Final Design Report

Motor & Inverter Selection and Integration

Regenerative Braking

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High Voltage Powertrain

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Problem Definition

The motor and inverters are responsible for the propulsion of the vehicle. Being such a key part of the tractive system, careful consideration is necessary. The inverter is responsible for the conversion of the DC power from the accumulator into 3-phase AC power. The motor then uses and converts this AC power into rotational kinetic energy observable as the torque applied to the wheels. Part of the necessary considerations is also the layout of the motors. From outboard or inboard, dual or quad, each have their own advantages and disadvantages. It was decided between the concept members that 2 outboard motors provided the most benefit. In addition to propulsion, the motor and inverters can also be responsible for regenerative braking should we choose to implement it. Since we have in fact chosen to implement regenerative braking this would also be a consideration when deciding on which combination of motor and inverter to use.

The operating conditions vary from the motor and inverter due to their locations. The motor will be located very near to the wheels for an outboard configuration, and should therefore be able to withstand the heavy vibrations/shock that may come from the wheel. In addition, since it would be located so far out from the rest of the car it should be resistant to water and dust. The inverter would be located nearby the TSAC and should be able to be mounted outside. It should therefore be water and dust resistant also. It may be necessary for an enclosure to be made for the inverter to meet these standards.

Both the motor and the inverter will need to be cooled due to the high current they will handle. It should therefore have a mechanism of some sort to achieve this, whether that is active cooling with a coolant such as water/oil/glycol or water, or passive cooling. The motor and inverter cooling systems much also be compatible with each other (if one is oil both must be oil etc) the only exception being one or the other being cooled by air.

Constraints

Rules

The rules relating to the motor, inverter and regenerative braking implementation are as follows:

- T6.1.10 [EV ONLY] The first 90 % of the brake pedal travel may be used to regenerate brake energy without actuating the hydraulic brake system. The remaining brake pedal travel must directly actuate the hydraulic brake system, but brake energy regeneration may remain active.
- T7.2.2 [EV ONLY] TS components may only use plain water, air or oil as the coolant.
- EV2.2.1 The TS power, measured by the Energy Meter, must not exceed +80kW.
- EV2.2.2 Negative TS power (regenerating energy), measured by the Energy Meter, is permissible and unrestricted.
- EV4.1.1 The maximum permitted voltage that may occur between any two electrical connections is 600VDC and for motor controller/inverters internal low power control signals 630 VDC.

- EV4.3.4 Where both TS and LVS are present within an enclosure, they must be separated by barriers made of moisture resistant insulating materials or maintain the following spacing through air, or over a surface:

Voltage	Spacing
U <100VDC	10mm
100VDC < U <200VDC	20mm
U >200VDC	30mm

- EV4.5.4 TS components and containers must be protected from moisture in the form of rain or puddles to a minimum of IPX2, see IN9.

Packaging

Since the motor configuration is 2 outboard motors, the motor selected will form part of the unsprung mass. It is therefore necessary to try and reduce the weight of the motor assembly as much as possible. With this, the size of the motor should be minimal as suspension must be designed around this assembly.

The inverter has fewer constraints over its mass and form factor, with the only factor being that it will be mounted within the monocoque but outside the TSAC, meaning it must be able to fit within this area.

Design Criteria

Motor & Inverter

As per T7.2.2, the motor and inverter must both be cooled by either plain water, air or oil. The motor and inverter must therefore support this rule to be considered legal.

As per EV2.2.1 the total output power must not exceed 80kW. Since the motor layout selected is two outboard motors, the power from each motor must not exceed 40kW. The selected motor may be capable of outputting more than this, but should never during the course of the race actually exceed the 40kW. If this is a concern, it should be able to be implemented in the inverter.

As per EV4.1.1, the motor and inverter must operate on no higher than 600VDC. This means a motor must be chosen which does not require a voltage higher than 600VDC to obtain the power and torque required to successfully complete the race. A motor can be capable of running at over 600VDC but as with the total power, must be limited to maximum 600VDC.

As per EV4.3.4, the high and low voltage systems must be sufficiently isolated in a single enclosure. Therefore, if the selection requires an enclosure to be designed for the motor or inverter this minimum separation must be observed. The motor and inverter should also not have low and high voltage IO within these separation guidelines.

As per EV4.5.4, the motor and the inverter/enclosure must be protected from moisture to a minimum of IPX2. This is important to consider if an enclosure is necessary for the inverter. It also means that should the motor not be protected to the necessary standard, then an enclosure will have to be made for it. Since the motor has a moving shaft, it is highly recommended that the motor selected is already capable of passing his standard.

As mentioned in the packaging portion of the constraints section, the motor must be able to fit in the un-sprung mass section of the vehicle. This means mass should be kept to a minimum as should the diameter of the motor. This is especially true since the vehicle will use 10-inch wheels which means the motor will be closer to the ground and suspension compared to larger wheel sizes. The inverter must also be able to fit within the monocoque but outside the TSAC.

The position of the motor means it must be able to withstand the heavy vibrations that may come from the wheel, but also the water and dust that may come from the ground nearby. Similar criteria apply for the inverter, but since it is located within the monocoque, it need only be protected against water and the slightest amount of dust. Vibrations should be minimal.

