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DEVELOPMENT OF A MODULAR AND SCALABLE HYBRID ELECTRIC CROSS DRIVE TRANSMISSION

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ABSTRACT

The paper presents the EMX Hybrid Electric Cross Drive transmission developed by Kinetics Drive Solutions to satisfy RCV as well as conventional tracked vehicle requirements. Key design characteristics are modularity to enable performance customization, scalability to suit various vehicle weight classes, and flexibility to adapt to latest advancements in electric motor/inverter technology and autonomous control. EMX1000 prototypes have been built and are currently undergoing testing on dyno as well as in vehicle. Future development includes refining the prototype design and scaling the design for a heavier weight class.

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1. INTRODUCTION

Most prototype vehicles in the Robotic Combat Vehicle (RCV) sector are currently using simple reduction boxes that often cannot meet performance requirements due to lack of multiple gear ranges and regenerative steering. To determine the requirements for EMX, existing products were benchmarked and potential customers for the RCV and similar programs were consulted. Through this exercise, it was apparent that there was a largely unfulfilled need for an electric cross-drive transmission in several weight classes, the most urgent of which being the 10-15 metric ton class applicable to the US RCV-M program.

The advantages as well as technical challenges of hybrid electric vehicle (HEV) technology in military vehicles are well documented [1,2]. The key advantages for hybridization are:

- Increased availability of on-board electric power
- Improved fuel economy
- Improved vehicle design flexibility
- Silent watch capability
- Silent mobility

The key technical challenges that are being actively pursued and reduced by industry are:

- High operating temperature electronics
- High energy density storage devices
- High torque and power dense traction motors

The EMX was designed to provide the vehicle integrator with an architecture capable of achieving all the potential advantages of hybridization with the flexibility to adapt as the technical challenges are overcome. The EMX is represented by Motor 1 and Motor 2 in the series hybrid architecture shown in Figure 1. The EMX can also be utilized in a fully electric vehicle without a generator.

The EMX1000 uses two electric motors to provide both propulsion and differential steering of the vehicle. The electric motors are controlled by two inverters that are connected to a DC Bus that provides the DC power for propulsion and steering. The average speed of the two motors affects the average speed of the two transmission outputs to provide propulsion, while differentiating the speed of the two motors affects the differential speed of the two transmission outputs, affecting steering.

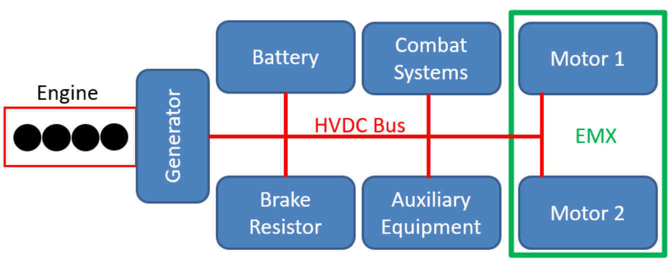

Figure 1: Series Hybrid Architecture.

2. EMX ARCHITECTURE

This is where KDS saw an opportunity and developed the EMX design architecture that is modular and can scale from 10-60T vehicle weight classes. The modular architecture shown in Figure 2 consists of a Core assembly containing the gear train and clutches. The Core assembly would be common within a given vehicle weight class. For example: 10-20 ton, 20-40 ton, and 40-60 ton classes would each be based on a common Core assembly scaled appropriately for the weight class. Figure 3 demonstrates two potential core assemblies, one a lighter

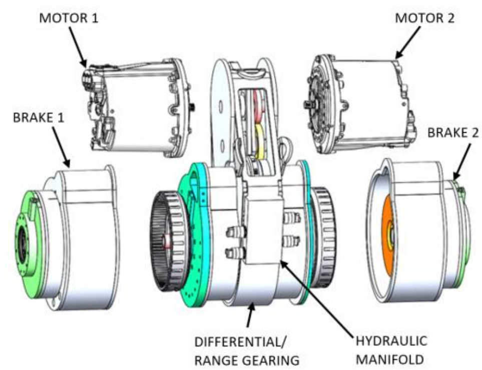

Figure 2: EMX Modular Architecture.

