Control and Performance Testing of Two Electric Vehicle Motors

Martin Robenhagen van der Bijl (s164328), Jacob Bollerslev (s163909),
Kristian Sten Holst (s163946) & Ari Menachem (s163956)

Department of Electrical Engineering, Technical University of Denmark, Course 31015 Introductory project - Electrotechnology

Abstract—**This study seeks to investigate the control and performance testing of two EMRAX 228 permanent magnet synchronous motors controlled by two emDrive 500 motor controllers. The motors and drives will be implemented in a Formula Student Electric Vehicle. The performance of the motors has been verified through a load and no load test, which ensures that the performance is in accordance with the datasheet provided by the manufacturer. The load test both verifies the motor's efficiency and the linear coherence between the torque current and the motor torque. Furthermore, the gain parameters for the PI-regulator controlling the motor in torque- and velocity mode were adjusted to make the motors respond with an appropriate output for a given target input. The performance of the motors are found to be satisfactory and our results are in compliance with the producers datasheet.**

I. INTRODUCTION AND PROBLEM STATEMENT

In this introductory project, we are investigating the control and performance testing of permanent magnet synchronous motors in an electric vehicle. The overall goal is to design a race car for the Formula Student Electric vehicle (FSE) competition. In this competition, engineering teams from around the world design, develop and compete with their individual electrically driven race cars. Designing an FSE vehicle requires a significant number of different engineering and management skills. In addition to overcoming technical obstacles of controlling the motors, we will gain experience working as part of a large, interdisciplinary engineering team. The scope of this project is to design a system consisting of two motors and two motor controllers which can handle an input from the accelerator pedal and respond with an appropriate output. The motors of the type EMRAX 228 are able to separately provide a continuous output up to 42 kW, and the drives of the type - a pair of emDrive 500s - can separately support up to 60 kW. Throughout the report, the terms 'drive' and 'controller' will be used interchangeably. Each motor is connected to a drive, ensuring control of the motors. Each drive contains different standard set motor parameters, i.e. 'integrated velocity' and input controls for the motor torque. The motor torque is controlled by an integrated four quadrant control, which enables accurate control of both increasing and decreasing motor torque in both forward and backward motion. The EMRAX 228 motors and emDrive 500 motor controllers were selected as suitable components for the vehicle prior to the start of this project. The project aims to solve the following problems, ensuring that the motor control system in the electric vehicle is able to perform and fulfil the rules of the FSE competition.

– How are the EMRAX 228 motors and emDrive 500 drives physically set up to allow testing of the performance of the motors and drives?

– How do we set up two-way real time communication between the emDrive 500, EMRAX 228 motor and a computer?

– How is compliance between the performance of the motor/drives and the rules of the Formula Student competition ensured?

– How do we regulate the two EMRAX 228 motors to respond with an appropriate output for a given input?

– How do we verify that the performance of each motor is satisfactory?

II. FORMULA STUDENT

The Formula Student competition is an educational engineering competition finding its roots in industry and high-profile engineers. The competition itself aims to advance enterprising and inspiring engineering students, spurring talented young minds to study science and technology. Vermilion Racing is the team representing DTU for the 2018 Formula Student competition in the UK. Vermillion Racing is composed of 50 students, primarily studying mechanical or electrical engineering. The team is divided into subgroups, each with their own area of responsibility, and as a result a central part of the project has been the cooperation between the different subgroups.

A. Requirements

The requirements for the implementation of the motors in the electric vehicle are defined by the rules of the FSE competetion. As the vehicle to be designed is an electric vehicle, a special set of rules applying only to electric vehicles (EV) is considered. Within the rules two terms are introduced: The Grounded Low Voltage System and the Tractive System. The Tractive System is defined as every part that is electrically connected to the motors and Tractive System accumulators. The Grounded Low Voltage System is defined as every electrical part that is not a part of the Tractive System. The rules specify that only electric motors are allowed and that motors must be connected to the accumulator through a motor controller. Furthermore, the maximum power drawn from the accumulator must not exceed 80 kW. The maximum permitted voltage that may occur between any two electrical connections in the Tractive System is 600 V DC and for motor controller/inverters internal low energy control signals 620 V DC. Lastly, it is a requirement that Tractive System components must be protected from moisture in the form of rain or puddles [1].

