Development of an Electric Powertrain System for a Formula SAE Race Car

M. Salameh, A. Gil, L. Kerr, E. Mohammadpour
Supervisor: Prof D. Oguamanam

In cooperation with: Ryerson Formula Racing (RFR)

Abstract

This paper describes the high-level design of an electric powertrain system for a Formula SAE electric race car. The objective of the project was to lay a basis which future teams can extend to complete the transition from internal combustion (IC) to electric propulsion. The authors employed lap time simulation and design theory concepts to compare and evaluate parts to be purchased, and completed detailed design of the cooling system and accumulator housing. The performance of the electric powertrain concept was evaluated against the 2019 IC vehicle, and exceeded the 145.5sec lap time target required for a top-5 competition finish. The objective of the project was met, with only the detailed electric circuit design remaining to complete the transition.

1. Introduction

The purpose of this project was to design an electric powertrain system, within the context of the Formula Society of Automotive Engineers Electric (FSAE-E) collegiate design competition. The competition cycle occurs annually - designing, building, and racing a fully student-built vehicle against teams from universities around the world. The work is done within the context of a comprehensive set of rules, aimed primarily at safety while still allowing for creative design [1]. With both presentation-style events and driving events, the car is tested for longitudinal and lateral grip, maneuverability, endurance (22km, ~25minutes) and energy efficiency.

In this capstone project, the authors set out to facilitate the transition from an internal combustion (IC) power unit to an electric power unit, by laying a foundation of knowledge on which future teams can build. With the mechanical and mechatronics backgrounds of the authors, the scope and objectives were mechanical focused, with only high-level electrical decisions being made. The scope of the design included evaluating and choosing the electric motor, motor controller, battery management system, battery cell chemistry and form factor, and designing the cooling system, and accumulator structure. These correspond to Sections 2-7 in this paper.

Electric Vehicle (EV) design is currently at a point of rapid technological development and substantial design variation. Some major papers in the field are reviewed here, see the technical report for a comprehensive review of the current state of art [2]. The authors were able to apply certain automotive-EV design concepts found in the literature alongside the demanding requirements unique to racing. According to Husain, Lithium-Nickel-Manganese-Cobalt (NMC) and Lithium-Iron-Phosphate (LFP) cells are preferred for racing EV applications [3]. de Santiago et al. summarize the different motor topologies currently used in EVs, noting that DC machines are easy to control but have low power density, and AC machines tend to be more difficult to control but have higher power densities and maximum speeds [4]. Permanent magnet synchronous motors (PMSM) tend to be preferred for racing application due to their high power density, intrinsic efficiency, and packaging advantages [4]. The University of Wisconsin team provided highly detailed technical documentation of their process - one of the few high-performing teams with publicly available documentation [5].

The design process proceeded with the establishment of design requirements through an understanding of the rules and performing proof-of-concept lap simulations. Concept development and detailed design was conducted with help of thermal and structural simulation.

2. Electric Motor

Motor requirements were set through an understanding of vehicle mass - a racecar should be “traction-limited”, having enough power to overcome the tires [2]. The vehicle lap simulation software Optimum Lap was used with an estimated vehicle weight of 159kg, alongside a benchmark 30kW motor (EMRAX 188), with conservative drivetrain efficiency of 85%. In
Figure 1 below, the power usage is overlaid on the 2019 endurance event course:

![Power usage across a lap](image)

**Figure 1**: Power usage across a lap

Through several iterations, a more conservative vehicle mass of 200kg was set based on the mass of a 6.4kWh battery pack, which allows for completion of the 22km endurance event with a 1.4 factor of safety. The motor power requirement was set just below the diminishing returns limit at 40kW. Various motors, both application-specific and others were compared, and a final decision was made on the EMRAX 208 PMSM - favoured for sufficient power, good data availability, and a track record of serving 30+ FSAE-E teams. The choice set the accumulator voltage at 470 VDC, and the current at 100A rms under max continuous conditions.

3. Motor Controller

The motor controller converts the driver’s torque request signal into a current output from the accumulator to the motor. As such, this piece of equipment must be capable of controlling and withstanding very high current and voltage magnitudes, and its design was beyond the resources of the authors. An AC motor controller is required to control the EMRAX 208 PMSM chosen as the drive unit. Five commercial AC controller models were evaluated using a weighted decision matrix, and the Drivetrain Innovation HV-500 was chosen for its low cost, suitable maximum current and voltage ratings, and the fact that it was designed in conjunction with EMRAX to control Emrax motors [6].

4. Battery Management System

The Battery Management System (BMS) is required by the rules, with the purpose of safely managing the voltages and temperatures of at least 20% of the cells [1]. Due to the 500+ cell-count, a purchasable single unit was preferable to multiple, or custom PCBs - to reduce risk of failure. A recommendation was made by energy storage solution company eV Fern Ltd for the Orion BMS2 (with configurations up to 180 cell inputs, satisfying the 20% requirement), with reference to their reliability, ease of operation and good service. A further benefit was CAN-Bus communication, working with the current team data logging architecture.

