INSPIRED KARTERS

DESIGN REPORT

(Supporting Document)

EDP Video | EDP Slides

By

Inspired Karters Electric

For

FSEV 2021

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1 . Introduction

Formula Bharat

Formula Bharat is an inter-collegiate competition which provides the opportunity for students from various universities across the country to design and fabricate a formula-style open wheeled race car. The event also gives the students a chance to contest with one another in areas of design, performance, cost analysis, business model, etc. Formula Bharat has a subsidiary event called the FSEV Concept Challenge

FSEV Concept Challenge

This report is the combination of multiple design reports pertaining to the electrical package of the car, along with the development and results of a lap time simulation which was self developed

This report aims at taking the reader through the design process of the team Inspired Karters Electric. The report extensively covers the challenges and constraints encountered in the designing of the electrical package for the upcoming edition of Formula Bharat. Further, the team's solutions are also presented comprehensively.

2.Lap Time Simulation

2.1 Introduction

The design of a Formula Student Vehicle hinges on the ability to model what happens in reality beforehand to predict and modify the design to suit our needs. A lap-time simulator is a primary analysis tool that helps evaluate design and guide the whole process.

2.1.1 Need for a Lap-Time Simulation

In an FSAE competition, the primary aim is to maximize the amount of points scored. Thus, the design of the vehicle and every design decision must be geared towards optimizing the amount of points gained. A lap time simulator is a simulation of the vehicle (which is abstracted into a mathematical model) as it goes around the racetrack. The primary output of a lap-time simulation is the time taken to complete the track, which is the primary parameter upon which points in all the events, especially Endurance, is awarded. So any design decision made by the team that directly affects the performance of the car can be quantified through the lap-time simulator in terms of the difference in Endurance time or acceleration time which in turn can be directly converted to points gain through the scoring rules(you can use the previous year event's scores to predict the score as the scoring is relative).Thus a Lap-time simulator is indispensable to every team.

It is useful to also decide which design improvement gives the most improvement of one's scores for the same amount of material resources, time and money involved. This is especially useful when a team is trying to improve on the previous year's design and wants to get "the biggest bang for their buck".An example decision would be whether to work for a 10kg mass reduction and thus spend extensive time in designing the car or reduce the designing phase and increase the time for testing thereby making the car more reliable in the event.This can't be directly compared with the points scored on track. This suggests that just lap time can't be an influencing factor while taking decisions. There needs to be some metrics which look Performance parameters and reliability to be able to understand the decision properly.

2.1.2 Performance parameters

Although lap time is the main parameter through which scoring is done (Fuel/Energy efficiency is also taken into account), it is not the only performance parameter that one must be concerned with while designing. Although it is one of the main parameters, we must understand that the lap-time simulation is an idealized simulation which is a highly abstracted model of reality.

One of the major abstractions is the human element of the driver driving the vehicle. The lap-time simulation assumes a driver that can use the car's potential to the fullest and then produces the consequent lap-timing. This idealization means that the lap-time produced by the simulation is generally the best possible lap time that is possible. But we need to create a design that also takes into account the ease of driving, which cannot be directly captured by just a single measure of lap time. To understand all of the parameters of driving, we can look at the steering response-quantify the dynamic understeer and understeer gradient-thereby be able to quantify the ease of driving(there are multiple test/standards to also achieve this).This is just one of many things that Lap-time as a parameter doesn't capture. So there exists many performance parameters that although doesn't directly affect the lap time in the simulation, it affects the performance in reality. Therefore, the lap time-simulation must be extended to include simulations of other components of vehicles to give other performance parameters like the steering response to help guide design of those corresponding components. Thus, the extended lap-time simulation is vital in design decisions of every level: from the complete vehicle level to subsystem level to component level. Thus, the aim is to model the complete vehicle during the lap.

Levels of Simulation:

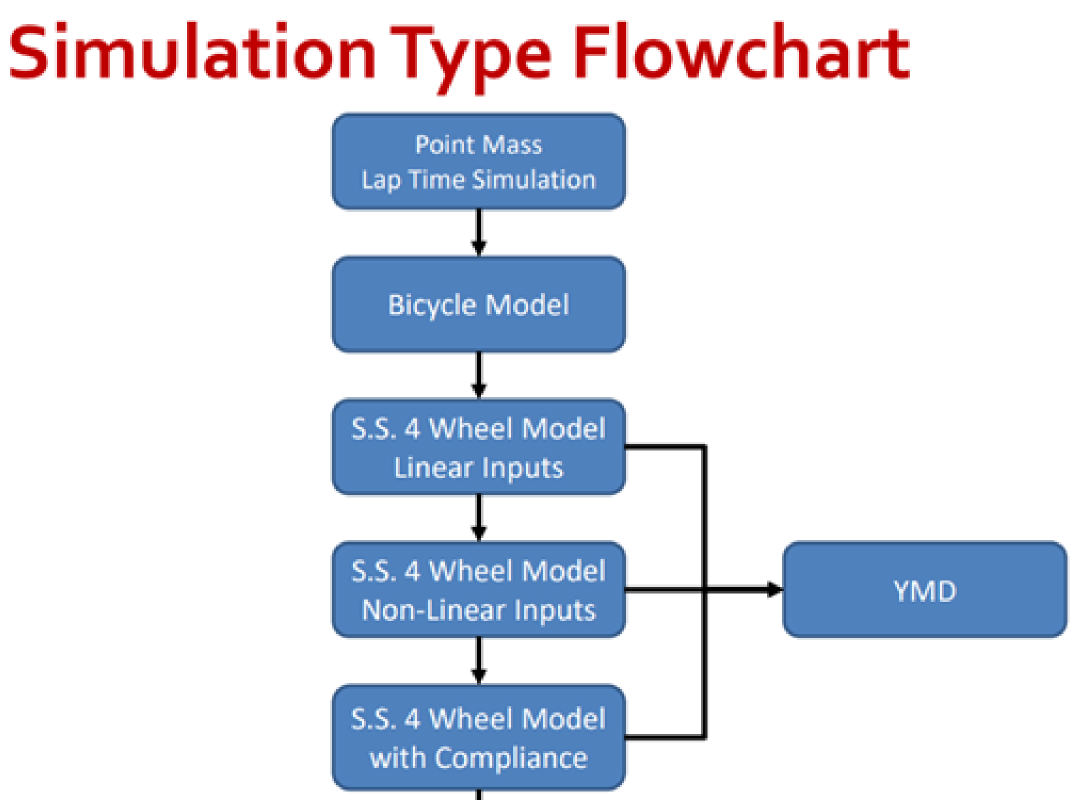


Fig 1 Different levels of Modelling [2]

The figure above shows the different levels of modelling a car with increasing complexity. As we go lower down, the complexity increases and returns in terms of ability to take design decisions for modelling decreases. Each model has a set of underlying assumptions that tries to capture a certain behaviour of the car and its corresponding influence on the performance parameters.

2.1.3 Motivation for Development of Indigenous Simulation

The first model (the point mass model) assumes a point mass in the place of the car and simulates it around the lap. This is the simplest model and commercial(academic) software called Optimum Lap with this model is available to the team. This is a very good software that helps with making major design decisions and is able to predict the lap time with a deviation of 10% from reality. Despite the ready availability we opted to create our own full body vehicle lap-time simulation for several reasons:

1.Subsequent increase in complexity of modelling increases the accuracy of the lap time predictions.

2.OptimumLap is not an open source software-therefore it is difficult to derive the performance parameters which is very important to design a lot of components.

3.Various models can be further built upon a lap-time simulation -basically a full vehicle simulation-which needs the code to be built ground up.

4.OptimumLap is developed for a CV while we required a simulation for EV.

5. We found a bug in the Optimum Lap software which made it significantly overestimate the energy/power required. This led to serious issues with regards to battery pack sizing.

Due to these reasons, we decided to develop a lap time-simulation starting from the point mass model and expanding it with increasing complexity to guide various design decisions. Currently we have developed the model up to the level of the Bicycle model while incorporating components of EV vehicles like battery modelling and motor modelling. The following slides from Claude Rouelle [4] summarize the inputs, outputs and the design decisions that can be taken from the implementation of point-mass modelling and Bicycle model.

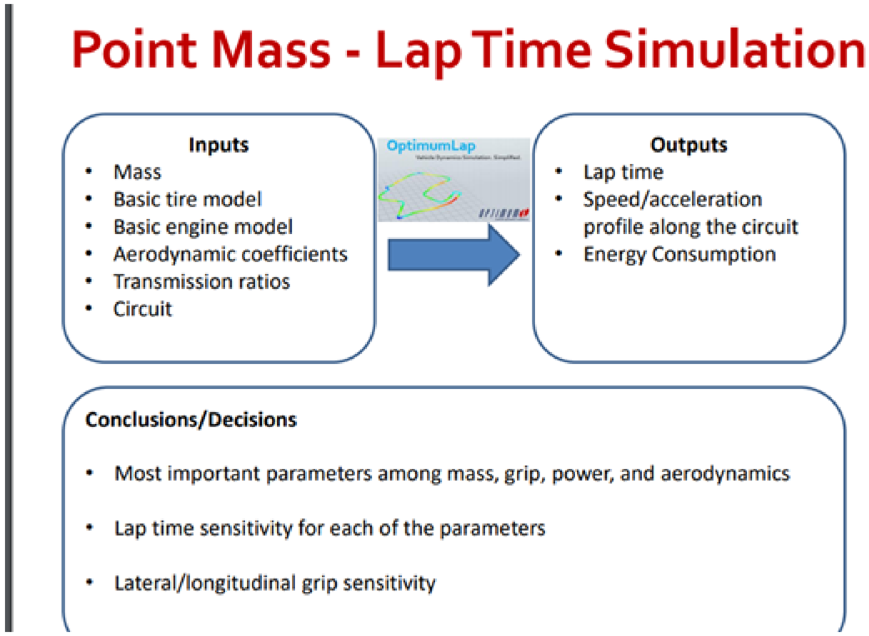


Fig: Point mass model [4]

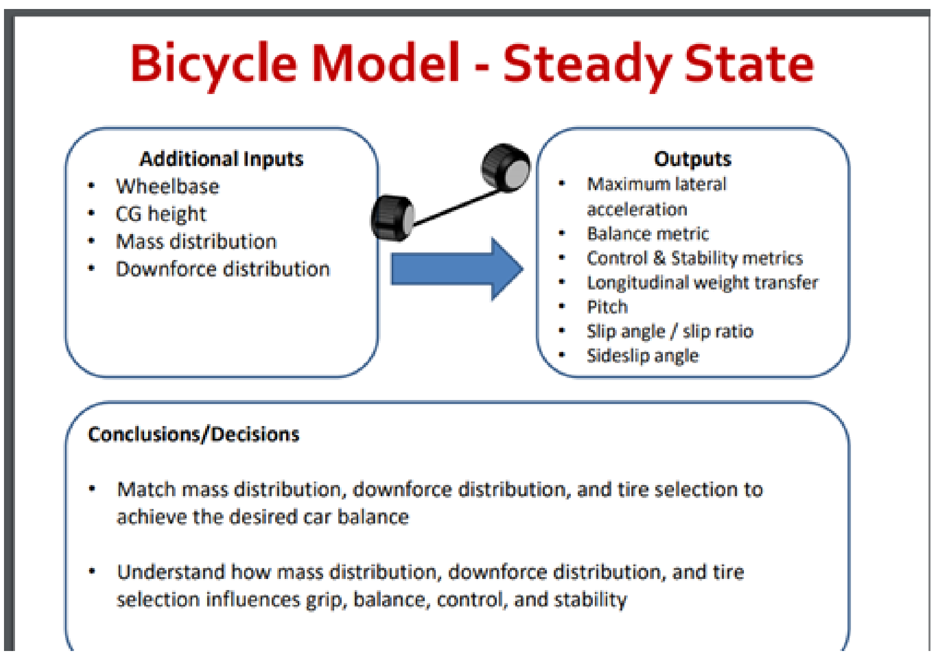


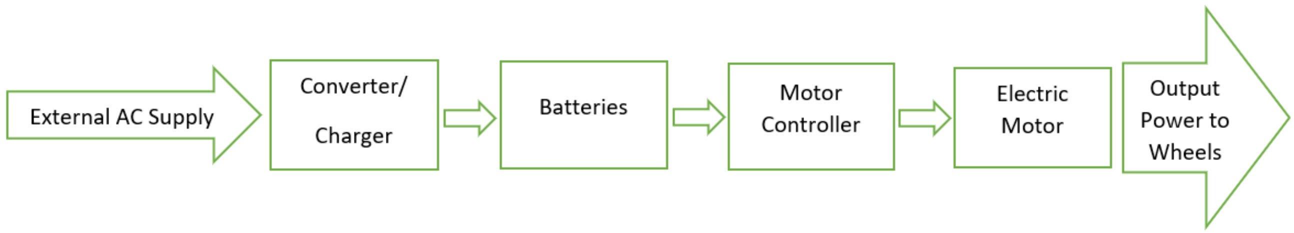
Fig: Bicycle model [4]

To read more about the lap time simulation done by the team, click here.

3. Electrical Powertrain

3.1 Motor Selection

The Electric vehicle has many components that include a charging module, converters, batteries, controllers and Electric Motor(s). The power flow in an Electric Vehicle can be shown as follows:-



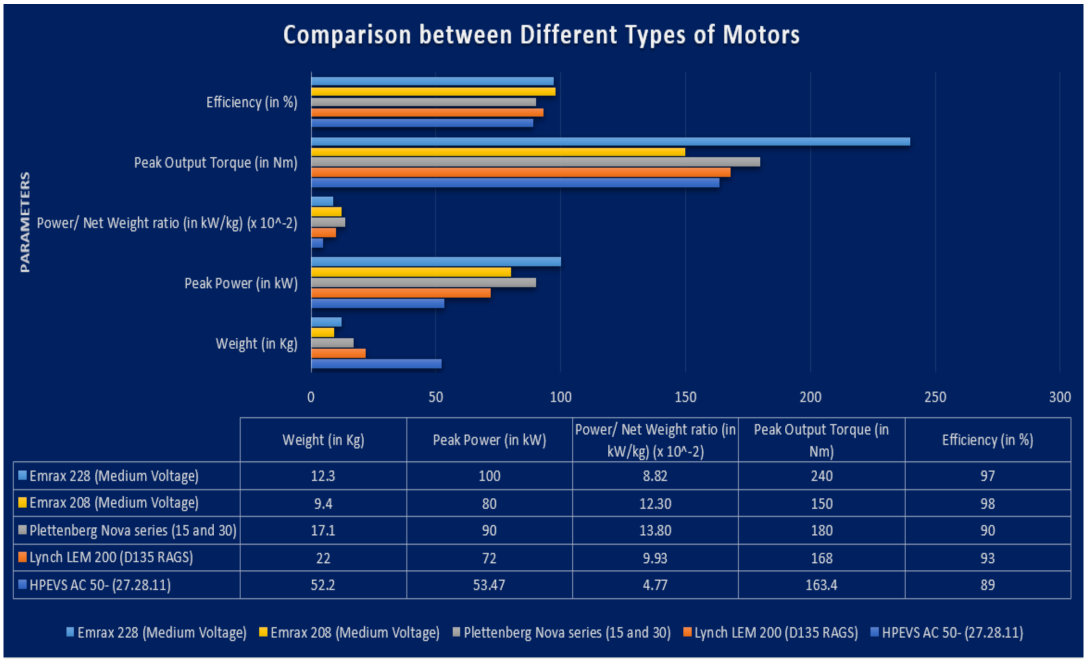
Therefore, it is clear that an electric motor determines the output characteristics of an Electric Vehicle as a whole, in terms of the output power, torque, speed, etc. While designing an Electric Vehicle, the Electric Motor is the first and foremost electrical component to be selected, thereby, making its selection crucial.

Our team wanted to achieve a benchmark while selecting the motor. This included achieving the maximum power, maximum speed and maximum efficiency with minimum weight and also making sure that it is quite compact and in accordance with the EV rules of the Formula Bharat rulebook. Moreover, the motor should be able to produce sufficient torque to overcome the force due to load and other external opposing forces, including rolling resistance force, aerodynamic drag, etc. to ensure the optimum performance of the car. Since the rulebook restricts the maximum power to 80kW power draw, the selection of the motor had to also take into consideration the peak torque output.

We did a survey on the different types of motors, used by other FSEV teams. This enhanced our thought process while selecting the Electric Motor. We compared the following motors, keeping in mind the above mentioned factors:-

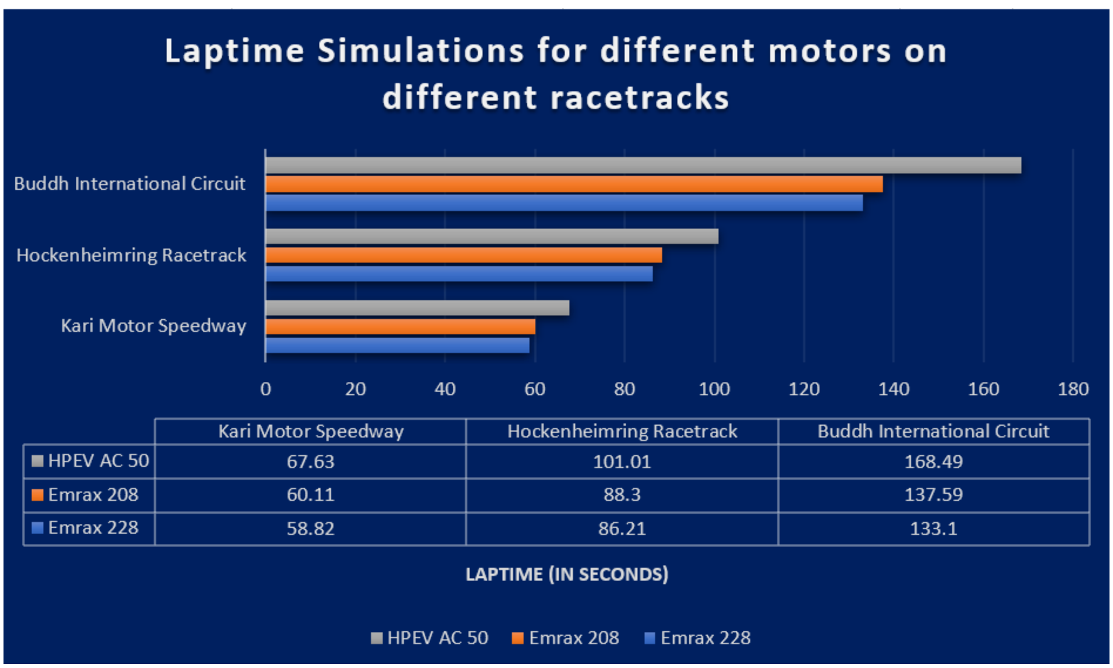
1) HPEVS AC 50- (27.28.11)
2) Lynch LEM 200 (D135 RAGS)
3) Plettenberg Nova series (15 and 30)
4) Emrax 208 (Medium Voltage)
5) Emrax 228 (Medium Voltage)

It is to be noted that the Emrax motors are PMSMs (Permanent Magnet Synchronous motor); Lynch motors are Brushed DC motors; HPEVS are AC Induction motors and the Plettenberg Nova series are BLDC (Brushless DC motors).



