EM-TECH

D6.1 – Smart e-corner and Smart e-axle assembly

EM-TECH - Innovative e-motor technologies covering e-axles and e-corners vehicle architectures for high-efficient and sustainable e-mobility

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Partners List

Abbreviation	Long Version
AVL	AVL LIST GMBH
AIG	ARMENGAUD INNOVATE GMBH
ELA	ELAPHE POGONSKE TEHNOLOGIJE DOO
I&M	IDEAS & MOTION SRL

POLITO	POLITECNICO DI TORINO
TRX	TRAXIAL BV
TUIL	TECHNISCHE UNIVERSITAET ILMENAU
UBATH	UNIVERSITY OF BATH
URBANGOLD	URBANGOLD GMBH
USR	UNIVERSITY OF SURREY

Abbreviations

Abbreviation	Full Form
AC	Alternating Current
AFM	Axial Flux Motor
DC	Direct Current
E-Gear	Electrical Gearing Actuator
EM	Electric Motor
EVs	Electric Vehicles
GUI	Graphical User Interface
HEVs	Hybrid Electric Vehicles
HiL	Hardware-in-the-Loop
ICE	Internal Combustion Engines
IWM	In-wheel Motor
MABX	MicroAutoBox
MiL	Model-in-the-Loop
NVH	Noise, Vibration, and Harshness
PC	Personal Computer
SPARC	Systems Platform Advanced Real-Time Controller
STARS	System Test Automation Real-time Software
VPN	Virtual Private Network
XiL	X-in-the-Loop

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Publishable Executive Summary

1.1 Overview of project

The EM-TECH project is advancing electric machine technology for automotive application through innovative solutions designed to enhance performance, sustainability, and efficiency. The project focuses on advanced cooling systems, real-time virtual sensing, optimized machine control strategies, electric gearing for operational flexibility, and digital twin-based design incorporating life cycle considerations. Additionally, it promotes sustainability by utilizing recycled permanent magnets and circularity-driven approaches in electric machines and related powertrain elements. These project components will power next-generation radial flux direct-drive in-wheel motors and axial flux motors, delivering competitive torque and power densities. Targeting passenger cars and vans, with scalability to commercial vehicles, the project aims to reduce energy losses, cut reliance on rare earth materials, and integrate magnet recycling for an affordable and eco-friendly future in electric mobility.

1.2 Deliverable Objective and Results

D6.1 focuses on the integration and testing of two advanced powertrain components: the smart e-corner and the smart e-axle. The In-Wheel Motor (IWM) from ELA is integrated into the smart e-corner at TUIL and the baseline On-board Axial Flux Motor (AFM) is mounted on the powertrain test rig at USR. In parallel, a smart e-axle will be implemented at USR, while the dSpace Scalexio Rapid Prototyping system at TUIL will operate a virtual Vehicle model within a X-in-the-Loop (XiL) framework. This setup allows for distributed real-time simulation and control across both sites.

The experimental configurations will be equipped with comprehensive instrumentation—voltage, current, torque, temperature, and vibration sensors—to measure electrical and mechanical performance, thermal behaviour, and Noise, Vibration, and Harshness (NVH) characteristics. Control and monitoring will be coordinated through the dSpace platform and through a secure Virtual Private Network (VPN) connection between USR and TUIL. This work will result in Deliverable D6.1.

1.3 Deviations, Impact and Recovery Actions

The scope of the Model-in-the-loop (MiL)/Hardware-in-the-loop (HIL)/XIL test scenarios for the e-axle-based use cases has been updated to reflect the change in project partnership from VAIONIC to TRAXIAL. This transition led to the introduction of a newly designed AFM with revised technical specifications, which required corresponding adaptations in the testing approach. The integration of these changes resulted in a delay in the finalisation of the activities associated with this Deliverable, along with minor updates to the configuration of the experimental setup and the cooling system design.

Another deviation lies in the fact that TUIL received the IWM from ELA and e-gear system from UBATH, whereas USR, on the other hand, received from TRX the baseline AFM electric motor paired with an inverter module sourced separately from I&M.

Nevertheless, the e-axle assemblies remain valid and are fully adequate to demonstrate the successful integration of the TRX AFM, the virtual gear transmission system from AVL, and the powertrain test rig available at USR, in line with the project's technical objectives.

2 Introduction

This deliverable presents the integration and validation of a smart e-corner system at TUIL and a smart e-axle system at USR, within the framework of a distributed XiL testing environment. The XiL setup establishes a real-time connection between the two sites via a Virtual Private Network (VPN), enabling synchronized co-simulation using dSpace Scalexio at TUIL and dSpace MicroAutoBox at USR. The system-level simulation is based on a full vehicle model, allowing for comprehensive testing and evaluation of advanced electric powertrain components.

The e-axle implemented at USR consists of a baseline Axial Flux Motor (AFM) from TRX, a virtual gear transmission system developed by AVL, and a powertrain test rig equipped with detailed instrumentation. This includes sensors for electrical and mechanical power measurements, thermal monitoring, and vibration evaluation to indicate NVH characteristics. At TUIL, an In-Wheel Motor (IWM) provided by ELA is integrated into the existing smart e-corner platform. The communication infrastructure, secured using Cisco RV340 VPN routers at both sites, supports robust and reliable Ethernet-based data exchange.

