EEA Conference & Exhibition 2019, 25 - 27 June in Auckland

Design and Development of the Powertrain Elements in a Formula SAE Electric Race Car

Thomas Galbraith
University of Canterbury Motorsport
University of Canterbury
Christchurch, New Zealand
thomas.galbraith@pg.canterbury.ac.nz

***Abstract*— Formula SAE is an international university engineering competition that over 600 teams enter to design, build and race a formula style single seat race car. Since 2016 the University of Canterbury has been developing electric vehicles to race in the Formula SAE Australasia (FSAE-A) competition, held in Australia at the end of each year. The University of Canterbury Motorsport (UCM) team has gained considerable prestige amongst the Formula SAE community for its bold engineering initiatives and highly professional build quality. On top of its record breaking appearances at the annual Australasia competition, UCM is ranked one of the top 25 teams in the world, as well as being the highest ranked team in New Zealand. The UCM electric vehicles feature four independent in-wheel permanent magnet 3-phase synchronous motors, coupled to the wheel by a custom designed planetary gearbox. The 120kW quadruple motor and inverter package is powered by an entirely student designed and built lithium-ion battery pack, optimised to provide the vehicle with enough capacity to last the 22km Endurance event at full race power. The vehicle's torque vectoring and traction control algorithms are implemented on a control unit which is also student designed, allowing the car to accelerate from 0-100km/h in under three seconds. The demanding power requirements of the four-wheel-drive topology can put a lot of stress on the batteries if not properly managed. As a result, residing with the vehicle's battery pack is almost the same number of electrical circuits and communication networks as the entire rest of the car. This provides the appropriate monitoring and protection systems needed for safe operation. This paper provides a summary of the technology and design processes implemented in a high performance, student developed electric race car powertrain.**

I. INTRODUCTION

Formula SAE is an international engineering competition that invites university teams to design, build and race formula style single seat race cars. The competition hosts both static and dynamic events where teams compete against each other; from presenting designs to expert judges and developing business models for their projects, to testing performance out on the track. The University of Canterbury Motorsport (UCM) team is New Zealand's highest ranked Formula SAE team and has been entering four wheel drive (4WD) electric cars in the Australasian competition (FSAE-A) since 2016. With exception of aesthetics, the most defining factor about any Formula SAE car is undoubtedly the powertrain and how it is implemented. Outright performance is achieved by simultaneously optimising designs for a range of criterion, including size, weight, simplicity, manufacturability, safety, efficiency and of course, power output. The powertrain is defined as part of the 'tractive system' which is the high current path (for an EV). The aim of this paper is to give a summary of the design and development process for the electrical powertrain components in UCM's electric vehicles. Since a large proportion of the low voltage (LV) electronics are for monitoring and protection of the tractive system components, aspects of the LV system are also discussed. A simplified block diagram showing the key elements cov-

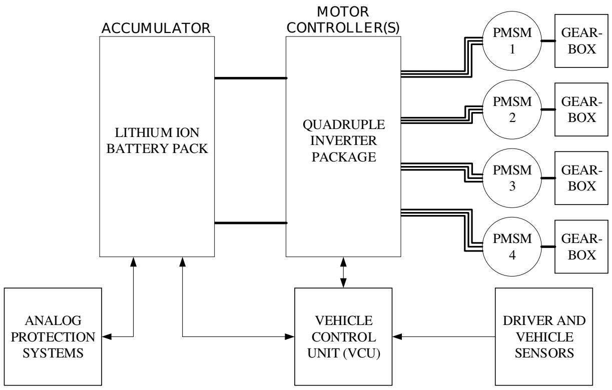

Fig. 1. Simplified block diagram of UCM's electric vehicle powertrain.

Fig. 2. UCM16 on track during Autocross at FSAE-A 2016.

ered in this paper is shown in Fig. 1. The design and development of the planetary gearboxes is also a very significant part of the powertrain, however, this will not be presented.

II. History of Electric Racing at UC

Following the success of UCM's 2015 combustion car, ultimately placing them 3rd in the internal combustion (IC) engine world rankings, the team was motivated to work on an entirely new challenge: the development of electric vehicles. At the 2016 Australasian competition it became the first EV in the history of FSAE-A to outright win a dynamic racing event, beating all contenders in both electric and internal combustion engine vehicle categories. Unfortunately, UCM16's cooling system struggled with the Australian heat and a mechanical failure in the rear wheel assembly rendered it unable to finish the 22km Endurance event, placing the car (Fig. 2) 12th overall.