	Weight (in Kg)	Peak Power (in kW)	Power/ Net Weight ratio (in kW/kg) (x 10^-2)	Peak Output Torque (in Nm)	Efficiency (in %)
Emrax 228 (Medium Voltage)	12.3	100	8.82	240	97
Emrax 208 (Medium Voltage)	9.4	80	12.30	150	98
Plettenberg Nova series (15 and 30)	17.1	90	13.80	180	90
Lynch LEM 200 (D135 RAGS)	22	72	9.93	168	93
HPEVS AC 50- (27.28.11)	52.2	53.47	4.77	163.4	89

(Note:- Power to weight ratio is calculated by taking the ratio of continuous power delivered by the motor and the total weight of the car.)



	Kari Motor Speedway	Hockenheimring Racetrack	Buddh International Circuit
HPEV AC 50	67.63	101.01	168.49
Emrax 208	60.11	88.3	137.59
Emrax 228	58.82	86.21	133.1

(Note:- Lap time simulations were done using Optimum Lap software. Due to unavailability of proper data, lap time simulations for other motors (Plettenberg and Lynch 200) couldn't be done.)

Detailed Analysis:-

- The HPEVS motor excessively weighs 52.2kg, leading to a poor power/weight ratio (0.0477 kW/kg). Although it is priced comparatively less and is robust, the HPEV being an induction motor, has high rotor losses (due to induced magnetic field).This reduces the overall efficiency as compared to the other motors. In addition to this, the Lap time simulations show that it has a poor lap time and lower acceleration.
- The Lynch LEM motors have to be used in pairs (weighing a high of 22 kg) in order to achieve a peak power of 72kW and a peak torque of 168Nm. They have a high efficiency of 93% and a low battery voltage requirement of 110V which proves to be advantageous. However, its power to weight ratio is 0.0993kW/kg which is comparatively low. Moreover, two motor controllers need to be used which further increases the weight. In addition to this, Lynch LEM are brushed motors which leads to problems like poor heat dissipation (due to limitations of the rotor), high rotor inertia, EMI generated by brush arcing, lower maximum speed as compared to a BLDC or PMSM motor, etc. We ruled out this motor as better choices were available.
- The choice between the Emrax motors and the Plettenberg Nova series motors was a difficult one; the former being a PMSM while the latter, a BLDC; whether to go for RWD or 4WD. In general, PMSMs have a higher efficiency and lower mass as compared to BLDCs. Moreover, BLDCs have a problem of torque ripples (at commutation), which is not the case with PMSMs. With a pair of Plettenberg Nova 15 and a pair of Nova 30, we could achieve traction control making this extremely advantageous for the performance of the car. However, the weight of the 4 motors of Plettenberg (17.1kg) used along with 4 motor controllers exceeds the weight of Emrax motor (9.4-12.3 kg) (which requires only 1 motor controller) nearly by 90%. The peak power achieved by Plettenberg motors (90kW) is 12.5% more than that of Emrax motors(80kW) while the peak torque is 20% more. However, Emrax has an efficiency of 98% which is higher than that of the Plettenberg motors (efficiency of 90%). After an exhaustive discussion amongst the team members and deliberation, we decided to go for a RWD layout for the sake of simplicity (this year the team would also be manufacturing its first Electric Vehicle) and thus, made us opt for the Emrax motors as the befitting choice in this FSEV Concept challenge and the upcoming FB 2021. The future plans of the team does include a transition from RWD to 4WD once an in depth research on 4WD and traction control has been completed and the appropriate motors are found.
- The final choice was to be made between Emrax 208 and Emrax 228. The peak output power of Emrax 228 medium voltage is 100kW which exceeds the limit of 80 kW as mentioned in the rulebook (because of which we can't entirely depend on the Lap time simulation results). Although, the peak output torque offered by Emrax 228 MV (240Nm) is more than that of Emrax 208 MV(150Nm), the power to weight ratio of Emrax 208 MV (0.123 kW/kg) exceeds that of Emrax 228 MV (0.082 kW/kg). In addition to this, the voltage requirement of Emrax 228 MV (470V DC) is 46.875% more than that of the Emrax 208 MV (320V DC), which would increase not only the size of the battery pack but also the overall weight of the car (by roughly 57Kgs). Handling such a high voltage would be a great risk factor for the safety of the team members, thus causing fluctuations in the reliability parameter. As compared to Emrax 208, Emrax 228 can achieve a higher acceleration, but a lower maximum speed, by using a lower gear ratio.

- Thus, Emrax 208 (Medium Voltage) is the best choice for us as it is a perfect blend of being light weighted, having a very high efficiency and high power, achieving an adequate lap time and achieving a relatively high peak output torque.

3.2 Motor Controller

After the motor's selection process is complete and the motor finally selected is the Emrax 208, the next step was to select a motor controller that is the most compatible with Emrax 208 while not putting pressure on any of the other HV and LV electrical equipment.

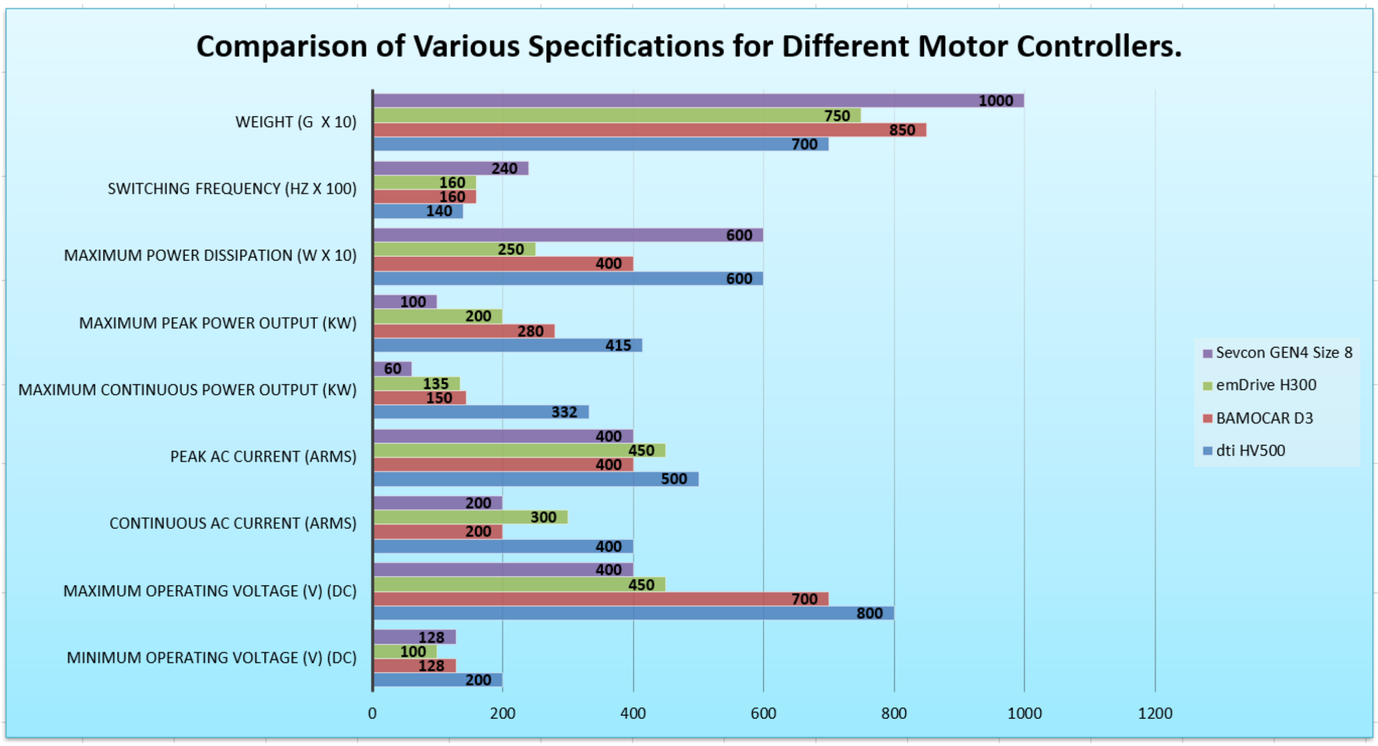
The motor controller is the electronics package that operates between the batteries and the motor to control the electric vehicle's speed, and acceleration, much like a carburetor does in a gasoline-powered vehicle. The controller transforms the battery's direct current into alternating current (for AC motors only) and regulates the battery's energy flow. Unlike the carburetor, the controller will also reverse the motor rotation (so the vehicle can go in reverse), and convert the motor to a generator (so that the kinetic energy of motion recharges the battery when the brake is applied).

Many factors influenced the selection of the motor controller, taking into consideration the events that wanted the most out of the vehicle like the Acceleration and the Endurance and efficiency events and keeping in mind the limitations of the rulebook. To make our motor controller selection the frontrunner, we surveyed the other available motor controllers that were used in any FS event before and compared the statistics concerning every one of them. The four narrowed down motor controllers in comparison were:

1. **dti HV500 (Drivetrain Innovation High Voltage Motor Controllers)**
2. **BAMOCAR D3 (Unitek Elektronik Industries)**
3. **emDrive H300 (Emsiso Advanced Motor Controllers)**
4. **Sevcon GEN4 S8 (Sevcon)**

The comparison majorly took place over the parameters that were of the utmost importance to the vehicle, keeping in mind the driver's rules and safety. We had to make sure that the controller's power output after having received the proper voltage from the accumulator was in the range, which was suitable for the efficient activity of the motor and did not fall behind the requirements whenever needed. The power output, the power dissipation without proper use as heat and sound, the temperature range for the motor controller's operation and efficiency derating with temperature changes were studied to keep the motor controller's efficiency at the peak. The motor operation in an EV is as good as the motor controller can provide. The motor demands were maximum power, maximum speed, maximum efficiency, and sufficient torque to overcome any kind of resistance in the drive like rolling frictional resistance and drag due to the vehicle aerodynamics. So, the motor controller had to be one that could provide maximum continuous power output while operating at maximum efficiency without overstraining and overheating its internal components.

Motor Controller Model				
	dti HV500	**BAMOCAR D3**	**emDrive H300**	**Sevcon GEN4 Size 8**
Specifications				
Minimum Operating Voltage (V) (DC)	200	128	100	128
Maximum Operating Voltage (V) (DC)	800	700	450	400
Continuous AC Current (Arms)	400	200	300	200
Peak AC Current (Arms)	500	400	450	400
Maximum Continuous Power Output (kW)	332	150	135	60
Maximum Peak Power Output (kW)	415	280	200	100
Maximum Power Dissipation (W x 10)	600	400	250	600
Switching frequency (Hz x 100)	140	160	160	240
Weight (g x 10)	700	850	750	1000
Specifications not elaborated in the chart				
Dimension (l/w/h): (in mm)	420 x 213 x 77	355 x 230 x 135	263 x 244 x 127	322 x 322 x 107
Cooling Mechanism	Integrated Water Cooling	Water / Glycol / Air / Oil Cooling	Water / Glycol Cooling	Water / Glycol / Air / Oil Cooling
Design Grading	IP65	IP65	IP65	IP66
Operational Temperature:	0°C to100°C (with significant efficiency derating)	0 to +45 °C (without derating); +45 °C to +65°C (derating in performance, reduction by 2% / °C);	-20°C to +60°C (derating is absent); +60°C to +65°C (with derating);	-30°C to +25°C (no current or time derating); +25°C to +80°C (no current derating, but reduced time at rated operating point); +80°C to +90°C and -40°C to -30°C (with derating);



Comparison of Various Specifications for Different Motor Controllers.

(NOTE: Power dissipation here refers to the amount of power that goes to waste and not supplied to the motor even after being taken from the accumulator, noise or heat, or any dissipation. Power output refers to the amount of power supplied from the accumulator to the motor considering the losses.)

One to One comparison

- Let us take a look at the Sevcon Gen4 S8 motor controller first. The team wanted primarily to perform the best in two of the highest-scoring events, Acceleration, and Endurance. These events demand a high supply of peak and continuous power and thus would generate much heat due to the load on the motor and controller. The Gen4 S8 had the most efficient temperature relation for efficiency, and the derating was absent for either very high or shallow temperatures (as seen from the table), neither of which were achievable under ideal power supply conditions. Comparing this with emDrive H300's temperature derating, the latter's efficiency drop would occur at temperatures lower than the former and thus would not be better than the former. However, with this huge pro favoring the Gen4 S8, when we look at the power outputs, both the peak and the continuous (100kW and 60kW respectively), we see that this motor controller stands nowhere near the others while having the same current supply rate (like the BAMOCAR D3). Even the dti HV500, which has a significant derating with temperature, can overshadow this problem by having a much higher power output (415kW and 332kW), thus bringing this above Gen4 S8. Looking at the switching frequency here (24kHz), a higher switching frequency will result in a smaller inductor but increase the switching losses in the circuit, which is evident from the power dissipation (6kW) across the other motor controllers on the table.The culmination if the low power output, the more weight of the motor controller (10kg), a high switching frequency,
- The dti HV500 was one of the first motor controllers taken into consideration and was turning out to be a promising one. Out of the ones taken for comparison, this one had the highest peak and continuous power output to the motor (415kW and 332kW respectively) and thus, if chosen, could have been able to sustain the power requirements for the Emrax 208 (80kW). The power dissipation value (600kW) is also the highest amongst the crowd and was way too high than what the team wanted to have. The peak and continuous values of RMS current (500Arms and 400Arms respectively) cause it to be functioning on huge amounts of electric current, which causes much heating of the motor controller and can also damage the electrical component surrounding it. Although these current values would be beneficial to the motor, not causing any hindrance to the motor. Still, as evident from the highest operating temperature being around 100°C, even after proper integrated cooling systems, there was much risk in installing other electronics around it without extra insulation from the other components, which would, in turn, add to the weight of the vehicle and thus increase the load, and expenses. Looking at the Sevcon Gen4 S8 and its operational temperatures, the derating in the controller's efficiency with an increase in temperature is way too eased for Gen4 S8 than for dti HV500. Even though the latter's (dti HV500) operating temperature is lower than the former (Gen4 S8), the clever use of liquid cooling in Gen4 S8 will not cause it to reach such high temperatures, thus causing constant efficiency. The minimum operational voltage for this dti HV500 (200V DC) was also too high as compared to the other motor controllers in question, like the BAMOCAR D3 (128V DC) or the emDrive H300 (100V DC). Thus if any failure were to occur in any of the individual cells or a group of cells in the accumulator, causing a supply of less than normal voltage to, the motor controller would not be able to function and thus keep the motor; hence the car running. Due to these factors, the dti HV500 was renounced as the team's motor controller choice.

- The next motor controller checked alongside the dti HV500 was the emDrive H300. Most attractive about this motor controller was its lower power dissipation than the other motor controllers in question (250kW, whereas the BAMOCAR D3 stands at 400kW, the dti HV500 is way up at 600kW). This fact allowed the team to think that they could ease the load onto the accumulator for the voltage demand and thus supply more power efficiently to the motor. However, the peak power output supplied by this motor controller (250kW) was not good enough, with respect to the other motor controllers as in the table, for the motor to be sustained and to keep it running in cases of sudden acceleration, like while at the start of the race line or during events such as Acceleration. The motor controller also falls short at the continuous power supply (135kW), although by a smaller amount compared to BAMOCAR D3, still, that small difference would make the vehicle underperform in the Endurance event. The previously mentioned two events are the most scoring events in the entire FSAE competition, and the team did not want to fall behind in those two major ones. Due to the weightage of the other factors against this motor controller, smaller factors like the nominally high switching frequency of the MOSFET or the IGBT installed inside dominate towards its infamy. Even though the operational range of voltage for this motor controller is way lower than the others, the price is also lower than most others ($2600), which favor this model, but the dominating stats were the power outputs. Thus this motor controller also did not meet the team's expectations completely
- The last decision to be taken fell between the BAMOCAR D3 and emDrive H300. After discussing the emDrive H300, factors favoring BAMOCAR D3 were the range of operational voltages (128V DC to 700V DC) which helps the motor controller to function at around both the extremes of the voltage supply from the accumulator, thus reducing the problems caused due to low voltage supply or short circuits. This case was not supporting the emDrive H300 as mentioned earlier. The maximum peak and continuous power outputs of BAMOCAR D3 (280kW and 450kW respectively) also triumph over emDrive H300. This motor controller(8.5kg) weight is more than that of the emDrive H300 (7.5kg), which is something that we thought about how to resolve. As a redemption, the BAMOCAR D3 offers air and liquid cooling(effective weight around 8.7kg), whereas the emDrive H300 only uses a liquid coolant (effective weight around 8.1kg). This factor caused a huge reduction in the motor controllers' effective weight difference and thus reduced the weight dependent factor for the BAMOCAR D3 and favored it more. The switching frequencies of both were the same (16kHz) and hence not a point for debate. Thus considering all the factors, the team sought Unitek BAMOCAR D3 as the most suitable motor controller for the vehicle and thus decided to install it in the vehicle

3.3 Electronic Torque Control

The motor is controlled using the torque control mode, and that requires a differential input signal to the motor controller. This requires the measuring of the pedal travel. The pedal travel is measured using the Accelerator Pedal Position Sensor(APPS).