The inverter should be compatible with CAN input. This allows us to control it using the vehicle-wide CAN bus implementation. Since regenerative braking is also being used, the inverter should be able to interpret "negative torque" or "braking torque" values and return power down the HVDC lines.

Regenerative Braking

As per T6.1.10 only the first 90% of the brake travel can be solely regenerative. It is therefore necessary that the brake pedal of the vehicle must directly actuate the hydraulic braking past 90%. The implementation of this is open to consideration. (hybrid or first X% solely regenerative braking)

As per EV2.2.2 the amount of regenerative braking that occurs is not limited, and can be controlled freely. It is therefore in our best interest to choose a motor and inverter with good regeneration capabilities.

The regenerative braking system should be intuitive to use, and provide minimal difference in braking efficacy when compared to hydraulic braking, so as to provide a safe and successful driving experience.

Initial Motor & Inverter Configurations

In order to decide the motor to be used, the following table was used, comparing the characteristics of each motor.

UGR-X24 Motor Selection

	Rim Diameter (mm)									
	254									
Motor Make & Model	EMRAX	AMK	Neu Motors	Plettenberg				MGM		Zytek
	188	FSE Kit (A2370DD)	4440	Nova 15 LW	Nova 15	Nova 30	Nova 50	REB30	RET60	ZPM-3
Mass (kg)	7.1	3.55	5.207	1.44	2.5	5	11.5	8.15	7.5	9.2
Diameter (m)	0.188	0.096	0.127	0.138	0.129	0.198	0.274	0.267	0.169	0.17
Length (m)	0.077	0.135	0.152	0.132	0.077	0.093	0.104	0.101	0.123	0.163
Peak Power (kW)	60	36.5	24	15	15	30	50	40	35	60
Peak Torque (Nm)	100	21		40	40	80	142	150	100	50
Continuous Power (kW)	37		12					30	25	40
Continuous Torque (Nm)	56	9.8								
Max Voltage (v)	490		400	120	320	320	320	800	800	400
Max RPM	8000	20000		8000	11000		5600	4000	8000	16500
Price (GBP)		15650	1500							
Power-Weight Ratio (kW/kg)	8.45	10.28	4.61	10.42	6.00	6.00	4.35	4.91	4.67	6.52
Torque-Weight Ratio (Nm/kg)	14.08	5.92		27.78	16.00	16.00	12.35	18.40	13.33	5.43

Table 1 - Possible motor choices and their performance characteristics.

This table shows the different options we considered. From this it can be seen that the standout options were the AMK FSE Kit, and the Plettenberg NOVA 15 LW. This is mostly down to their compact and light nature, whilst maintaining a sufficient peak power, as can be seen by their impressive power-weight ratios. They do have a significant difference in the max torque that can be generated, but that will be addressed later in this section. The EMRAX 188 was a solid contender, however its weight and its large diameter made it too unwieldy to be a good fit for our vehicle parameters. Motors offered by Zytek, MGM and Neu Motors were all too heavy and/or lacked power to be considered. Ideally, the Plettenberg NOVA 30 motors provide the best compromise between the power, mass and size. Therefore the motors chosen to be considered further were the NOVA 30, NOVA 15LW, and AMK FSE A2370DD motors.

The AMK FSE motors come as a package with their own inverter, so consideration on which inverter to use was not necessary. For the NOVA series motors, the manufacturer supplies motor controllers at different power ratings. The following Plettenberg controllers were researched:

UGR-X24 Controller Selection

Controller Make & Model	Plettenberg			
	MST140-200	MST140-250WK	MST 400-133	MST400-200WK
Mass (kg)	1.5	2	2.28	2
Length (m)	204	304	238	304
Width (m)	135.5	135.5	135.5	135.5
Height (m)	61	~100	~120	~120
Continuous Power (kW)	30kW	35kW	47kW	70kW
Max Voltage (v)	140	140	370	370
Max Current (A)	200	250	133	200
E-RPM Limit (RPM)	240,000	240,000	240,000	240,000
Price (GBP)				
Interface	CAN2.0, RS232, A	CAN2.0, RS232, A	CAN2.0, RS232, A	CAN2.0, RS232, A
Cooling	AIR	WATER	AIR	WATER
Regen	YES	YES	YES	YES
Motors Controllable	1	1	1	1

Table 2 - Possible controller choices for the NOVA series motors.

Simulations

Each motor configuration was simulated using OptimumG's OptimumLap software. This allowed us to get track times for each motor under the same conditions, giving us solid data on which to base our decisions. As stated previously the motors considered were the Nova 15 LW, Nova 30 and the AMK FSE A2370DD motors. Each of these motors had their performance data provided by the manufacturer inserted into the OptimumLap software and tested against the FSAustria 2012 track, which we believe to be as close to the FSUK track as possible. Since not all vehicle parameters such as aerodynamic performance were yet known, the test vehicle used was the UGR-X23 vehicle from last year's concept competition. It is worth noting that the data inputted to OptimumLap from the manufacturer are the motors at their peak powers. However, the turns in the track would not allow for peak power to be sustained very long so it was decided that these simulations would be representative of if the motor was implemented in real life with the limited peak power use. Being able to simulate the limited peak power output would have been ideal, however between software limitations in OptimumLap (being built originally for combustion vehicles) and the limited information given by the manufacturer, this was the compromise that had to be done.