The 2017 team set out with ambitious plans to optimise the electric car with a focus on weight and performance. The team designed a very complex car, including mechanical features that had never been seen before in Formula SAE. Unfortunately, a minor mistake during a major manufacturing stage forced the team to be required to build a second, entirely new chassis. This setback, coupled with typical unexpected delays, crippled the project and it soon became clear that the car was not going to be ready before the December competition.

In 2018 UCM took the learning's from 2017 and almost entirely re-built the electric car whilst also building a new IC engine car, entering them both at the Australasian competition in December. UCM18-E's performance put the teams EV development program back in the spotlight after it took home three podium finishes: 1st in Business Presentation, 2nd in Endurance and 3rd in Autocross. Unfortunately, an unexpected electrical bug during the Acceleration event denied the team from starting. However, the team's performance across all other areas secured a 4th place overall, narrowly missing another podium finish. UCM18-E (Fig. 3) was also the first Australasian built 4WD EV (and New Zealand's first EV) to finish the Endurance race in the event's 18 year history.

Fig. 3. UCM18-E battles the rain during Endurance at FSAE-A 2018.

III. Drivetrain

There many drivetrain topologies to choose from when building an EV. The most common drivetrains seen in Formula SAE electric are:

- RWD with a single motor and inverter (using a chain and sprocket)
- RWD with two motors (using either a chain and sprocket or planetary gearbox)
- 4WD with hub mounted planetary gearboxes in each wheel

The following considerations were made when choosing to build a RWD or 4WD car [1]:

- Performance analysis of RWD vs 4WD using the tyre model
- Implementation of torque vectoring, traction control and regenerative braking
- Compatibility of available motors with various inverters

Given that a vehicle propels forward due to the reaction force between the tyre and the road, a 4WD powertrain is inherently capable of exerting more propulsive force than a RWD car of the same weight. Similarly to producing a forward movement, a car's ability to corner faster is based on the amount of lateral force the tires can exert on the ground. The ability to control all four wheels independently allows the yaw rate of a race car to be changed dynamically by control algorithms, allowing the lateral and longitudinal force on the wheels to be maximised at all times [1]. The load transfer during braking also enables a 4WD EV to regenerate more energy than would be possible with a RWD car.

When UCM decided to transition to electric, four out of the five highest ranked EV teams in the world had 4WD cars [1]. Given the clear performance advantages, the characteristics of a 4WD car aligned best with the team's goals. The equally evident added complexity of building a vehicle that featured independently controlled hub motors only complemented UCM's ambitious engineering design mentality.

The three most popular 4WD electric drivetrain options in 2016 were:

- Self-developed inverters and motors
- Self-developed inverter with off-the-shelf motor
- Formula SAE specific inverter and motor kit from AMK (Germany)

The AMK package was chosen by UCM as it allowed the team to avoid compatibility issues between a motor and an inverter, which was not tolerable given the tight project timeline [1]. The kit comprises of four silicon IGBT inverters packaged together and four permanent magnet synchronous motors (PMSM), as shown in Fig. 4 and Fig. 5 respectively. The kit can provide a continuous power output of 49.2kW and peak of 120kW. The inverters are configured using an AMK software package that allows over 500 parameters to be modified. Most of these are for setting limits for the protection of hardware, but also include performance altering variables. The most useful of these being control gains for the internal torque and velocity PID controller, to adjust the response of the motors to a given control signal sent by the vehicle control unit (VCU).

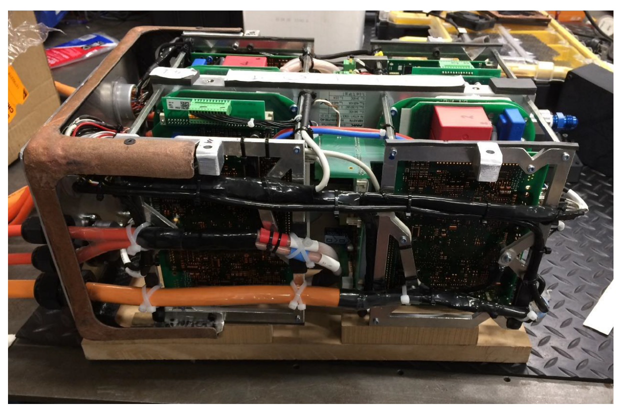

Fig. 4. AMK KW26 inverter package [1].