III. COMPONENTS

The motors selected for the vehicle are a pair of EMRAX 228 Permanent Magnet Synchronous Motors (PMSM). EMRAX motors are developed for applications in aircraft or electric vehicles where the requirements for reliability are very high. The EMRAX motors are capable of delivering a high torque (and furthermore high power) at low rotational speeds. The PMSM is in principle a synchronous motor with the modification of replacing the field circuit with permanent magnets. This modification eliminates the rotor copper loss which causes the PMSM to have a very high efficiency. Furthermore, the PMSM has increased flux density in the air gap, resulting in increased motor power density and torque-to-inertia ratio. The lower rotor inertia ensures a fast response. In addition to this, the PMSM has a number of mechanical advantages, e.g. low noise and vibrations and a compact structure. Thus, the PMSM has great potential in demanding motion control applications [2]. The EMRAX motor ranks as the best high power density motor in the global market and is able to achieve a power density up to 10 kW/kg. Hence, the EMRAX 228 motor was deemed a suitable motor for the Formula Student electric vehicle.

The motors are the Liquid Cooled (LC) low voltage variant of the EMRAX 228. The motors are designed to have a maximal battery voltage of 130 V and a continuous motor power of 28-42 kW (at 3000-5000 rpm). The continuous motor current is rated to be 450 Arms. The design of the EMRAX 228 comprises an external rotor with six holes for mounting. The motor winding are of the three-phase star type [3].

The EMRAX 228 is designed to be used either as a motor or a generator. When operated by a motor controller, the performance characteristics in the generator mode is similar to the characteristics in the motor mode. Hence, the technical data and performance graphs are identical for the two modes. If the generator is operated without the use of a motor controller, the power and torque is approximately 50% lower, as there is no control of the electrical-mechanical angle. The technical layout of the EMRAX 228 appears in figure 1.

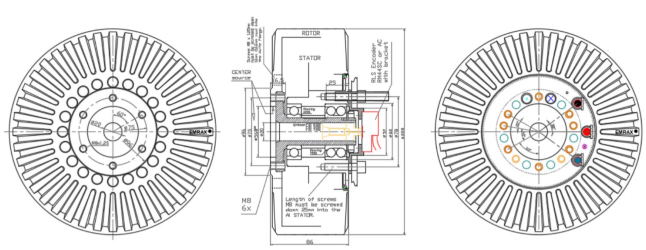

Fig. 1. Technical drawing of EMRAX 228 [3].

As specified in the ruleset each motor is required to be connected to the accumulator through a motor controller. The drives selected to control the motors (as recommended by EMRAX) are a pair of Emsiso emDrive 500 motor controllers. The emDrive 500 controller is designed to be waterproof if used along with the correct connector for input and output signals. The communication port of the emDrive 500 is compatible with the AmpSeal 35-pin connector. When using the emDrive 500 with this connector the drive achieves waterproof properties. Thus, the requirement regarding protection from moist is met. Remaining connections will be protected using insulating tape and heat shrink.

IV. PREPARING A MOUNT SUITABLE FOR TESTING

The EMRAX 228 motor is able to achieve a peak rotational speed of up to 6500 RPM. Thus, it is vital to properly secure the motors mechanically prior to any testing. Angular fittings were added to the solid metal plane constituting the ground surface of the test setup. While the two motors are not connected mechanically, there is no necessity for the motors to be parallel. However, this is a requirement when the motors are connected for load testing. This led to the decision of keeping the motor mounts parallel, thus securing stability. Four m8 threaded rods encased in steel pipes placed in each corner of the steel motor mounts were used to fasten the mounts to the angular fittings and to ensure mutual stability between the motors.

V. EVALUATION OF THE PERFORMANCE OF MOTORS AND DRIVES

A. Establishing communication between the motor controller, motor and encoder

In order to control the motor with the emDrive 500 the correct motor parameters must be programmed to the drive. This is done using the software emDrive Configuration Tool, provided by Emsiso [4]. Communication between a computer and the drive is facilitated through a USB-to-RS-232 interface.