The figures 1-3 show the lap times around the FSAustria 2012 track against the final drive ratio. One can see from these graphs that they all seem to lie between 45 and 50 seconds. With the AMK motors pulling slightly ahead at around 45 seconds compared to the ~47 seconds for the Nova 30 and 50 seconds for the Nova 15 LW.

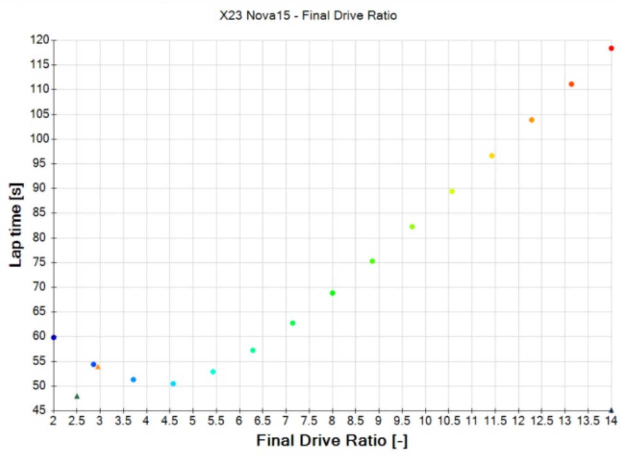

Figure 1 - FSAustria 2012 Nova 15 Lap Times vs Drive Ratio

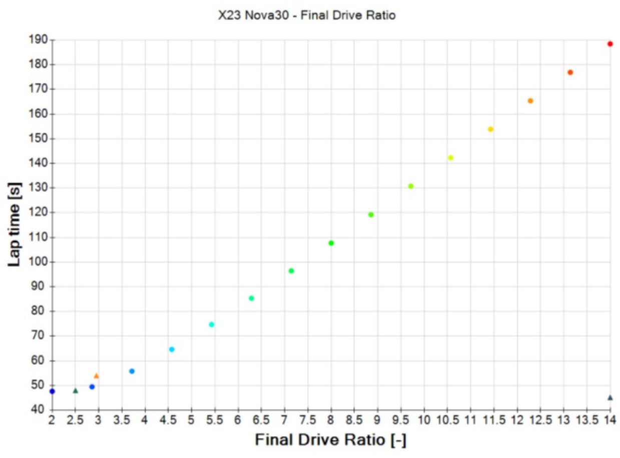

Figure 2 - FSAustria 2012 Nova 30 Lap Times vs Drive Ratio

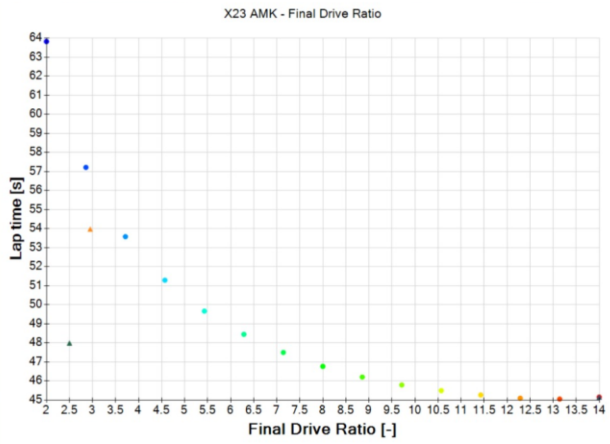

Figure 3 - FSAustria 2012 AMK Motor Lap Times vs Drive Ratio

The motors were also tested on a section of long straight track. This allowed us to observe its acceleration characteristics but also how they would perform in such a setting. Figures 4-6 are the graphs generated from this simulation. From these graphs it can be seen that once again the Nova 15s have the worst time. No matter what gear ratio is used it never reaches below 5 seconds in lap time. The Nova 30 and AMK motors however both edge below the 5 second line, with the AMKs placing slightly faster than the Nova 30s.