IV. Accumulator

An accumulator is defined by Formula SAE as an energy storage container that may include batteries or super capacitors. For UCM, it is purely battery storage. The following section aims to give an overview of the design decisions made over the past three years and how the main accumulator sub-systems work together the mechanical design of the accumulator container led to the UCM16 accumulator needing to reduce the number of cells. It was finally constructed of Samsung 18650 Li-ion cells, spot welded in a 7p108s configuration. The complexity of the spot welding process (for a pack this large) and difficulty physically interfacing with the chosen BMS motivated the move to a pre-packaged, Samsung 18650 brick for UCM18-E, as shown in Fig. 6.

Fig. 5. AMK DD5 30kW PMSM [1].

to form an FSAE-A rules compliant, lithium battery pack.

A. Energy Source

Since UCM16 was the team's first EV, there was no energy consumption data to base the accumulator capacity requirements off. To ensure the car was going to finish the 22km endurance race, a race car lap simulation tool was used. A model of UCM16 was made in the software based on the calculated performance parameters of the car. The vehicle model was then simulated on a FSAE-A competition track from a previous year which generated an estimate for the amount of energy consumed for the endurance event [1]. The FSAE-A competition allows for time between events to charge or swap accumulators, hence it was designed to only last the duration of the most energy intensive event. By taking into account approximate regenerative currents, feedback from established overseas teams and including some factor of safety, UCM16's accumulator was required to be approximately 8.5kWh [1]. Extensive research into available and popular battery technologies was carried out, and the required number of series and parallel cells determined for each common EV battery type available on the market. The chosen cell chemistry was selected based on the calculated overall weight and a documented reputation of the cell being successfully used in EV's previously. Despite being designed for seven cells in parallel and 141 in series (7p141s), insufficient tolerances in the mechanical design of the accumulator container led to the UCM16 accumulator needing to reduce the number of cells.

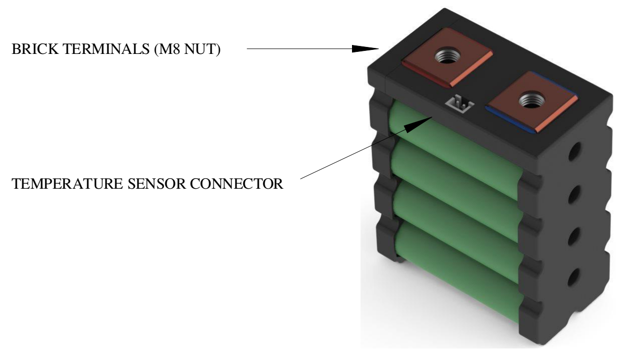

Fig. 6. Lithium-ion building block used in the UCM18-E accumulator [2].

The pre-packaged 18650 bricks were only available in an eight-parallel configuration in 2017, so the pack's capacity was increased. The number of series cells was also increased to 120. After the 2018 season, the team was able to record sufficient data on the stress put on the cells during racing. It was discovered that the nominal pack voltage of 432V forced the motors to operate in a lower efficiency region compared to if the pack was closer to the FSAE-A competition limit of 600V, causing an increase in heat dissipation in the stator windings. As expected, the decrease in voltage also caused a proportionally larger amount of current to be drawn for the same power output, increasing i^2R losses in the cells.

An important factor that had not been considered in the battery pack design previously was the large temperature rise Li-ion has when discharging above, or even close to its' continuous current rating. This was discovered after testing with the 2018 accumulator. There is a strict 60°C temperature limit for accumulators at the competition, with disqualification being the consequence if violated. Testing in New Zealand did not reveal any thermal issues in the accumulator, however, the ambient temperature at the 2018 Australasia competition was around 30°C. With insufficient data to calculate the expected rise over the 2018 Endurance track, the maximum torque limit sent to the inverter by the VCU was decreased significantly in an act to reduce the tractive current draw. Despite placing 2nd and 3rd in Endurance and Autocross respectively, the car was actually performance limited to about two thirds of its capability.

