltage. This becomes a problem if there is a need to diagnose for faults and analyse the batteries within the battery box without opening them.

A digital BMS is more sophisticated than analog BMS and is capable of measuring each cell voltage and possibly more, such as its temperature and its condition and report these data. These data could be invaluable in allowing an analysis of the state of the cell.

The table below summarises the capabilities of both analog and digital BMS technology

BMS technology	Capabilities		
	Reports individual cell voltage	Balance the battery	Protect the battery
Analog	✖	✔	✔
Digital	✔	✔	✔

Table 4 The difference between analog and digital BMS.

Within the REV team both BMS technologies had been utilised and previous tests had also been done mostly on the analog and the table below shows the BMS technology used in different electric vehicles.

Vehicle name	BMS technology
REV Eco	Analog
REV Racer	Digital
2009/10 FSAE prototype	Analog
WA EV Trial Ford Focus	Analog

Table 5 The BMS technology used in different vehicles.

The above table or the tests mentioned above does show that Analog BMS is much superior to a digital BMS. It is just that analog BMSs are easier to work with due to its simplicity and cost. On the other hand, former REV student, Mr. Thomas Walter who worked on User Interface on REV Racer had also proved the importance of measuring the voltage of each cell and reports these data when one cell displayed an unusual behavior during the first test drive [14]. It was later found that it was caused by a loose connection causing one of the cell's voltages to drop faster than all the other cells. If goes unnoticed, the performance of the car would be dropped and in worst case, could cause a fire hazard.

3. Design approach

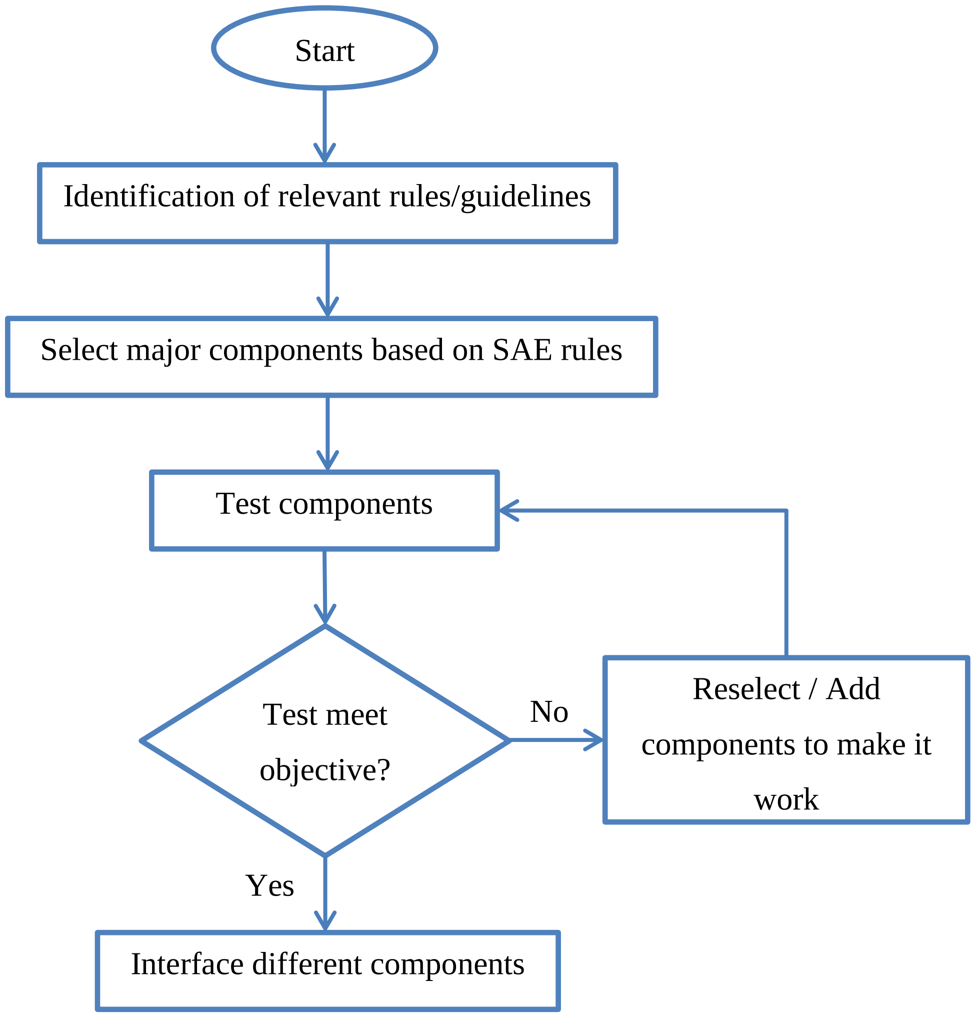


Figure 12 Design approach.

The design of the electrical system is primarily based on complying with the Formula SAE rules and interfacing different components to achieve full and working electrical system. The design approach has been divided into process steps illustrated in the above figure. The reverse flow arrow indicates that adjustments need to be made on the components in order to meet its objective.

Identification of the competition rules relevant to the electrical design is the first and most important step as it dictated the restraints on the electrical design and ensured the vehicle is compliance to the rules and eligible to enter the competition. This has been identified in section 2.1.

The next step began with selection of major components that are required by the Formula SAE rules and used by comparing the advantages and disadvantages of various components currently available in the market. It is also important to consider when selecting these components there are also constraints concerning such as financial resources, complication of implementation and the required space needed. This has been discussed in section 1.4.

In order to achieve the objective of having a working electrical circuit, the major components that impact the most on the circuit need to be tested to fully understand how it works and assess its performance and reliability so that it will not compromise the overall design. If the component is found to be less likely to work together, a workaround should be implemented and then re-assess the impact of the additional Understanding how the components work help to make interfacing different components easier.