The XiL methodology, employed in this collaborative initiative between USR and TUIL, facilitates remote testing of physical hardware within a synchronized virtual environment. This approach enables detailed system-level validation, supporting the iterative development of next-generation electric drivetrains.

Section 3 presents a Hardware-in-the-loop (HiL) testing facility at USR, including the test rig components description. Section 4 demonstrates the HiL testing of E-Axle with TRX AFM and inverter provided by I&M. Furthermore, the virtual gearbox model from AVL was compiled in the Simulink model test rig and introduced at USR. In Section 5, the cooling system design at USR for testing the AFM motor is fully illustrated.

In Section 6 the test rig setup for evaluating the e-corner system at TUIL is described in detail, including the configuration of the test bench and the various subsystems integrated into the testing environment.

Finally, Section 7 provides an in-depth overview of the XiL communication architecture via VPN, and the detailed communication demonstration between the USR and TUIL including the relevant signals.

3 Hardware-in-the-Loop testing facility at USR

This section provides an overview of the HiL test rig facility available at USR, detailing its key components and system architecture. The HiL setup is designed to support advanced testing and development activities, particularly in the context of electric powertrain systems. Following the general description of the facility, we focus on its specific application within the EM-TECH project, where it has been employed for the testing and validation of e-axle systems with TRX onboard AFM motor.

This facility is primarily employed to assess the dynamic performance, fuel consumption predictions, and steady-state efficiency characteristics of Electric Vehicles (EVs) and Hybrid Electric Vehicles (HEVs). It enables realistic simulation and analysis of electric and hybrid powertrain configurations under controlled laboratory conditions, effectively bridging the gap between simulation models and physical systems.

Figure 3.1 HiL test rig at the USR

Figure 3.1 illustrates the HiL test rig located at USR, which serves as a platform for evaluating automotive drivetrain systems.

The HIL test rig comprises of five key subsystems, each playing a critical role in supporting comprehensive drivetrain testing:

- **Dynamometers (dynos):** These apply controlled mechanical loads to the drivetrain, simulating real-world driving conditions to evaluate system response and performance.
- **Dynos Control System:** Responsible for managing the operation of the dynos, this subsystem ensures precise control of torque and speed profiles in accordance with test protocols.
- **Electric Power Subsystem:** Provides regulated DC power to the electric components of the drivetrain, simulating the energy supply from vehicle batteries or external sources.
- **Real-Time Simulation Platform:** Facilitates the execution of detailed vehicle and environment models in real-time, enabling accurate emulation of various driving scenarios and operational conditions.

- **Thermal Management System:** Comprising cooling units for the transmission, motor, inverter or engine, this system maintains desired temperature conditions, ensuring consistent and repeatable test environments for thermal performance evaluation.

This integrated facility represents a vital resource for advanced research and development in electric and hybrid vehicle technologies, supporting both academic inquiry and industrial innovation.

3.1 Dynos

The test rig includes **three asynchronous dynamometers** that are used to replicate the power input from an internal combustion engine (ICE) or an Onboard electric motor (EM) and road load conditions on vehicle wheels.

Each dyno within the test rig is equipped with high-precision torque and speed sensors, enabling accurate measurement and control of mechanical output. These dynos operate within a closed-loop control framework, ensuring real-time responsiveness and stability during testing procedures. When integrated with the real-time simulation system, this configuration enables detailed and reliable evaluation of drivetrain behaviour under a wide range of operating conditions. The dynamometers are controlled by the HORIBA system, which will be described in detail in the following section.

3.2 SPARC hardware platform

The Systems Platform Advanced Real-Time Controller (SPARC) is a versatile and high-performance hardware platform designed for a wide range of automotive and mechanical control applications. SPARC offers a scalable and flexible architecture capable of controlling up to five motors simultaneously within a real-time environment, making it well-suited for both simple and complex test scenarios.

The real-time capabilities of the SPARC system enable highly precise and responsive control during testing operations. By minimizing communication delays, the system ensures that data is processed and acted upon almost instantaneously. This rapid feedback loop is critical for applications requiring tight control tolerances, such as powertrain and brake testing, where even slight delays can impact accuracy and repeatability. Real-time communication enhances the reliability of test results and supports more efficient and effective development workflows.

3.2.1 STARS software

The System Test Automation Real-time Software (STARS) software serves as the central interface for configuring and controlling dynos within the HORIBA testing environment. It provides a script-based framework to define test routines, enabling users to specify control modes tailored to the requirements of each test scenario.
In a HiL configuration, integration between the dSpace system and the STARS platform is facilitated via Controller Area Network (CAN) communication ensuring synchronized operation across systems.

Communication between the SPARC controller and external systems is typically handled via Ethernet. This allows SPARC to connect either to a PC running a dedicated stand-alone graphical user interface (GUI) or to a PC equipped with the STARS software suite. In summary, The HORIBA control system integrates both hardware and software for real-time test management.

SPARC: A modular controller with real-time capabilities for managing up to 5 motors. It supports CAN and Ethernet communication and can operate standalone or with full automation via STARS.

STARS Software: Used to configure and control tests through a GUI. It allows custom scripting, control mode selection, and integration with simulation platforms such as dSpace via CAN interface.

3.3 Inverter Subsystem

Each motor is powered by a dedicated Emerson Industrial Automation inverter. These manage the DC-to-AC conversion, ensuring controlled power delivery. These inverters are integrated with the Dyno control system, which manages voltage and current profiles and interfaces with the control software. To enable accurate measurement and control during testing, the rig is equipped with high-precision torque and speed sensors. These sensors are essential for capturing real-time data that supports performance evaluation and control feedback.