High current discharge experiments and simulations using actual vehicle data, carried out by the 2019 team, aimed to allow optimisation of the number of series and parallel cells needed for UCM19. The thermal characteristics of Li-ion is inherently difficult to model, especially when regenerative currents are included. Nonetheless, as a result of the analysis, the UCM19 pack will revert back to a seven parallel cell configuration whilst having a peak voltage of 580V (7p138s).

B. Accumulator Management System

The accumulator management system (AMS) has the primary responsibility of monitoring the voltage and temperature of all the cells in the pack. An off-the-shelf battery management system (BMS) is used to balance the cell's voltages, whilst a student designed temperature monitoring system (TMS) supervises all of the cell temperatures [3]. The BMS and TMS together form the AMS, as shown in Fig. 7.

The BMS implemented is made-to-order from a specialist in Colorado, USA. The system features a 'distributed' topology, where each of the cell balancing circuits is individually mounted on the 18650 bricks (Fig. 8). Alternative to a 'centralised' BMS, the distributed system allows the heat generated from the balance currents to be spread throughout the accumulator container, instead of being concentrated at a single location. There is also no need to have 'flying' balance wires connecting to each cell terminal throughout the container. With this system, only two pairs of galvanically isolated communication wires connect the BMS of an accumulator segment (12-15 bricks) to the central BMS controller (Fig. 9); improving the safety and modularity of the system. The main disadvantage of a distributed system is that there are more components to be packaged at the cell, rather than all at a single location elsewhere in the container. Which can make the mechanical design and layout more difficult.

Whilst the TMS has seen one revision to improve the packaging and functionality, the BMS has not been changed significantly since its original installation in 2016. An alternative was trialled in 2018 but was soon abandoned due to lack of engineering support from the supplier. The next improvement to the AMS will be the implementation of a self-developed BMS that incorporates the TMS as well.

C. High Voltage Front End

The HV front end primarily consists of the accumulator isolation relays (AIR's), fuse, current sensor, precharge and discharge systems, as well as the contactor controller (AMS). The precharge circuit is required to limit the inrush current caused due to the large intermediate capacitor on the DC input of the inverter when the main contactors (AIR+ and AIR-) are closed. The discharge circuit works in a similar manner, but discharges the intermediate capacitor when the contactors open. The location of the precharge and discharge systems are shown in Fig. 10. Since the discharge system operates on the inverter side of the contactors, it is mounted outside of the accumulator container.

The HV front end (Fig. 11) was initially designed in 2016 to carry a continuous current of 100A. However, power data gathered during testing in 2018 revealed that the vehicle was operating very close to this limit when driven at a fast pace. The 2019 system has therefore been upgraded to operate at 150A continuous. In addition, the new system will feature HV contactors with auxiliary windings so that the state of the relay armature can be monitored by LV electronics; creating an additional level