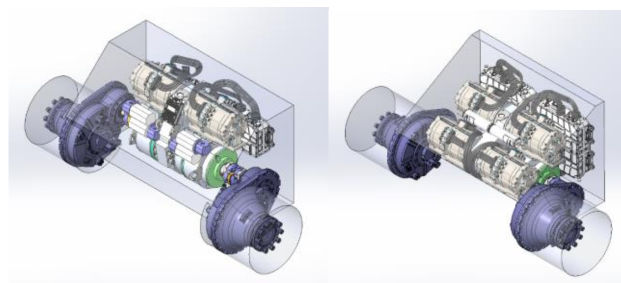

Figure 3: EMX Scalable Architecture.

model with one pair of propulsion motors and the other a heavier variant with two pairs of motors. Mounted to the Core are brake assemblies and electric machines that can be scaled for the particular vehicle size.

One of the key benefits of the EMX design is that it does not require dedicated steer motors, saving the cost and weight of 1 or 2 additional electric motors and inverters that would sit idle or lightly used during the majority of driving. As shown in Figure 4, the drive motors are connected through a differential which divides their drive torque between the range gearing and a conventional double-differential regenerative steering system.

The drive motors are geared directly to their respective steering planetaries, so full steering torque is always available to the outputs regardless of which range the gearbox is operating in. This gearing path doubles as the first range reduction. In higher ranges, the average speed of the drive motors is passed through the center differential into the range gearing and added to the outputs by the steering planetaries.

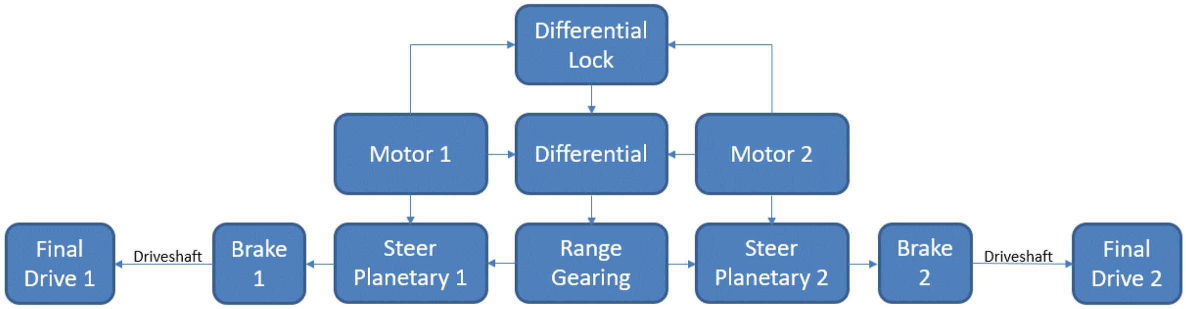

Figure 4: EMX Gearing Architecture.

Steering is initiated by varying the speed of each drive motor. When driving straight in any range the drive motors operate below their maximum speed, so the motor connected to the outside track in a turn can be sped up to initiate the turn. If a single drive motor fails, the vehicle can still limp home using a differential lockup clutch that can be engaged to lock both motors together. This allows the vehicle to drive straight using only one drive motor. As the control software is capable of using the brakes as a redundant steering backup, the two service brakes can then be applied independently to steer the vehicle.

The Core assembly contains a multi-speed powershift gearbox which allows smaller motors to be used while maintaining sufficient tractive effort capabilities (typically 0.7*GVW continuous, 0.9*GVW peak single sided) and top speed (typically 72 km/h). The EMX1000 prototype utilizes a 3-speed gearbox, but the architecture is easily adaptable to include a nearly unlimited number of intermediate ranges.

Another key benefit to the EMX design is that it is motor/inverter agnostic. It is well understood that there is still need for improvement in motor technology to achieve the desired performance in the full range of operating conditions [1,2]. The motor mounting plates are modular and thus allow the best suited motors for an application to be incorporated as shown in Figure 5. The gear ratio to these motors can also be configured easily to utilize the full performance of a given motor. This is important as it allows EMX to adapt to rapidly changing motor technology with minimal effort. It also facilitates adaptation to different vehicle configurations, supply voltages, etc. with significantly less effort than would be required for a more highly-integrated motor.