The accelerator pedal position sensor is used for measuring the travel of the accelerator pedal. According to rulebook two sensors must be utilized as APPSs and in case implausibility of values of the two sensors persists for more than 100 ms, the power to motor is completely shut down.
The implausibility is defined as a difference of more than 10% of pedal travel.

3.4 Motor Mounts

The motor will be mounted on both ends, thus 2 different mounts were prepared, 1 for the live end and the other for the dead end. Difference in their design comes as the dead end has wires and connections to the motor while the live end is free of obstructions.

The dead end mount was directly bolted on the motor and attached to the chassis. Slots were made for cooling connections and smaller holes to allow the mount to be bolted on the motor.

The live end mount was mounted on top of bearings attached to the motor shaft.

The first step in designing the mounts was locating fixtures for the mount on the chassis. Using these points and the motor location, geometry of the mounts was made by also considering accessibility, compactibility, and weight of mounts. Material used was Aluminium 6 series because it was lighter and more readily available than materials like Mild Steel.

Upon running simulations, the design was finalised after obtaining a satisfactory factor and mass.

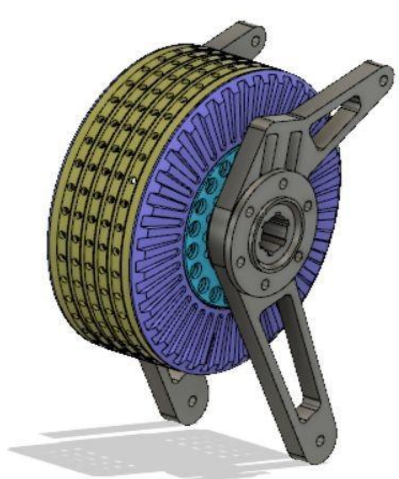


Fig: Motor mount

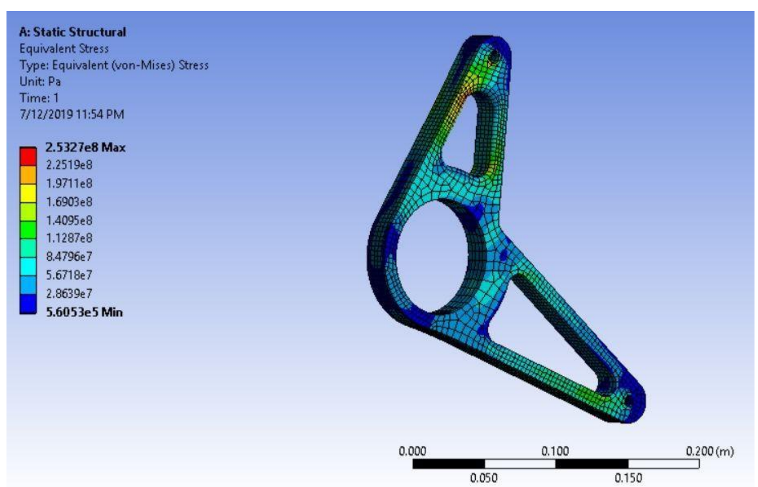


Fig: Mount Simulation

3.5 Drivetrain

Sprocket Design, Chain Tension Calculation, and Chain Selection:

It is imperative that the number of teeth on both the sprockets be a whole number. Hence, in this iterative design process, the number of teeth on the driving and driven sprockets were finalised to be 10 and 56—giving rise to the optimum gear ratio of 5.6. To proceed further with the design, it is necessary to finalise the pitch of the sprocket which is an important input in calculating the dimensions of the sprocket and ultimately the tension in the chain that will be generated by the operating torque. However, the pitch of the sprocket should match that of the chain for smooth operation, and the chain tension has to be known to decide the chain number. To resolve this catch-22 situation, it was assumed that chain 41 with a pitch of 12.7 mm (0.5 in) would be a suitable fit.

With the knowledge of the number of teeth and the pitch of the sprocket, the pitch circle diameter of the driving and driven sprockets were calculated as 40 mm and 226 mm respectively. Using these values, the chain tension was calculated to be 6.36 kN. The average tensile strength of the chosen chain is 10.7 kN which gives rise to a safety factor of 1.68. Hence, the chain-drive system is designed to withstand the working load, but at the same time, the chain is also the weakest part of the drivetrain assembly which means that it will fail before any other critical or expensive component. Chain failure is much less dangerous, and the replacement is also cheap and simple.

$$Pitch\ Diameter = \frac{Pitch}{\sin\left(\frac{180}{Number\ of\ teeth}\right)}$$

$$For\ the\ driving\ sprocket,\ number\ of\ teeth = 10;$$
$$Hence,\ Pitch\ Diameter = \frac{12.7}{sin\left(\frac{180}{10}\right)} = 41\ mm$$

$$For\ the\ driven\ sprocket,\ number\ of\ teeth\ = 56;$$
$$Hence,\ Pitch\ Diameter\ = \frac{12.7}{sin\left(\frac{180}{56}\right)}\ = 226.5\ mm$$

As the tyre's traction limit was reached before the motor generated the maximum torque, the limiting condition to find the tension in the chain was taken to be the tyre-slip condition. That is, the maximum tension in the chain occurs just when the tyres are about to slip. The tyre's traction limit was found out to be 1530 N from experimental data. As the car uses two wheel–drive system, the chain tension must generate a torque to slip both the tyres.

$$Torque\ in\ sprocket = Tyre\ Traction\ Limit \times Radius\ of\ Tyre$$
$$= 1530\ N \times 0.23495\ m \times 2\ (Both tyres) = 718.947\ \text{N-m}$$

$$Torque\ in\ sprocket = Chain\ Tension \times Radius\ of\ Sprocket$$
$$Chain\ Tension = \frac{\text{Torque in Sprocket}}{\text{Radius of Sprocket}} = \frac{718.947\ \text{N-m}}{0.113\ \text{m}} = 6362.36\ N$$

A minimum angle of wrap of 120° meant that the sprockets should be at least 186 mm apart. However, to prevent disengaging of the chain due to excessive slacking, the upper limit was also set to be sixty times the pitch of the chain – 762 mm. Considering other design and space constraints, the centre-to-centre distance was finalised as 254 mm, giving an angle of wrap around the smaller sprocket of 140 degrees

4 . Accumulator

4.1 Cell chemistry and model selection

Parameters considered for selection of cell chemistry:

1. High Energy Density (Wh/L)
2. High Specific Energy (Wh/kg)
3. High Specific Power (W/kg)
4. Charging and Discharging abilities
5. Ecologically sound
6. Sustainable

Considering all the possibilities shown above, model no- **AMP20M1HD-A** of **A123** was selected due to less number of cells required, leading to compact accumulator design and providing high power density.
It also had added advantages such as low internal resistance, safer operation due to inherent resistance to thermal runaway. General specifications of the cell are shown below.

Name	A123	Melasta	Samsung	Bestgo	TEAMGIANT	Melasta
Model Number	AMP20M1HD-A	SLPBB042126	INR18650-25R5	BCPNE20T	HR3780156240	HP49C260
Column2	Lithuim-ion	Lithium-ion	Lithium-ion	Lithium-ion	Lithium-ion	Ni-Zn
Type	Pouch	Pouch	Cylindrical	Pouch	Pouch	Cylindrical
Specific Energy (Wh/kg)	131	190	206	180	210	213
Specific Power(W/kg)	1333	2400	1627	361	628	286
Energy Density(Wh/L)	247	445	545	372	395	525
Weight(g)	495	126	45	410	565	45
Energy(KWh)	0.064845	0.02394	0.00927	0.0738	0.11865	0.009585
No. of cells required	90	245	633	79	49	613

Specification	Value	Notes/Comments
Peak 10s Discharge power	820W	SOC = 100%, Tcell = 23 °C, Assumed DCR = 2 mOhm (nominal)
DCR Impedance ACR Impedance	1.5 – 3 mOhm 0.78 mOhm	10s, 240A, @ 50% SOC 1kHz, @ 50% SOC
Operating Temp Range	-30 °C to +60 °C	Ambient around cell
Storage temperature range	-40 °C to +65 °C	
Weight	495 grams	+/- 10g
Cycle Life To 80% Beginning of Life (BOL) capacity	3000 cycles	100% Full DOD cycles, 1C/-2C @ 23 °C, 8 – 14 psi face clamp pressure

Specification	Value	Notes/Comments
Nominal Capacity	20 Ah	
Minimum Capacity	19.5 Ah	25 °C, 6A Discharge, 3.6V to 2.0V, at BOL
Nominal Voltage	3.3V	@ 50% SOC
Voltage Range	2.0 to 3.6V	Fully Discharged to Fully Charged
Absolute Maximum terminal voltage	4.0	Above which will cause immediate damage to the cell
Recommended maximum charge voltage	3.6V	
Recommended float charge voltage	3.5V	
Recommended end of discharge cutoff	2.0V	
Recommended standard charge current	20A	to 3.6V
Recommended maximum charge current	100A	to 3.6V , Cell temperature < +85 °C
Pulse 10s charge current	200A	23 °C ≤ Tcell < +85 °C, Vcell < 3.8V
Maximum discharge continuous current	200A	23 °C ≤ Tcell < +85 °C, SOC = 50%
Pulse 10s discharge current	600A	23 °C ≤ Tcell < +85 °C, SOC = 50%

4.2 Electrical Parameter Estimation

An electric vehicle's source of energy is its battery pack. It is one of the largest components of the vehicle. Making a battery pack not only requires a thorough understanding of the electrical aspects , but the purpose of the vehicle usage has to be kept in mind. The size of the battery pack was determined carefully considering multiple parameters which must follow the rules of the Formula Bharat Competition.

CONSTRAINTS

1. **Weight**
   The battery is the heaviest component of the electric vehicle. It is important to strike balance between the weight and the energy requirement.

2. **Chassis Size**
   The battery has to be fitted in the chassis in a way that it is easily removable for charging and fitted properly when in use.

The following hand calculations were done in order to determine the parameters required:

- **Determining Battery Voltage**

  The motor **EMRAX 208 Liquid Cooled** was selected and the nominal battery voltage was determined using its power and current requirements.

  Continuous Power Output: 30-32 kW
  Continuous Current: 160 Amps (RMS)

  Nominal voltage * Continuous Current input = Continuous power output

  Therefore, **Estimated nominal voltage = 282.2 V**

- **Determining Battery Capacity**

  The longest event of the competition is ENDURANCE. The rules don't allow us to charge the battery in between. It is a 22km event and thus the minimum range of the battery pack should be 22km.
  The average power and average speed were considered from the simulation results.

  Minimum Range = 22km
  Average power = 16.212 kW
  Average Speed = 60 km/hr
  Calculate time = Range/Average speed = 22/60 = 0.367 hours
  Energy required = Average power * time = 5.94 kWh

  Therefore, **Energy Capacity Required = 5.94 kWh**
  This value is very close to that calculated using the lap time simulation software which was **5.87 kWh.**

- **Determining Battery Power**

  The event also has an acceleration sub-event. This event requires the vehicle to have the maximum acceleration i.e. reach the maximum velocity(and with it the maximum Kinetic Energy) within the least amount of time.

  Since Power = Change in Kinetic Energy / Time , the higher the power, the better the acceleration.

  The rulebook has limited the Power output of the battery to 80W for safety reasons. The Battery pack was designed keeping it in mind.

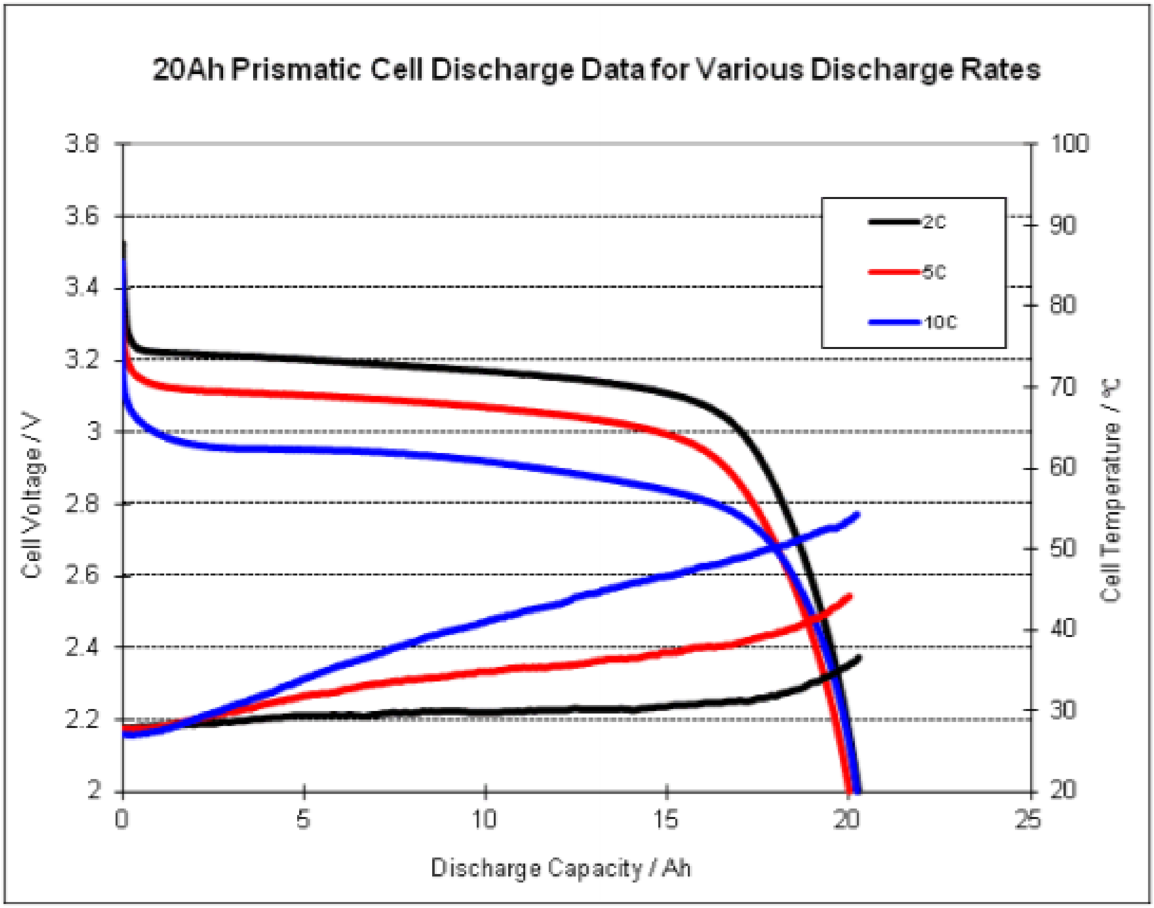
  Now as per the datasheet of the cells used, the peak 10s discharge power was 820 W for a single cell. So for 90 cells(The battery pack is 90s1p), we would get a peak power output of 90*0.820kW.

  Peak Power Output = 73.8kW for 10s

4.3 Cell Configuration

Pack sizing methodology was followed for cell configuration:
1. Increase series count of cells until the desired voltage is reached.
2. Increase parallel count of cells until the desired energy capacity is reached.

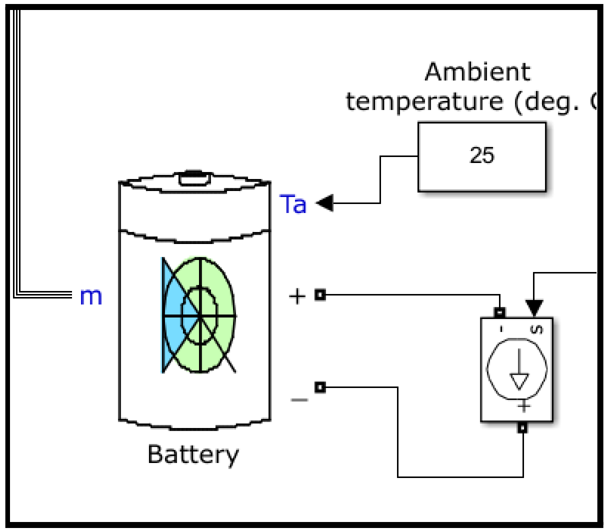
- The maximum voltage of 19.6Ah A123 cells is 3.3V. Initially, the team came up with a configuration of 96s1p. It fulfilled both the voltage and energy requirements.
- Then after doing some analysis of the discharge profile of our cells, we figured out that very little amount of the total energy is stored at maximum voltage. The voltage of the cells falls to 3.2 almost immediately. We also found out that by dividing the area under the curve(shown below) between 3.2 and 3.3 by the total area under the curve, only 0.5% of the total energy is stored in this range.
- Thus we can charge the cells only up to 3.2V, this increases the capacity gain. Thus our new configuration now would be 90s1p. With this configuration we can divide our battery into 6 modules each with 15s1p. This also does not break the rule that each cell stack should not exceed 120V.