The last step of the design approach is to interface different components together to ensure that they interface with each other and work as what was intended. This will requires adding minor components that are relevant.

4. Components selection

4.1 Battery Management system

Because the accumulator packs are based on lithium ion technology, a BMS is essential. It is the job of a BMS to ensure that the cells in the accumulator packs are operated within their Safe Operating Areas (SOA). The topology of the BMS is distributed consists of several BMS modules depending on the number of cells in series and a master.

There are dozens of BMSs commercially available ranging from analog BMS to digital BMS, making selection somewhat daunting. The table below compares the different BMSs that look promising in term of price and features

BMS	BMS technology	Price	Feature
Elithion Lithumate Pro	Digital	~$700 (with sponsorship)	SOC, RS232, precharge and GUI
Elithion Lithumate Lite	Digital	~$550	SOC and GUI
BMS Master (EVMS) + EV Power BMS module	Analog	~$550	Precharge and contactor control

Table 6 Comparison of different types

Elithion Lithumate BMSs utilise digital BMS technology and have also been used by other Formula SAE-Electric competitors such as RMIT and Kansas University while EV-power BMS modules and BMS master (EVMS) utilise analog BMS technology and have been used extensively by the REV team. The price of the different BMSs is very competitive and features vary between each BMS.

After several discussions with the supervisor, it was decided to use EV-Power BMS modules and EVMS. There are many reasons for this decision. Firstly, previous tests had been done on EV-power BMS module on its quiescent current and it was found the BMS module consume very little power and while EVMS is currently being tested in the WA EV Trial Ford Focus. Analog BMS is also much easier to work with compare to digital BMS and can be easily diagnosed. Support can also be easily organised as they are made by local suppliers.

4.1.1 BMS module

An analog BMS module (CM-90) from EV-Power is used and mounted on each groups of parallel cells, to detect under voltage and overvoltage. It is only suitable for $LiFePO_4$ batteries because of its operating voltage limits. Adjacent cells modules are connected through a single-wire, daisy chain loop which is NC when all the cells are within its safe operating voltage limits (2.6V to 4.0V) and open circuit otherwise [15]. The BMS module is also capable of balancing the cell it is attached to when the voltage reaches 3.6V by shunting regulation up to 1000mA. The figure below shows the BMS modules mounted on each cell and its daisy chain loop.

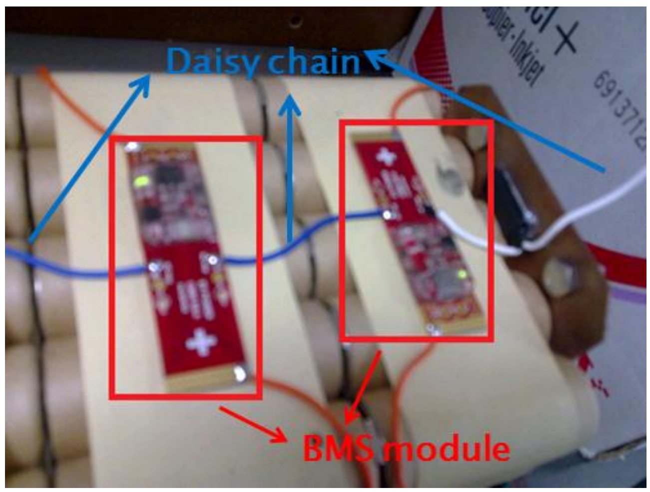


Figure 13 BMS module and its daisy chain.

4.1.2 BMS Master (EVMS)

The BMS Master used in the vehicle is manufactured by ZEVA [16]. It is very unique compare to other BMSs that were compared previously. It combines several common functions required by an EV into one device such as:

- Charger/drive interlock which not many BMSs have implemented. It ensures that the vehicle cannot be driven while charging is in progress, and vice versa. This is achieved by controlling the contactors used in the vehicle.
- Monitoring the daisy chain of the BMS modules, providing visible and audible warning and take action to protect the battery pack when a cell goes out of its SOA by either stopping the charger or disabling the drive system.
- Staged precharging to slowly charge up motor controller’s internal capacitors.
- Status light and buzzer that provide feedback on the vehicle status.

4.2 Charger

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 were set. Firstly, the charger must be suitable for charging the accumulator packs of 51.2V. It also must be high power rated such that it can withdraw as close as the maximum power (~2.4kW) from a standard 10A GPO socket to allow fast charging. Weight will not be considered as it 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 requirements is also set in choosing the most suitable charger and they are as follow:

Parallel operation: The charger has the ability to be connected in parallel with another charger for higher power output to allow fast charging. This might also be useful if N+1 redundancy is required in an operation.

Control input: Charger could be control through its control input such that it can stop from charging when the battery is fully charged.

Price: Chargers can be quite expensive, ranging from $200 to $1,000 dollars. Obviously, the cheaper the charger is the better and the more it would be considered.

Programmable: A charger with a fully programmable charging profile for complete control of the output voltage and current profile of the charge. It could be optimized for more effective charging and future development

Efficiency: The higher the efficiency the better not much energy is will be wasted as heat.

The table below summaries the different chargers that meet the objectives

Charger	Max power	Price	Control input	Programmable	Parallel able	Efficiency
Kingpan KP4830KL	1800W	~$695	No	No	No	~88%
QuickCharge SCPXU-4840	1920W	~$920	No	Yes	unknown	unknown
TC Charger TCCH-H58.4-25	1500W	~$450	Yes	Yes	Yes	~93%
TC Charger TCCH-H58.4-30	2000W	~$500	Yes	Yes	Yes	~93%

Table 7 Comparison of chargers.

