Selection of Major Components of Tractive System and Accumulator for a Formula Student Vehicle

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Abstract – *This paper gives an overview on a cognizant strategy while selecting the major components of tractive system and accumulator for a formula student electric vehicle. This study was compiled according to the rules specified in the 2020-21 FSAE. We have also taken into account the battery management system, motors and other electrical management systems along with a brief description about their working and specifications.*

Key Words: BMS (Battery management system), cell chemistry, motor, pre-charge & discharge circuit and cell.

1. INTRODUCTION

Formula SAE is an international engineering competition that invites university teams to design, build and race formula style single seat race cars. Team Alpha 4ZE is a student team based in Jamia Millia Islamia, currently working on electric vehicle. An electric powered car has few primary components like motor, battery and shutdown system etc. Lithium ion batteries are generally used because they give better performance and range and they are light weighted. The choice of an electric motor still remains one the main tasks while designing the electric racing car because, it is the motor that specifies dynamic and high-speed characteristics and that's the reason we have used such a motor which can be integrated easily within a new or existing powertrain, drivetrain or differential is used. Thus, outright performance is achieved by simultaneously optimizing designs for a range of criterion, including size, weight, simplicity, manufacturability, safety, efficiency and of course, power output.

2. INTRODUCTION TO TRACTIVE SYSTEM

The Tractive System is the part of the Vehicle that carries the current to power your motors. This includes all the High Voltage equipment's like Accumulator, Inverters, motors and the motor controller. The other components that belongs to TS as per their work and ratings are AIRs (Accumulator isolation relays) , Pre Charge Relay, Discharge Relay, HVDs (High Voltage Disconnects), Fuses etc. In order to boost battery life and efficiency, the battery management and module design approach needs to be improvised by using partial discharge cycles and avoiding high charge and discharge currents, because high currents play excessive stress on batteries and thus reducing cycle life. Limiting battery temperatures extends battery life as well.

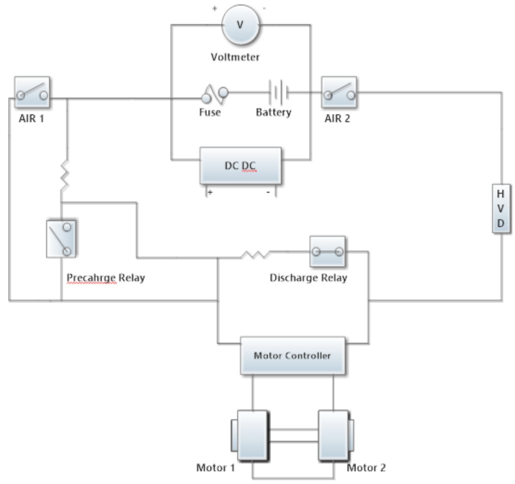

Fig -1: Tractive system schematic

The schematic shows the tractive system of the vehicle which includes the AIRs which are normally open relays to isolate the cells when the Tractive system is turned off. The pre charge relay and the discharge relay are used to reduce initial surge currents and prevent the vehicle from driving off respectively. The DC-DC convertor is used to increase voltage from a partially lowered battery voltage thereby saving space instead of using multiple batteries to accomplish the same thing.

2.1 Motors

EMRAX motors which can be integrated easily within a new or existing powertrain, drivetrain or differential is used. It is mounted at the rearmost structural section of the chassis. EMRAX motor proves to be the optimal electric motor choice for automotive OEMs and conversion specialists and its efficiency lies between 92-98%.

Table -1: Motor Specification

Motor manufacturer and Type:	EMRAX 188(HV)
Motor Principle:	Advanced axial flux synchronous motor
Maximum continuous power:	23kW
Peak Power:	52 kW
Input Voltage:	430 VDC
Nominal Current:	100 A
Peak Current:	200 A
Maximum Torque:	90 Nm
Nominal Torque:	40 Nm
Cooling Method:	Air Cooling

Table -2: Motor Controller Specification

Motor Controller Type:	ZEVA MC1000 DC
Maximum Input Voltage:	175 VDC
Maximum Continuous Power:	45 kW
Maximum Peak Power:	150 kW
Output Voltage:	150 VAC
Maximum continuous output current:	300 A
Maximum Peak Current:	1000A (for 1 min)
Auxiliary supply voltage:	12 VDC
Control Method:	CAN bus
Cooling method:	Fans, Ducting