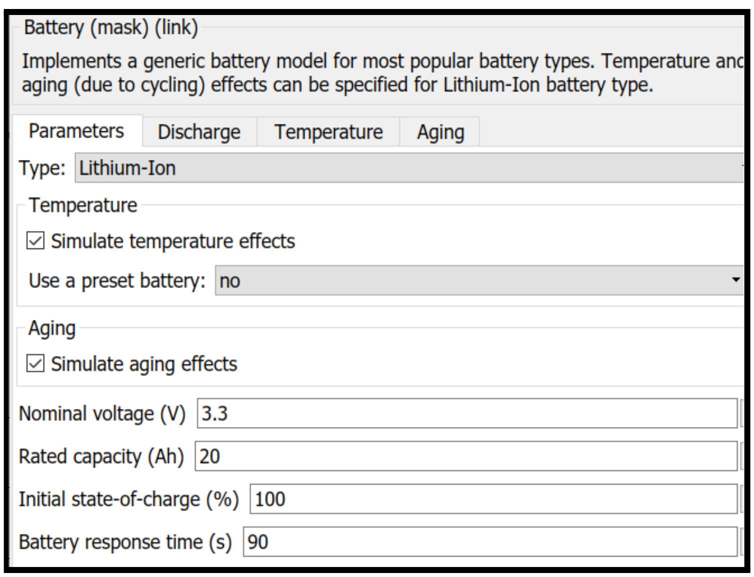
4.4 BATTERY MODELLING ON MATLAB-SIMULINK

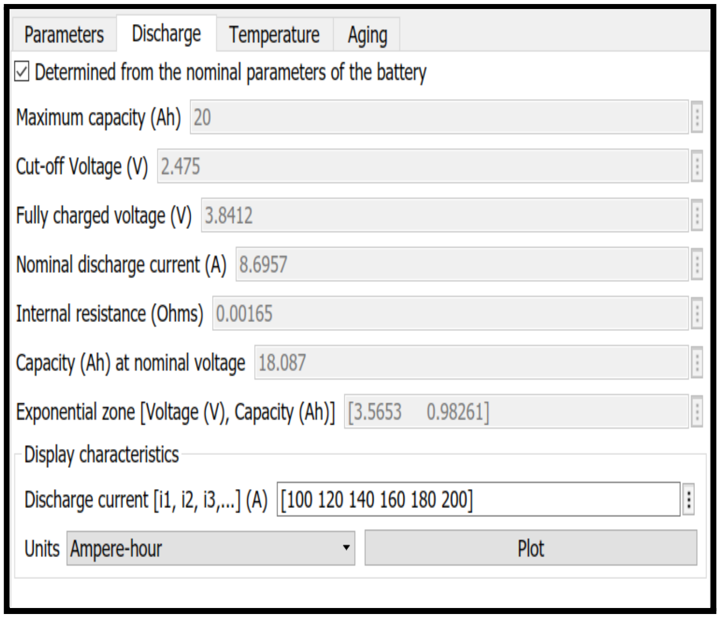
For the purpose of battery modelling we have used pre existing blocks in MATLAB software to simulate the Temperature, Age, Capacity Fade with age, Voltage and SOC of cell and running it on preset current profiles which are similar to the ones we are going to face in the Endurance race.

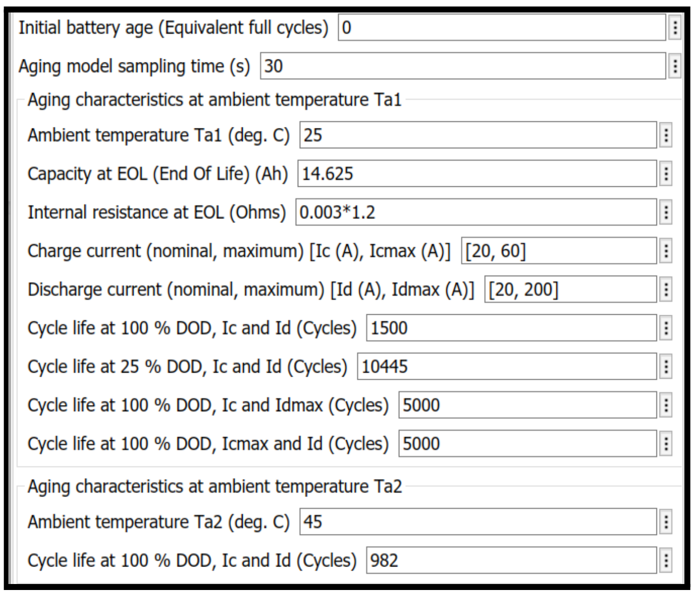
4.4.1 BATTERY BLOCK IN MATLAB



The battery block in MATLAB is a self contained set of equations which model several battery chemistries and can be used to extract valuable information about our cell's performance. The input parameters to this block as interpreted from the datasheet is as follows:





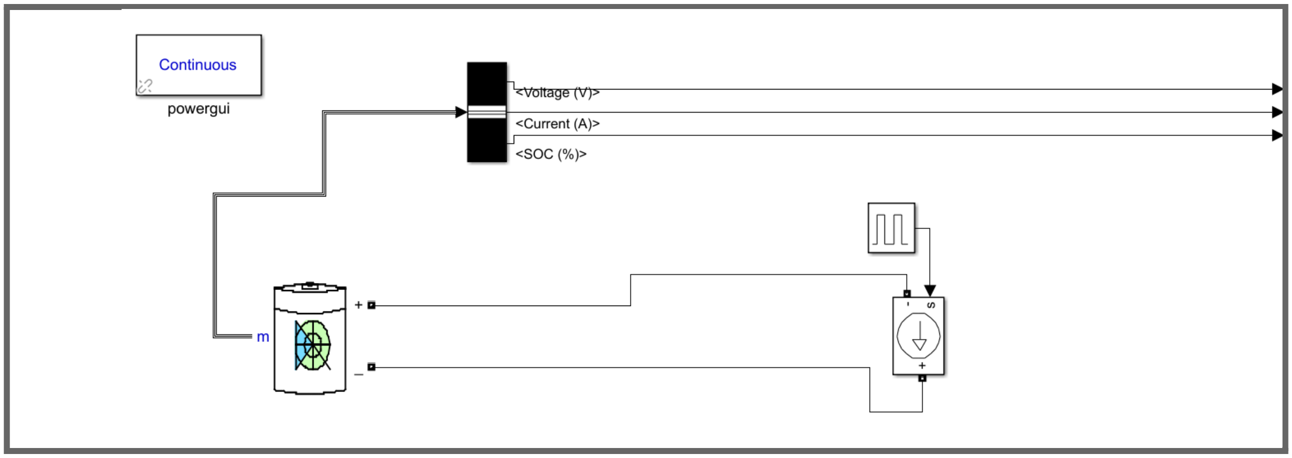


These parameters have been used for all the models which are presented below have been used throughout the models presented.

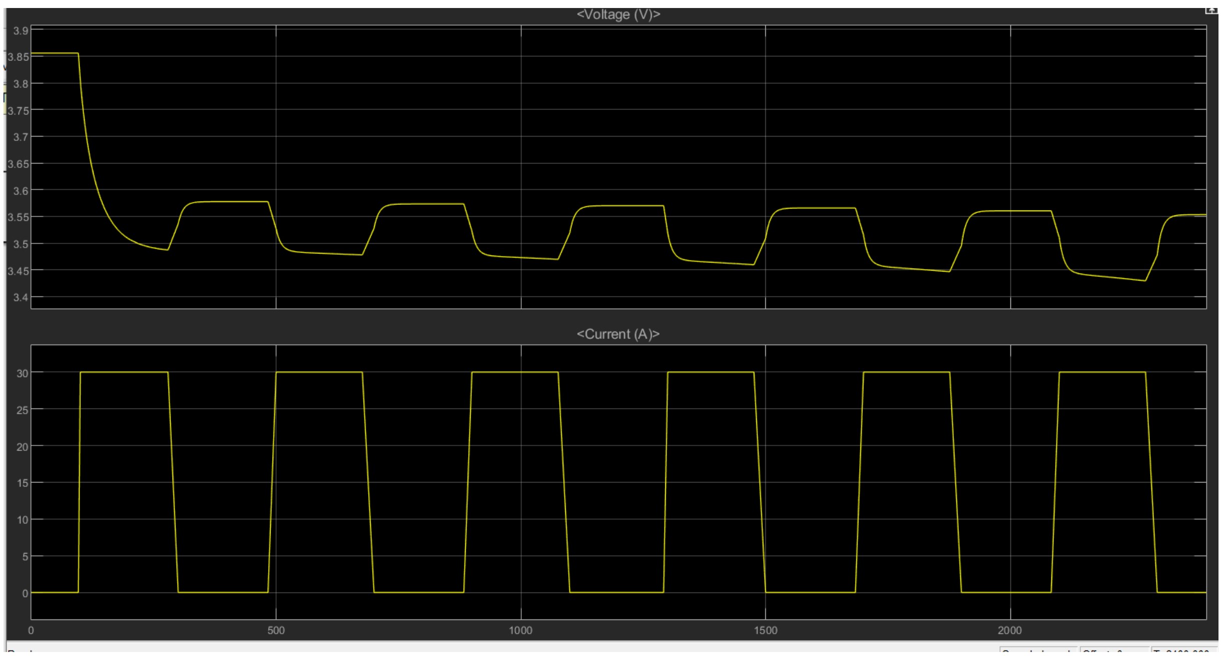
The battery block can conveniently be used to study discharge characteristics of the cell since it provides three output ports Voltage, Current and SOC of the battery to study them.

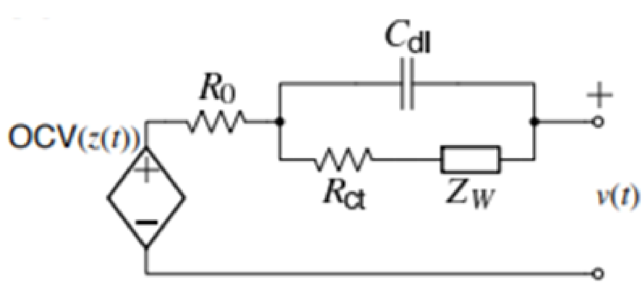
4.4.2 PULSE DISCHARGE TEST

It is standard procedure to run the any cell through a pulse discharge test to get a quick approximation of the parameters for an ESC(Enhanced Self Correcting) model of Li-ion cell. Due to the unavailability of a Cell-Cycler at our institute we have used a simple cell model to simulate the results of the same.



The results of the test were really close to the actual expected results



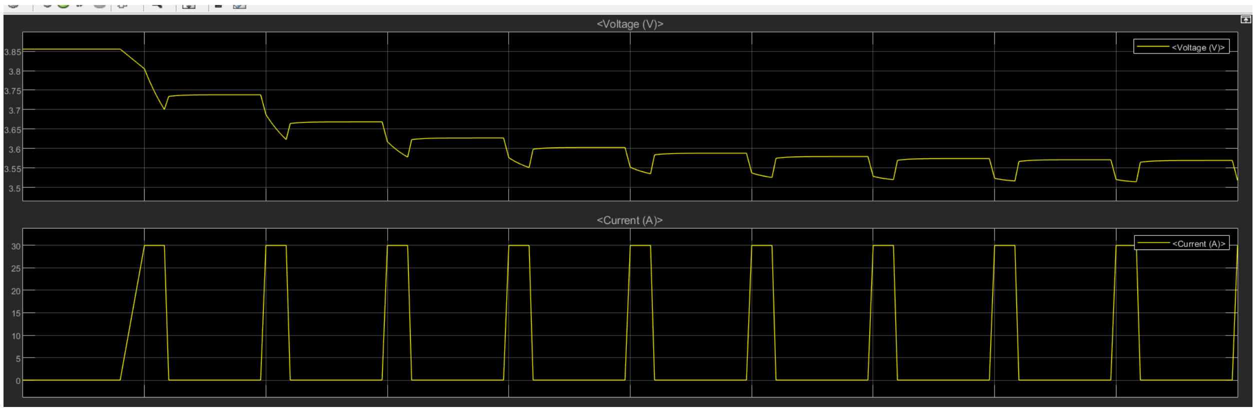


The estimated parameters from this experiment, using a single RC pair circuit

1. R_0=1.667e-3
2. R_1=1.633e-3
3. C_1=438mF

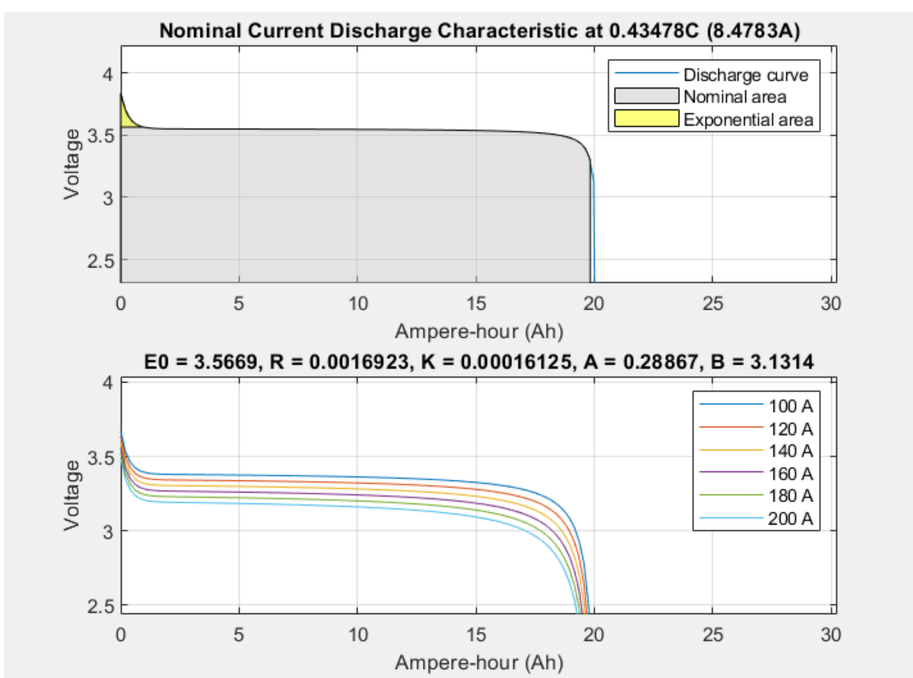
More results can be obtained from the model by tweaking parameters of the experiment like the pulse discharge current and pulse widths.

1. Heavier discharge pulse results in a sharper fall from the exponential zone to the baseline nominal voltage
2. An effect which is noticeable in short high current pulses is that, as the number of pulse progresses periodically the relaxation time of the battery after the pulse got higher after each pulse (i.e. the smoothness of the kink increased after each pulse) as demonstrated in figure below

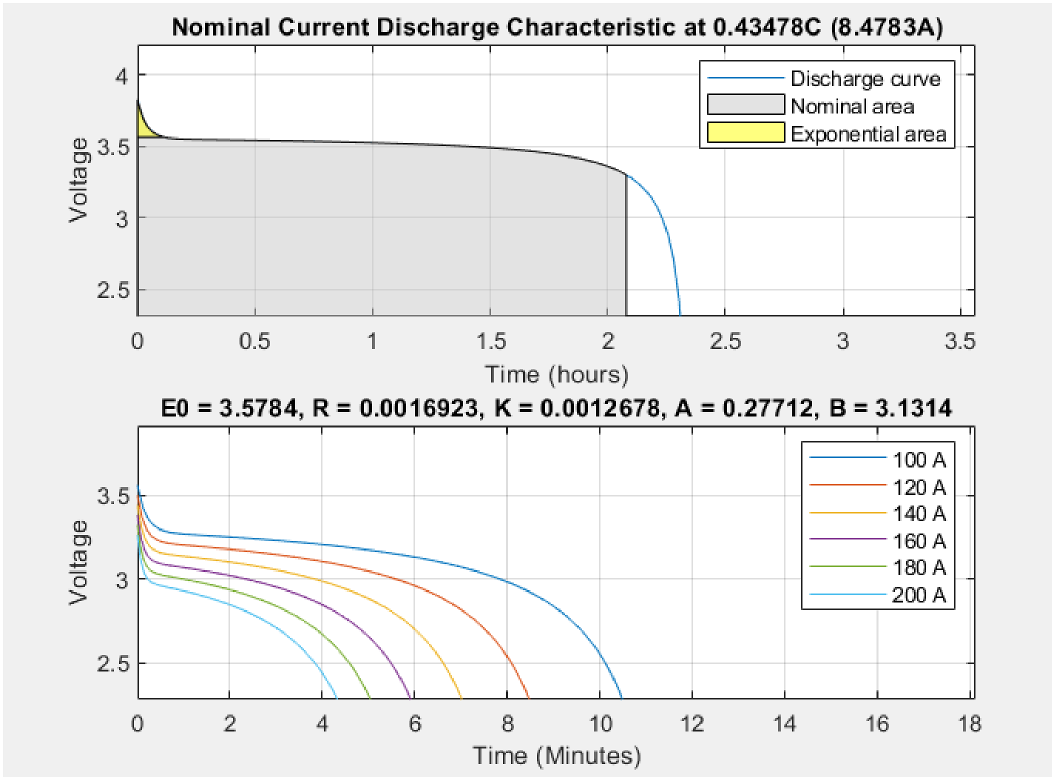


4.4.3 VOLTAGE-DISCHARGE CAPACITY & VOLTAGE-TIME EVOLUTIONS FOR DIFFERENT CURRENTS

It is essential to understand our cell's capacity to hold charge and also its terminal voltage evolution with time. For the following data we have used different continuous discharge currents to see how the interested variables evolve.