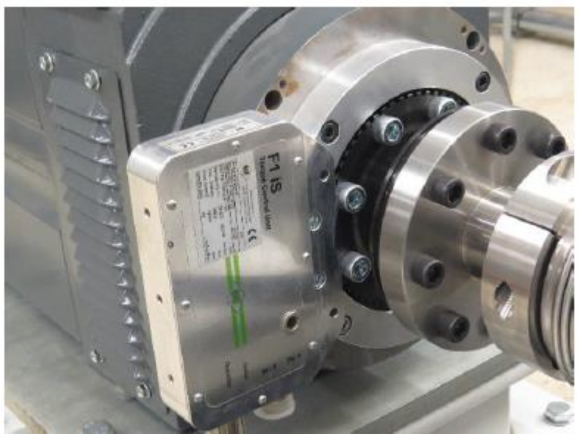


Figure 3.2 Torque sensor installed on Dyno 1 [1]

The torque sensor installed on Dyno 1 is illustrated in Figure 3.2, providing insight into its configuration and integration within the test rig. The specifications of the torque sensors used for the dynos are summarized in Table 3.1.

Table 3.1 Technical specifications of torque sensors installed on dynos [1]

Dyno	Rated Torque	Max Speed	Accuracy Class
Dyno1	750 Nm	10,000 rpm	0.2%
Dyno2	1900 Nm	12,000 rpm	0.1%
Dyno3	1900 Nm	12,000 rpm	0.1%

It is worth noting that Dyno 1 is equipped with a torque sensor rated for 750 Nm, which slightly exceeds the maximum torque capacity of the Dyno itself. In contrast, Dyno 2 and Dyno 3 are fitted with sensors rated at 1900 Nm. This variation reflects the differing performance characteristics and intended use cases of the individual dynamometers. Speed sensors are also installed on each dyno to monitor rotational speed during testing. Due to the differing operational speed ranges of the dynos, the maximum rated speed of each sensor varies accordingly. For example, Dyno 1 is equipped with a speed sensor rated for 16,000 rpm, while Dyno 2 and Dyno 3 are fitted with sensors rated for 6,000 rpm.

(a) (b)

Figure 3.3 (a) Speed sensor installed on Dyno 1 [2]; (b) Speed sensors installed on Dyno 2 and Dyno 3 [3].

The Figure 3.3 illustrates the speed sensors across the three dynamometers. In Figure 3.3(a), the high-speed sensor on Dyno 1 is shown, rated for up to 16,000 rpm to accommodate higher rotational speed requirements. Figure 3.3 (b) displays the sensors used on Dyno 2 and Dyno 3, each rated for up to 6,000 rpm, reflecting their lower operational speed ranges. The key specifications of these sensors are presented in Table 3.2.

Table 3.2 Technical specifications of speed sensors installed on Dyno 1, Dyno 2, and Dyno 3 [2].

Dyno	Max Speed	Output Signal	Operating Temp. Range
Dyno1	16,000 rpm	10–30 V	-10 °C to 100 °C
Dyno2	6,000 rpm	10–30 V	-20 °C to 80 °C
Dyno3	6,000 rpm	10–30 V	-20 °C to 80 °C

3.4 Power Supply Subsystem

The test rig uses a power supply from M&P GmbH that provides regulated Direct Current (DC) power for testing components. It can be controlled locally or remotely via CAN and includes status monitoring signals. The system features Alternating Current (AC)/DC and DC/DC converters that manage voltage and current efficiently, support energy recuperation, and allow precise control of output voltage and current. This ensures reliable and flexible power delivery for a variety of test scenarios. The key electrical specifications of the two main power supply units are summarized in Table 3.3.

Table 3.3 Specifications of the power supply units used in the test rig, detailing AC and DC power ratings, input/output voltages, and current capacities.

Specification	CabAC	CabDC
Power	160/200 kW	160/200 kW
Input	460 V AC	650–820 V DC
Output	650–820 V DC	0–800 V DC
Current	250 A DC	550 A DC

Table 3.3 summarizes the key electrical specifications of the two main power supply units: the CabAC and the CabDC. Both units offer power capacities of up to 200 kW, with differing input and output voltage ranges tailored to their roles within the system. The CabAC unit operates from a 460 V AC input and provides a DC output voltage between 650 and 820 V with a maximum current of 250 A. In contrast, the CabDC unit accepts a DC input voltage within the same range and delivers a variable DC output voltage up to 800 V, supporting currents up to 550 A. This configuration enables efficient and adaptable power management critical for the test rig's performance.

3.5 Real-Time simulation system

The real-time simulation system is built around the dSpace MicroAutoBox (MABX) II prototyping platform [4]. This system enables closed loop testing by integrating a DS1401 processor board with a dedicated I/O board that supports analogue and digital input/output, CAN communication, and Ethernet connectivity, as shown in Figure 3.4.

Figure 3.4 The dSpace MicroAutoBox II [4]

The MicroAutoBox II performs real-time simulations of drivetrain and vehicle subsystems, interfacing with physical components via high-speed I/O. Its primary function is to act as a bridge between Simulink-based control models and the actual hardware under test. It can simulate dynamic behaviour using mathematical models and execute control scenarios in real-time. Experimental test data is recorded and stored for post-processing and analysis.