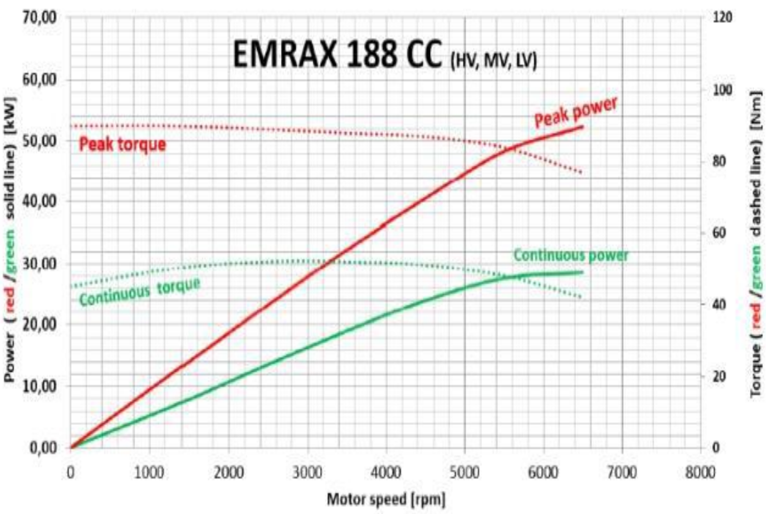

Chart -1: Plot of power V/s torque V/s motor speed for an EMRAX motor

2.2 Motor Controller

A motor controller basically controls the overall performance of the motor which might include a manual or automatic means for starting and stopping the motor, selecting forward or reverse rotation, selecting and regulating the speed, regulating or limiting the torque, and protecting against overloads and electrical faults. The motor is operated by a ZEVA MC1000 DC motor controller. The motor has software on-board that varies the voltage supply to the motor based on input directly from the motor as well as CAN messages from the ECU. Voltage effectively controls target motor speed and current controls the torque. It is placed as per wiring in the rear part of the car.

3. CELLS

Cells are the building blocks of an Electric Vehicle as several cells are connected in series and parallel to form a battery module, and then modules are further grouped to form a Battery pack depending upon the overall capacity and the potential of the accumulator. The battery pack is the energy storage device which accepts energy and releases it to provide power to the electric vehicles. As cells are the most basic unit, hence it's very important to select the right cell for the vehicle. The six primary battery performance metrics which must be traded off are: -

- Specific energy density
- Specific and total power
- Cell and pack safety
- Cell and pack life
- Total battery cost system
- Cell performance

3.1 Types of Cells

The cells used widely in today's life are:-

- Cylindrical Cells
- Prismatic Cells
- Pouch Cells

Cylindrical cells are the most common cells in today's use and are known for their low costs and ease in manufacturing and good mechanical stability. The cells can withstand high internal pressures without deforming and the design has good cycling ability and high specific energy. On the other hand, the cells are heavy and have low packaging density due to space cavities. These cells are commonly used for portable applications.

Prismatic cells offer thin profile, light weight and more effective use of space. The rectangular shape provides better layering and gives product designers increased flexibility. The cost of manufacturing of these cells is more as compared to other cells; thermal management is less effective and are relatively sensitive to deformation in high-pressure situations. The prismatic cells are used in electrical powertrain and energy storage systems.

Pouch cells offer simple, flexible and lightweight solution to battery design and deliver high load currents. They perform best under light loading conditions and with moderate charging. They make most efficient use of space and achieve 90–95 percent packaging efficiency. Although easily stackable, provision must be made for swelling. While smaller pouch packs can grow 8–10 percent over 500 cycles, large cells may expand to that size in 5,000 cycles. It is best not to stack pouch cells on top of each other but to lay them flat, side by side or allow extra space in between them. In these cells extreme swelling is a concern and the pressure created can break the battery pack and can even damage the electronic circuit boards. The pouch cell is growing in popularity and offer similar applications to the prismatic cell.