After careful comparison of the capabilities of each charger, TC Charger TCCH-H58.4-30 is chosen as it suits the best as it provides the most power per dollar and also provides opportunities for future development from its additional functions. It also has protection features such as thermal self-protection, short-circuit protection, reverse connection protection and input low-voltage protection [17].

The peak voltage of the charger is set to the recommended maximum voltage of the accumulator packs (58.4V) which is the voltage when they are fully charged. The charger features a Constant Current, Constant Voltage (CCCV) charge curve as shown in the figure below, making them ideal when operated in conjunction with the BMS. The charger has a control input that can be used to control the operation of the charger.

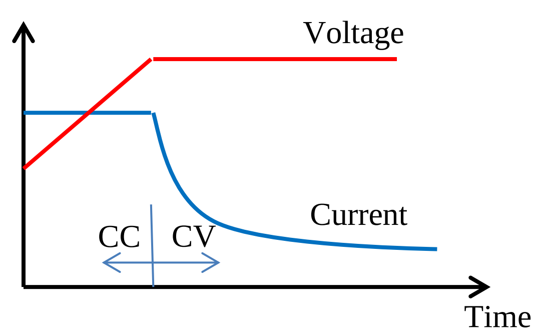


Figure 14 The characteristic plot of CCCV charger.

4.3 High voltage disconnect (HVD)

A High voltage disconnect (HVD) is necessary for electric race cars like Formula SAE-Electric due to the nature the vehicle operate under and is required by the rule. The HVD must be able to disconnect at least one pole of the tractive system as defined by the rule. To achieve this it must be somehow be placed along the tractive system wiring. The HVD provides isolation between the battery pack and tractive system and protection for the user working on the tractive system during downtime situations or rescue operation after an incident. The analogy of HVD is simple but finding a suitable one for the vehicle is challenging or possible need to be properly designed from the scratch. The mechanism of the HVD will also be inspected by Formula SAE inspector during Electrical Tech Inspection [4].

Most aftermarket products for High Voltage disconnect are either for 3-phase AC applications or are rated at low current rating or too bulky. After an intensive looking at aftermarket products, a possible candidate was found and it is a Double Pole Double Throw (DPDT) sealed manual battery switch made by Gigavac as shown in the figure below. The switch is rated at 500A continuous at pole and capable of handling up to 2500A at each pole but it is rated up to 32Vdc. Further enquires were made to the manufacturer on the feasibility of the switch. The switch is suitable for 60Vdc application with compensation of its current rating dropped to 400A at each pole. The switch is more than sufficient for our system as the total continuous current drew by the motors is approximately 400A.

Figure 15 Gigavac BD9521 [18].

4.4 Fuse

The main purpose of a fuse is to protect the batteries during a short circuit situation, with secondary protection for controller or motor failure (direct short). There are many different types of fuses available on the market ranges from Slow Acting to Very Fast Acting fuse, making selection somewhat daunting.

The type of fuse that suits our application is ANN type fuse (Very Fast Acting) commonly used in lift truck with an application up to 80Vdc. The fuse rating is selected based on the time-current characteristic curve of that particular fuse type. This curve shown in the figure below shows how much current the fuse can handle for a given amount of time before it fail.

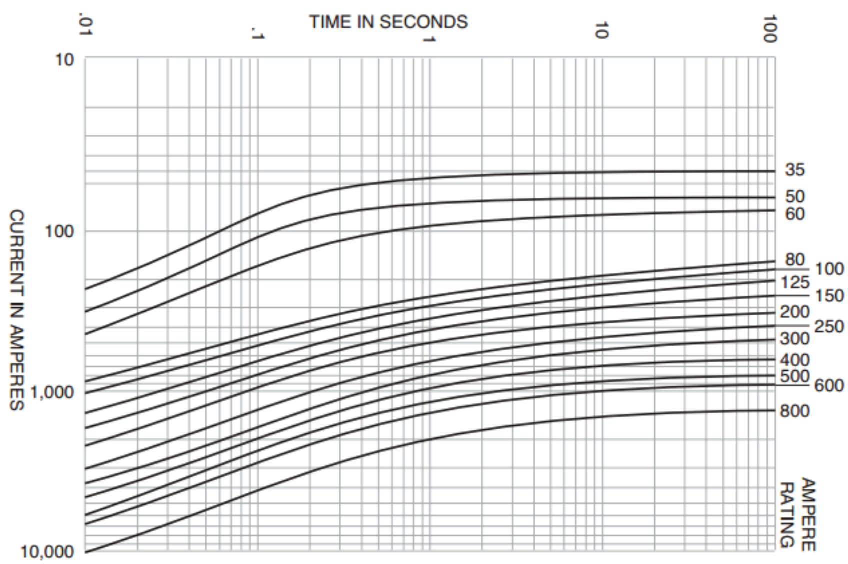


Figure 16 Time-Current Characteristic Curve of ANN fuses [19].

Using the curve and current rating of the accumulator packs, an 800A fuse was selected. The fuse chosen was slightly overrated. This is to ensure that during a controller or motor failure, the current level may not be sufficient to blow the fuse but still capable of protecting the accumulator packs from direct short circuit.

4.5 Contactor

A contactor is basically a relay which is capable of carrying large amount of current. The job of contactor in an EV is to connect and disconnect power from the batteries to the motor controller. A number of objectives for finding suitable battery charger for the vehicle were set. Firstly, the contactor can be operated by a low voltage control circuit of 12Vdc. The current rating of the contactor's contacts needs to be rated for DC operation and capable of handling the continuous load current of 400A.

The following table summarises the different type of contactors that is suitable for the vehicle

Contactor	**Price**	**Contact current rating (continuous)**	**Coil current rating @12Vdc**
Nanfeng ZJW400A	~$70	400A	1.2A
Gigavac GX200	~$180	400A	0.3A
Tyco EV200	~$220	500A	0.13A

Table 8 Comparison of different contactors.