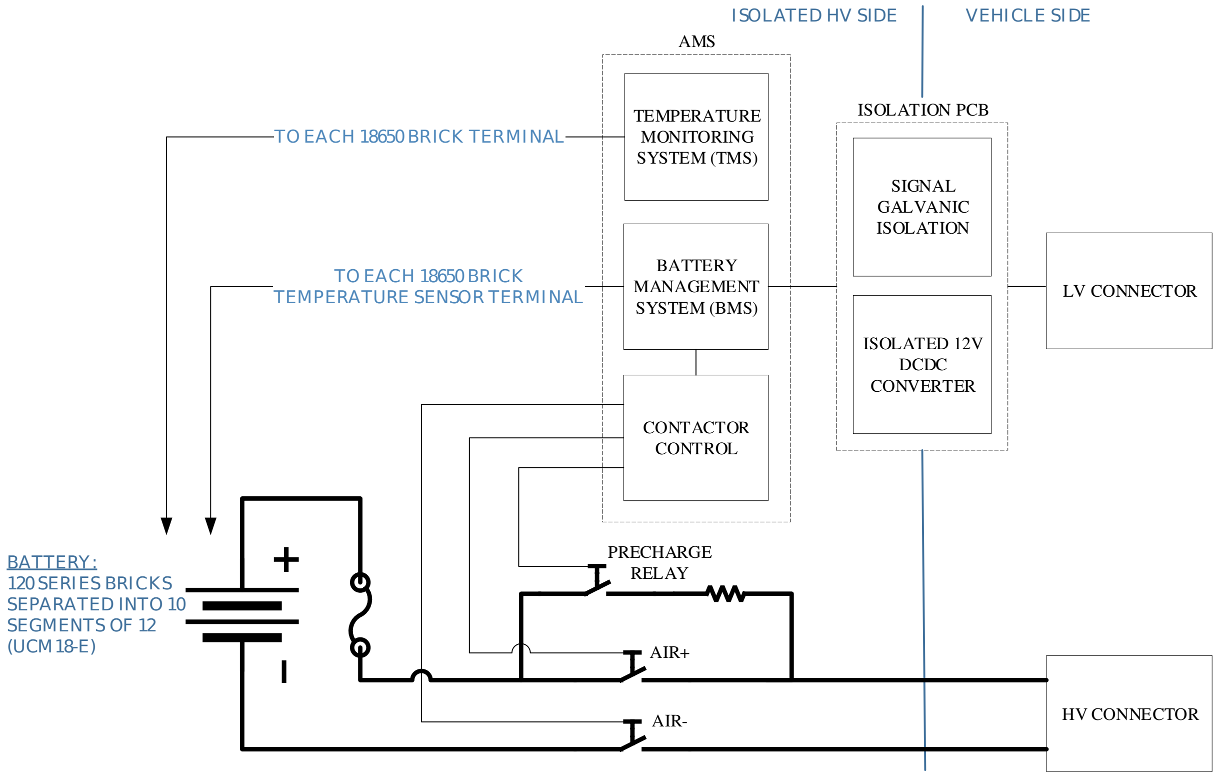

Fig. 7. Block diagram showing the main accumulator sub-systems.

of redundancy for the indication of the main contactor's state. This would be useful in the very unlikely situation the relays are opened under load and the relay armature is welded to the yoke.

V. Isolation and Protection Systems

FSAE-A EV rules specify that the entire tractive and grounded low voltage (GLV) systems be completely galvanically separated. For systems that monitor the tractive system and communicate with GLV electronics (such as between the AMS, HV front end and the VCU), isolation barriers must be present. The 12V (LV) supply, CAN Bus communication and discrete fault signals between the accumulator and car are implemented with isolated DC-DC converters, optical transceivers and optical transistors respectively.

The integrity of the isolation is actively monitored in the vehicle using an insulation monitoring device (IMD). The IMD is a device specifically designed for unearthed DC drive systems in EV's and monitors the insulation between the HV tractive system and the GLV ground [4]. The device (shown in Fig. 12) is set to trip when the insulation resistance falls below the FSAE-A requirement of $500\Omega/V_{\text{pk}}$. The 2018 IMD would be triggered if the HV insulation resistance fell below 252kΩ (for the 504V accumulator).

The IMD is one of four analogue (no programmable logic) protection systems that is capable of directly breaking the supply to the main contactors if tripped. The other three are; the precharge/discharge over temperature circuit (PDOC), which monitors the temperature of the precharge and discharge components; brake system plausibility device (BSPD), which compares the brake signal against the tractive system current draw; the AMS, which is triggered if cell voltage or temperature limits are exceeded in the accumulator. These four analogue fault circuits are 'latched' if triggered, meaning they will stay active even if the LV