To ensure optimal performance from the accumulator, a significant amount of time needs to be devoted in the cell selection process to study various things of cells like its charging and discharging capacity of cell, its packing efficiency, its temperature variation data, maximum power it delivers, its weight, its specific energy and its maximum discharge current. The pouch cells are preferred due to the following reasons: -

- High packaging efficiency
- Low weight
- Large capacity and small internal resistance
- Ensures safety

3.2 Cell Chemistry

A chemical cell converts chemical energy into electrical energy and a chemical reaction takes places inside the battery and causes electric current to flow. In electric vehicles the selection of cell chemistry is an important part and the factors considered while determining the cell chemistry are: -

- High energy density (Wh/kg)
- High power density (KW/kg)
- Fast charging and Discharging ability
- Longer life cycles
- Eco-friendly

In the EV technology the Li-ion cell chemistry is recommended due to its durability and high-performance values under different load conditions. The leading Li-ion cell chemistries are: -

- LCO (Lithium Cobalt Oxide)
- LMO (Lithium Manganese Oxide)
- NMC (Lithium nickel manganese cobalt oxide
- LFP (Lithium Iron Phosphate)
- NCA (Lithium Nickel Cobalt Aluminum Oxide)

NMC has an overall good performance and excels on specific energy and has lowest self-heating rate and is leading battery chemistry for light-duty hybrid and electric vehicles. NCA also demonstrates high specific energy and very reasonable specific power. However, the cobalt concentration in NCA causes it to be more expensive than NMC. Lithium titanate demonstrates relatively low specific energy and specific power, but it's very long-life span, excellent cold weather performance, and very high safety have made it the choice for some commercial applications and certain lightweight electric vehicles.

Table -3: Voltage, Specific energy and volumetric energy for Li-ion batteries cell chemistry.

Material	Voltage (Average V/s Li/Li^+)	Capacity (mAh/g)	Crystal Density (g/cm^3)	Tap Density (g/cm^3)	Specific Energy (Wh/kg)	Volumetric Energy (Wh/L)
LCO	3.8	150	5.10	2.9	570	2907
LMO	4.0	110	4.31	2.5	440	1896
NMC	3.7	170	4.75	2.5	629	2988
LFP	3.4	160	3.60	1.5	544	1958
NCA	3.7	185	4.85	2.5	685	3322

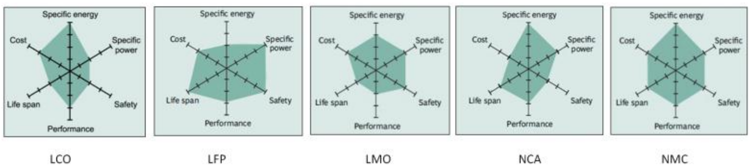

Fig -2: Relative performance, functional and safety characteristics of six leading Li-ion battery chemistries.

4. BATTERY MANAGEMENT SYSTEM (BMS)

A battery management system (BMS) is essential to the design and functionality of the tractive accumulator. In simple terms, a battery management system is capable of monitoring/protecting the battery, balancing cells, estimate state of charge, maximize performance and be able to report to users and/or external devices.

The BMS was selected based on three categories:

- analog versus digital
- topology
- custom v/s off the shelf

I. A digital BMS is better, as it is capable of sensing each cell individually, this advantage allows the BMS to charge or discharge at cell level, as well as locate which cell might be at fault.

II. Centralized is compact, least expensive option and easy to replace and since all the voltage and thermistor tap wires are processed within a single BMS. This reduces error and eliminates the need to design individual circuit boards.

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III. We chose an off the shelf BMS because our team lacked the required electrical experience to carry out such an extensive task.

The battery on our car is composed of 96 pouch cells (24 series and 4 parallel) for a combined 7.9 kilowatt-hours at a maximum of 100.8 volts. The BMS utilized in our design is the Orion BMS 2 from Ewert Energy Systems. The major factors that drove our decision were that this BMS is a digital one and had a centralized topology. Certain other factors were considered, including whether it could communicate over CAN, how many cells it could monitor both with voltage and temperature, and whether it was isolated from its voltage taps.

The Orion BMS 2 is commercially available and designed specifically for electric and hybrid vehicles. It is available in increment of sets of 12 cells from 24 cells up to 180 battery cells or a variety of different battery chemistries and supports 4-180 cells in series per BMS unit. Since we have 24 series groups to monitor, we had to acquire a BMS with a 24 cell or above configuration. The Orion BMS operates at 12v 250Ma, capable of measuring state of charge, discharge current limit and charging current limit.