4 HiL testing of E-Axle with TRX AFM and I&M inverter

This section presents the HiL testing configuration established at USR facility for evaluating an advanced e-axle system for the EM-TECH project. The system under investigation integrates a high-performance Axial Flux Motor (AFM) developed by TRX and a precision inverter unit from I&M. Together, these components form a compact and efficient electric propulsion assembly tailored for next-generation mobility applications.

The HiL test environment enables real-time emulation of drivetrain dynamics, providing a robust platform for validating motor-inverter interactions under varying load and operating conditions. At the core of this setup is the Traxial AXF300-85s axial flux motor, a yokeless, dual-rotor machine designed to maximize torque density, efficiency, and space savings. Its flat geometry and innovative magnetic structure make it particularly suitable for constrained automotive packaging and high-efficiency operation.

To drive the AFM, the I&M inverter is employed, delivering three-phase AC power through programmable control strategies. This inverter supports high-frequency switching, advanced current regulation, and flexible interface capabilities, ideal for both control development and performance benchmarking.

The schematic of the test rig used for the TRX AFM testing is shown in Figure 4.1.

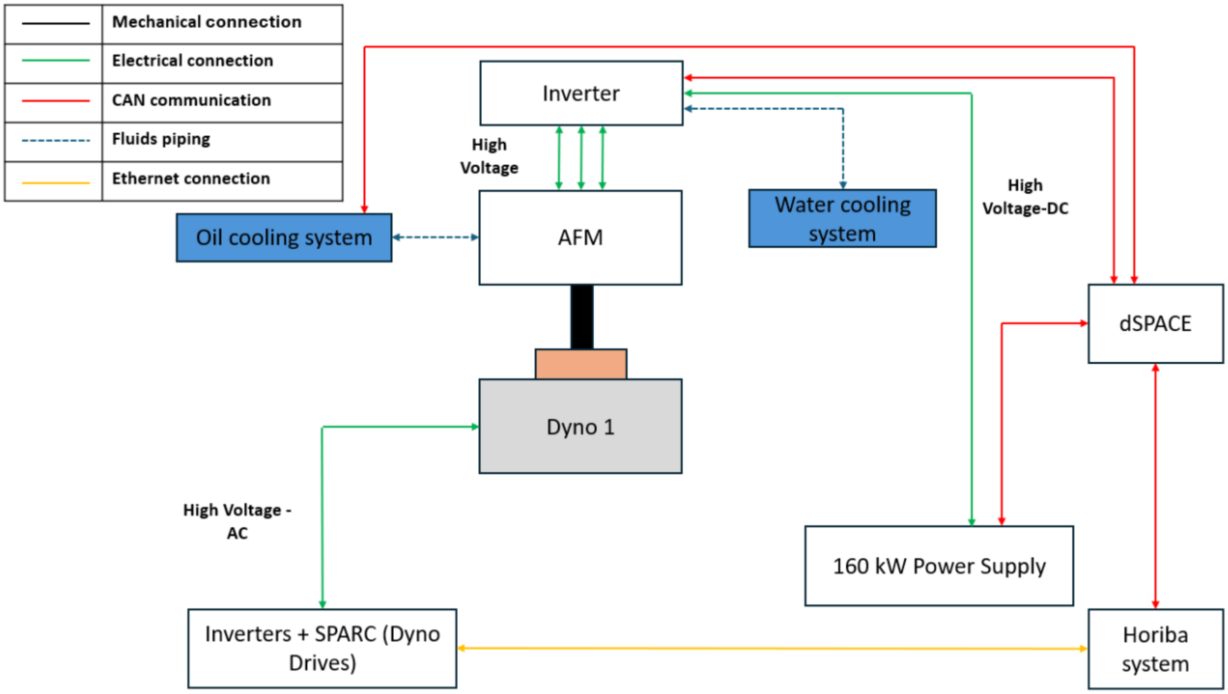


Figure 4.1 Schematic layout of the HiL test rig for TRX AFM testing.

It illustrates the integration of key components including the AFM, I&M inverter, power supply, cooling system, and real-time control interfaces, providing a comprehensive overview of HiL setup.

The HiL configuration also includes a virtual transmission model from AVL, enabling dynamic simulation of real-world drivetrain scenarios. This allows comprehensive testing without the need for a physical gearbox.

To ensure the system operates within thermal limits during testing, an integrated cooling system has been installed. The AFM is oil-cooled and lubricated to reduce bearing friction and thermal buildup, while the inverter is liquid-cooled as required. The cooling infrastructure includes pumps, fans, temperature and pressure sensors, flow meters, and accelerometers to monitor and manage thermal performance throughout the test cycles.

The USR HiL test rig is part of a distributed XiL testing framework in collaboration with TUIL through a secure Ethernet-based VPN connection, real-time communication is established between the two sites using Cisco RV340 routers. This enables synchronized operation between dSpace MicroAutoBox II at USR and dSpace Scalexio at TUIL, allowing for remote control, monitoring, and signal exchange. The XiL setup supports geographically distributed testing and validation of complex powertrain systems, enhancing development efficiency and research collaboration.

This integrated HiL and XiL framework provides a robust environment for developing, validating, and optimizing e-axle systems under realistic operating conditions.

4.1 Onboard motor (USR)

The Traxial AXF300-85s is an axial flux electric motor designed to deliver exceptional power density, efficiency, and compactness.