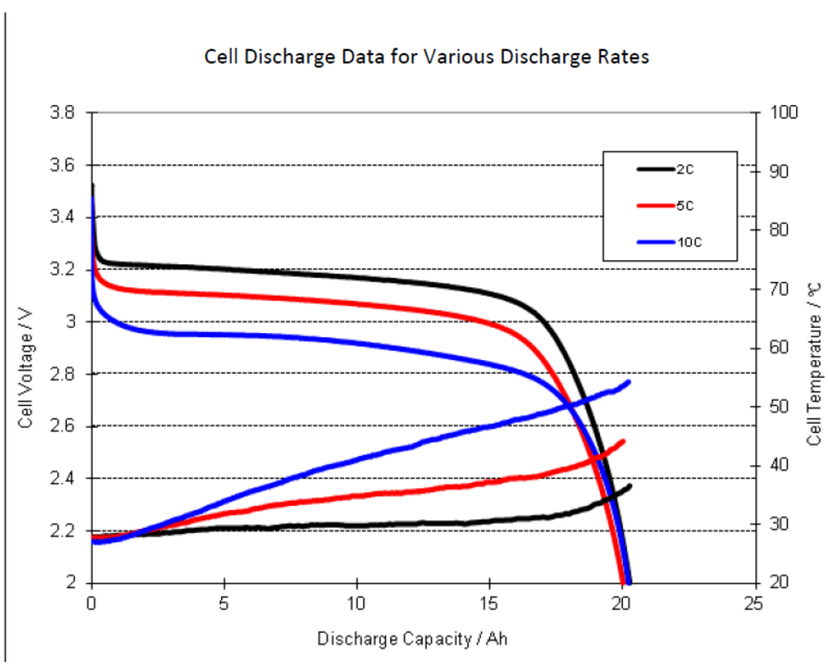


For a single cell we can see that the capacity tends to decrease significantly by about 3Ah on doubling the current requirement. (Cell parameters obtained from datasheet for all the simulations are present at the end of this section)



Now for time-evolution plots of the voltage,

The time evolution is straightforward in the sense that a higher current requirement takes up the cells capacity in a shorter amount of time. For an actual graph from the manufacturer we have



We can see that the first plot almost closely resembles the actual datasheet values.

4.5 Battery Management System

After a complete analysis of our requirements, we selected **ORION BMS 2**.

Main Features

- Monitors every cell voltage in series
- Field programmable and upgradeable
- Intelligent cell balancing (efficient passive balancing)
- Enforces min. and max. cell voltages
- Enforces maximum current limits
- Enforces temperature limits
- Professional and robust design
- Monitors state-of-charge
- Retains lifetime data about battery history

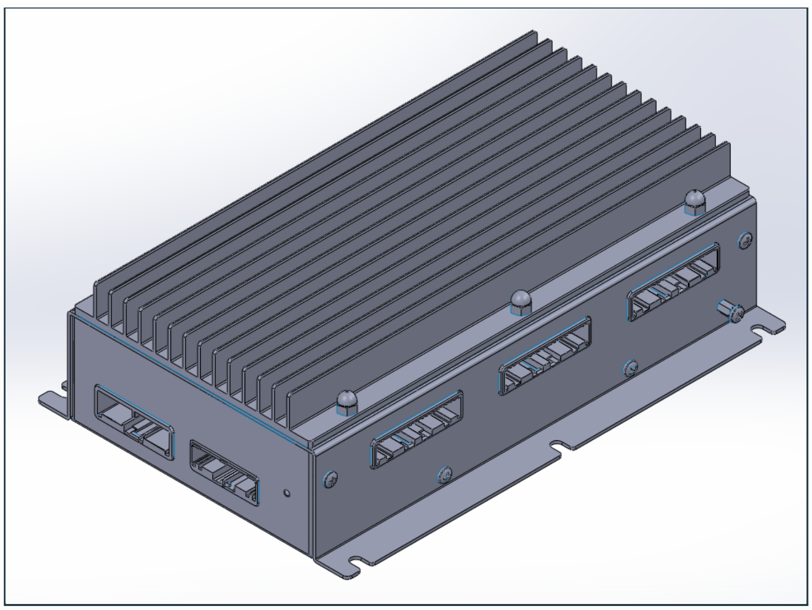


Fig: ORION BMS 2

To know more about our BMS, click here.

4.6 Container and Module Design

- Initially we were planning to use aluminium to make the accumulator container as aluminium is less dense than steel and we thought that the aluminium container would be considerably lighter than a steel container.However, due to height constraints we had to switch over to steel as the walls of the container can be made thinner and the overall height of the container would fit below the chassis side members.
- When the weight of the steel and aluminium containers were compared it was seen that both the containers had a similar weight of approximately 23kg.The accumulator has a total of 90 cells in 90s1p configuration.The 90 cells are divided into 6 modules of 15 cells each. All the cells in each module are connected in series and all the modules are connected in series as well.
- Each module has 3 columns and 5 rows of cells.According to the EV5.3.2, each module can weigh at most 12 kg, have a maximum voltage of 120 V and maximum energy of 6 MJ, all of which are fulfilled with the 15 cells per module configuration.Each module consists of a steel rack which holds the 15 cells.
- The rack is fastened to the internal vertical walls of the container using bolts so that the module is held in place and withstands the accelerations that the car may experience in case of a crash, as mentioned in EV5.5.9.The rack also helps in maintaining an air gap between the cells, which is needed for cooling. Cool air will be pushed through these gaps by the fans.
- Each module is sandwiched between 2 FR4 sheets which is a fire retardant material and 2 nomex sheets which provide electrical insulation. This is in accordance with EV5.4.7. Each module is separated by the internal vertical walls of the container, which are made of steel. The walls help in mounting the modules to the container.

  Each module is connected to the next one with the help of RADLOKs which are required as per EV5.4.5.The top of all the modules is covered by a polycarbonate/FR4 sheet which acts as an insulator and prevents any small metallic debris or tools from falling onto the cells and shorting them(EV5.4.7)

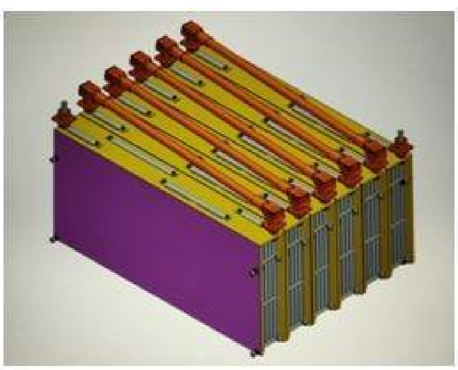


Fig: Isometric View 1

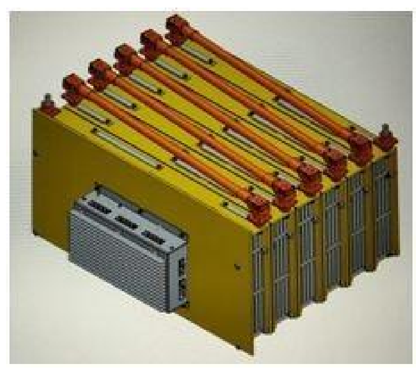


Fig: Isometric View 2

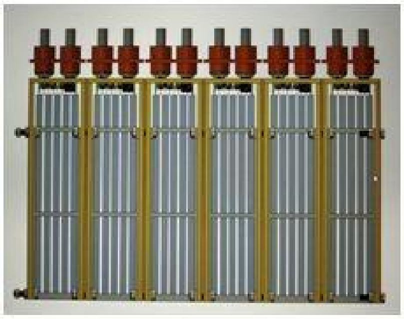


Fig: Orthographic View 1

Fig: Orthographic View 2

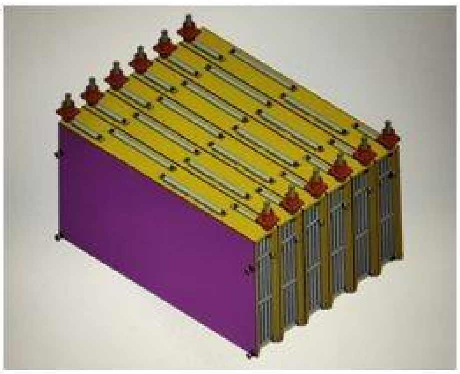


Fig: Isometric View 1 with Radloks

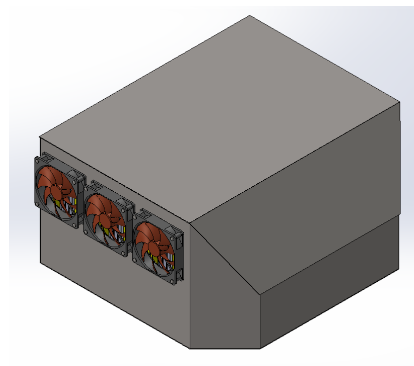


Fig: Final Battery with Container and Fans

Fig: A module with cell mounts

Fig: Fully Constructed Module without Radloks

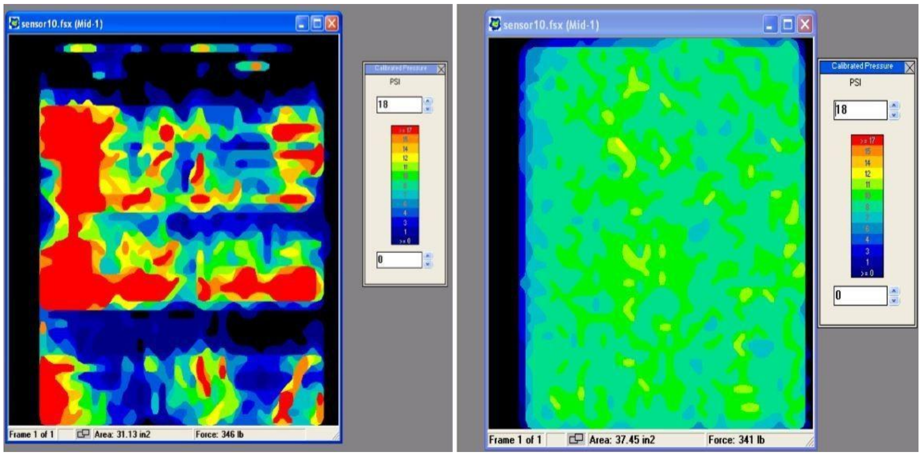


Fig: Pressure on cell face without neoprene and with neoprene

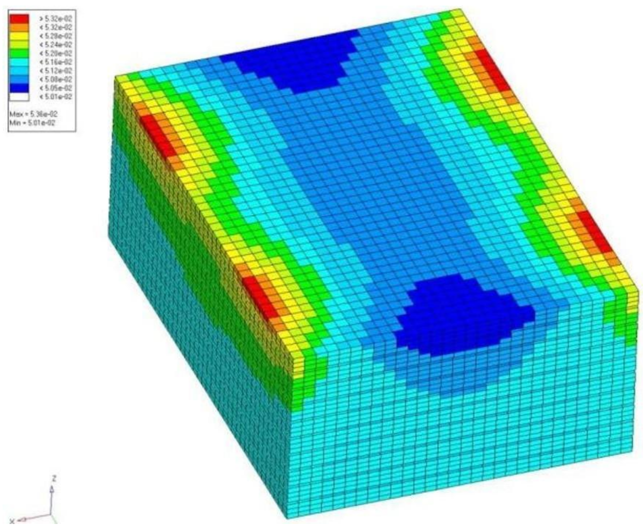


Fig:Pressure map across the surfaces of each cell in a stack

4.6.1 Stress Simulations on container and it's mounts:

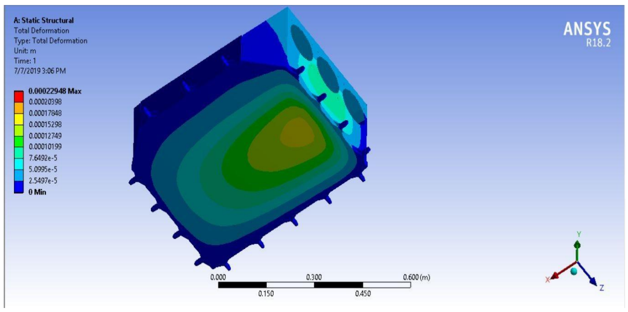
According to FSAE Rules the cell/segment mounting system must be designed to withstand the following acceleration:

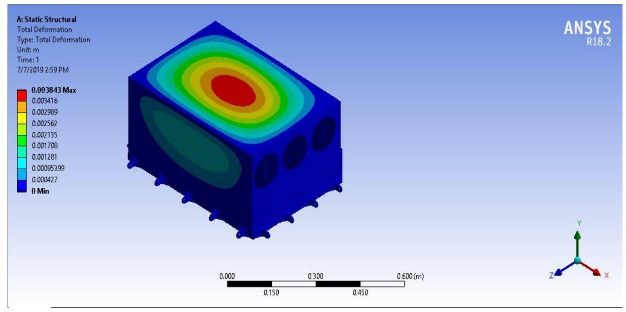
a. 40g in the longitudinal direction (forward)

b. 40g in the lateral (left/right)

c. 20g vertical (up/down) direction

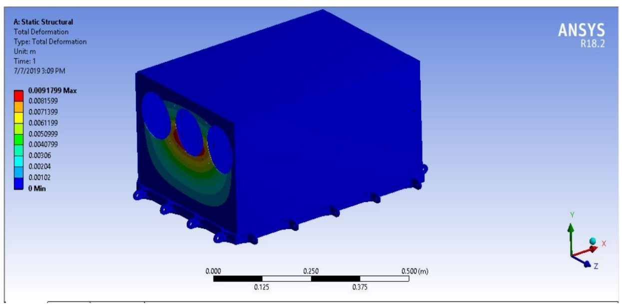
Stress Simulation on container:

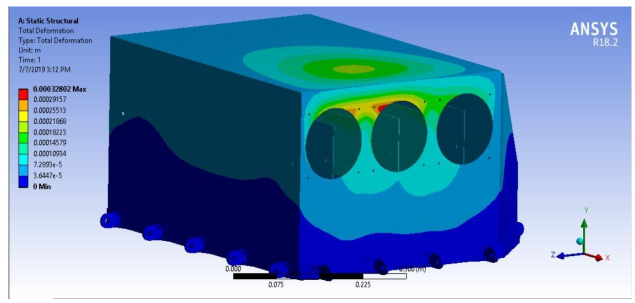




View1: 20g Vertical loading (safe deflection)

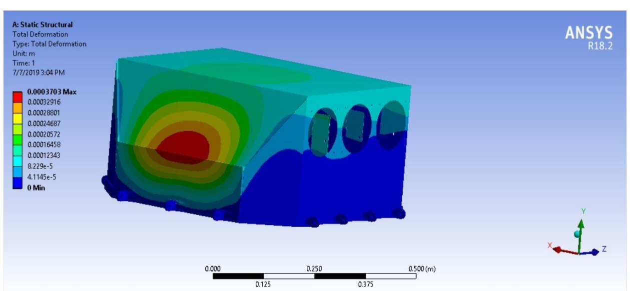
View2: 20g vertical loading (safe deflection)

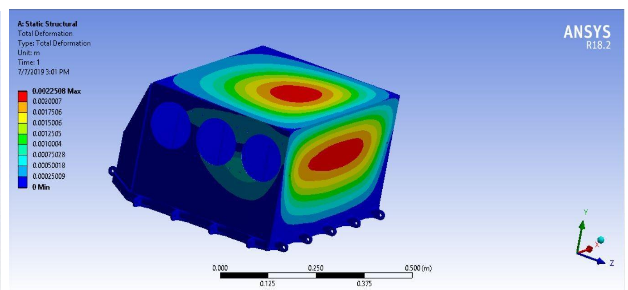




View1: 40g lateral (safe deformation)

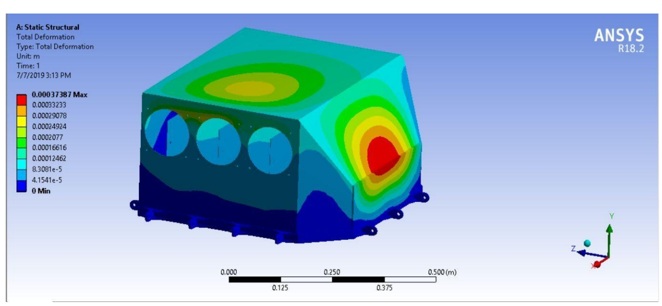
View2: 40g lateral (safe deformation)





View1: 40g longitudnal (safe deformation)

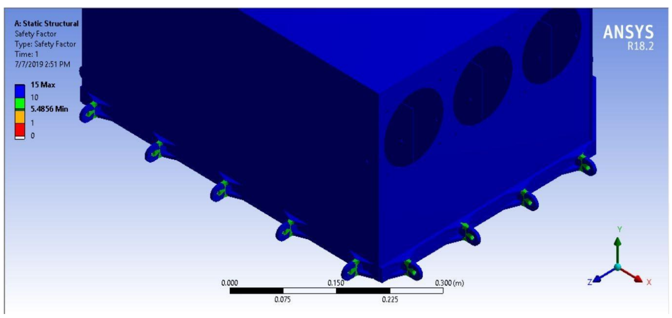
View2: 40g longitudnal (safe deformation)

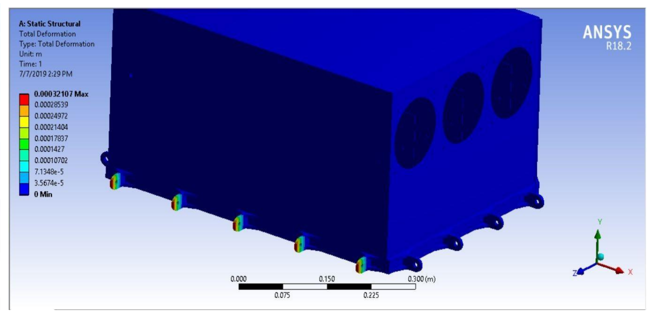


Combined (40g lateral+40g longitudnal+20g vertical) safe deformation

The analysis is done by providing fixed support the bolt holes for container mounting. The particular analysis is done to make sure that the accumulator container remains intact and the cells are not damaged under impact or collision. The above images clearly portrays that the accumulator pack can withstand the force of 20g and 40g and thus is successful in the designing.