B. Calibration of the motor and setting parameters in the drive

Calibrating the EMRAX 228 required blocking the motor, as the motor can not produce any torque if it is running freely. For blocking the motor, following ideas were considered:

1. Screw a metal bar to the motor and make a new angular fitting to the aluminium plane.

2. Make use of the existing structure, make a bar with holes and secure it diagonally to two threaded rods.

3. Use only one of the threaded rods to secure it.

Being a low torque setup, the most important criteria was easy manufacturability and thereby low production time instead of strength. An additional criteria was ease of mounting on the motor. A metal bar or using the existing structure both proved impractical and did not provide the necessary stability. The third solution was chosen, by loosening the threaded rods, and bolting the metal bar with three holes - two to fit to the motor and one for the metal rod. The block proved sufficient when tightened properly.

The parameters of the drive were set using an unofficial guide provided by Emsiso. The parameters set include 'motor rated current', 'number of motor poles' and 'motor rated torque'. The values were found in the datasheet of the EMRAX 228. The emDrive 500 enables the option to use the connected motor either in 'velocity mode' or 'torque mode' - using the motor as either a motor or a load, respectively. The drive utilizes a PI-regulator to control the motor in torque- and velocity mode. Recommended values for the P- and I-gain in both torque- and velocity mode appeared in the unofficial guide by Emsiso. Initially the motor was tested with these recommended values. The test showed that the recommended values for the velocity PI-regulator were sufficient, with a P = 8000 and an I = 10. However, the test showed that the recommended values for the torque PI-regulator had to be adjusted. The recommended values for the torque PI-regulator are P = 300 and I = 350. The adjusted values were P = 600 and I = 450. Figure 2 shows the test condcuted when setting the gain parameters for the torque PI-regulator. The goal was to ensure that the regulator's output matched the input.

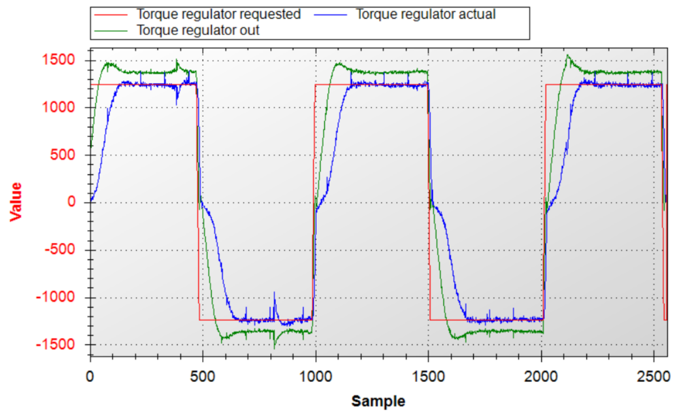

Fig. 2. Setting gain parameters for the torque PI-regulator as seen in the emDrive Configuration Tool [3]

C. Experimental investigation of the motor performance

The performance of the motors will be verified through a no load test and a load test. The test results will be compared with the values listed in the datasheet for the motor. To perform the tests on the two motors a solid setup has to be configured to keep the two motors in place while they are being operated either with load or no load. Therefore, the following setup has been created to carry out performance tests on the motors and drives. Furthermore, liquid cooling has been added to ensure that the motors and drives are not overheating. The setup is powered by an amplifier, set to 50 V DC and kept in an enclosed cage during operation. This avoids any potential danger in the form of human contact with the wires or if something breaks loose while the motors are spinning. When performing the load test, one motor will drive the other, thus making one a motor and the other a generator. The generator is connected back to the motor, creating a feedback system. To accomplish this test a transmission shaft connecting the motor and generator has to be created. The following shows the different ideas for how to create this connection between the motor and generator.

1. Using a rectangular steel pipe with 6 holes in each site to fit into the motor.
2. CNC machine a connection.
3. 3D print a connection.
4. Use an industrial clutch with grip.

Initially the third solution was chosen because it saved time, compared to the second solution, which did not require any access to the workshop. Unfortunately, the material in the 3D print was too uneven, which made the connection between the motor and generator too unstable.