The AXF300-85s utilizes a yokeless stator design, which eliminates the heavy iron yoke found in conventional radial flux motors. This results in a significant reduction in weight and material usage, improving both power-to-weight ratio and manufacturing efficiency. The segmented structure also enables easier cooling and enhanced fault tolerance.

Compared to radial flux designs, axial flux motors offer shorter magnetic paths, reduced copper and iron losses, and higher torque density. The AXF300-85s maximizes these advantages through precision engineering and advanced magnetic materials.

The motor is optimized for maximum efficiency across a wide range of loads and speeds, making it ideal for applications that demand both high performance and energy savings. It's especially well-suited for electric drivetrains, where range and battery life are critical.

With its flat, disk-like form factor, the AXF300-85s offers a space-saving solution without compromising torque or power output. Its geometry allows for easy integration into constrained spaces, such as compact propulsion systems.

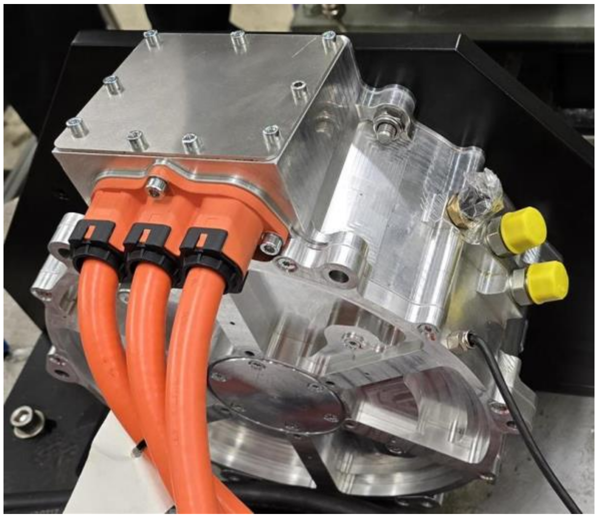


Figure 4.2 TRX axial flux motor featuring a yokeless, dual-rotor single-stator design.

Figure 4.2 shows the physical TRX AFM, available at USR. The AFM is mounted at USR test rig for HiL testing purposes. To operate the TRX AFM, a compatible inverter is essential. Electric motors do not operate directly from a DC power source; instead, an inverter is required to convert the supplied DC voltage into a three-phase AC with controllable frequency and amplitude. This allows precise control of the motor's speed and torque.

4.2 Virtual transmission system

To enhance the performance of the on-board TRX AFM in terms of energy efficiency and torque amplification, a virtual gear transmission system developed by AVL has been integrated. This virtual transmission model accurately incorporates the torsional dynamics of the gearbox and half shaft, enabling precise simulation of torque response under varying load conditions. By modelling the dynamic interaction between motor and drivetrain, the system effectively replicates torsional oscillations within the drive shaft. A schematic diagram of the virtual gearbox model integrated in the experiment test model is shown in Figure 4.3.

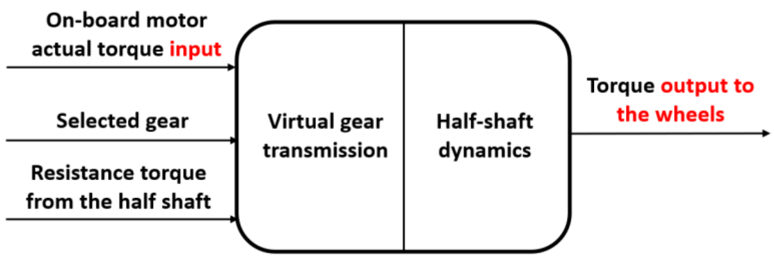


Figure 4.3 Schematic diagram of the virtual gearbox model

The actual torque measured from the test rig is fed into the virtual gear transmission model, while the vehicle model running in TUIL provides the wheel speed and angle via an Ethernet connection through a router. Based on the wheel speed and wheel angle received from TUIL, along with the output wheel speed and angle generated by the virtual gear transmission model, the half-shaft dynamics model calculates the resistance torque acting on the gear transmission. This resistance torque is then transmitted back to the vehicle model in TUIL, completing the closed-loop simulation. The AVL virtual gear transmission features a three-stage, two-gear configuration designed to achieve high torque multiplication and enable adaptive gear selection based on the motor's torque-speed profile. This allows for the optimal gear to be engaged at any given operating point, thereby enhancing power efficiency and overall performance. The design comprises helical gear pairs mounted on parallel shafts, with bearing supports, as illustrated in Figure 4.4.

Figure 4.4 Two-stage helical gear transmission developed by AVL

4.3 Inverter from I&M

For the TRX AFM motor, the I&M inverter is employed to deliver the required electrical input and enable advanced control functionalities. The I&M inverter supports high switching frequencies, accurate current regulation, and customizable control strategies, making it well-suited for dynamic testing and performance evaluation of axial flux machines. Its robust architecture ensures safe operation under various load conditions, while offering the flexibility needed for research and development environments.