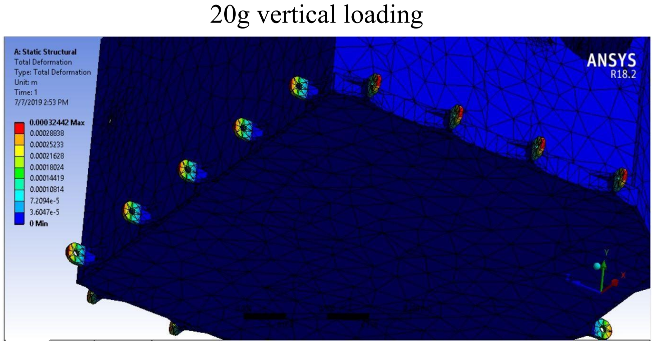
Stress Simulation on mounts:

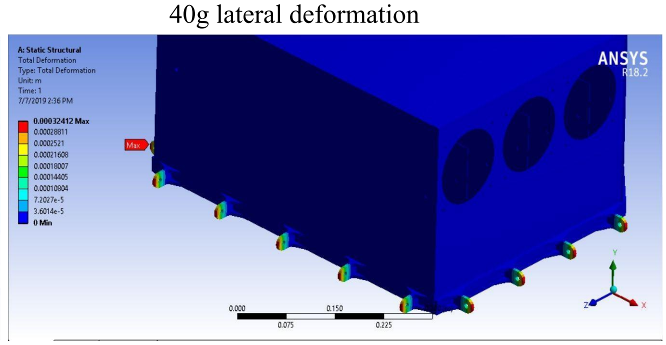




20g vertical loading

40g lateral deformation





Combined (40g lateral+40g longitudnal) deformation

Combined (20g vertical+40g lateral+40g longitudnal)

The stress simulation on mounts were done by keeping the container fixed and then applying the necessary required force in the required directions. The deformation is shown pictorially above and it can be successfully concluded that the mounts are rigid enough to withstand the forces. Hence the mount design is also successful design.

4.7 **Charger**

After going through various chargers, the best suited for our battery was selected. Model number- **DA3K3M17-360.**

It has the following features:

- Constant power and constant voltage state automatic conversion, effective saving time
- Active power factor correction≥0.99
- Input over/under-voltage protection
- Output over/under-voltage protection
- Output over-current protection
- Output reverse connection protection
- Over temperature protection
- CAN communication intelligent fault alarm and protection function
- all volume, large power density
- Control guidance function connected with charging pile(optional)
- Functions of remote detection, burning, fault inquiry, etc.

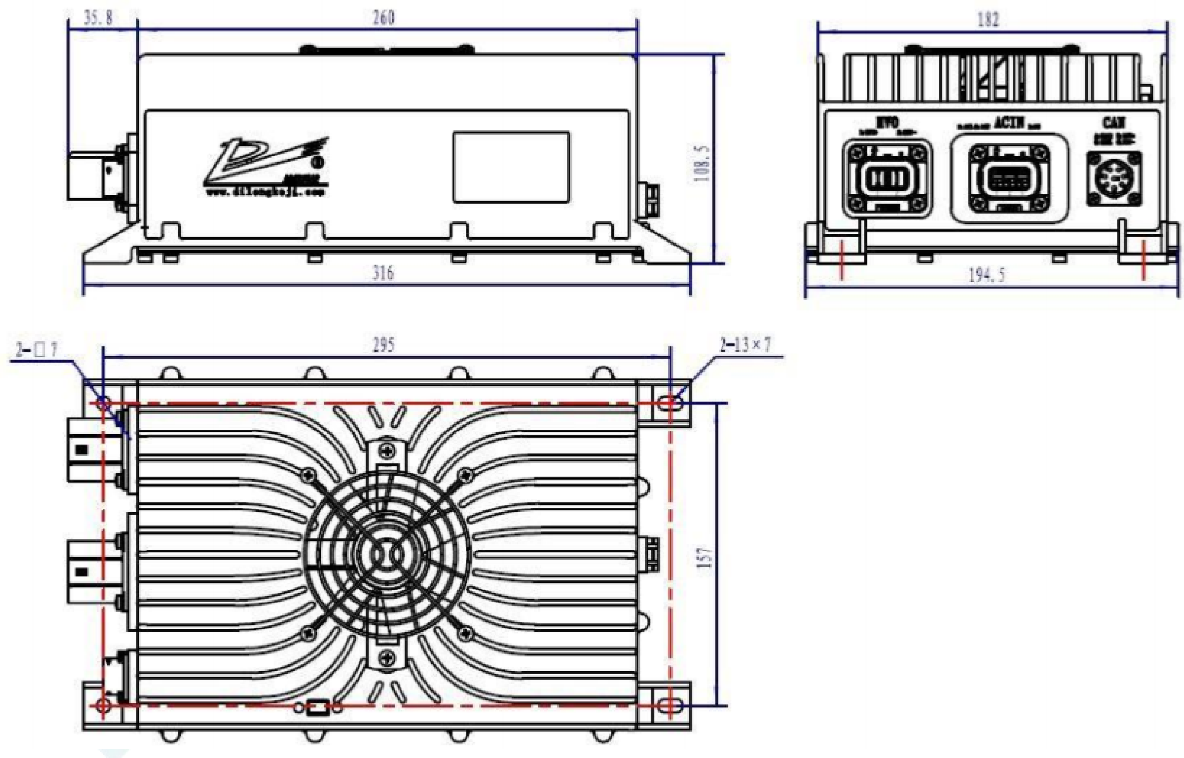
Specification/ Unit \ Model			DA3K3M17-360
Mains Input	Rated Voltage	Vac	220
	Voltage Range	Vac	85 ～ 264 (Input 85-176, automatically drop to 1200W）
	FREQ RANGE	HZ	47～63
	Efficiency(max)	%	≥95
	Power Factor		≥0.99@220Vac,rated power
	Current(MAX)	A	≤16@220Vac
Mains output	Rated Output Voltage	Vdc	360
	Constant voltage output range	Vdc	250 ～ 420 (According to the customer battery final decision)
	Max Current	A	12
	Constant power output	W	3300
	Output voltage accuracy	V	≤±1%Vo input 176Vac-264Vac，output 10%-100% load
	Line regulation	%	≤±0.2%Vo input 176Vac-264Vac，output 100% load
	Load regulation	%	≤±0.5%Vo input 220Vac，output 10%-100% load
	Ripple and noise	mV	≤±3%Vo 20M oscilloscope Twisted-pair cable test.

Charger Specifications

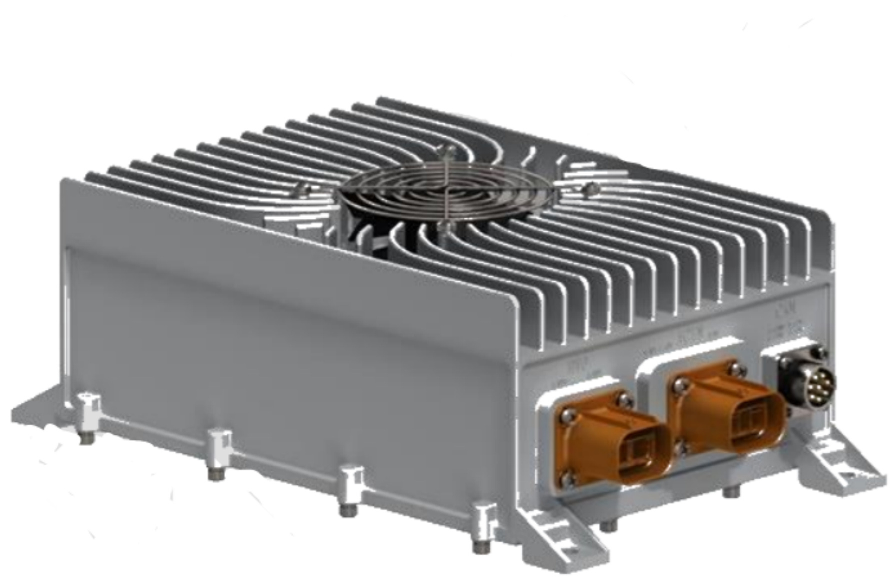
Auxiliary supply	Rated output voltage	Vdc	12
	Rated output power	W	2 （Activate BMS）
Property	Input over-voltage protection	Vac	≥275
	Input under-voltage protection	Vac	≤80
	Output Over-current protection	A	Io≥120%
	Output under-voltage protection	Vdc	≤200
	Output over-voltage protection	Vdc	≥421
	Over-temperature e protection	℃	85±5
	Output short circuit protection		yes (CPU intelligent control)
	Reverse polarity protection		yes (CPU intelligent detection)
	Dynamic response	us	≤200
	CAN communication		No CAN communication
	Operating temperature		-40℃ ～ +85℃ （ Intelligent derating shell temperature above 70 ℃）

Work environm ent	Storage temperature		-45℃～+105℃
	Operating humidity	%RH	20-90（No condensation）
	Storage humidity	%RH	10-95（No condensation）
	Vibration		QC/T413-2002(Other parts required)
	Cooling mode		Air cooling
Safeguard	Isolation Voltage		shell←input→output:2.8KVdc; Output→shell:2KVdc; Auxiliary Output→shell:700Vdc
	Insulation resistance	MΩ	input—output—shell＞10 (25℃,70%RH)
	IP Grade		IP67
Structure	mode of connection		Waterproof aviation connector
	weight	Kg	5
	Size	mm	316*194.5*108.5

Charger Schematics



Charger Images



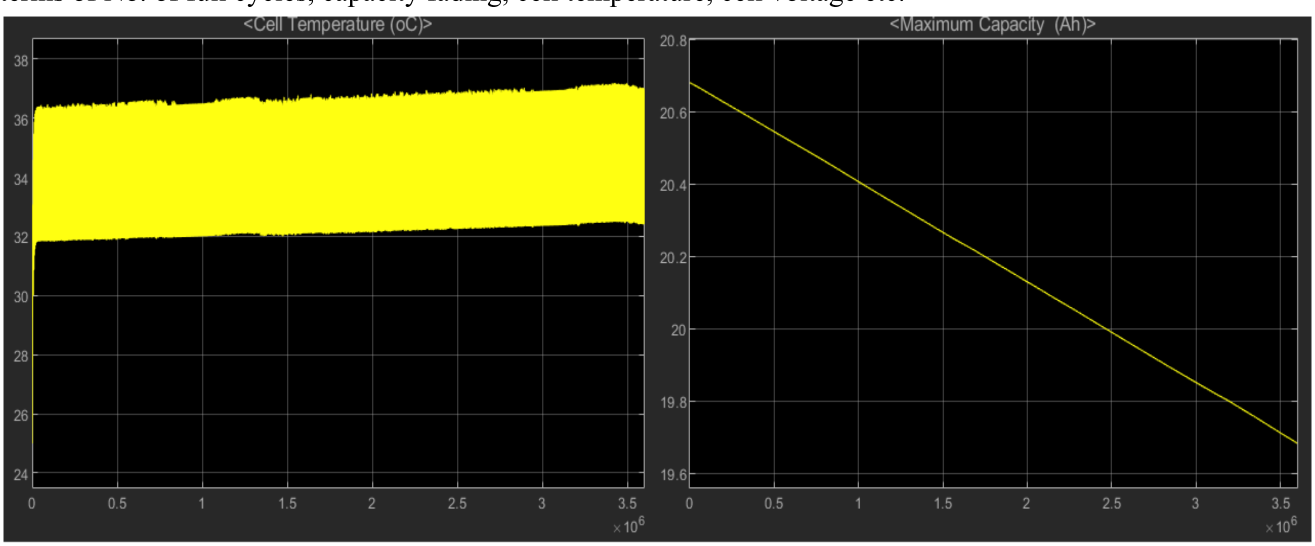
4.8 SINGLE CELL AGEING MODEL AND BATTERY CAPACITY EVOLUTION

We used the pre existing battery model along with a discharge profile and automatic charging logic to simulate continuous charging and discharging of the battery for almost 1000h (more than a month) which covers our testing and assemblage timelines so as to provide practical results towards ageing and capacity decrease of battery.

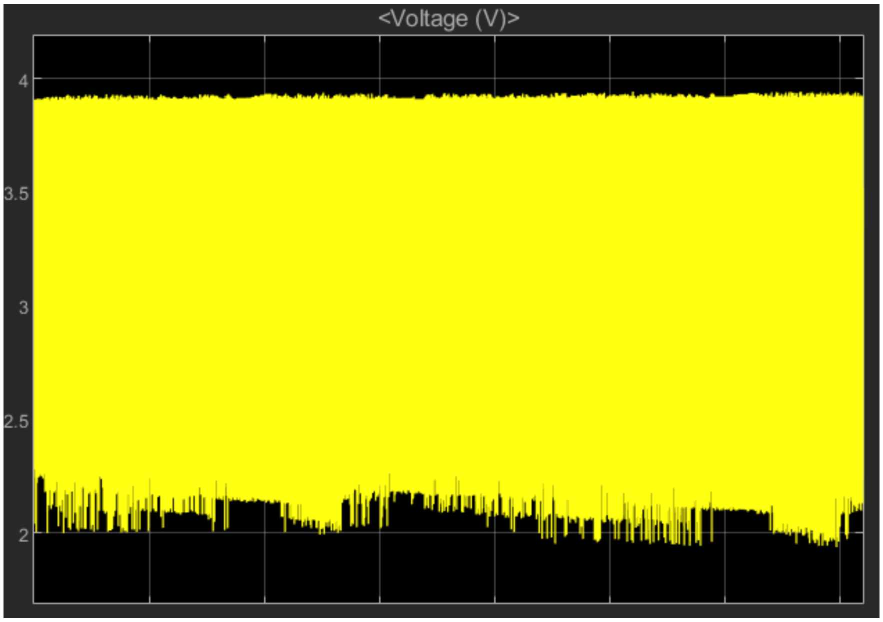
Capacity fading of Li-ion battery can occur due to variety of reasons (it is a research area), mostly due to the transition metal ions which interact with a region of the battery called the solid-electrolyte interphase, which forms because of reactions between the highly reactive anode and the liquid electrolyte that carries the lithium ions back and forth. For every electrolyte molecule that reacts and becomes decomposed in a process called reduction, a lithium ion becomes trapped in the interphase. As more and more lithium gets trapped, the capacity of the battery diminishes. Another theory for capacity fade attributes it to the electrode resistance varying with age (D. Zhang et.al.). In this paper, the authors attribute total cell impedance rising with age as a major factor which affects the total capacity of the cells. We know that cell impedance varies with SOC and is higher in the discharged state.

4.8.1 MODEL-1

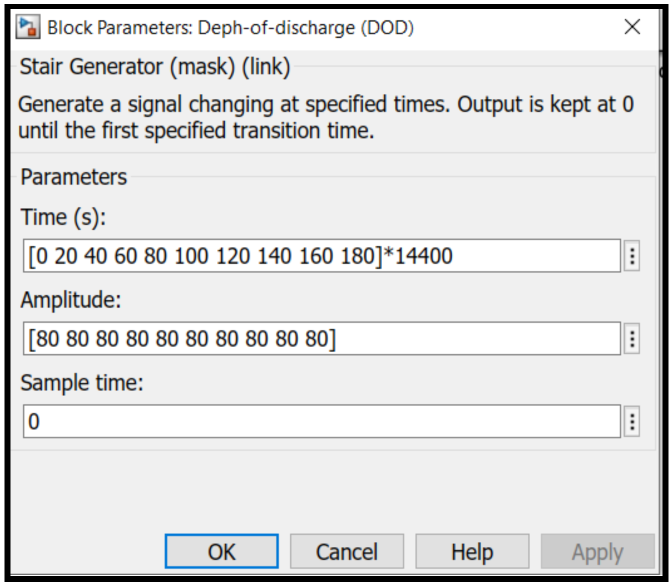
The first model uses a repeating discharge cycle for 1000h to measure the battery's response in terms of No. of full cycles, capacity fading, cell temperature, cell voltage etc.

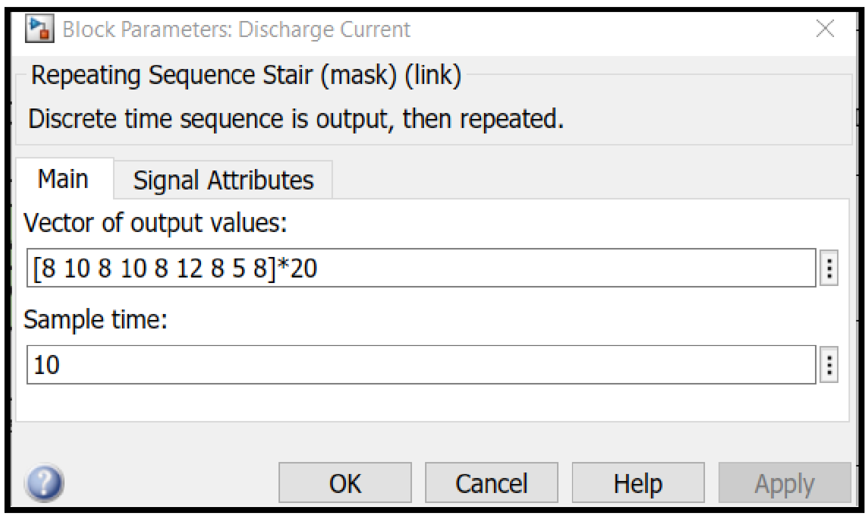


As a repeating discharge profile is applied to the cell its maximum capacity is diminished as its age(equivalent full cycles) increases. A linear relationship is seen here as the age increases and the capacity decreases. Capacity fade is not yet showing evidence of having heavy discharges accelerating the same.



Above images show the results obtained on discharging the cell according to a fixed discharge profile given below:





In the above parameters we have used a constant Depth of Discharge limit of 80 i.e. SOC of 20% which is considered to be a safe limit for EV Discharging. Discharge profile is not aimed at being used to simulate real time racing demand but is a pragmatic EV discharge requirement for the racing conditions needed.