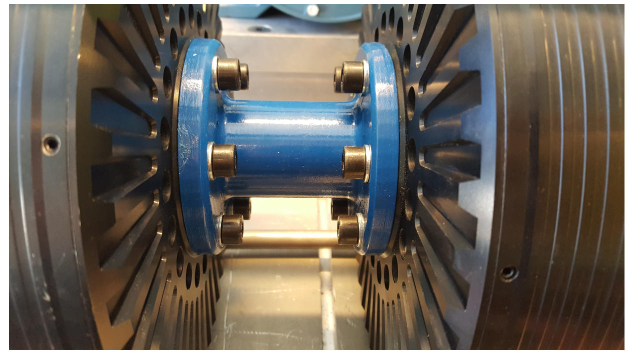

Fig. 3. A 3D print prototype was developed, but proved insufficient in precision

This led us to start considering producing one in a CNC machine. By utilising SkyLab facilities we manually constructed a new transmission shaft. An improvement was made to the connection, so it had a shaft in each site, going into the motor to ensure the connection would be precisely in the middle. The transmission shaft, a handmade aluminium rod, was made to 19.99 mm and the mating hole is 20.00 mm. In cooperation with the tool shop a change was made to the drawings. Instead of having a rod in the middle of the connection, a rectangle was added since is was much faster to process.

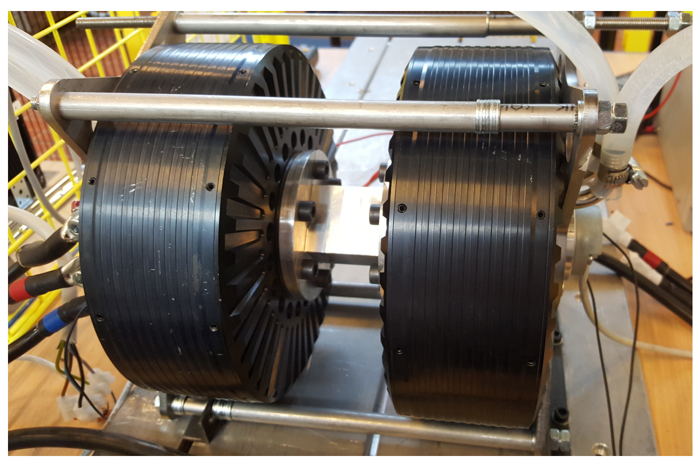

Fig. 4. Transmission shaft mounted on the final setup for the load test

The generator will act as a load, because it will be operated in a torque mode and the motor will be operated in a velocity mode where the motor is set to a target velocity, i.e. 500 RPM. When the load increases its torque, the motor will increase its torque the same amount to counter the load and maintain its target velocity, which results in an increase of current delivered to the motor, called torque current, I_q. The load test will also verify that there is a linear coherence between an increase in torque current and the generated torque by the motor. The load's increase in torque is done in intervals by changing its target torque in steps of 50. The target torque is a measure for how much current the load is drawing. Both motors are rated for 450 Arms, and the motor which acts as a load will have its target torque increase in intervals of 50. The required increase in motor current is given by the following equation:

$$I_{req} = \frac{targetTorque}{1000} \cdot 450\, Arms \tag{1}$$

The target torque is used to calculate a percentage, where a target torque equal to 1000 will make the motor draw its motor rated current, which is 450 Arms. The relation between the torque current and torque is given by the product of the motor's torque constant and the torque current. The torque constant for the EMRAX 228 motor is equal to the following:

$$K = 0.27 \frac{Nm}{A} \tag{2}$$

This torque constant is used for a low voltage setup and can be found in the datasheet for the motor.[3] The setup when implemented in the FSE vehicle will be supplied by a 130 V DC battery and this is considered a low voltage in the datasheet. The torque applied by the motor is then given by:

$$\tau = I_q \cdot K \tag{3}$$

Some of the input power to the motor is lost both in the electrical wires and as rotational loss inside the motor. The output power from the motor will be transferred as mechanical power through the transmission shaft connecting the motor and generator and then it will be converted back to electricity in the generator. The power that the generator creates is then fed back into the motor, through the feedback. The amplifier will only supply the motor the amount of power which is lost in the wires and as rotational loss in the motor. This setup makes it possible to verify the motor's efficiency, which according to the datasheet for the EMRAX 228 motor lies between 92-98% [3]. The motor will be tested at different speeds, 500-, 750- and 1000 RPM at different loads. The power and current delivered to the motor will be measured by a power analyser. The power analyser is also used to calculate the rotational loss in the motor at the different speeds.
To calculate the rotational loss in the motor, named M1 the generator will be used as a motor and referred to as M2 in the following. The amount of power delivered to M2 with M1 connected to it via the transmission shaft will be measured. M2 will then be operated in velocity mode and M1 will be operated in torque mode with zero torque, meaning M2 is seeing no load except from the amount required to rotate M1. Afterwards the connection between M1 and M2 is removed and the power delivered to M2 is then measured again. The difference in the power delivered to M2 is then equal to the amount of extra power needed to simply rotate M1. This extra power is considered a loss, referred to as $P_{rotational}$ because it is converted to rotational energy instead of electrical energy. The rotational loss will be different at each speed, so the measurements have to be done at 500-, 750- and 1000 RPM. Furthermore, there will be a loss in the three phase wires, which has to be accounted for. The resistance of the wires will be calculated with the following equation:

$$R = \frac{\rho\, L}{A} \tag{4}$$

Where, ρ is the resistivity of the cobber wire, which is $\rho = 0.0225 \cdot 10^{-6}\ \Omega \cdot \text{m}$ and L is the length of the wire in meters, and A is the cross sectional area of the wire in square meters. Each phase wire has a length of 0.7 m and the cross sectional area of each phase wire is 50 mm^2, which results in the following resistance of each wire: $3.15 \cdot 10^{-4}\ \Omega$.

The loss in each phase wire is given by the following:

$$P_{wire} = I_q^2\, R \tag{5}$$

The efficiency of the motor can then be calculated by the following:

$$\eta = \frac{P_{in} - 3\, P_{wire} - P_{rotational}}{P_{in}} \tag{6}$$

Where, P_{in} is the input power delivered to the motor, P_{wire} is the cobber wire loss and $P_{rotational}$ is the rotational loss in the motor. P_{wire} is multiplied by 3, since there are three phase wires, each with the same loss. The efficiency of the motor will then be calculated for every increase in load, because the torque current and hence input power changes.

D. Load test of the motors

The following result was acquired from the test where the motor was operated at 500 RPM.

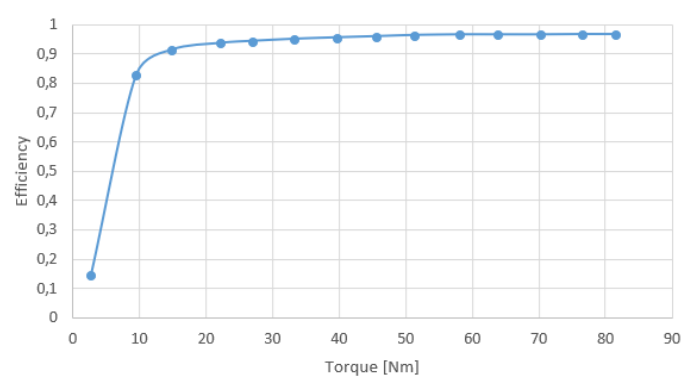

Fig. 5. Efficiency of the motor at 500 RPM

It can be seen that the first measurement in figure 5 gives a low efficiency at around 12%, however, the motor sees no load except the amount required to rotate the load. After a small increase in load, from 2 Nm to 9 Nm the efficiency increases significantly to 82%. The efficiency continues to increase and saturates at around 96%. The next test was conducted at 750 RPM, and the following result was acquired.

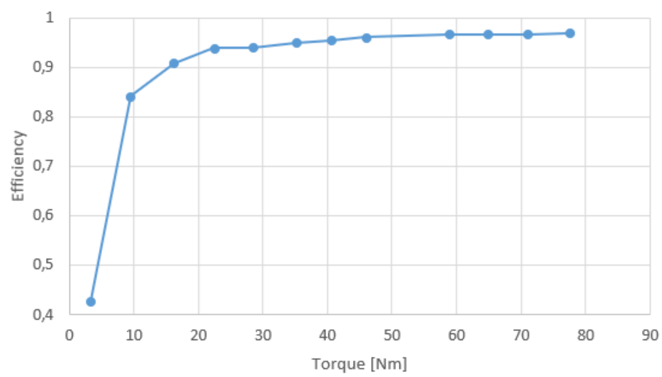

Fig. 6. Efficiency of the motor at 750 RPM

The first measurement in figure 6 shows the same result as the test at 500 RPM. The efficiency of the motor is quite low when there is no load on the motor. The first measurement is around 2 Nm, which is simply the amount the load is exerting on the motor when it is being rotated. The last test is conducted at 1000 RPM as seen in figure 7. However, for all speeds tested the efficiency saturates at around 96%, and according to the datasheet for the EMRAX 228 motor, the efficiency lies between 92-98%. Furthermore, an electric motor is more efficient at higher loads due to the majority of the input power at low loads are used to overcome the rotational loss. However, for higher loads the torque current increases, and thus the input power increases which means that the losses will have a less effect on the efficiency of the motor.