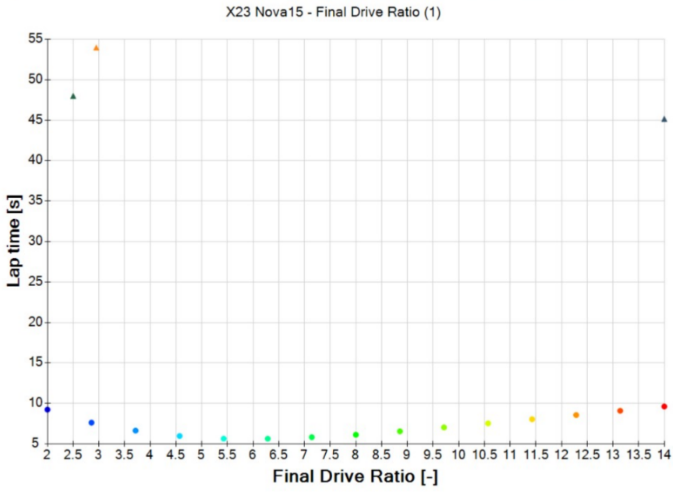

Figure 4 - Long Straight Nova 15 Times vs Drive Ratio

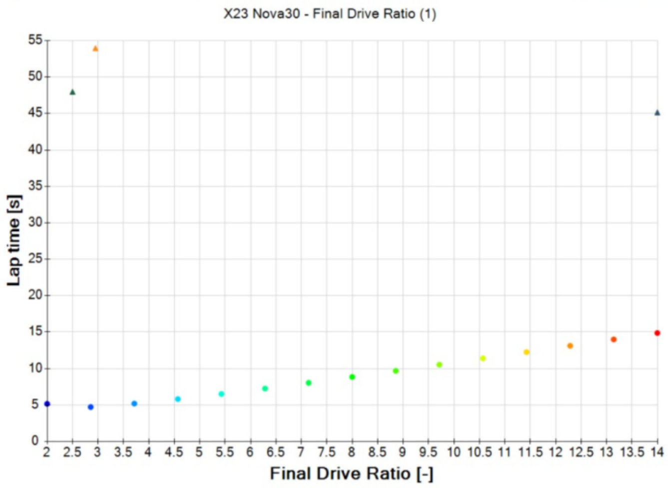

Figure 5 - Long Straight Nova 30 Times vs Drive Ratio

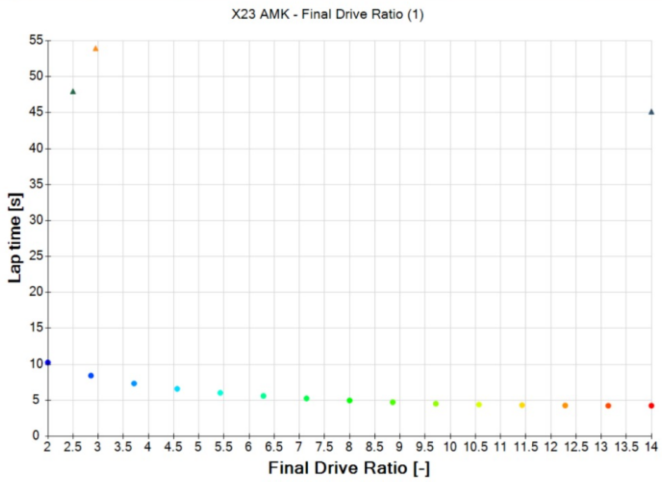

Figure 6 - Long Straight AMK Times vs Drive Ratio

These graphs show how we ultimately concluded that the AMK motors are better suited to our vehicle. Whilst the Nova 30 and AMKs are similar in performance, the lighter and smaller AMKs outshine the Nova 30, making them the best choice for this vehicle.

Regenerative Braking

Why regenerative braking?

Using regenerative braking allows for a smaller braking system on the rear wheels, saving on weight and space. It also allows for the race to be completed with an accumulator of lower capacity. This usually is tied to the mass of the accumulator meaning regenerative braking and help decrease the weight of the accumulator, which is usually one of if not the heaviest assembly in the vehicle. The efficiency of the vehicle is also increased as less energy is lost to heat in the form of friction during hydraulic braking.

Simulation Methodology

The source for simulation data to be analysed was the OptimumLap FSAustria 2012 lap. The most important data exported from OptimumLap for the purpose of regenerative braking was the “Engine Speed” (the motor speed) and the brake pedal position values. Ideally if OptimumLap allowed for it, the best data to use would have been the brake torque values. These datapoints however cannot be exported or viewed in OptimumLap. Therefore some validation had to be done to figure out how exactly the software was simulating braking. Through using various test tracks and test vehicles and analysing the data using a MATLAB script, it was determined that OptimumLap uses the friction coefficients of the wheels provided to the software, and assumes 100% brake pedal to be making full use of the friction of the tyre (right before slipping occurs). It was therefore possible, using the other parameters supplied to the software to calculate the brake torque at any point of the simulation, shown in figure 7.

Now that brake torque values were known, it was possible to find the current/power output of the motor during times of regenerative braking. Unfortunately the data provided by AMK for the torque and power characteristics are only available as graphs in a datasheet. As such, using software the graph was digitised and made available as a .csv file. This allowed for the graphs to be used in a MATLAB script. A script was written that used the brake torque and motor speed values to find the power output for every moment of braking in the simulation. Consider the battery voltage being 600VDC and figure 8 is obtained.

Simulation Results

Figure 8 shows how whilst more regenerative braking than figure 9 is possible, the vehicle is limited by the charging current of the cells in the accumulator being ~26A. The blue line, the max regen current possible, shows the maximum possible regen current at that moment in time based on the speed of the motor. As the possible current increases with the speed of the motor. If the vehicle was not limited by the charging current (if a better cell configuration was possible) then the amount of energy regenerated rises to 33.6483Wh or over 10%. The usage of peak charging current was considered but that would lead to a less predictable braking efficacy so was decided against.

Expected Energy Usage Per Lap:	326.8Wh
Estimated Energy Regenerated Per Lap:	23.5Wh
Estimated % Energy Regenerated:	7.2%

Table 3 - Expected regenerative braking figures based on OptimumLap simulation and MATLAB analysis.