Tyco EV200 contactor is found to be the best candidate among the others due to its lower power consumption and small in size. However, due to financial constraints ZJW400A contactor was chosen. Not to mention, at least four contactors are required (two per box). Spending close to a thousand dollars for contactors would not be sustainable for the team. A compromise had to be made by using cheaper contactors. In addition to this, the competition is also scored based on the cost of the vehicle.

5. Component Testing

5.1 BMS Master (EVMS)

The EVMS is one of the most important components of the electrical system as it performs several management functions of the electric drive system. To fully understand how the EVMS works and to achieve a complete and working circuit, several experiments are needed to be conducted. A wiring diagram has been provided by manufacturer on the how to connect each terminals together [16]. However it is only support certain electrical configuration of an actual car which is not fully relevant to our application but could be adjusted to meet our requirements. There is also little information on how the different inputs of the terminals correspond to different outputs. The reliability and performance of the EVMS are also taken into account.

Experiment 1

The first set of experiment is to obtain the truth table on the corresponding inputs and outputs of the EVMS's terminal. Using the information on how each inputs and outputs are connected from the given wiring diagram, a likely idea of what each inputs and outputs give are determined and this is as shown in the table below.

Inputs		**Outputs**	
Key In	Charge sense, BMS In	Main Ctr, Aux Ctr	Drive Enable relay, Charge Enable relay
12V = 1	GND = 1	12V = 1	Close = 1
GND / Float = 0	Float = 0	0V = 0	Open = 0

Table 9 The corresponding inputs and outputs parameters.

Throughout the experiment, a permanent 12V supply is connected to the 12V inputs of EVMS' supply terminals else it will not work and defeat the purpose of the testing. A truth table is constructed with various inputs and outputs. The result of the experiment is as shown in Table 10.

Inputs			Outputs			
BMS In	Charge Sense	Key In	Charge Enable	Drive Enable	Main Ctr	Aux Ctr
0	x	x	0	0	0	0
1	0	0	0	0	0	0
1	0	1	0	1	1	1
1	1	x	1	0	0	1
0→1	x	x	0	0	0	0
1→0	x	x	0	0	0	0

Table 10 The truth table of the EVMS

Charge Enable = 12V**.** Charge Sense**.** BMS In

Main Ctr = **Drive Enable** = 12V**.** Key In**. (**Charge Sense)'**.** BMS In

Aux Ctr = **Main Ctr + Charge Enable** = 12V. [Charge Sense**.** BMS In + Key In**. (**Charge Sense)'**.** BMS In]

Two significant findings were found in this test. First of which is when the charge sense input is equal to 1 (or grounded), only auxiliary contactor (Aux Ctr) is powered. On the preliminary design shown in Figure 17 the positive charger output connector is connected after the main contactor. Since the main contactor is open, charging will not work. As a result, the positive charger output connector need to be re-connected between the main contactor and the additional contactor that is required to isolate the positive pole of the battery as according to the rules. Due to little space available in the battery box, the main contactor had to be placed outside the battery box. This is as shown in Figure 18.

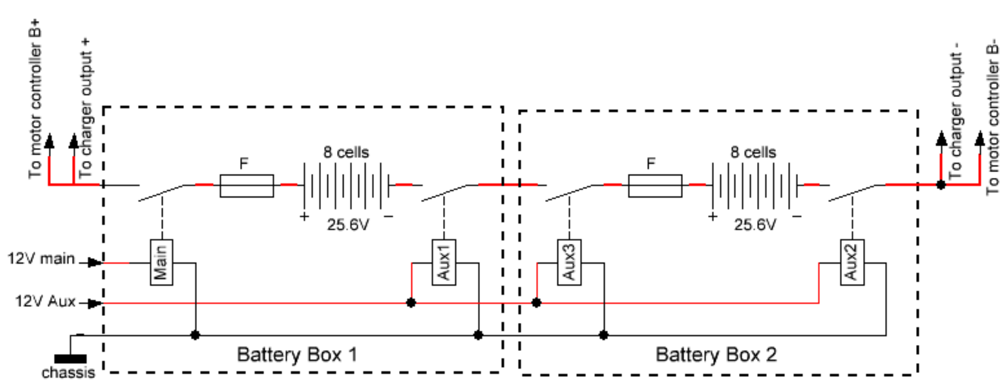


Figure 17 Preliminary design of the tractive system accumulator

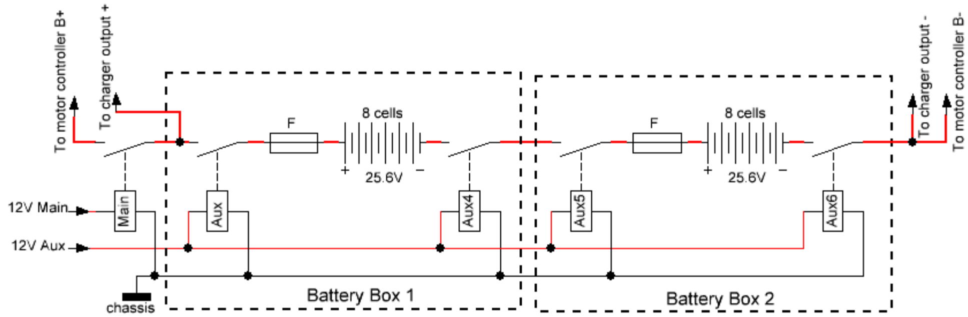


Figure 18 The new design of the tractive system accumulator.

The second of which is when BMS In input transits from 1 to 0 (which mean BMS module detects an error), it takes the EVMS approx. 10s to compute its following outputs.