The BMS can read cell voltages from 0.5 to 5 volts. The accumulator pack consists of lithium ion cells, the maximum cell open circuit voltage limit is set to 4.2 volt and minimum open circuit voltage limit set to 3 volts. It has a measurement resolution of .1 mV resolution with a ±5mV accuracy rating. If the voltages get near the limits it opens the accumulator insulation relays (AIRs).

This BMS is designed to work in high noise environments and in harsh temperatures ranging from -40 to 80 degrees Celsius. The temperature limit is set to be 65 C and if this temperature is exceeded it opens the AIRs.

All the sense wires are electrically and magnetically isolated by the BMS. In the case that an error is detected and the BMS needs to open AIR's, it switches the internal relay which connects to the internal shutdown circuit. Galvanic isolation between the tractive system and the grounded low voltage system connections occurs within the BMS. The Orion BMS comes with a current sensor with an amperage rating of choice, which is 500A for this design.

Table -4: Specification Table for Orion BMS 2

Specification Item	**Min**	**Type**	**Max**	**Unit**
Input Supply Voltage	8		30	Vdc
Supply Current: Active		<2		Watts
Supply Current: Sleep		450		µA
Operating Temperature	-40		80	C
Sampling Rate for Current Sensor		8		mS
Sampling Rate for Cell Voltage		25	40	mS
Isolation between cell tab #1 and chassis	1.5			kV_{rms}
Isolation between cell tab #2 and chassis	2.5			kV_{rms}
Isolation between cell tab connectors	2.5			kV_{rms}
Digital output switching voltage			30	V
Digital Output sink continuous current			175	mA
Cell voltage measurement range	0.5		5	V
Cell Voltage measurement Error			0.25	%
Cell balancing current			200	mA
Cell current(operating)		0.5		mA
Cell current (sleep)		50		µA
Thermistor Accuracy		1		C
Cell voltage resolution		0.1		mV

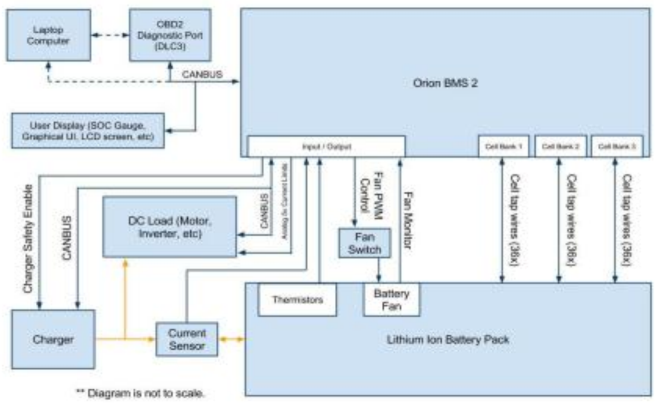

Fig -3: Overview of system connections for BMS

5. PRECHARGE AND DISCHARGE CIRCUIT

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. In our application using a large battery and powerful load, this inrush current is very high. The pre-charge circuit is required to charge the circuitry between the accumulators and the motor controller to 90% of the maximum operating voltage (600VDC) before closing the second AIR. This must be done to protect the motor controller and other components from the very large inrush current. Pre-charge relay is located in the lower accumulator container.

The Pre-charge circuit consists of:

- A pre-charge resistor, to limit the inrush current (R1)
- A contactor (high power relay) across the pre-charge resistor (K2) to bypass the resistor during normal operation

The pre-charge circuit may have:

- A pre-charge relay (K1), to keep the load from being powered through the pre-charge resistor when the system is off
- A contactor in line with the other end of the battery (K3) to isolate the load when the system is off.

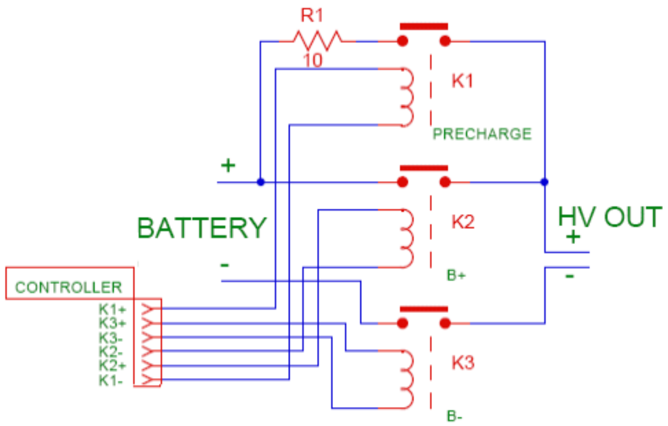

Fig -4: Typical Pre-charge Circuit

In the most basic form, the pre-charge circuit is operated as follows:

- Off: When the system is off, all relays / contactors are off
- Pre-charge: When the system is first turned on, K1 and K3 are turned on, to pre-charge the load, until the inrush current has subsided
- On: After pre-charge, contactor K2 is turned on (relay K1 may be turned off to save coil power)

Formulas:
Voltage: $V = I \times R \times e^{(-t/RC)}$
Current: $I = (Vb/R) \times e^{(-t/RC)}$
Energy dissipated :$(CV^2)/2$
Power dissipated: E/T
Instantaneous power: V^2/R
We got the following results by using a 100-ohm resistor over a 100.8 VDC:

- Max current – 1.008 A
- Actual Pre-Charge time – 3.50 seconds
- Discharge time to drop below 60V – 0.865 seconds
- Power dissipated during pre-charging event – 27 Watts
- Peak Power – 159 Watts

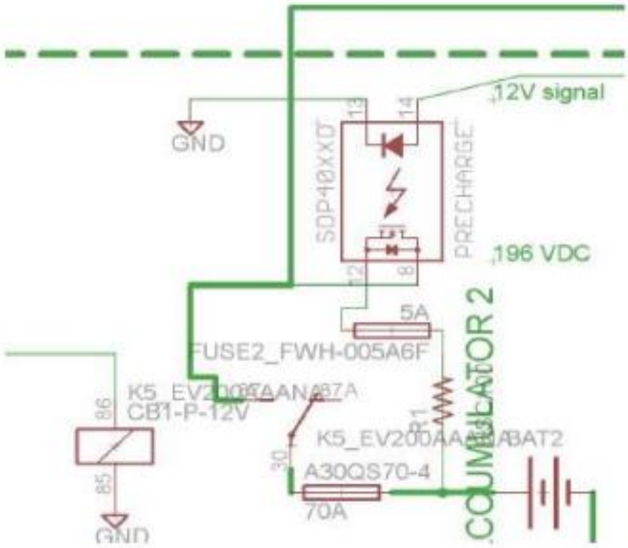

Fig -5: Pre-Charge Circuit Diagram

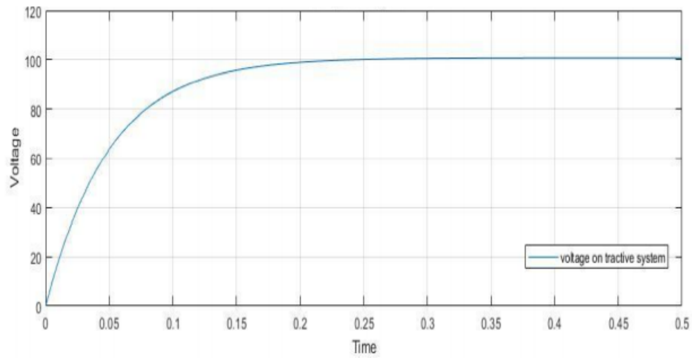

Chart -2: Pre-charge circuit plot of percentage maximum voltage V/s time

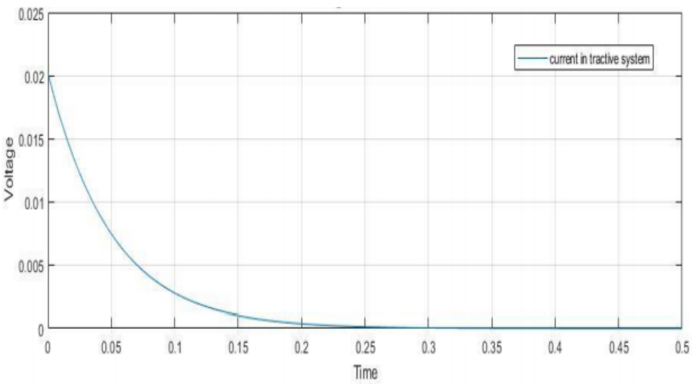

Chart -3: Pre-charge circuit plot of current V/s time

Table -5: General data of Pre-charge resistor

Resistor Type	Chassis Mount Wirewound Resistor
Resistance	100 Ω
Continuous power rating	75 W
Overload power rating	375W for 5 seconds, 150W for 20 seconds
Voltage rating	1400V
Cross-sectional area of the wire used	0.82 mm^2