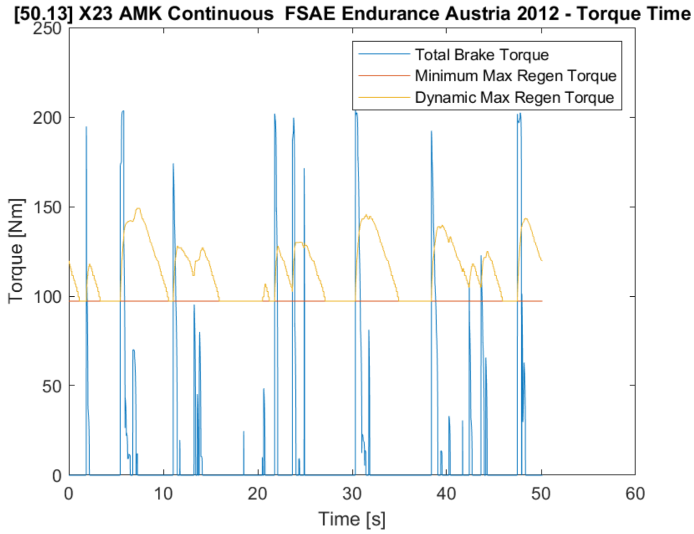

Figure 7 - Graph showing the amount of brake torque simulated and the amount of regen capable.

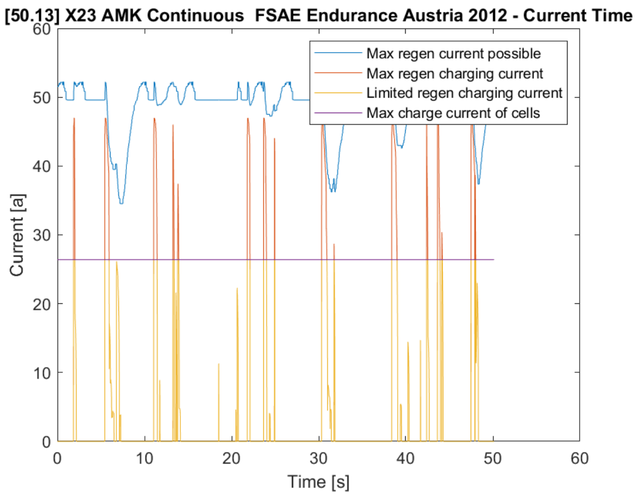

Figure 8 - Graph showing the regen current possible over the course of the simulation.

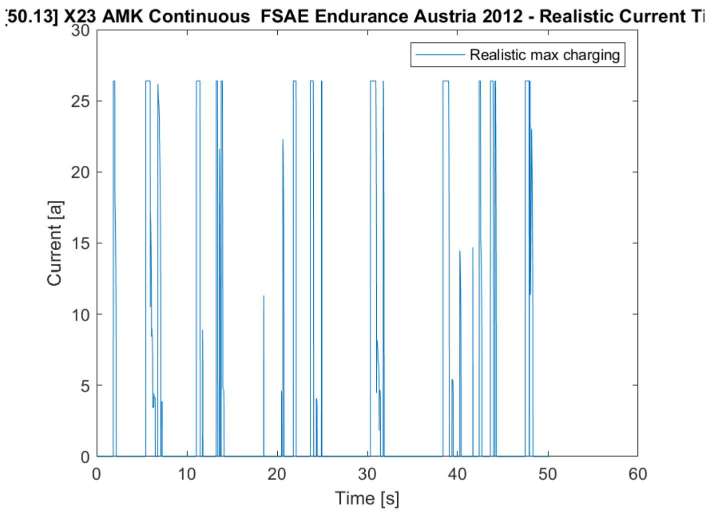

Figure 9 - Graph showing the expected regen current.

Final Design & Validation

Design Description

The final design utilises the AMK 2WD Racing Kit. This set up consists of two DD5-14-10 motors and one K26-S5 2WD inverter to go with them. The inverter behaviour is programmed prior to the competition and triggered via the CAN bus.

Since the AMK inverter does not come with an enclosure and has high voltage and low voltage components completely exposed, the construction of a custom enclosure is necessary, with the IO shown in figure 10 being available from outside.

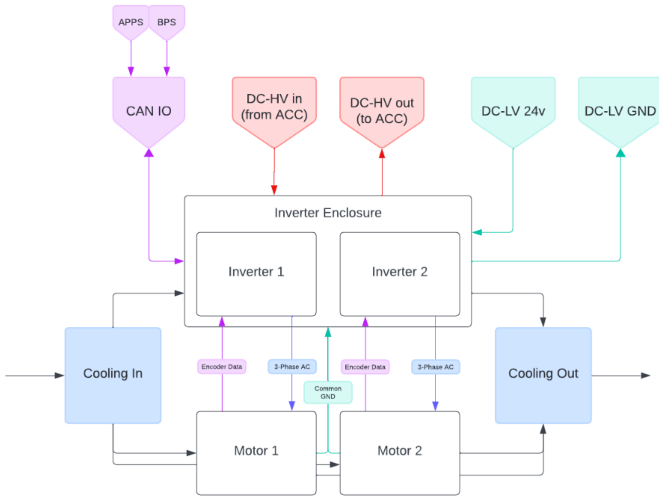

Figure 10 - diagram showing the input and outputs of the inverters and motors.