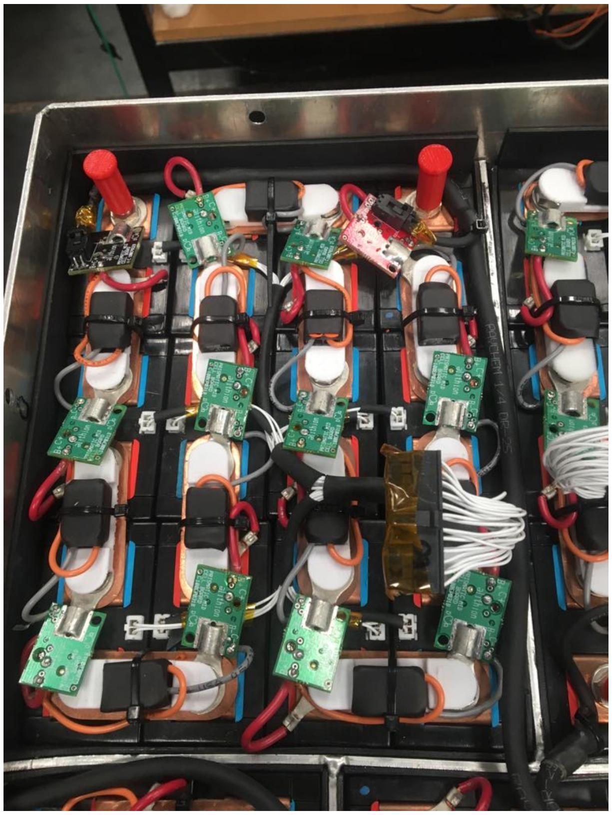

Fig. 8. BMS cell monitoring PCBs mounted on the 18650 bricks.

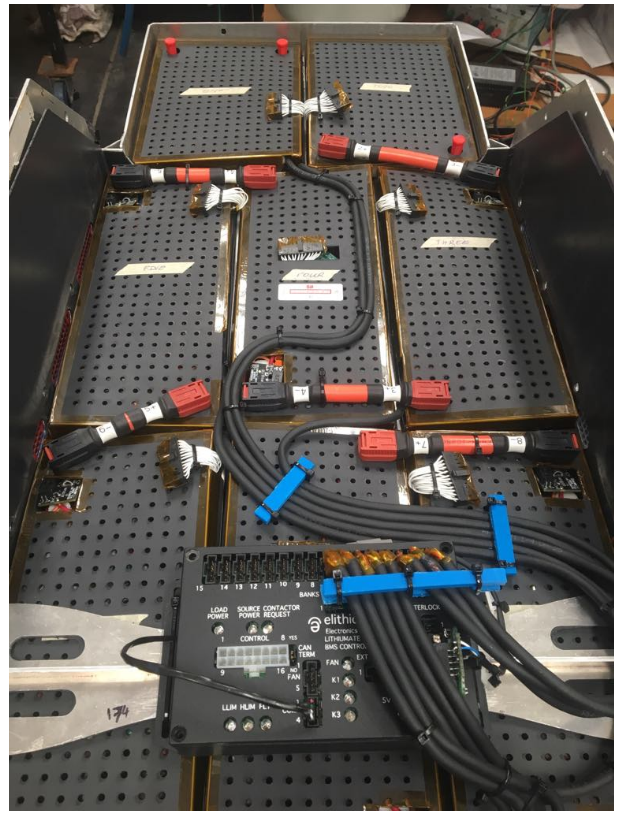

Fig. 9. Cell board communication wires connecting to the BMS master controller.

power is cycled. They can only be reset via a button that is outside the cockpit.

The AMK inverter is also equipped with protective monitoring functions including short-circuit/ground fault, intermediate circuit overvoltage, excess temperature at the motor/inverter and over current protection. The team has also configured the inverter to de-rate the torque delivered to each motor based on how close the drivetrain is getting to the current and temperature limits.

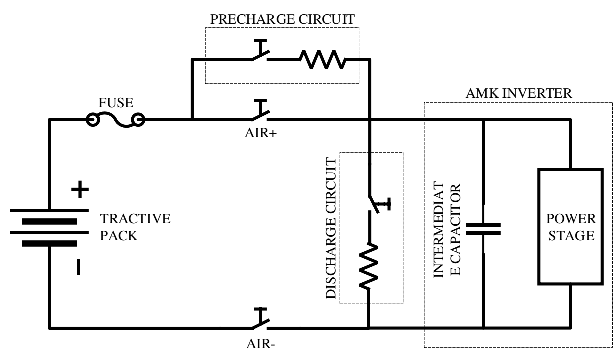

Fig. 10. Block diagram of the UCM16 and UCM18-E HV front end.