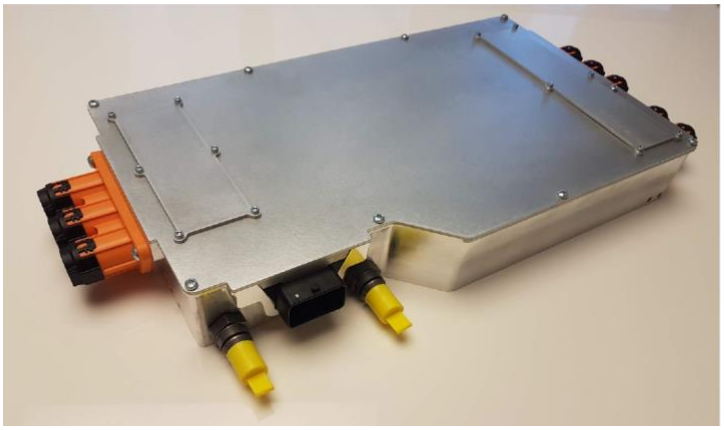
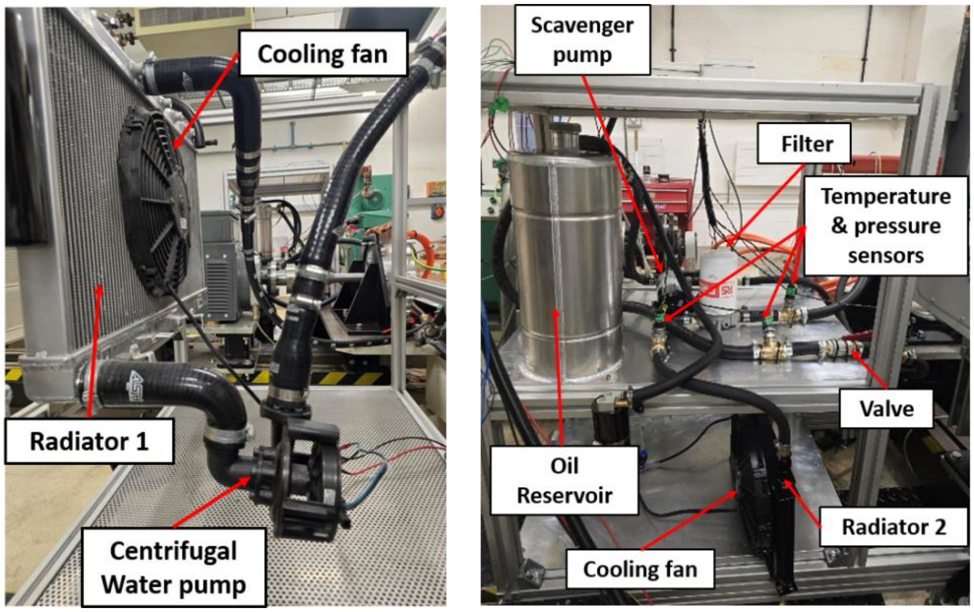


Figure 4.5 I&M inverter. The inverter converts DC input into controlled three-phase AC output, enabling precise speed and torque control of the TRX AFM motor during experimental evaluation.

Figure 4.5 shows the inverter from I&M. This inverter is responsible for supplying and controlling the three-phase AC power required by the TRX axial flux motor during testing operations.

5 Cooling system for EM-TECH project

The cooling systems shown in Figure 5.1 are employed on the HIL rig to regulate the temperature of the TRX AFM motor and the inverter from I&M, thereby preventing overheating and ensuring stable operation during testing.



a) (b)

Figure 5.1 Cooling systems for the (a) inverter (b) motor

The TRX AFM is cooled and lubricated with oil, which helps extract heat from the windings and magnetic core and reduces friction in the bearings. Effective thermal management allows the motor to operate at higher performance levels by preventing excessive temperature rise. In contrast, the inverter is cooled using a water-glycol mixture. The circuit diagram depicted in Figure 5.2 provides a detailed overview of the components and their arrangement.

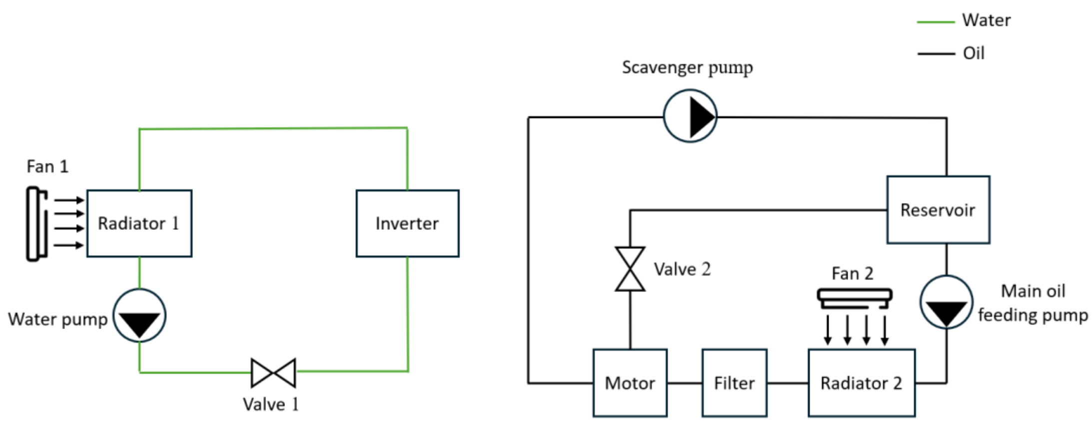


Figure 5.2 Schematic diagram of the cooling circuit

The key components indicated in Figure 5.2 are:

- **Centrifugal water pump:** This pump operates within a voltage range of 3 VDC to 15 VDC. At 13 VDC, it is capable of delivering a maximum flow rate of 115 $\mathrm{L/min}$. The pump features 38 mm inlet and outlet ports.