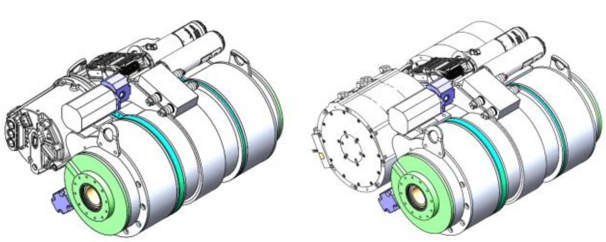

Figure 5: EMX Motor/Inverter Flexibility.

The EMX design is also capable of incorporating an in-line final drive into the brake assemblies, with either a coaxial or offset output shaft. As well, the transmission mounting arrangement at the outputs allows for the transmission to be rotated about its axis and mounted at the optimal angle for a given space claim.

3. CROSS DRIVE TRANSMISSION ADVANTAGES COMPARED TO INDEPENDENT SPROCKET DRIVE

Applications utilizing independent sprocket drives for the LHS and RHS tracks have the following disadvantages when compared to utilizing the EMX cross drive transmission:

1. If an element in one drive fails, only one track on the intact side can be driven to continue vehicle movement in the independent sprocket drive architecture.

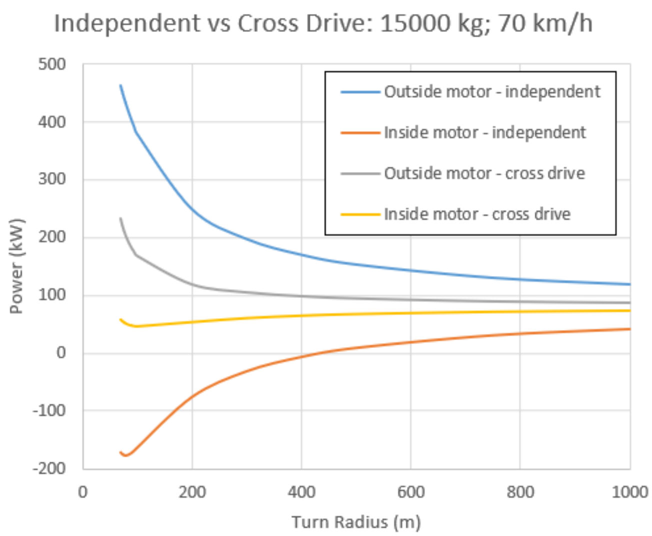

Figure 6: Power requirements of independent drives vs cross drive.

2. Motors need to be larger to independently provide the power required for steer events when compared to regenerative steering systems: Figure 6 shows a comparison for an example vehicle. In this case, the EMX architecture with cross drive steering allows reduction of propulsion motor power by more than 50% for a given turn radius compared to direct drive.
3. Steering becomes inefficient as the inside track must often be slowed down (power absorbed) to enable steering:
   a. Either the inside track must have a brake to slow it sufficiently (very inefficient), or:
   b. The inside track's motor becomes a generator (more efficient than a brake but losses occur turning mechanical power into electrical power, thru the power control unit, then back into mechanical power at the outside track's motor). This does occur in some operating conditions with the EMX cross drive but to a much lesser extent: Figure 6 shows that high speed turning generally does not involve one motor reversing torque.

4. SAFETY & REDUNDANCY

The EMX system incorporates several areas of redundancy to ensure safety and reliability as a drive-by-wire or autonomous system:

1. Redundant electronic control modules to ensure fail-safe operation: in case of failure of one controller, the other will assume control to either maintain mobility or safely stop the vehicle.
2. Redundant brake valves: a center brake circuit as well as independent left and right brake valves provide redundant service brake function. This also serves as a redundant steering backup while avoiding additional steering hardware, providing emergency differential brake steering in case of a motor failure.
3. Separate spring applied, hydraulically released park brake actuators provide emergency braking in the event of service brake failure or hydraulic supply failure.
4. Ability to operate at reduced performance with as little as one functional motor and/or one functional clutch.