Purple – Data; Dark Blue – AC; Red – DC; Green – LV; Light Blue – Cooling;

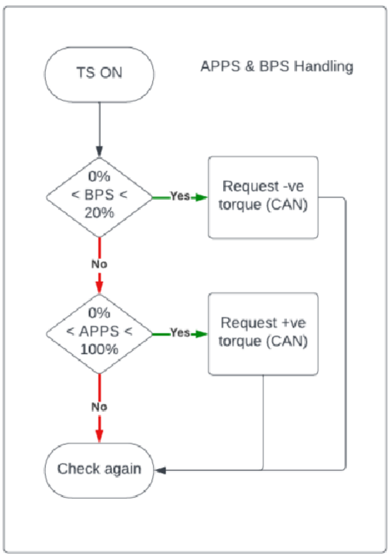

Figure 11 - Flowchart showing the handling of the driver interfaces (APPS & BPS).

Figure 11 shows how the brake and accelerator pedals are interfaced with the motors and inverters. In the diagram 20% is used as the limit for the regenerative braking, however that is a placeholder figure where the actual value would be the percentage of braking on the rear wheels which is done using regenerative braking.

CAD

Inverter

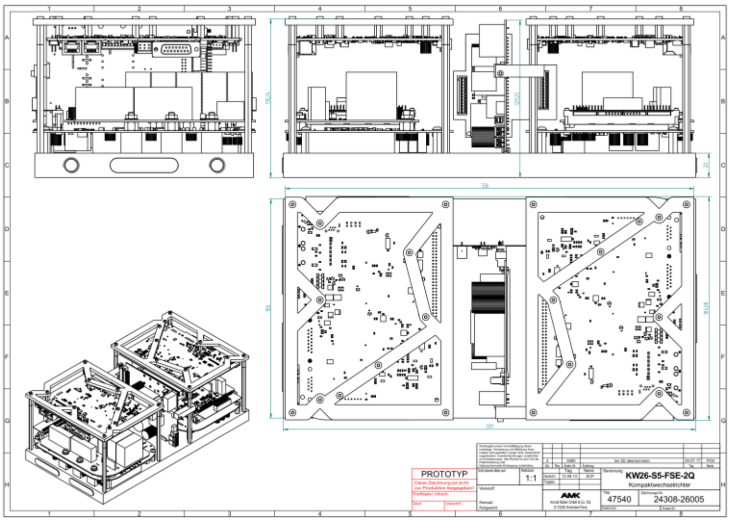

Figure 12 - Technical drawing of the AMK KW26-S5-FSE-2Q inverter.

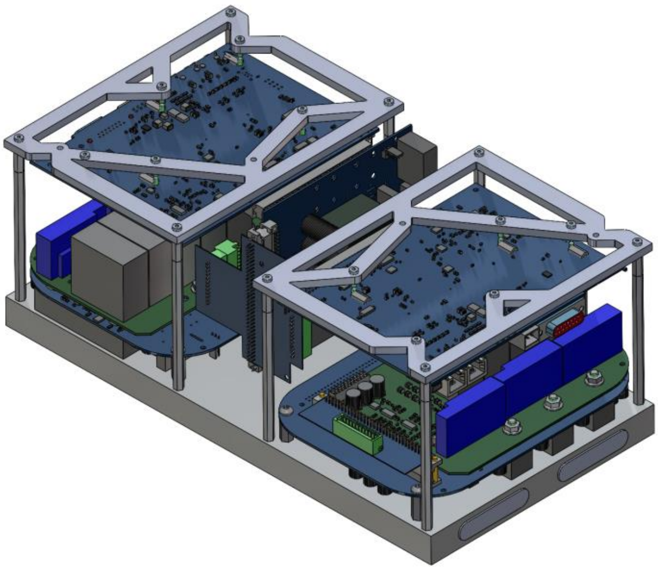

Figure 13 - CAD drawing of the inverter.

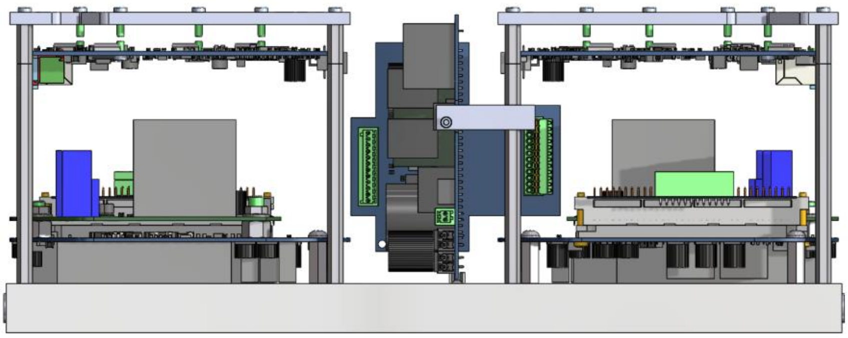

Figure 14 - Side profile of CAD file showing the 2 sides for each wheel.