Experiment 2

As shown in the last figure, the whole system requires up to 5 contactors however the EVMS only able to control up to two contactors. An experiment need to be conducted to test whether the EVMS is able to supply the currents to close the five contactors by connecting main contactor on EVMS main contactor terminals and four aux contactors connected in parallel on EVMS aux contactor terminals.

From the experiment, the EVMS failed to supply enough currents to close the contactors. This is expected as each contactor requires 1.2A and the EVMS is only limited up to 5A. A workaround is needed to be implemented such that EVMS is still able to control the five contactors. The workaround is to use external relays that will control the currents that drive the main and aux contactors. This is as shown in the figure below.

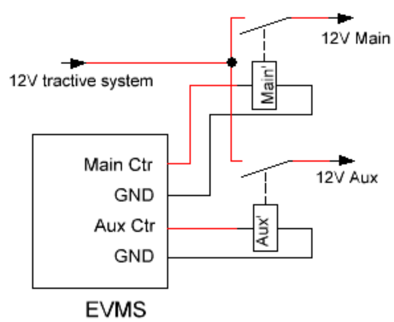


Figure 19 The additional relays on the EVMS terminals

With this workaround the EVMS could indirectly control the contactors without overstressing itself. A second experiment was tested with the additional relays on prototype board and proved that it is working as it was intended.

Precharge circuit

Motor controllers in electric vehicle typically have a large internal bank of capacitance with very low Equivalent Series Resistance (ESR). As a result, when initially connecting a battery to the motor controllers, there is an inrush current (could easily reach over 1000A) followed by a voltage surge due to battery and cabling inductance [20]. Both current spike and voltage surge may cause several problems to other components such as:

- Damaging the motor controller or other capacitive load,
- The accumulator packs itself which are not rated for the inrush current,
- Blowing the main fuse before the vehicle can even run and
- In most common case, welding of contactor's contact which cannot be determined by just looking.

A precharge circuit will solves these problems, without limiting the operating current of the tractive system. The EVMS has a precharge circuit built-in. The sequence of how the precharge circuit works in the EVMS is when the vehicle is initially powered; the precharge circuit will first enable the pre-charge relay, enabling the resistive pathway as shown in Figure 20 with blue line. Then after approximately 1-2s of precharging [16], when it detects a sufficiently low current flowing through the precharge resistors, the circuit enables the main contactor and current can now pass through the less resistive pathway.

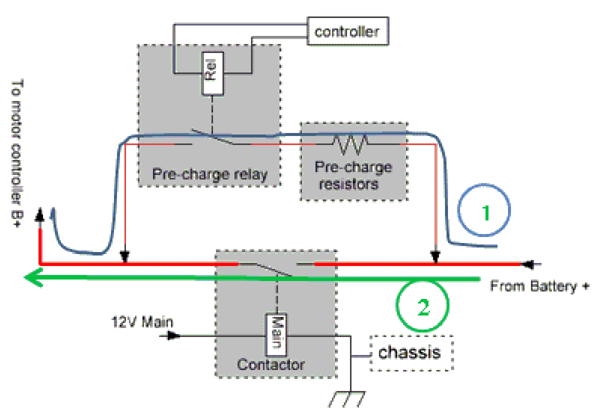


Figure 20 Precharge circuit

Even though there is a precharge circuit, an early switch on the main contactor before the capacitors are fully charged could still be disastrous as mentioned earlier. Contactor manufactures recommends charging the capacitor to 95% state of charge before closing the contactor [21]. Lower state of charge could cause contactor's failure. Calculation is needed to ensure the capacitor is charged to 95%.

Calculation is also needed to check whether the precharge resistor used in the EVMS is appropriate for long-term reliable operation of the precharge circuit. The precharge resistor used in the EVMS is rated at 50Ω 20W (2x 100Ω 10W resistors are used)

Calculation – Failure of precharge resistors

During precharge stage, the circuit could be modeled as a simple RC circuit. Every time constant,$\tau = R * C$, the capacitor increases in charge by 63.2%. As a rule of thumb, the capacitor is fully charged after a time of approximately 5τ (99.3%).

Therefore, the power dissipated by the precharge resistor is then equal to energy in the charged capacitor divided by time taken to fully charge the capacitor:

$$P = \frac{E}{T} = \frac{CV^2}{2T} = \frac{V^2}{10R}$$

Given that the accumulator packs are 58.4V max and resistor is rated at 50**Ω**, the power dissipated in the precharge resistor is therefore equal to 6.82W. This is only 34.1% of what the precharge resistor could take. The instantaneous power which is ten times of the power dissipated would not be a worry too as the resistors used (wire wound type) could handle peak up to ten times of its continuous rating. Therefore, they are less likely to fail from overheating.

Calculation – Capacitor charged to 95%

In order to charge the capacitor up to 95% state of charge, the time required to precharge is at least 3τ. With the given information on the min precharging time (1s) and the rating of the resistor used, the maximum capacitance the precharge circuit could take is given by

$$C = \frac{T}{3R} = \frac{1}{150} = 6.667mH$$

Due to no available information on the motor controller’s capacitances and the inaccuracy of measuring capacitance with multimeter, it is impossible to determine whether the capacitances in the motor controller will be charged to 95% state of charge. More information is required

6. Interfacing different components

6.1 Interface the drive and charge interlock of the EVMS

From the component testing, in order to power the tractive circuit, the Key In terminal of EVMS must see 12V and main and aux contactors will be closed. On the other hand, in order to charge the accumulator packs, the Charge Sense terminal must be grounded while Key In terminal is either grounded or floating. This whole things can be implemented and interface together by using Double Pole Triple Throw (DP3T) switch. This connection is shown in the schematic below