5. POWER MANAGEMENT

In a series hybrid configuration with a common HVDC bus, power management is critical to ensure all of the various consumers receive the power required to perform their respective functions. Being the largest consumer, it is often necessary for the drive system to limit its draw on the batteries or the generator unit; however, the relationship between the torque output of the motors and the total DC power input of the system has many variables including motor speeds, battery voltage, temperature, etc. Ideally, to account for all the possible factors affecting input power, the power would be closed-loop limited, but direct closed loop of input power using torque is made impossible by the relationship of input power and speed, where changing motor rotation direction inverts the

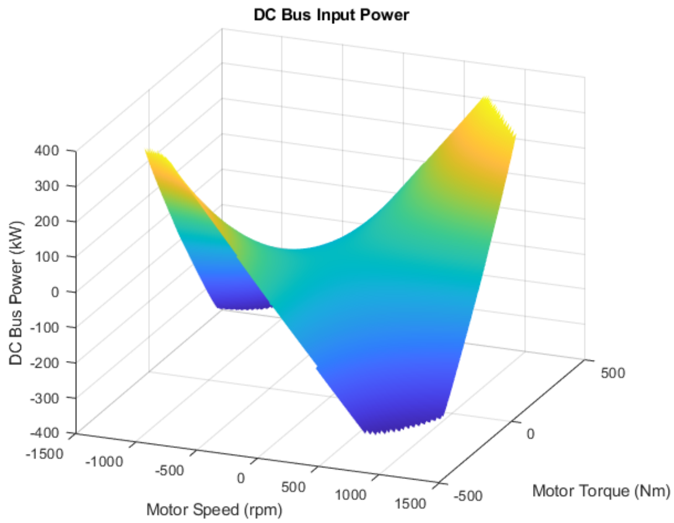

Figure 7: Motor Input Power vs Speed and Torque.

direction of the relationship between torque and power as shown in Figure 7.

A closer look at the relationship at and near zero speed shows the worst case for closed-loop control where input power increases both sides of zero speed due to motor efficiency loss. In this case, to close loop the

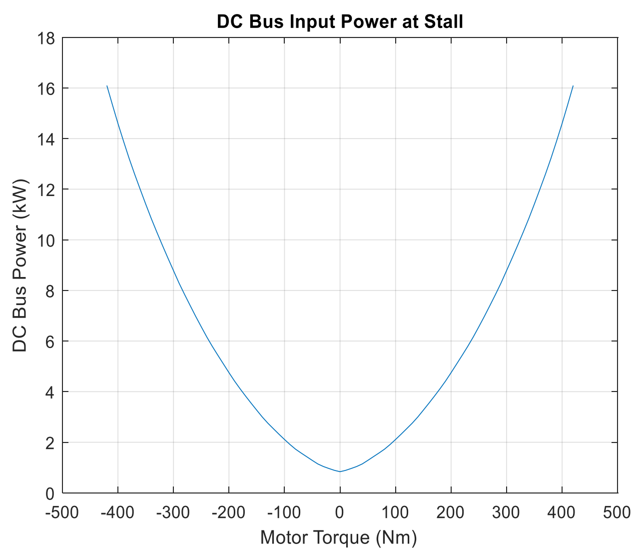

Figure 8: Motor Input Power vs Torque at Stall.

input power with torque above zero, positive gains are required, and if torque is below zero, negative gains are required as shown in Figure 8.

This issue is further complicated in the case of a cross-drive system where two motors manage two objective functions: steering and propulsion. It is necessary for a cross-drive system to provide priority to steering over propulsion. In some extreme cases, the steering demand can exceed the capacity of the HVDC supply. In these rare cases it can be advantageous to supplement the steering with differential braking, which the control must do instantly and seamlessly. Also, at very low speed it is desirable to prioritize a certain amount of power for the drive, to ensure the vehicle can maintain stationary holding.

To solve this issue and to be able to determine the correct motor torque limits as a function of an input power or current limit, the controller needs a way to account for the non-linear, 3-dimensional relationship between these variables.

To provide lookup tables with the accuracy required to achieve the input power limit would require a 5- or 6-dimension table, resulting in too large of a data set to be deployed on a typical micro-controller. To address this issue, the relationship between the DC bus input power, total torque, and differential torque of the motors was expressed as a polynomial, rather than just a lookup table, thereby enabling calculation of one variable as a function of the other two in real time.

To account for variation in efficiency caused by temperature, bus voltage, etc., the input power target is closed looped to ensure accurate power limiting. The final system structure with input power closed-loop, differential torque limiting, and total torque limiting is shown in Figure 9.