Table -6: General data of Pre-charge relay

Relay Type	Omron G2RL-24 DC12
Contact arrangement	DPDT
Continuous DC current	8 A
Voltage rating	300 VDC
Cross sectional area of the wire used	0.82 mm^2

Table -7: General data of Pre-charge fuse

Fuse type	Bussmann/Eaton
P/N:	FWH-005A6F
Continuous current rating	5A
Maximum operating voltage	500 VDC
Type of fuse	Fast Blow
I^2t rating	15 pre-arc, 40 clearing
Interrupt Current	50 kA

The discharge circuit allows energy stored in the motor controller's to be discharged after the tractive system is shut down. The circuit consists of a normally closed relay in series with a dissipation resistor, setup to discharge the maximum high voltage across the motor controller's internal capacitor. When the system is powered on, the relay opens and the system operates as normal. When the shutdown system is off, the open, and when the HVD is removed, the discharge circuit is closed, and the discharge resistor will discharge energy to less than 2V in 5 seconds. Discharge relay is located in the lower accumulator container. The discharge relay coil is in parallel with the AIR coils, and connects to ground. The HV+ is wired directly to the common, and the HV- is attached to the NC output on the discharge relay. When the GLVMS opens the circuit, the NC contact closes the discharge circuit, discharging all of the capacitance on the motor controller in <5 seconds. The fuse in discharge circuit is identical to the one used in pre-charge circuit.

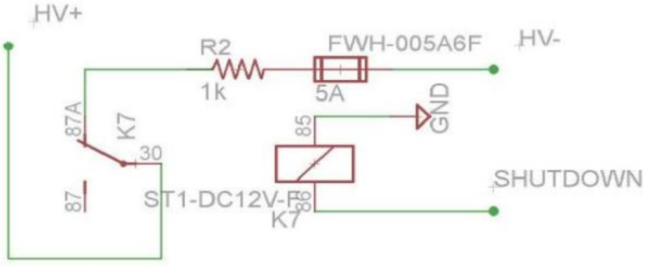

Fig -6: Discharge Circuit Diagram

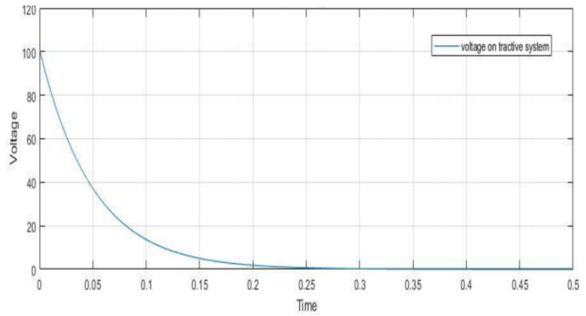

Chart -4: Discharge Circuit plot of voltage V/s time

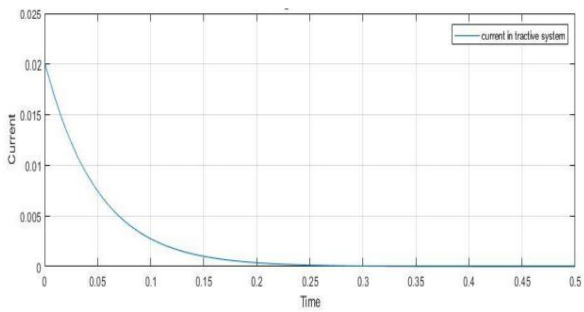

Chart -5: Discharge Circuit plot of current V/s time

Table -8: General data of Discharge Circuit

Resistor Type	Chassis Mount Wirewound Resistor
Resistance	100 Ω
Continuous power rating	75 W
Overload power rating	375W for 5 seconds, 150W for 20 seconds
Voltage rating	1400 V
Maximum Expected Current	0.7 A
Average Current	0.3 A
Cross-sectional area of the wire used	0.52 mm^2

6. CONCLUSION

The aim of this paper is to summarize the working and selection criteria of the major components of a formula student car. The FSAE guidelines have been thoroughly followed while working on this paper.

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