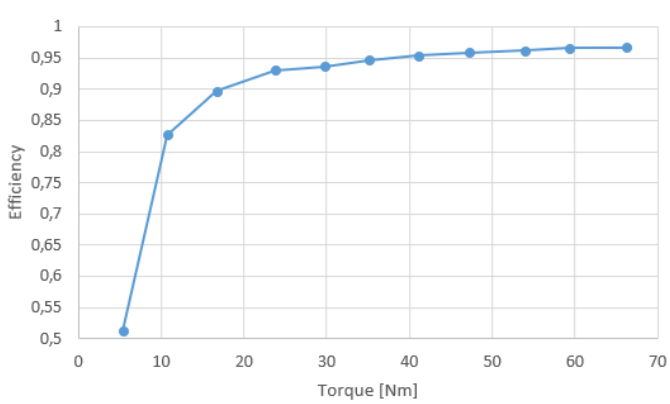

Fig. 7. Efficiency of the motor at 1000 RPM

This is clearly seen on the three graphs, because as soon as a small load is applied, around 9 Nm the efficiency of the motor increases significantly. However, the efficiency will reach a peak as seen on the graphs. Eventually the motor will reach a stall torque if the load is continued to being increased, which results in the motor stalling. This setup was limited to 300 Arms because when the motors are implemented in the FSE vehicle, the shared amount per motor will be 300 Arms, because the batteries supply 600 Arms. This also means that only one motor is able to reach its full potential, which it requires 450 Arms to reach, resulting in the other motor being supplied 150 Arms. Furthermore, the motors never reach an output of 80 kW, because the batteries maximum can supply 600 Arms, and their voltage lies between 100-130 V, which gives a total maximum output of 78 kW. Moreover, this test showed that the motor was able to provide a torque of around 70-80 Nm depending on the speed when reaching a torque current of 300 Arms. The continuous torque for a speed of 500-, 750- and 1000 RPM is around 110-120 Nm according to the datasheet[3], which means that our tests were below the continuous values, however, these tests still proved that the motor has an efficiency between 92-98% as stated in the datasheet. Furthermore, these tests show that there is a linear coherence between the torque current, I_q and the torque produced by the motor. The following graph show the linear coherence between the torque current and the torque at the different speeds. This linear coherence between the motor torque and torque current can also be found in the datasheet for the EMRAX 228 motor. As seen during the tests, when the torque current increases the torque produced by the motor increases, and the torque constant creates the connection between these two values, which gives the equation which was introduced earlier. The datasheet for the EMRAX 228 motor also contains a similar graph as figure 8 showing the relation between the motor torque and the torque current, and it also shows a linear coherence between the two. However, as seen on the graph in the datasheet[3] when the torque current exceeds 300 Arms and the motor torque exceeds 200 Nm the coherence between the motor torque and torque current no longer is linear.

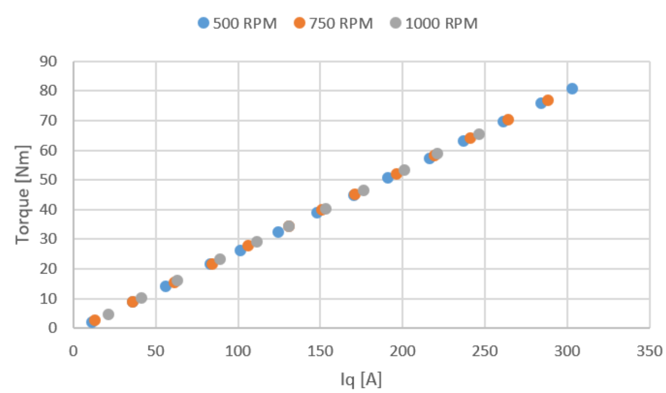

Fig. 8. Linear coherence between motor torque and torque current, I_q at 500-, 750- and 1000 RPM

E. No load test of the motors

The following test was conducted to test how much current each motor would draw with no load connected to the motor. The amplifier used for this test could only supply up to 30 Arms, which limited the speed of the motor to 1400-1500 RPM. As seen from the two graphs drive 2 is drawing a higher current and supplying the connected motor with a greater current compared to drive 1. As seen on the graphs the difference between the drives occurs when the motors are set to 1000 RPM. This might have an impact on the final system, when the drives and motors are implemented in the FSE vehicle. Either the drive is faulty or some of the settings inside the drive are set incorrectly. However, we verified that the two drives had the same settings in the emDrive Configuration Tool, which means that it is unknown as to why one drive is drawing a higher current after the motor exceeds 1000 RPM.