6. EMX CONTROL

Minimum inputs required from vehicle controller:

- Left Sprocket Speed and Direction
- Right Sprocket Speed and Direction

Or:

- Average output speed and direction

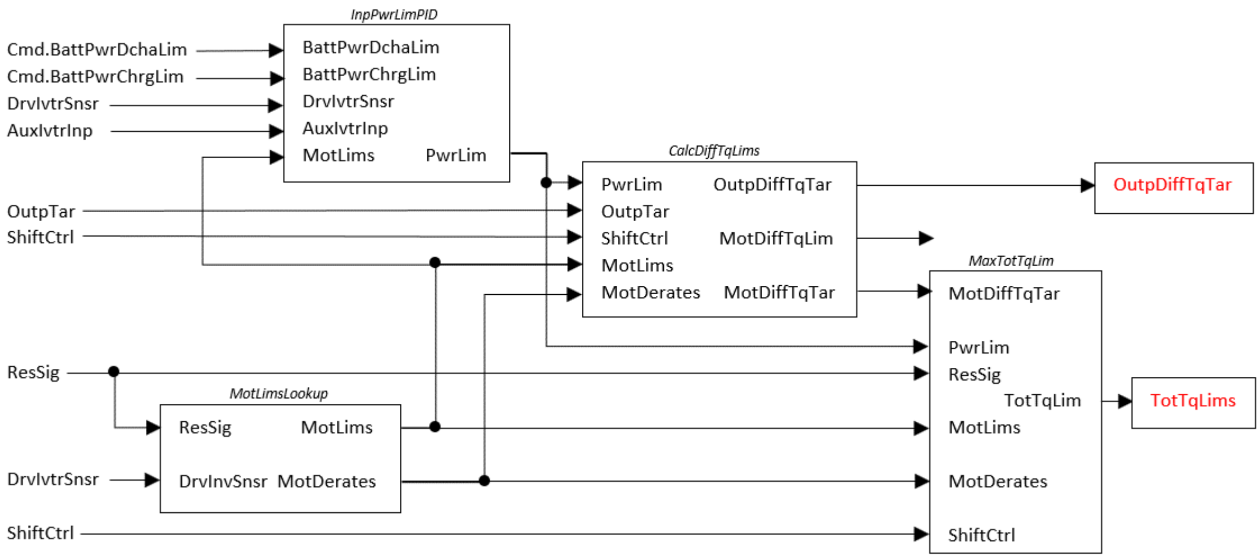

Figure 9: Power and Torque Limiting Module Structure

- Differential output speed and direction

Braking is automated to achieve the speed target. Regenerative and friction braking are coordinated based on power limit, battery state of charge, and available motor torques to achieve the desired output speed and differential speed commands

Optional inputs from the vehicle controller that can be used to provide additional functionality are:

- Vehicle Inclination
- Operating mode

7. PERFORMANCE

Prototype EMX1000 units have been built and tested on both transmission and chassis dynamometers as well as in the field. All functions have been verified and full endurance testing is pending. Performance on the dyno agrees well with initial simulations. Vehicle integration and testing is currently underway with a launch customer, with performance and controllability already exceeding the incumbent sprocket drive system. Figure 10 shows data from an example test run in the vehicle, with acceleration to approximately 65 km/h then a steering and braking maneuver. Figure 11 shows the EMX prototype installed in the KDS dyno facility.

8. DEVELOPMENT STATUS

The EMX1000 prototype is currently at TRL7 in a customer vehicle. Integration, testing, and tuning is ongoing.

The next development steps include refining the prototype design, as well as scaling the design for heavier vehicles (30+ tons or 60-70 tons).

9. CONCLUSION

The EMX Hybrid Electric Cross Drive transmission provides the vehicle integrator with a drive solution capable of all the advantages of hybridization with the flexibility to adapt as the technical challenges of HEV technology in military vehicles are overcome.

Key design characteristics are modularity to enable performance customization, scalability to suit various vehicle weight classes, and flexibility to adapt to latest advancements in electric motor/inverter technology and autonomous control.

EMX1000 prototypes have been built and are currently undergoing testing on dyno as well as in vehicle. Future development includes refining the prototype design and scaling the design for a heavier weight class.

10. INTELLECTUAL PROPERTY

Kinetics has filed for intellectual property rights surrounding this novel concept.

11. REFERENCES

[1]RTO applied vehicle technology panel. In All Electric Combat Vehicles (AECV) for Future Applications. Technical Report No. NATO RTO, TR-AVT-047, June 2004.