Motor

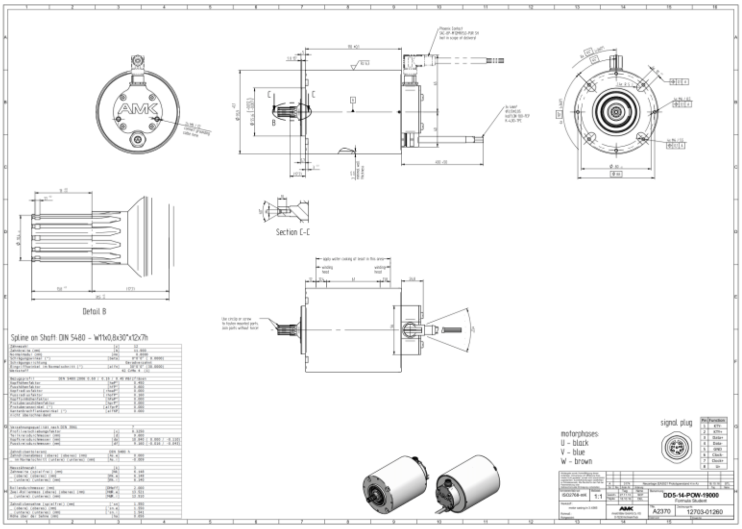

Figure 15 - Technical drawing of the AMK DD5-14-POW-19000 motor.

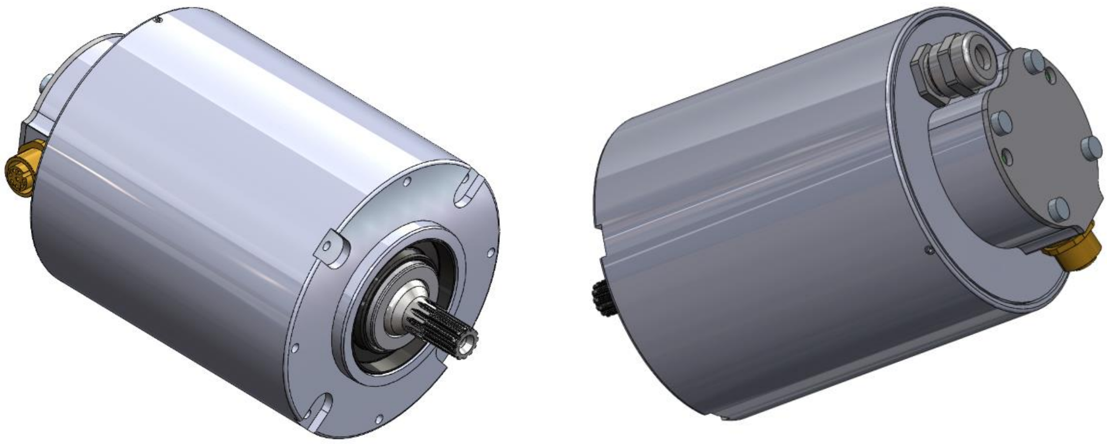

Figure 16 - CAD drawing of the motor.

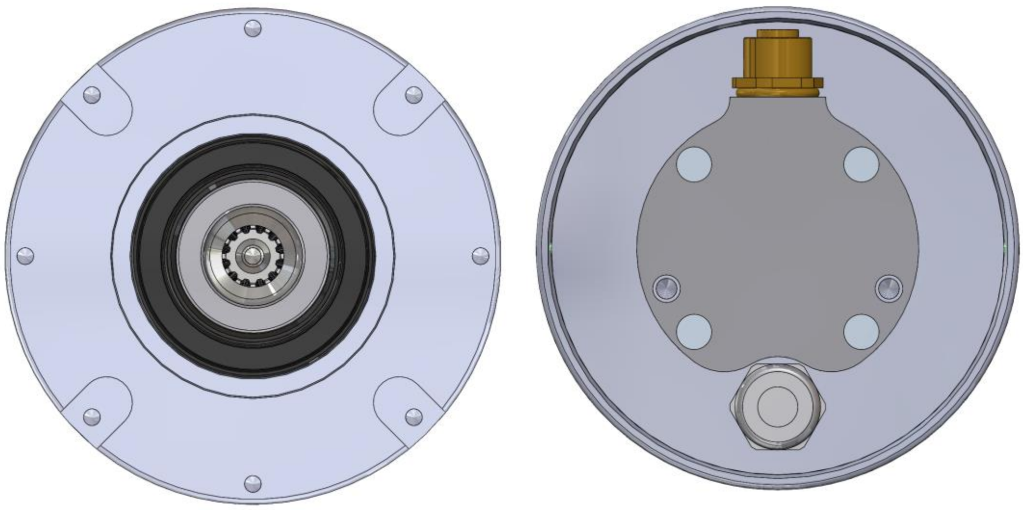

Figure 17 - Ends of the motor CAD.