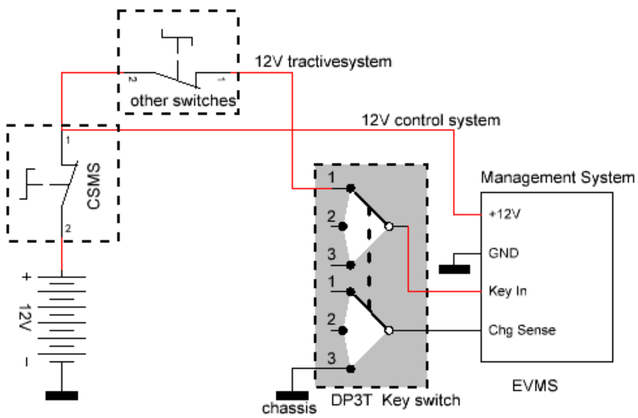


Figure 21 Interface the drive and charge interlock

When the key switch is in position 1, the vehicle is driving mode

When the key switch is in position 2, the vehicle is off / idle.

When the key switch is in position 3, the vehicle is in charging mode

6.2 Interface with charger

In order to prevent from overcharging the battery, the BMS master must be able to control the charger to cease the charging. To achieve this, the control input of the charger and the Charge Enable relay inside the EVMS are utilised. On charger side, the charger can be controlled by connecting or disconnecting +12V and ENABLE of the control inputs. If ENABLE is disconnected, charging will cease. Upon re-connection, the charger will recommence charging.

On the BMS master side , when charging is allowed, the Charger Enable relay of EVMS will be closed. When there is an error detected on the BMS module (which means that particular cell is overvoltage) the charger enable relay will be opened. This clearly shows that the two components can be connected directly and work perfectly together. The schematic in Figure 22 shows the connection between Charger control inputs and the EVMS's charge enable relay.

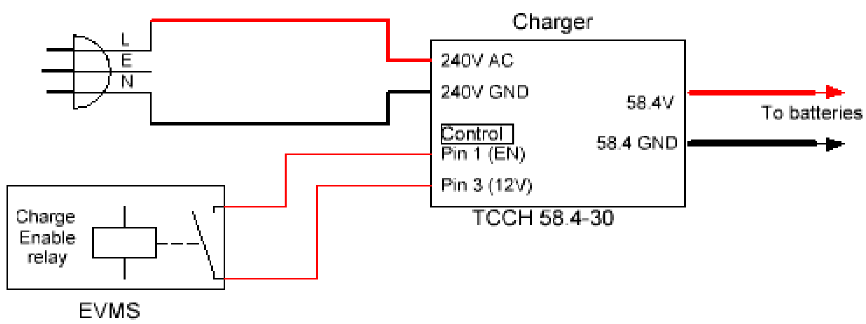


Figure 22 Interface between EVMS and charger

6.3 Interface with motor controller

In order to protect the accumulator packs when it is nearly empty, the BMS master must be able to shut down the motor controller to prevent further discharging. This can be done by either shutting down the motor controller supply/enable line or by removing the throttle signal to the motor controller. The throttle signal is powered by the motor controller therefore by shutting down the motor controller supply/enable line; there will be no response from the throttle as well. Shutting down the motor controller supply/enable line provides more redundancy compare to just removing the throttle signal.

To protect the accumulator packs from over discharge, the control input of the motor controller and drive enable relay inside the EVMS are utilised. On motor controller side, the motor controller is controlled by connecting or disconnecting the battery voltage and its enable line. If battery voltage is not present on its enable line, the motor would not work and vice versa. On the BMS master side, when driving is allowed the Drive Enable relay of EVMS will be closed. When there is an error detected on the BMS module (which means that particular cell is undervoltage), the drive enable relay will be opened. This clearly shows that the two components are working perfectly together and be connected directly. The schematic below shows the connection between the motor controller and EVMS

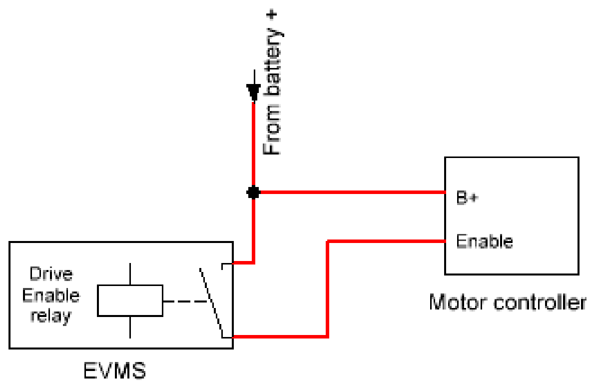


Figure 23 Interface between EVMS and motor controller

7. Additional components added to the electrical circuitry

7.1 Measuring points

There are three measuring points installed in the vehicle, two tractive system measuring points (TSMP+ and TSMP-) and a control system ground measuring point (CSMP). The purpose of these measuring points is to check isolation of the tractive system. It will be used during the electrical system test done by the Formula SAE inspector. They are also needed to ensure the isolation of the Tractive system of the vehicle for possible rescue operations after an accident or when work on the vehicle is done [4]. These measuring points are protected by ABS enclosure (65L x 60W x 40H mm) that can be opened easily with screwdriver. Each tractive system measuring point is secured with a current limiting resistor of 5kΩ (two 10kΩ resistors in parallel) and connected to positive and negative motor controller supply lines. The CSMP is directly connected to the chassis. The connection of these measuring points can be seen in figure below.