- **Cooling fans (fan 1 and 2):** Each fan has a diameter of 280 mm and can deliver an airflow of up to 1,410 m^3/h at 0 mm H_2O static pressure, and 220 m^3/h at 12.5 mmH_2O.
- **Radiator 1 and 2:** High-performance aluminium radiator designed for automotive applications. This unit is the OEM radiator fitted on the Subaru WRX/STI for radiator 1, and MOCAL for radiator 2 as the automotive transmission oil cooler.
- **Valve 1 and 2:** These are ON/OFF control valves used to control flow within the system, enabling maintenance and controlling of the flow rate.
- **Scavenger pump:** is a lightweight, self-priming, positive displacement pump delivering 3.5-7.5 L/min at up to 4.13 bar, with flow rate proportional to motor speed, requiring a 12V DC, 10A power supply for transmission oil application.
- **Main oil feeding ump:** The Brushless Electric Oil Pump, available in 24VDC, delivers up to 30.3 L/min at pressures up to 5.5 bar, supports various fluids (oil, hydraulic, transmission, gear lube), and features advanced protections and control options including On-Off, PWM, and J1939 CAN for diagnostics and feedback.
- **Reservoir:** A universal dry sump tank designed to collect oil from the two outlets of the motor, with a maximum capacity of 2 gallons.
- **Filter:** An RS oil input filter is installed near the motor cooling inlet to ensure proper oil cleanliness, featuring a 10 µm filtration rating, a maximum pressure capacity of 12 bar, and a permitted oil flow rate of up to 65 L/min.

The main oil feeding pump is connected to the dSpace system via CAN communication. ON/OFF and speed commands are transmitted from dSpace, while motor speed feedback is sent back to dSpace and shown in the graphical user interface (GUI). The centrifugal water pump, scavenger pump, and cooling fans are connected to the dSpace I/O board and are manually controlled through the GUI using a simple ON/OFF strategy via mechanical relays. These relays are used to switch the 12V DC power supply to the respective components. Once the motor and inverter are operational, the cooling systems are activated and controlled based on temperature readings from the cooling circuits.

5.1 Pumps

The EWP 115 pump by Craig Davies [5] is used to circulate a water-glycol coolant mixture for cooling the inverter. Table 5.1 below outlines the pump's main specifications: it can deliver a flow rate of up to 115 L/min at a pressure of 0.45 bar, with a maximum supply current of 10 A.

Table 5.1 Pump characteristics for the inverter cooling

Characteristic	Unit	Value
Operating voltage	V DV	3/15
Maximum current	A	10

Flow rate	L /min	0-115
Maximum pressure	bar	0.45
Pump weight	Kg	1.15

The EMP OP80 oil gear pump [6] is implemented as the primary feeding pump in the oil cooling circuit of the TRX AFM motor. This electrically driven 24V pump is capable of delivering a flow rate of 30 l/min at a pressure of 5.5 bar when operating at 5000 rpm. Operational commands and status information are communicated to dSpace via the CAN protocol. The key pump characteristic is presented in Table 5.2.

Table 5.2 Pump characteristics for the motor cooling

Characteristic	Unit	Value
Operating pressure (maximum)	bar	5.5
Oil viscosity (maximum)	cSt	~5000
Flow rate	L /min	0-30
Maximum current	A	25
Pump weight	Kg	4.3

Tilton scavenger pumps [7] are used to extract oil from the motor's dry sump. These pumps are self-priming and capable of handling an air/oil mixture, with a maximum flow rate of 9.1 L/min. They are controlled via a relay connected to the digital output board of the dSpace system. To prevent motor flooding, the scavenger pumps must be activated before switching on the main oil feed pump. Table 5.3 outlines their key specifications.

Table 5.3 Pump Characteristics for Motor Cooling – Oil Suction from Motor's dry pump

Characteristic	Unit	Value
Operating pressure (maximum)	bar	3.5
Flow rate	L /min	4.6-9.1
Maximum current	A	6.6
Pump weight	Kg	1.6

5.2 Fan

The radiators are equipped with fans manufactured by SPAL [8], which facilitate forced air cooling to enhance heat dissipation. Each fan is driven by a waterproof motor with an IP68 protection rating, ensuring durability and reliable operation in demanding environmental conditions. A sealed, waterproof connector is also employed to maintain system integrity. The key technical specifications of the fan assembly are summarized in Table 5.4.

Table 5.4 Fan characteristics

Characteristic	Unit	Value
Operating voltage	V DC	12

Air flow blowing (Maximum)	m^3/h	1410
Air flow suction (Maximum)	m^3/h	1320
Fan weight	Kg	1.1

5.3 Temperature and pressure sensors

The PST-F1 sensor from BOSCH [9] shown in Figure 5.3 is a combined temperature and pressure sensor used within the cooling circuit to monitor critical operating conditions at various measurement points.

Figure 5.3 Temperature and pressure sensors installed in the oil cooling circuit

These include the stator outlet flow, inlet temperature, sump outlet temperature, and sump outlet flow, ensuring reliable operation of the motors. The sensor provides a temperature measurement range of -40 °C to 150 °C and a pressure measurement range of 0 to 10 bar. Pressure is measured using a piezoresistive element, which is actuated by a silicon diaphragm in direct contact with the fluid. The sensor outputs an analogue voltage signal with a sensitivity of 400 $\mathrm{mV/bar}$ and an offset of 500 mV at a 5 V supply. This signal is read by the analogue input channel of the dSpace system. For temperature measurement, a 4.6 kΩ pull-up resistor is required in series with the signal output and the 5 V power supply. As the sensor's resistance varies with temperature, the resulting voltage change is interpreted using a look-up table provided in the datasheet to determine the corresponding temperature, which is then displayed in the GUI.