RESULTS

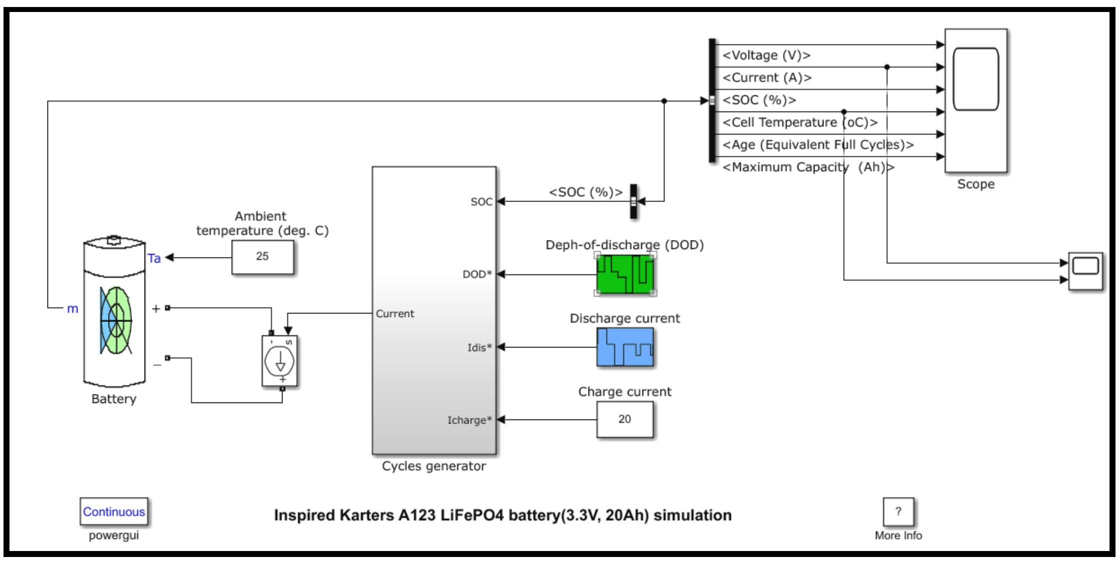
The cell temperature is a healthy 35-36° Celsius at best and cell voltage hovered around the healthy limits of 3.8-2V which is approved by the manufacturer

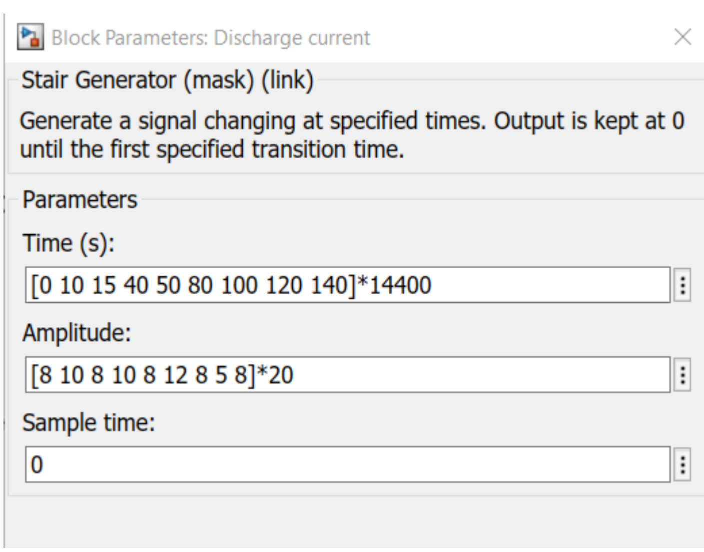
A noticeable capacity fade from about 20.65Ah(maximum at highest possible cell voltage) to about 19.8Ah. This has occurred while the battery was charged and discharged about 250 times. Cell manufacturer has specified that about 80% BOL capacity will be attained by the end of 5000 cycles. This is a conservative estimate upon using nominal charging current of 20A and staying within the voltage limits of the battery.

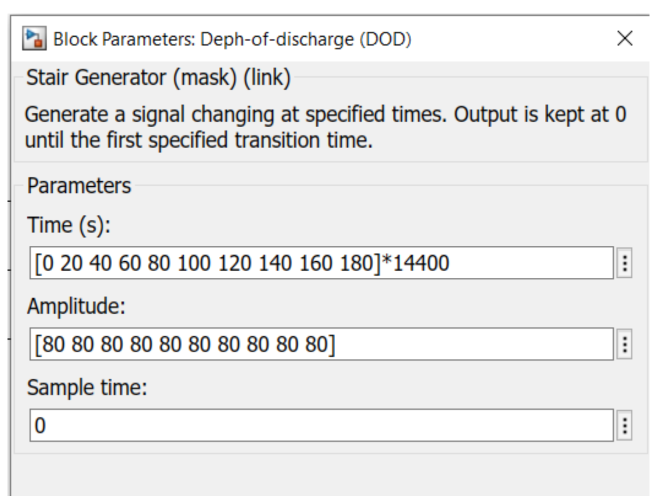
In the above model we have used 20A nominal charging current.

4.8.2 MODEL-2

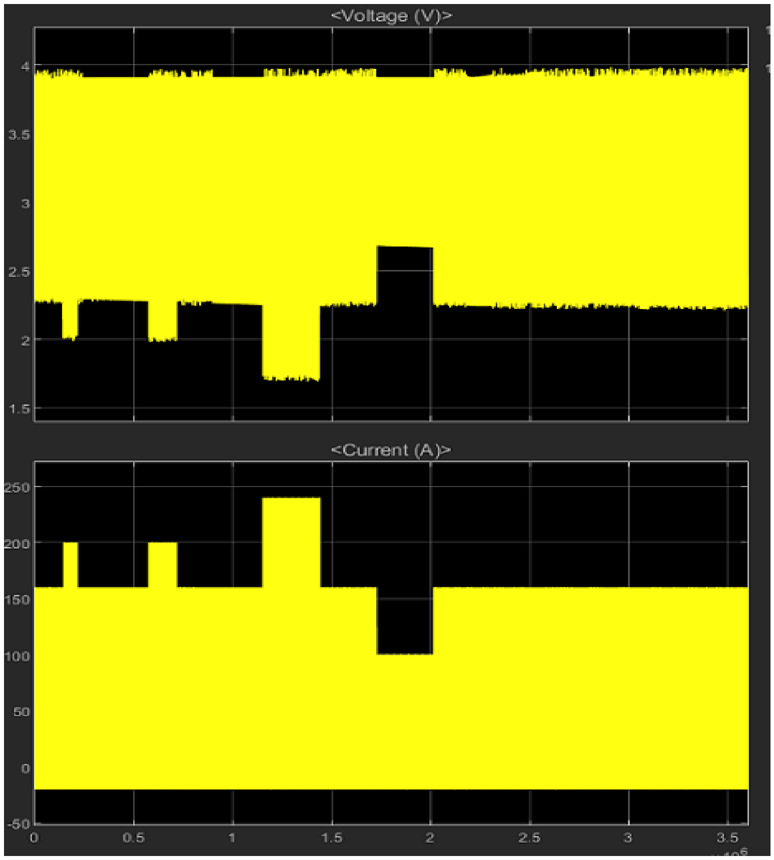
Here we are also presenting a few more model results on a different discharge profile in which we use a constant discharge current until the battery reaches 20% SOC. This can be used to model the acceleration event, motor bench testing events, etc.

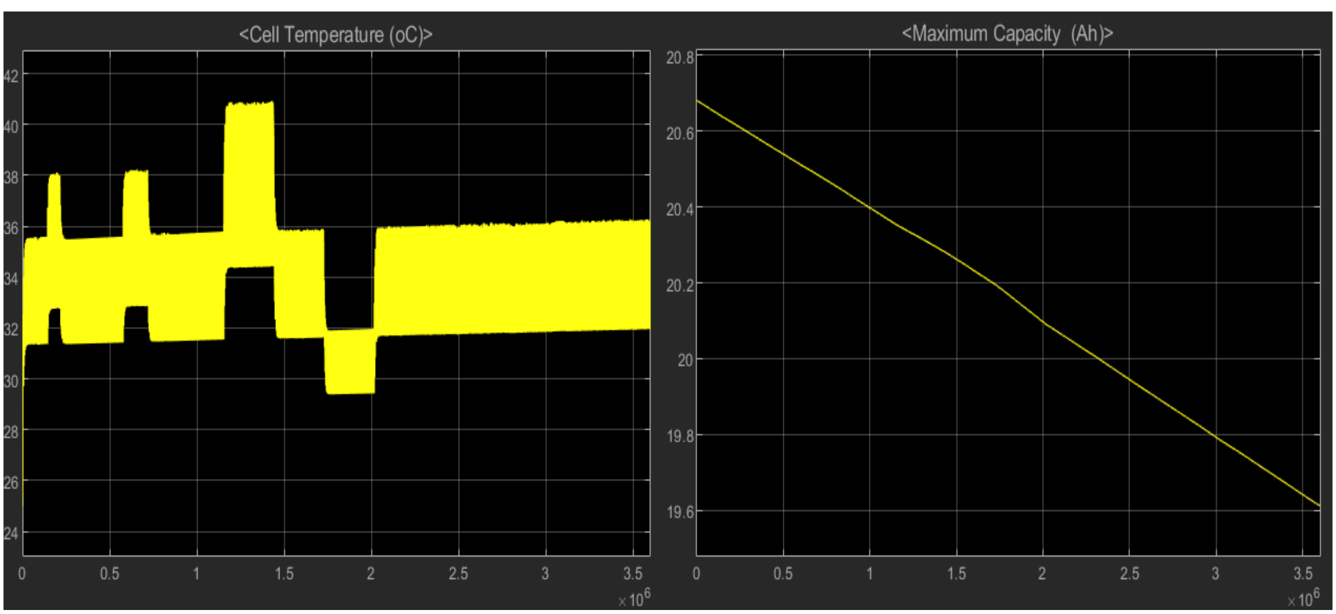






Results are as follows:





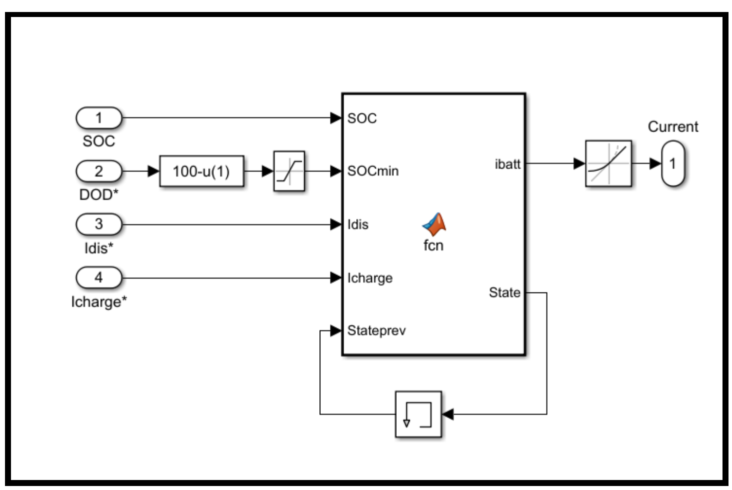
RESULTS

Results are pretty straightforward :

1. Heavy discharging currents cause a raise in cell temperature. Maximum allowed temperature is 60°C, and even at a high discharge of 10C the cell is maintaining at about 40°C
2. While in a heavy discharge situation the temperature rise can affect open circuit voltage of the cell and hence since most Li-ion cells have a negative temperature coefficient, we can see that the voltage drops below the nominal safe limit of 2V when the cell temperature reaches 40-42°C
3. As opposed to the earlier discharge profile we can see here that the heavy constant charge discharge cycle can create sustained high temperature fluctuations, more than the repeating current discharge profile used in the first model
4. Wrt the first model the results of this record a heavier drop (about 0.2Ah) in capacity for the same number of cycles

4.8.5 MODEL EXPLANATION

Cycles generator



Cycles generator is a MATLAB function which discharges and charges the battery, factoring into account the SOC, Depth of Discharge specified and the discharge current.

```
function [ibatt,State] = fcn(SOC,SOCmin,Idis,Icharge,Stateprev)
%#codegen
State=Stateprev;
if(Stateprev==1 && SOC<=SOCmin)
    State=0;
end
if(Stateprev==0 && SOC>=99)
    State=1;
end
if (Stateprev==1)
    ibatt=Idis;
else
    ibatt=-Icharge;
end
```

This code takes care of the charging and discharging depending upon the DOD and Idis limits set by us. The State and Stateprev variables are used to identify the current and previous states in terms of 1 and 0(0-charging and 1-discharging). The memory block stores the current state, generates a time lag and makes it the previous state.

4.9 Thermal Management

The primary aim to keep the temperature of all cells under the safe limit of 50C (safe limit is 55C, buffer of 5C)

To read more about our battery thermal management system, click here.

5. Control and Safety Circuits

5.1 Central Network

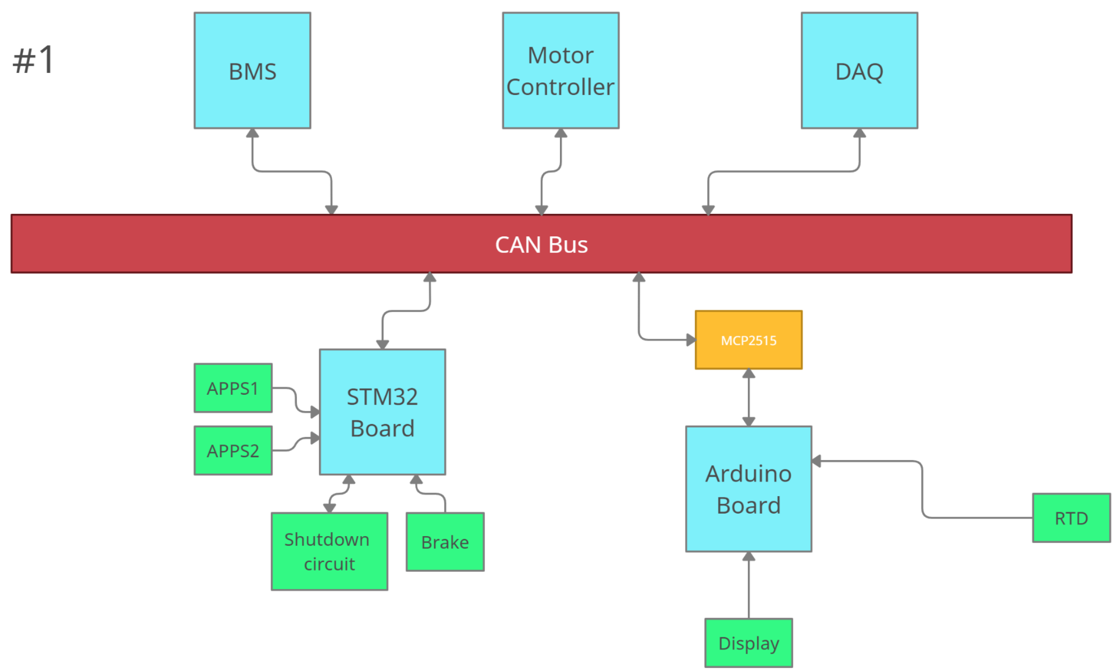
The central network is divided into 3 further networks:

1) Central CAN network connecting the DCM, Motor controller, BMS and the DAQ

2) DAQ network that involves other mechanical sensors like IMU. This network also connects the DAQ to the dashboard to display various signals (mainly Speed and SOC).

3) BMS to Motor controller network for varying power transmission and limiting the current limits based on real time calculations.

5.1.1. Vehicle Control Unit (VCU)



For the purpose of the main Electronic Control Unit (ECU) within the VCU, STM32F42Z Nucleo MCU is used. The board has 2 in- built CAN 2.0 B controllers for connecting it to our CAN network. A secondary ECU is also implemented with an Arduino Uno board which mainly serves the purpose of relaying data to and from the dashboard display and driver interface.

The main module's I/O pins include:

Inputs :
ADC : APPS
GPIO Pins : RTD button
Status signals : Brake Pedal signal, Shutdown signal

Outputs : CAN network (in output/transmit-only mode) , RTD buzzer, Standby LED.

The module's main functions include the following:

1) Torque Encoder - 2 X12 Bit ADC converter of the module will receive the APPS signals in two different channels and the customized coded logic will turn this into an appropriate signal output which is then provided to the Motor controller/driver. Given that there is no implausibility, the logic will perform a weighted average of the APPS value, which will then be scaled as per the Motor controller's requirement.The signal is sent to the main CAN network and will also be provided to the DAQ via the same channel.

   The Brake status signal will disable the Torque encoder(software logic) while the brakes are applied. This will further improve the entire breaking process. This will be achieved using a software interrupt for the braking process.

   The Software will also perform error check in the following ways :

- Short circuit to ground and short circuit to supply,comparing the corresponding digital values from the APPS to hardcoded values that indicate ground and supply respectively, and values that correspond to impossible angles of the pedal.
- Checking the 10% implausibility, the values are sampled every 1ms, sampling is hardware triggered from a timer on the microcontroller.
  Average of 5 consecutive values are taken for both the analog channels corresponding to the two APPS,and for these averaged values the 10% error is checked.
  Iterative process of 20 times occurs to check for implausibility, if at the end of the iteration , there is a majority that has positive indication to the 10% implausibility then the DCM comes back to stand-by mode. The driver would have to bring the car back to RTD by dedicated action.
  Furthermore, an unique "APPS error" message will be sent over the CAN network (to the motor controller and the DAQ).

2) RTD (Ready to Drive) - The car, by default would be in stand-by mode and the dashboard would contain a LED to indicate this status (the software equivalent of this logic would be on the DCM). A dedicated RTD button on the dashboard would be directly connected to the DCM via its GPIO pin. The Brake pedal signal would be checked by the DCM before changing to RTD mode. Also, the RTD buzzer would be activated at the same time. The CAN network would also be notified about this.

The car will turn back to stand-by mode in case of following:

a) APPS error has occurred (DCM has customized logic for this).
b) Shutdown is initiated (Shutdown signal).

3) Post - Shutdown sequence - After the hardware shutdown has been triggered, the circuit would be sending the shutdown init status to the DCM. This would be followed by an unique "Shutdown init" CAN message to both BMS and DAQ. This message would kill the power supply process from the battery by signaling the BMS to turn the Voltage low (Hardware Shutdown system opens the circuit but this additional feature would ensure that no voltage is applied to the open circuit as well, thus removing chances of charge - arching).