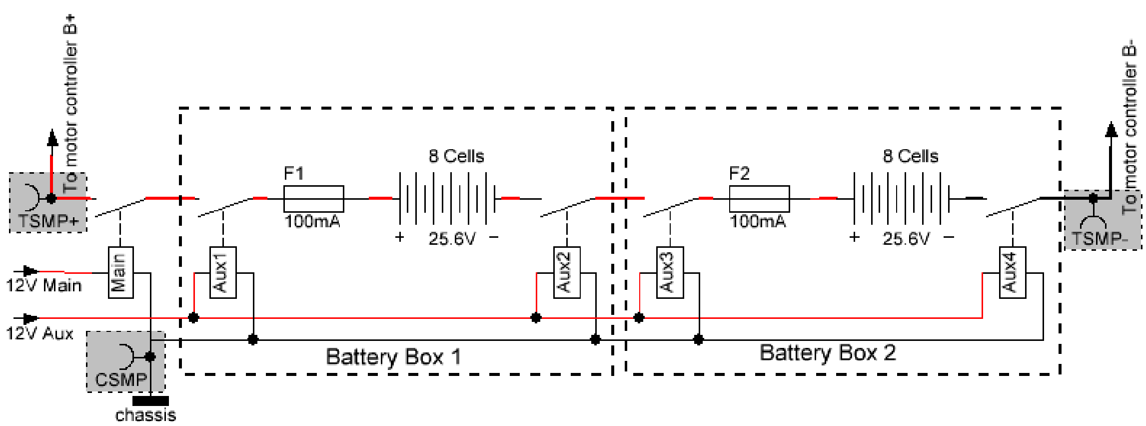


Figure 24 Battery box schematics showing measuring points

7.2 Tractive System Active Light (TSAL)

The tractive system active light (TSAL) is installed on the vehicle whenever there is high voltage present outside the battery boxes. This is installed for safety purposes. The light will lighted up when it is either in driving mode or charging mode. This provides some awareness to the surrounding people on the status of the car. To achieve this, TSAL is connected directly on the aux contactor terminals of EVMS. This light draws about 200mA so sharing the terminal with the additional relay will not have adverse effects on the EVMS itself. The light is mounted at the highest point of vehicle with tube clamp.

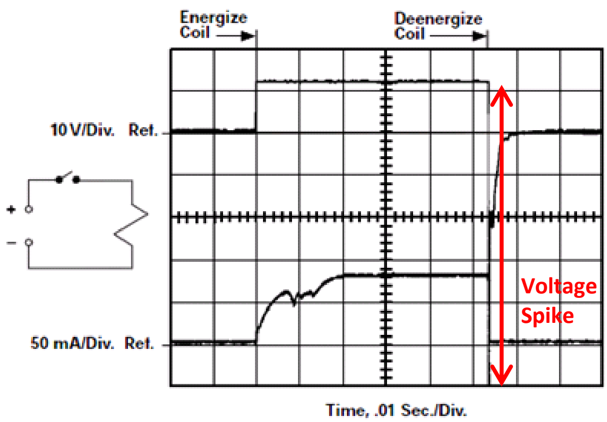
Figure 25 TSAL mounting

7.3 Relay's coil suppression

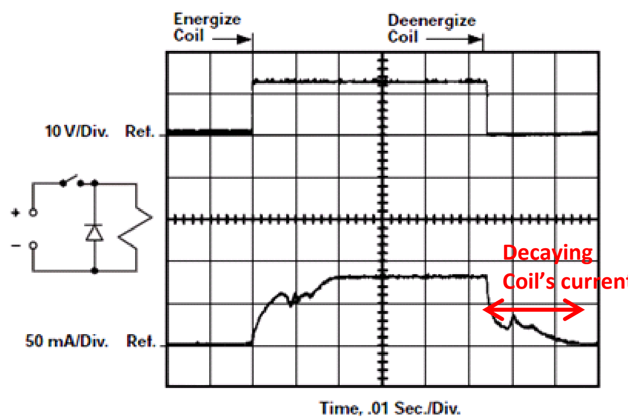
Contactors are usually a normally open contact and have an electromagnet coil inside for closing the contacts when energised. When the relay is de-energised, the collapsing magnetic field in the coil induced a large voltage transient in an effort to maintain current flows as seen in Figure 26(a). The induced voltage transient may be in the magnitude of hundreds or even thousands. This relatively large voltage transient can create Electro-Magnetic Interference (EMI), semiconductor breakdown, and switch wear problem.

There are many ways to avoid this. One very common practice is to simply paralleling the coil with a general purpose diode. The diode will block the reverse polarity of the coil induced voltage. This diode shunt provides maximum protection to the relay but it has adverse impact on the relay's switching performance due to the slowly decaying coil current, and resulting magnetic flux seen in Figure 26(b). It is important to realize that the net force available to cause the contact to open is the difference between the magnetic restraining forces and the spring opening forces [22]. A slowly decaying magnetic flux means the less net force integral available to accelerate the armature open [22].

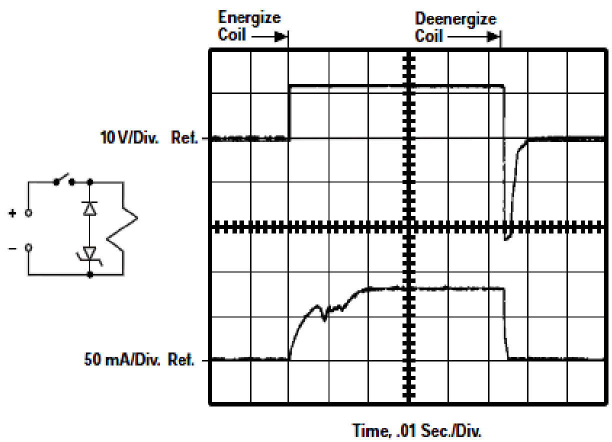
A near optimum decay rate can be obtained by using a Zener diode in series with a diode [22]. When the coil source is interrupted the coil current is shunted through this series arrangement, maintaining a voltage equal to the Zener's reverse bias voltage until the coil energy is dissipated [22]. This is illustrated in Figure 26(c).