5. Battery Cell Chemistry and Form Factor

Several candidates were found for pouch and cylindrical cells, primarily for NMC. LFP had greater safety and cycle life. However, gravimetric energy densities of approximately 110Wh/kg for LFP and 200Wh/kg for NMC meant that with industry-standard safety measures in place, the safety advantages of using LFP were not worth the weight penalty of nearly 30kg [7], [3]. With the accumulator designed to store enough energy for one endurance event, (22 km), the number of discharge cycles in one season is 14 (for 300km average yearly running), much lower than the 250-500 rated cycles of typical NMC cells [8]. A discharge rate of 15-20A per cell was needed to meet the 100A motor current requirement, depending on cell capacity and number of parallel cell connections. Further, pouch cells were more expensive per cell, while the use of a smaller number of higher capacity cells met neither the discharge nor the voltage requirement. Pouch cells are also more risky structurally, requiring careful support structures with allowances for thermal expansion. After consideration of these factors, the cell chosen was a cylindrical Samsung 40T, with 21700 form factor and NMC chemistry [8]. With its high capacity, cell count was reduced to 520, relative to 700+ for smaller 18650 Samsung 25R cells, easing BUS bar manufacturing, while meeting the 100A current requirement.

6. Cooling System

Liquid cooling was chosen to ensure complete thermal control and robustness against external variations. Typical driving conditions of the race car will vary from -10 to +30c, at varying speeds, making accurate air-cooling predictions difficult. Due to time constraints, the accumulator cooling was treated separately from the motor controller, BMS, and motor cooling circuit, with potential for re-evaluation upon further analysis. In terms of radiator sizing, two EK-XE360 computer radiators were used alongside six
Vardar EVO 120 BB fans, with PWM to allow for energy saving once the vehicle is moving, and ram air is induced. Further, two INTG1 brushless-DC magnetic drive pumps were employed, contributing to an overall system safety factor of 2 over the 1496W of heat dissipation predicted.

For the accumulator, heat dissipation per-cell was calculated in a simplified manner using ohmic heating, for the conservative assumption of constant peak discharge (20A per cell) for 25 minutes (22km endurance at typical pace). In an individual-cell discharge test at 20 A, the 40T cell reached 62°C, just above the maximum cell temperature permitted by the rules [9], [1]. When enclosed, the cells are likely to overheat, with a cooling solution preferred to running at a reduced pace. As such, several solutions were preliminarily explored including conductive fins on the container, and a quick-disconnect water cooling system, both in the aim to keep the accumulator water resistant (IP65) and removable for technical inspection. However, further decisions are highly dependent on electrical design - busbar mounting, as well as more detailed simulation and physical testing of clustered battery cells. Overall heat distribution in the system is seen in Figure 2.

![Figure 2: Heat output per component.](image)

### 7. Accumulator

The FSAE Rules specify strict requirements for the accumulator, including restrictions on the weight and energy per segment, strength and mounting requirements for the container, and insulation specifications [1]. The total system voltage and required energy capacity determined via lap simulation, the data from the chosen Samsung 40T cell, and the requirements imposed by the competition rules were used to determine the number of series and parallel connections between cells in the accumulator. These requirements are summarized in Table 1.

<table>
<thead>
<tr>
<th>Description</th>
<th>Nominal requirement</th>
<th>Type of requirement</th>
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<tbody>
<tr>
<td>Segment voltage</td>
<td>&lt; 120 V</td>
<td>Rule</td>
</tr>
<tr>
<td>Segment Mass</td>
<td>&lt; 12 kg</td>
<td>Rule</td>
</tr>
<tr>
<td>Segment Energy</td>
<td>&lt; 6 MJ</td>
<td>Rule</td>
</tr>
<tr>
<td>Total system voltage</td>
<td>≥ 470 V</td>
<td>Performance</td>
</tr>
<tr>
<td>Total system energy</td>
<td>≥ 6.4 kWh</td>
<td>Performance</td>
</tr>
</tbody>
</table>

The configuration parameters such as cells per segment and parallel connections per segment were iteratively changed, and the configuration which satisfied all the requirements and yielded the lowest number of required cells, and consequently weight and complexity, was chosen as the preferred configuration. This configuration consists of sections of 26 cells in series, with four of these sections connected in parallel per segment. A total of 5 of these segments are connected in series, resulting in a total of 520 cells in the accumulator.

The FSAE rules specify that the accumulator must be sufficiently strong to withstand a 20 g force in the vertical direction, and a 40 g force in the lateral and longitudinal directions [1]. Furthermore, the container must include 8 mounting points for an accumulator in the 33 - 40 kg range, each of which must be strong enough to withstand 15 kN in every direction [1]. Aluminum 6061-T6 was chosen for the container and brackets due to its availability, weldability, and high strength to weight ratio relative to steel. SolidWorks Simulation was used to perform a finite elements analysis on the designed container and mounting brackets, employing 10-node tetrahedral elements to capture complex geometry. The container and mounting brackets successfully passed these simulations after several design iterations. The simulated result of the final mounting bracket design sustaining a 15 kN load in the vertical direction is shown in Figure 3.

![Figure 3: Simulation of a mounting bracket.](image)
8. Validation of Performance

Predicted EV lap times were found, through correlating the IC car model to competition data. To place top-5 out of the 40 teams in the Lincoln (Nebraska) FSAE-E competition, a 145.5s simulated endurance lap time was required. With a simulated lap time of 135.7s, the EV design met the target. The very substantial 9.8s margin, can help mitigate the effects of unforeseen circumstances, as well as allowing a more relaxed pace in the competition - reducing the risk of failures. Further, a confirmation of the final vehicle mass with the given component selection was performed. Overall, the EV car is predicted to be 191kg, relative to 210kg of the IC car. The powertrain weight breakdown is in Figure 4:

![Figure 4: Weight Breakdown](image)

9. Conclusions and Recommendations

The motor, controller, BMS, cell type, cooling system, and accumulator housing were sourced and designed to meet the FSAE rules and the RFR performance requirements. Preliminary evaluation of the EV concept indicates that it exceeds the designed targets. Future teams should complete detailed design of the circuitry required to run the system and meet the rules, and perform more thermal simulation and physical testing of the components.

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References