[2]P. Sivakumar, R. Reginald, G. Venkatesan, H. Viswanath, and T. Selvathai, “Configuration Study of Hybrid Electric Power Pack for Tracked Combat Vehicles,” Defense Science J., Vol. 67, No. 4, pp. 354- 359, July 2017.

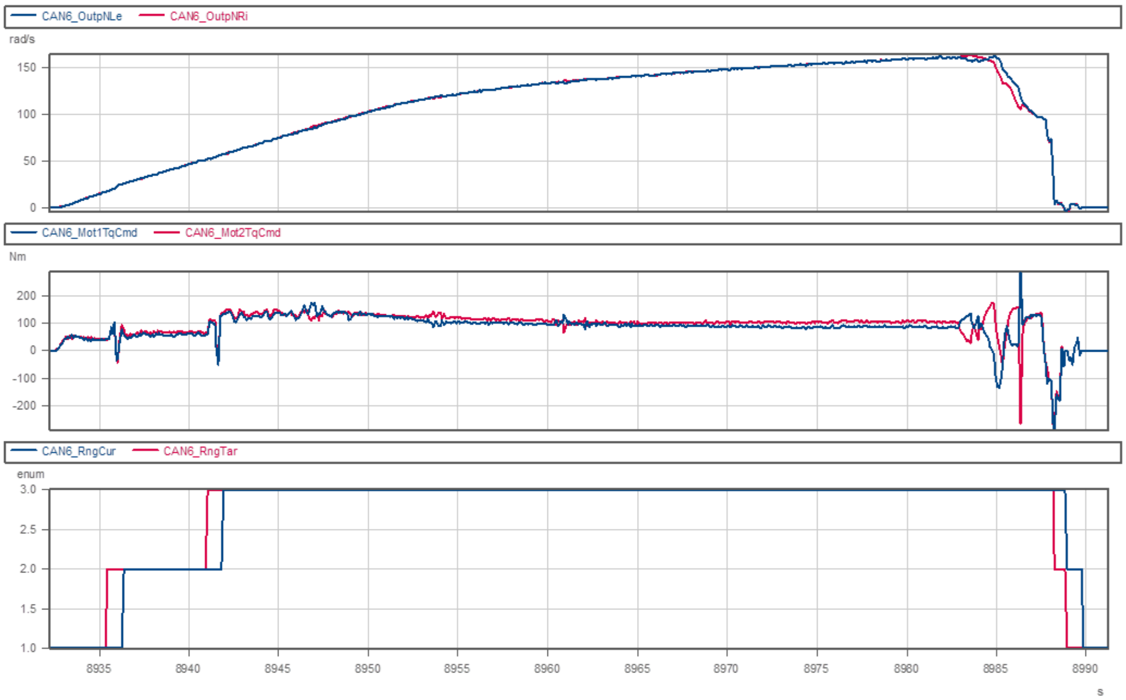

Figure 10: EMX1000 Vehicle test run.

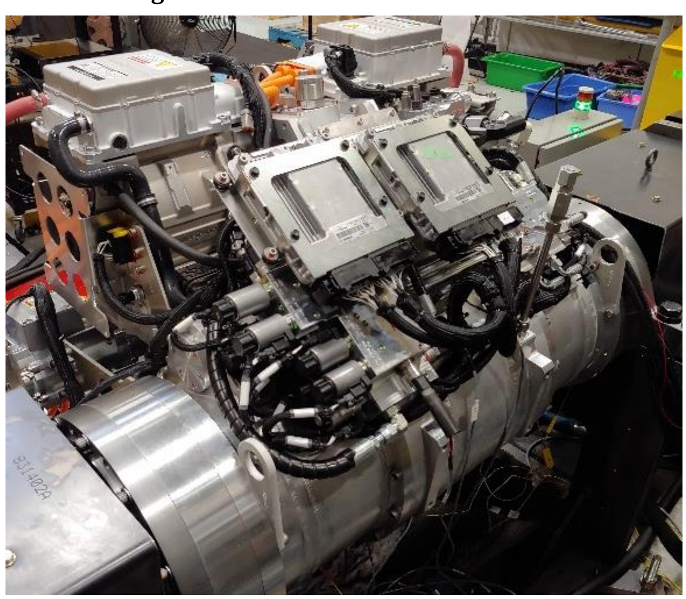

Figure 11: EMX1000 Dyno testing.