VI. Vehicle Control Unit

The VCU is a student designed PCB that is responsible for enabling all of the drive functions. A block diagram of the PCB is shown in Fig. 13. The VCU ensures that the car is only enabled to drive after a strict set of Formula SAE rule requirements are met, this includes validating all sensor readings and checking the state of the tractive system. Once the tractive system is livened and the vehicle is in 'drive' mode, the VCU carries out real-time vehicle dynamic algorithms using the driver and vehicle sensors to produce the control messages for the AMK inverter. These student developed algorithms include vehicle torque vectoring and traction control.

The tractive system is precharged when an

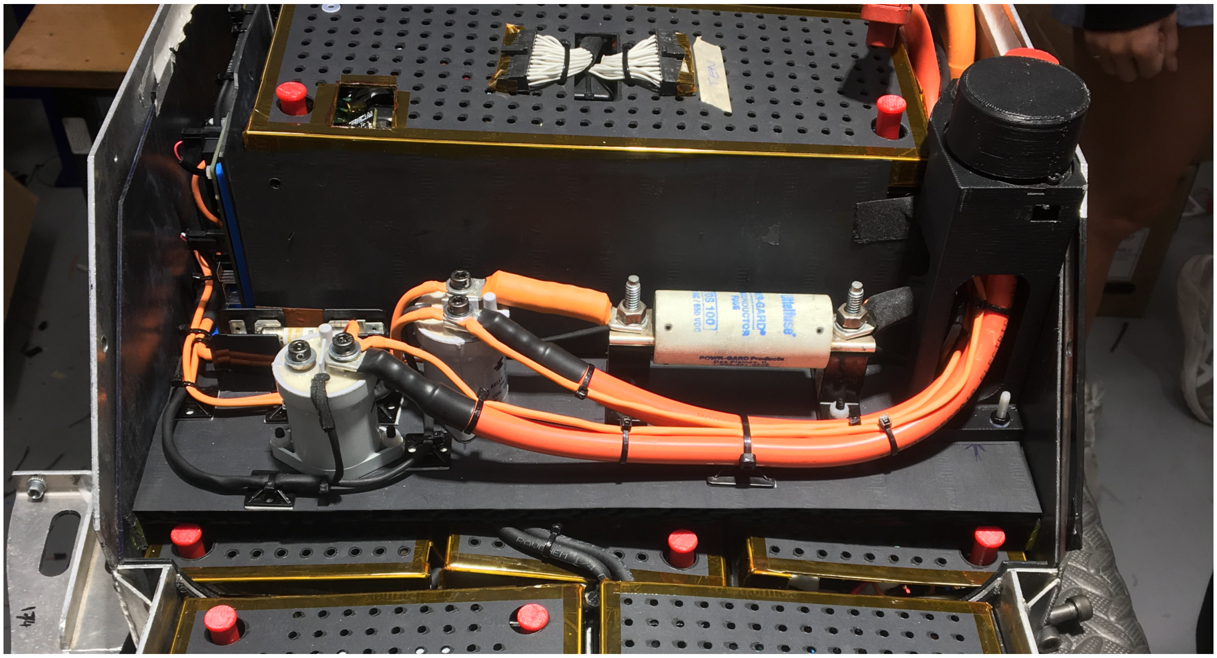

Fig. 11. HV front end of UCM18-E's accumulator. In the forefront is the main contactors and the tractive fuse.

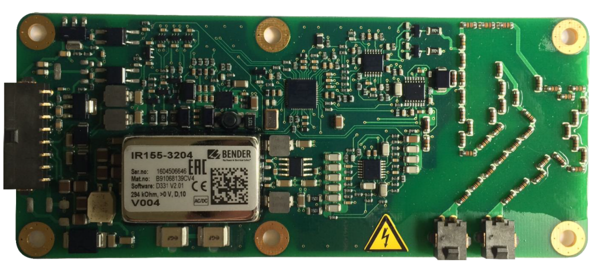

Fig. 12. Image of the Bender Isometer IMD [1].