Inverter Enclosure

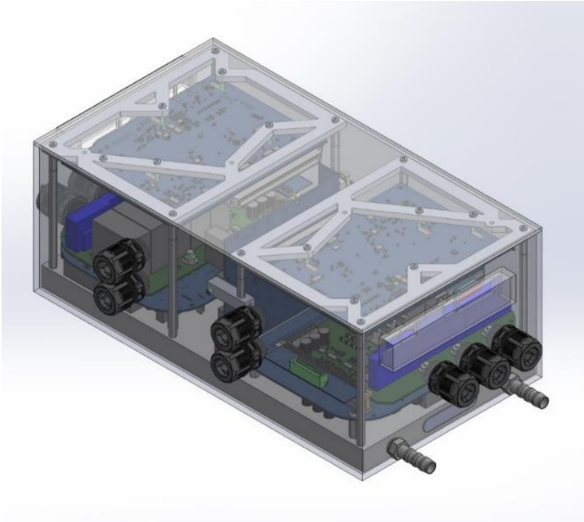

Figure 18 - Cad drawing of the inverter in its enclosure.

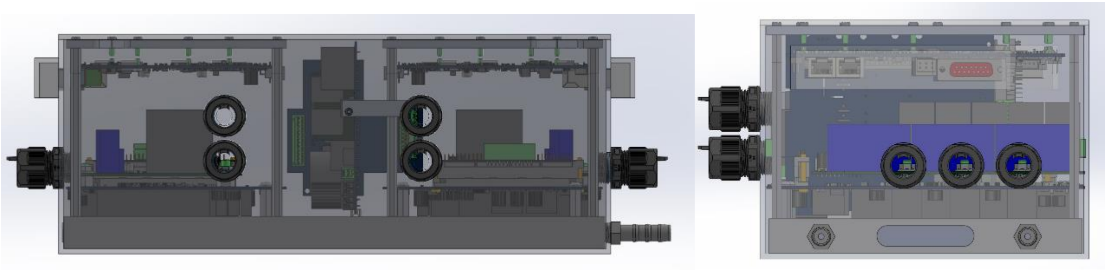

Figure 19 - Side profiles of the inverter enclosure CAD

M&I Subassembly

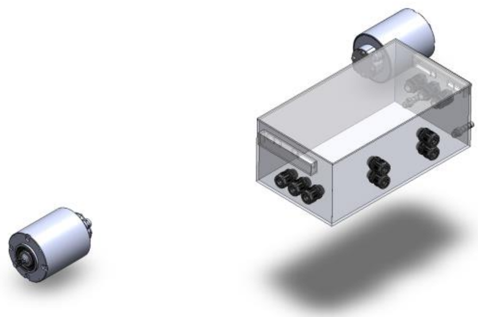

Figure 20 - Motors and inverter in correct place.

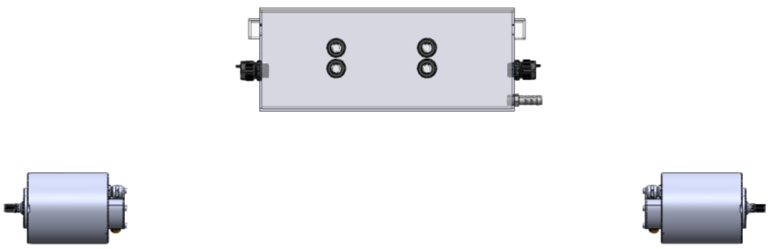

Figure 21 - Motors and inverter in correct place.

Justification

For the motor and inverter the choices are justified by the simulations graphed in figures 1-6. These simulations show the final choice of the AMK motor as the ideal choice. Ideally this would be justified by real world testing, however given the price of the motor and inverter this was not viable. The inverter enclosure meets the design criteria outlined earlier. It uses high voltage cable glands to ensure waterproofing and safe passage of high voltage cables through to the inverter, but also the barbed cooling connections to connect the inverter to the motor and inverter cooling solution.

Cost

The AMK FSE kit has an upfront cost of € 20,300.00. However it is reduced to € 15,650.00 with AMKMotion sponsorship. This cost includes the motor and inverter, software license for programming the inverter, a USB cable, training on using the kit for 2 people, and 10 hours of support by phone or email. The regenerative braking can be implemented for no extra cost. There would be some smaller costs manufacturing the inverter enclosure, for the materials and fittings used.

Manufacturing & Testing

Not much is required in the manufacturing sense with the motor and inverter. The only thing that needs “manufacturing” is the inverter enclosure, which given it is a box with holes in it for passing cables/pipes through, is not too heavy a task and can be done in-house. The motor and inverter themselves are ordered in from the manufacturer AMKMotion.

The only thing necessary for integration is the cables to connect everything together. The cables used will line up with what is used for the rest of the power electronics and HVP assembly. This is to prevent confusion and possible error which could lead to damage or harm. Testing for this can be done outside the vehicle before setting it up in the vehicle, to allow for easy debugging.

Evaluation

The final design achieves the goals set out in the problem and criteria well. It provides a high performance powertrain system whilst following all the rules set out in the FSUK 2024 rulebook.

Had there been more time and expertise on the team CarMaker simulations could have been prepared for the 3 final contenders for motor choice. This would have provided better simulation data than is provided by OptimumLap. The reason this wasn’t done was simply the lack of a proper CarMaker set up, meaning to test each motor configuration in the software would take too long.

The regenerative braking estimates are currently using the OptimumLap data to achieve the estimated power usage and estimated regenerated power. If there was a way to use data not from OptimumLap, such that more reliable brake torque data can be inputted into the MATLAB script, then more reliable estimates could be made. This could be via CarMaker or Assetto Corsa.