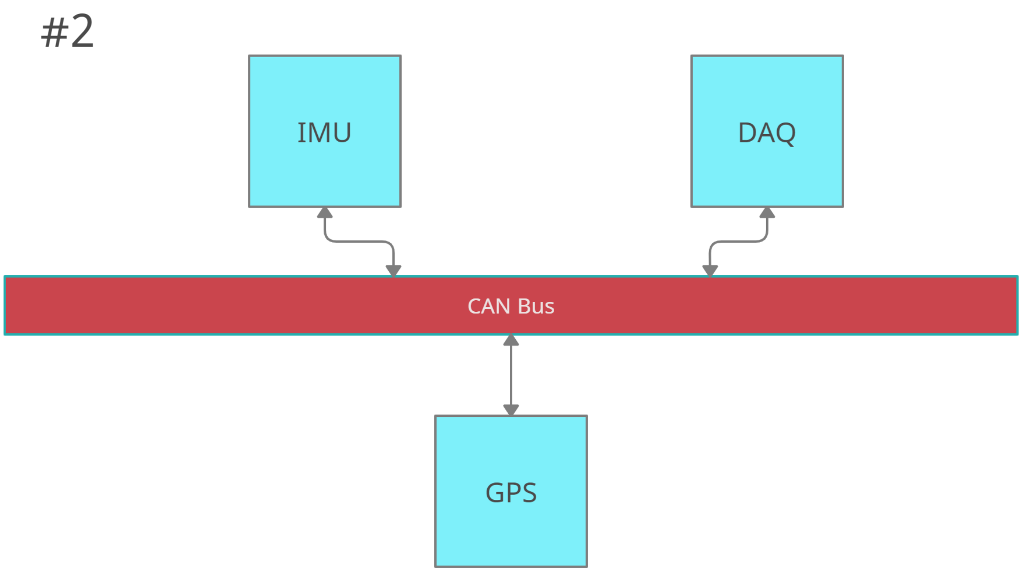
This series of events would also turn the car to stand-by mode automatically.

5.1.2. Data Acquisition System

The DAQ is made using commercially available Kvaser Memorator Pro 2xHS V2 USB to CAN Data logger. It stores the main CAN network's data and also stores the data from other mechanical sensors. The dual CAN input bus helps it intake the 2 different sets of data simultaneously. The features are explained in detail :

1) Dashboard connectivity - The DAQ will be connected to an additional controller, an Arduino Uno that decrypts the CAN messages through an MCP2515 module and sends some chosen signals to the dashboard display. This includes APPS signals averaged with the Speed calculated by the Motor controller, and the SOC and SOH from the BMS. This will additionally contain a wireless module to send the real time data to Laptop (in the pit) for further analysis. The Kvaser product provides the functionality to log and stream data at the same time.
2) Second CAN channel - This will include the data coming from various other sensors used for mechanical data analysis. This would include IMU and GPS for road data (and would be sent sequentially). It will also include Motor speed and would be directly fed to the dashboard connected controller.
3) DCM message priority shift - Any priority based controller has a problem of network starvation. To avoid this, the highest priority node will have an additional logic to shift its priority based on certain features. This would be triggered in case of : constant signal(high signal) is maintained (5% change allowed) for more than 3s, or the low priority signal is at critical condition. Other than these, the low priority message would be triggered after constant intervals as well.
4) Additional Application Layer Protocol - This would be necessary because the starved message should not lose any information. In case of starvation of following:
    a) BMS - The SOH and SOC value would be passed in the same message. Also, the average of all the values of SOH/SOC would be sent (starting from the last sent message)
    b) DCM - The first bit of the message would be the control bit. Thereafter, if the control bit indicates the starved message, the initial half dataframe would be the time-average starved message.

The commercial DAQ has additional features that involve message filtering based on a trigger. These logics are written as the Kvaser - t-scripts. Additionally Kvaser's CanKing and CANalyzer simulations and LabView simulations can be done with the help of proper API based Frameworks.

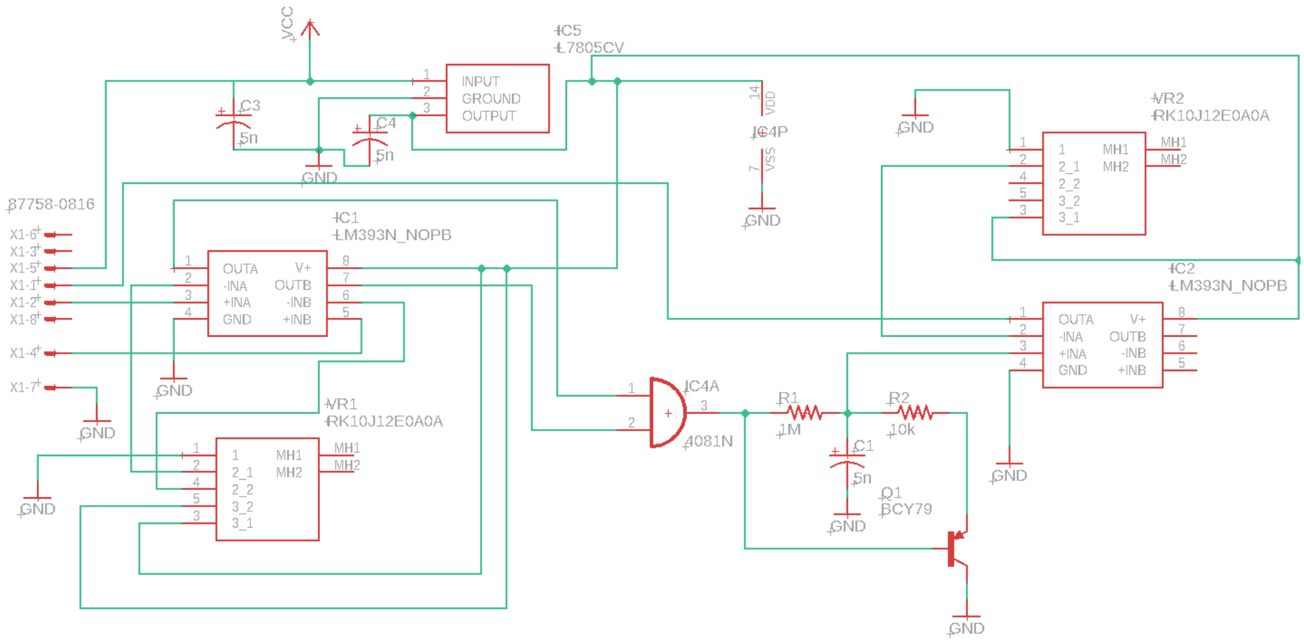


5.2. Safety Circuits and Sensors

5.2.1 Brake System plausibility device

The Brake System Plausibility Device (BSPD) essentially ensures that the acceleration pedal and brake pedal aren't pressed simultaneously for more than 500ms. Signals from the accumulator current sensor and one of the brake pressure transducers are taken and compared against a threshold value. The threshold voltage of the main accumulator current sensor corresponds to 5kW power being delivered to the motors.

Schematic-

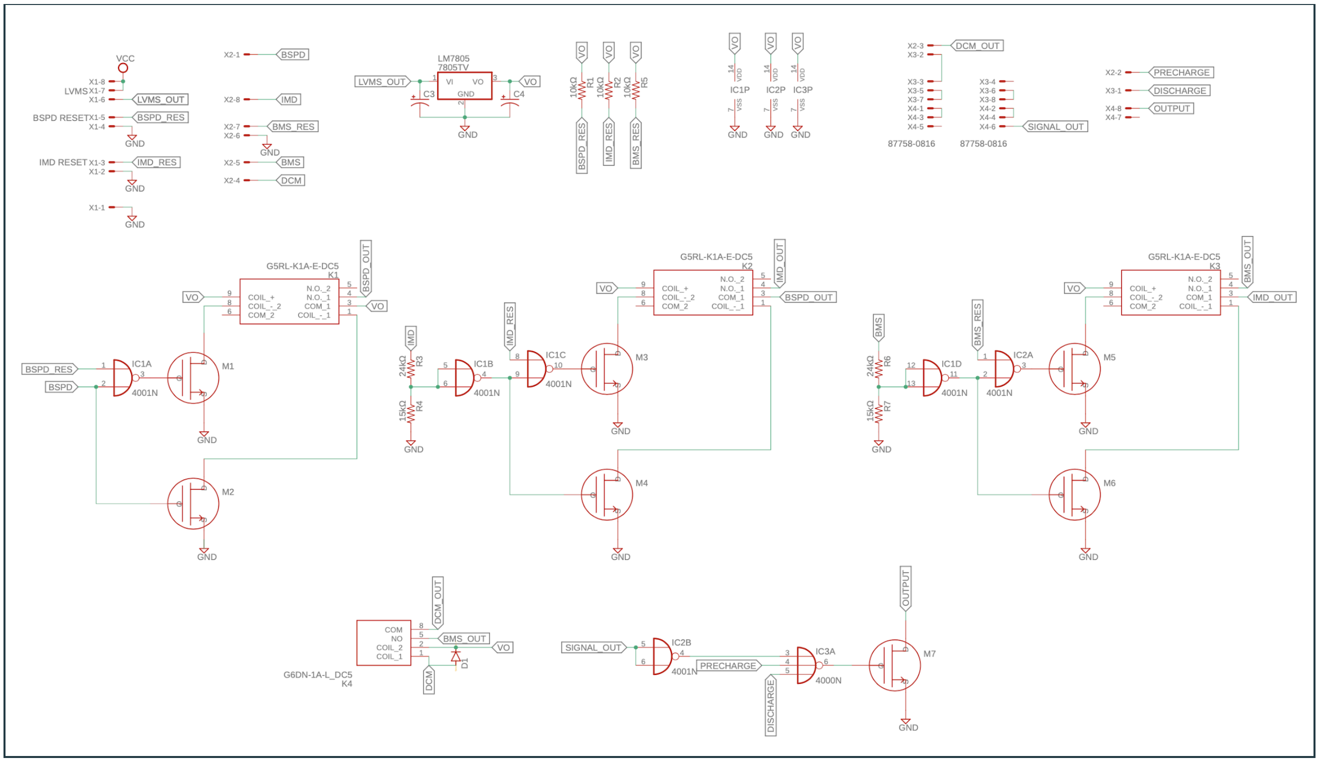


An AND gate will check if both the inputs are above the threshold voltages after the signals pass through a comparator. In case both the signals are above the threshold values, the circuit checks for persistence of this signal by charging a capacitor. After 0.5s, the RC circuit will repach a voltage above the threshold voltage set by the potentiometer. The output signal is sent to a BPS Latch.

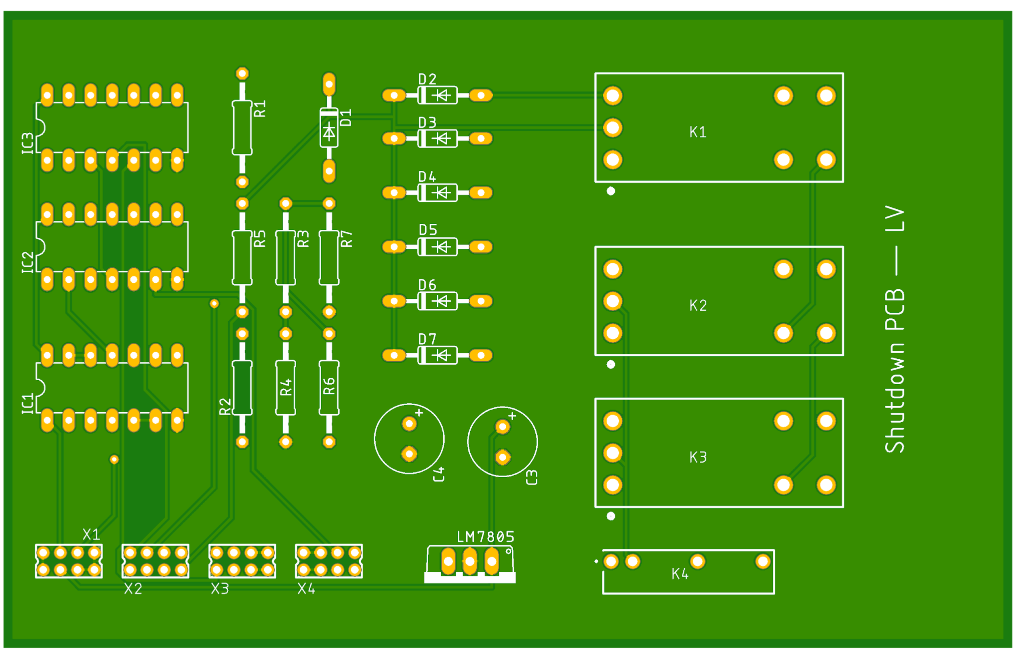
5.2.2. Shutdown Circuit

The shutdown circuit is a series connection of components, which comprises the BSPD relay, IMD relay, BMS relay, DCM relay, shutdown buttons, inertia switch, BOTS, HVD, and the TSMS connected in series. The precharge relay is closed for 1s during the precharge time and then latched to its position. The discharge time is taken as 1s.

Schematic:


VCC
LVMS_OUT
BSPD_RES
IMD_RES
GND
BSPD
IMD
BMS_RES
BMS
DCM
LM7805
7805TV
VI
VO
GND
C3
C4
DCM_OUT
PRECHARGE
DISCHARGE
OUTPUT
SIGNAL_OUT
87758-0816
G5RL-K1A-E-DC5
K1
K2
K3
BSPD_OUT
IMD_OUT
BMS_OUT
4001N
M1
M2
M3
M4
M5
M6
M7
IC1A
IC1B
IC1C
IC1D
IC2A
IC2B
IC3A
4000N
G6DN-1A-L_DC5
K4

PCB CAD:


IC3
IC2
IC1
R1
D1
R5
R3
R7
R2
R4
R6
D2
D3
D4
D5
D6
D7
C4
C3
K1
K2
K3
K4
X1
X2
X3
X4
LM7805
Shutdown PCB — LV

5.2.3. Pre-Charge - Discharge

Precharge Circuit

The precharge circuit is a protection circuitry for the motor controller.

Consider a case where there is no precharging mechanism present:
The motor controller has an intermediate capacitance that is charged up before the inverter (controller) starts functioning. The low series resistance as well as no back EMF of the Tractive System would lead to sudden inrush of a large value of current into the motor controller capacitor causing the tractive system fuse to blow. This would happen every time, and even after replacing the fuse , we won't be able to start the car as the fuse may blow again.

Considering the natural response of the capacitor:

$$i_C = \frac{V_S\left(1 - e^{\frac{-t}{RC}}\right)}{R}$$

Where:
Ic - Capacitor current
V_S - Accumulator Voltage
R - Circuit Resistance
C - Intermediate Capacitance

Since the value of the resistance is very low, the current flowing into the capacitor would be very high, blowing the Tractive System fuse.
Thus, to ensure that the fuse does not blow out at regular intervals we intend to use a resistor which increases the series resistance so that the intermediate capacitance of the motor controller can be charged to a safety limit as specified by the Formula Bharat Rulebook.
The circuitry used is called a **pre-charge circuit.**.

Calculations:

Rule book states that the precharge circuit should charge the immediate capacitance by at least 95% before closing of AIR.

We know that the capacitance of the circuit is 320uF and the resistance chosen is equal to 1k ohm.
Therefore,
Time Constant(T) = 0.32s
Tractive System voltage = 320V
95% of Tractive System voltage = 304V
Time required to charge up to 95%can be calculated by:-

304 = 320(1 - e^(-t/T))
t = 0.958s
Therefore we have chosen t = 1 sec.

Heat generated by resistor during this period = ½ CV^2
= 16.384J
Rating of resistance chosen = 35W*1s
= 35J
which is greater than heat generated in the charging process.

For timer :-
t = (1.1)RC
t = 1 sec

Therefore R = 1kOhm (**Pre-Charge Resistor**)
C = 320uF

Discharge Circuit

When both the AIRs are closed and the Tractive System is active, intermediate capacitance of the motor controller stores energy. When the Drive Control Module shifts to the StandBy mode, the discharge circuit discharges the energy stored in the capacitor.
Discharging the intermediate capacitance protects the engineer working on the car when it has been switched to standby mode and the TSAL is lit green.
It involves the usage of a resistor connected in series with the capacitor. The discharge relay receives a control signal to switch to the ON position, allowing intermediate capacitor's stored energy to be removed as heat.

$$i_C = \frac{V_S\left(e^{\frac{-t}{RC}}\right)}{R}$$

Natural Response of Discharge Circuit

Calculation:

We know that the capacitance of the circuit is 320uF. Resistance chosen is equal to 1k ohm.

Therefore,
Time Constant(T) = 0.32s
Tractive System voltage = 320V

Time required to discharge upto 95%can be calculated by:
16= 320(e^(-t/T))
t = 0.958s

Therefore we have chosen t = 1 sec.

Heat generated by resistor during this period = ½ CV^2
= 16.384J
Rating of resistance chosen = 35W*1s
= 35J
which is greater than heat generated in the discharging process.

For timer :- t = (1.1)RC
t = 1 sec
Therefore R = 1kOhm (**Discharge Resistor**)

5.2.4. TSAL - AIL

Tractive System Active Light

The tractive system is active when any of the following conditions are true:-

1. An Accumulator Isolation Relay is closed.
2. The pre-charge relay is closed.
3. The voltage outside the accumulator container exceeds 60 V DC or 25 V AC RMS. This implies that at least the voltage of all DC-link capacitors needs to be measured even with the HVD removed.

Active means TSAL must blink continuously in red color.
Otherwise, TSAL must remain in green color.

Accumulator Indicator Light (AIL)

We need an indicator to show whether voltage greater 60V (DC) is present behind AIR or not so that the person about to work on the vehicle is aware of the high voltage.

To know more about our schematics, simulations, and PCBs, click here.