(a) Typical DC relay without diode



(b) Typical DC relay with diode



(c) Typical DC relay with diode and Zener

Figure 26 Operate & Release Dynamics Coil V&I [22]

To simplify the implementation into each contactors used in the vehicle, 2x 13V Zener diodes are used with its anode connected to back-to-back. Replacing a diode with a Zener diode will not affect the performance of the switching either. In fact, this will regulate the voltage and prevent overvoltage on the coil's terminal.

7.4 Temperature switch

Since the BMS module could not measure the temperature of critical points of the accumulator, it is necessary to install temperature switch as it is required by the rules. The temperature switch used is a kind of thermostat which adapts on using bimetal disc as temperature sensing element. It is a Normally Closed (NC) contact under normal operation. The contact becomes open circuit when the temperature is above the preset temperature. It has the same terminology with the BMS module daisy chain – open circuit when cell voltage is outside the SOA. Therefore the temperature switch could be used by connecting it along the daisy chain. The preset temperature for the temperature switch is about ~65°C and it has a hysteresis of ±20°C. This switch is place on each sides of accumulator pack's metal plate as shown in the figure below.

Figure 27 Temperature switch's location indicated by red box.

8. Conclusions

This project aimed to design an electrical circuitry for Formula SAE-Electric 2012 that is in compliance to the latest Formula SAE rules. Comparing with the existing electrical circuitry, most of the rules set by the rules committees are explored and can be said much safer to work with in the case of maintenance. Part of the electrical circuitry was also done together with a collaboration of other students as the scope of the electrical system for the car is quite large. The electrical circuitry between tractive system side and control system side can be found in Appendix 1. The implementation of the electrical circuitry however is still on-going.

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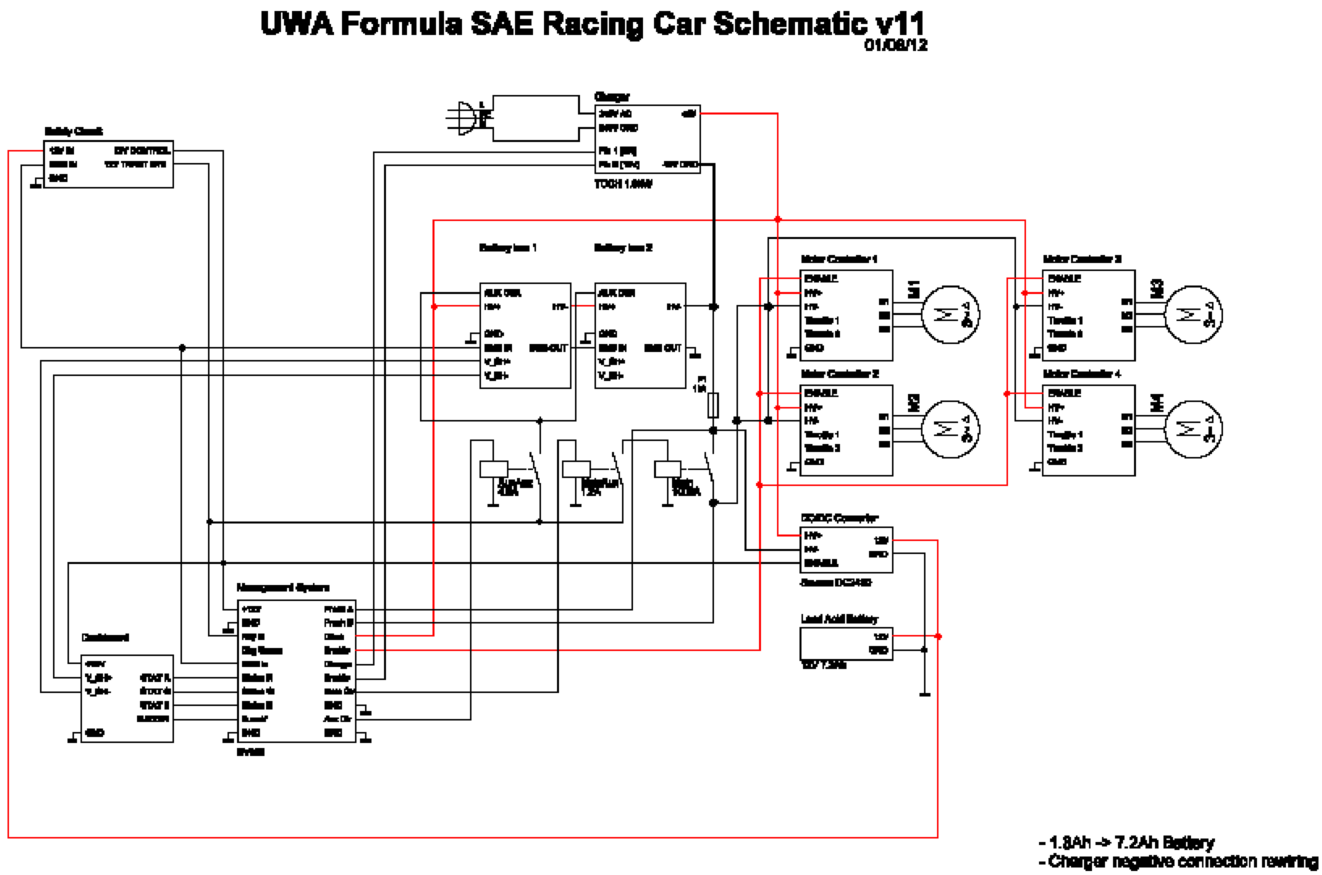
[24] Alex Schere and Davip Susanto

Appendix 1



Tractive and control system of the vehicle [24]