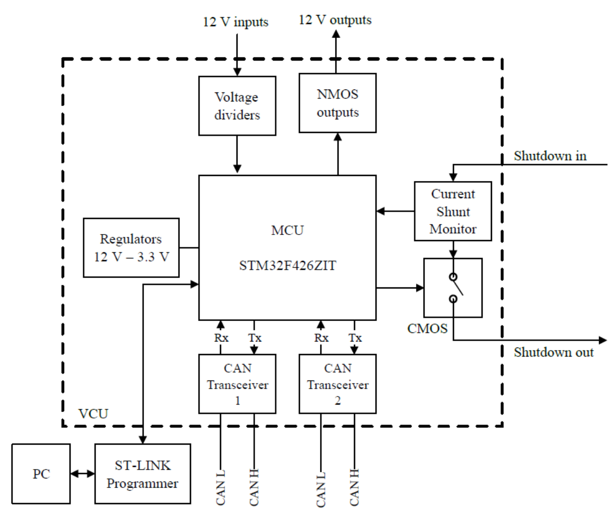

Fig. 13. Block diagram of the UCM18-E vehicle control unit PCB [5].

enable message is sent from the VCU to the AMS. After precharge, the vehicle can be put in to 'drive' mode; following the successful completion of a start-up sequence that involves the simultaneous push of the brake pedal and press of the dashboard 'start' button. In addition to the CAN Bus control, the VCU also has direct control over the HV contactors via the 'shutdown' circuit, as shown in Fig. 13. The shutdown circuit carries the energising current for the main contactors and precharge relay coils. The VCU is able to react to issues and implausibilities with varying degrees of severity, from slowly de-rating the motors proportional to temperature, or disabling the tractive system entirely.

VII. Future Developments at UCM

A future improvement to be made to the UCM electric powertrain is the development of a lithium polymer (LiPo) pouch cell accumulator. Due to the power/energy density ratio of the LiPo battery chemistry more closely matching the requirements of UCM's Formula SAE cars, changing from Li-ion 18650 cells would allow the physical size and weight of the accumulator to reduce. Safety and simplicity have been the principal reasons for using pre-packaged Li-ion bricks until now, at the expense of additional weight. To improve the form factor of the accumulator packaging, the team is investigating the development of a custom designed BMS that can integrate tightly with the cells whilst also satisfying all FSAE-A temperature monitoring rules as a single AMS unit (as mentioned in Section IV-B).

The inverter that comes with the AMK package uses silicon IGBTs packaged against an aluminium cooling plate with sizeable air gaps between components. The University of Canterbury has begun research in to the design and build of a potential replacement inverter package featuring silicon carbide (SiC) MOSFETs. This will not only reduce the physical size of the unit, but also reduce the heat generated by the switches, significantly improving efficiency.

In addition to new planetary gearboxes, a focus for a branch of the 2019 powertrain team is the advancement of the vehicle dynamic algorithms in the VCU. This involves the implementation of new high fidelity sensors and an improvement on the algorithms themselves. This work will have a direct impact on the performance of the vehicle.

VIII. Conclusion

The powertrain elements of the UCM electric vehicles are developed immensely each year, with every car well out performing it's predecessor. The optimisation of lithium battery packs, protection systems and supervisory electronics is a unique and highly rewarding project for electrical engineering students at the University of Canterbury. Whilst keeping safety paramount, the team aims to continue being immersed in new technology to enhance learning and ultimately build faster race cars.

References

[1] M. Barham, “Design and Development of the Electrical Systems in an Electric Formula SAE Race Car,” University of Canterbury, Christchurch, 2017.

[2] Energus Power Solutions, ‘Li2x4p25R: Li-ion building block 3.6V/20Ah/18C‘, 2017. [Online]. Available: https://www.energusps.com/shop/product/li2x4p25r-li-ion-building-block-3-6v-20ah-18c-229?category=3. [Accessed: 21 April 2019].

[3] T. Galbraith, C. Jaine, C. Lane and J. Smith,“Development of Electric Racecar Electronics“ University of Canterbury (unpublished), Christchurch, 2017.

[4] Bender, ‘ISOMETER IR155-3203/IR155-3204‘, 2019. [Online]. Available: https://www.bender-uk.com/products/insulation-monitoring/isometer_ir155-3203ir155-3204. [Accessed: 29 April 2019].

[5] A. Chen, B. Maurer, H. Mander and S. Kuipers, “Formula SAE Electric Racecar,“ University of Canterbury (unpublished), Christchurch, 2018.