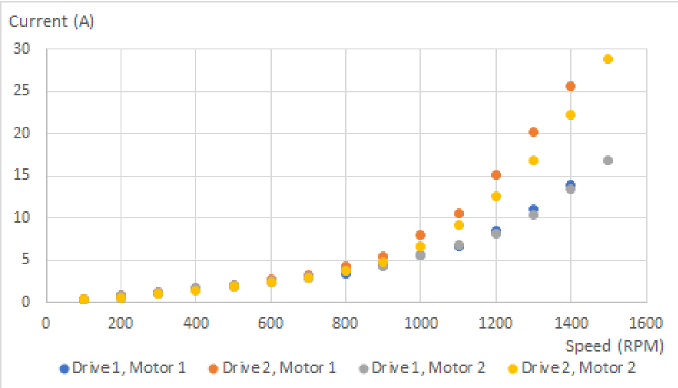

Fig. 9. Current usage by drive and motor at varying RPM

VI. DISCUSSION

To further investigate the motors and drives it would be rewarding to conduct further testing on the physical setup. To enhance the quality of the data, the same tests could be done on both motors and controllers. This approach would ensure that every possible variation would be accounted for. Moreover, in the setup of the controller and motor, we introduced a PI-regulator to guarantee an appropriate output for a given input. The designed regulator was able to follow a step input, which indicates that it can follow any input. However, when the controllers and motors are implemented in the FSE vehicle a ramp input should be supplied instead of a step input. This will give a much more controllable increase in output, i.e. speed, instead of it being an instantaneous change in speed. The instantaneous change in speed will result in a high acceleration and will cause wheel spin, which is not desired.

VII. CONCLUSION

The physical test setup was implemented using the integrated steel motor mounts, angular fittings and threaded rods encased in steel pipes. Stability when spinning the motors was ensured by mounting the motors perfectly parallel to each other. Real time communication between the motors, drives and a computer was achieved using a USB-to-RS-232 connection along with the emDrive Configuration Tool. It is confirmed that the motors at no point will reach an output power of 80 kW as the batteries are capable of supplying up to 600 Arms, and due to their voltage lying in the range of 100-130 V DC, giving a total maximum output power of 78 kW. Waterproof properties of the Tractive System are ensured as the drives with AmpSeal 35-Pin connectors mounted are waterproof. Additional connections are secured using insulating tape and heat shrink. The PI-regulator controlling the motor in torque- and velocity mode has been regulated and is able to respond with an appropriate output for a given target input. The torque mode regulator gain parameters were determined as $P = 600$ and $I = 450$. The velocity mode regulator gain parameters were determined as $P = 8000$ and $I = 10$. Furthermore, the load tests showed that the motor's efficiency saturates at around 96%, which agrees with the stated efficiency in the datasheet, 92-98%. Finally, the load tests showed that there is a linear coherence between the torque current and motor torque.

ACKNOWLEDGEMENT

The authors wish to thank Nenad Mijatovic for his technical assistance. Furthermore, the authors wish to express a special thanks to Bjarni í Dali and the PowerLab technicians. Lastly, thanks to the Formula Student Electric DTU - Vermilion Racing team.

REFERENCES

[1] Institution of Mechanical Engineers, 'Formula Student Rules 2018', 2018. [Online]. Available: `http://www.imeche.org/docs/default-source/1-oscar/formula-student/fs-rules_2018_v1-1.pdf?sfvrsn=2`. [Accessed: 19- Jun- 2018].

[2] A. Emadi, *Advanced Electric Drive Vehicles*. 2015, p. 147.

[3] EMRAX, 'User's Manual for Advanced Axial Flux Synchronous Motors and Generators', 2017. [Online]. Available: `http://emrax.com/wp-content/uploads/2017/10/user_manual_for_emrax_motors.pdf`. [Accessed: 19- Jun- 2018].

[4] Emsiso, *Starting with emDrive*. [Unofficial].