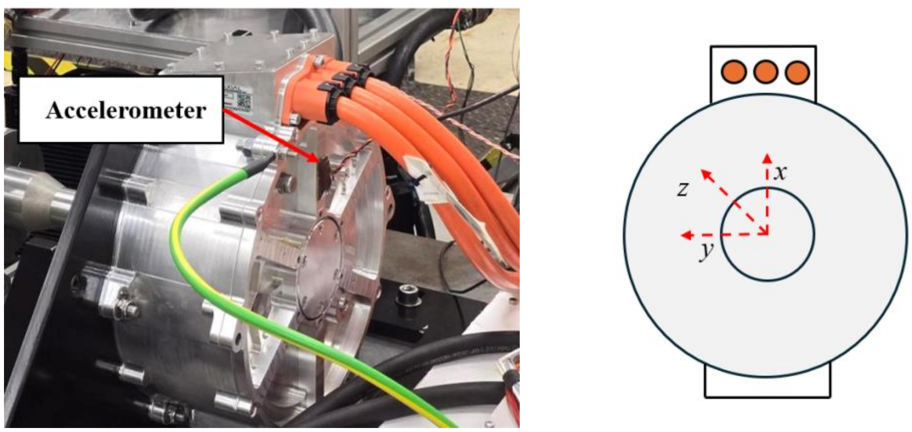
5.4 Flow rate sensors

The SBY432 flow transmitter [10], shown in Figure 5.4, provides precise and rapid flow detection with a response time of 10 ms, even under high-pressure conditions. Powered by a 24 V supply, the sensor delivers a linear analogue current output ranging from 4 to 20 mA, corresponding to a flow rate of 0.3 to 15 $\mathrm{L/min}$. It is interfaced with the dSpace analogue voltage input via a current-to-voltage converter module, which outputs a corresponding 0–10 V signal.

Figure 5.4 Flow rate sensor installed in the oil cooling circuit

5.5 Accelerometer

The three-axis accelerometer ADXL330 [11], integrated into a circuit board as shown in Figure 5.5 (a), is mounted on the motor casing to measure acceleration along the x and y axes for monitoring radial vibrations. The orientation of the sensor axes is illustrated in Figure 5.5 (b). The accelerometer features a measurement range of $\pm 3\ g$, a bandwidth of up to 1600 Hz, and a sensitivity of 300 $\mathrm{mV/g}$. The offset voltage at 0 g is 1.77 V for both the *x* and *y* axes. The analogue voltage output from the accelerometer is acquired by the analogue input of the dSpace system, where it is converted to acceleration values in units of m/s^2.

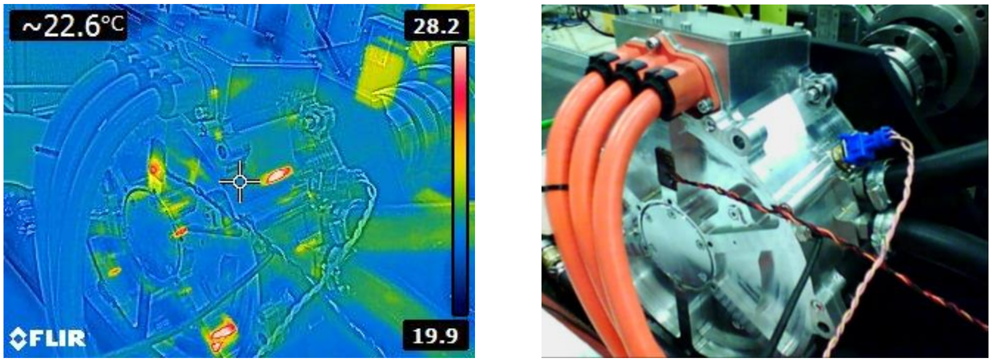


(a) (b)

Figure 5.5 Accelerometer mounting configuration: (a) motor Casing Installation; (b) axis allocation for radial vibration monitoring

5.6 Thermal image camera

To measure the hotspot temperatures of the motor during operation, a FLIR E4 thermal imaging camera [12] was used. This device captures temperature distribution as a two-dimensional thermal map, providing a detailed view of the motor casing's surface temperature profile. It offers a thermal sensitivity of less than 0.15°C at 30°C and supports a temperature measurement range from –20°C to 250°C. The camera is equipped with a fixed-focus lens featuring a 45° × 34° field of view and a minimum focus distance of 0.5 meters. By positioning the camera appropriately, the hotspot temperatures on the motor casing can be accurately detected and measured, as illustrated in Figure 5.6. Thermal data is stored as fully radiometric JPEG images, which include embedded temperature information for further analysis.



(a) (b)

Figure 5.6 Picture from the thermal-imaging camera (a) thermal image (b) real AFM image

6 In-wheel motor

6.1 E-corner test setup

The rig consists of a powertrain emulating a quarter of a vehicle, specifically the power electronics responsible for controlling the electric motor and the electric motor itself, which simulates one wheel of the vehicle. A photo of the test rig is shown in Figure 6.1.

An AVL DynoSpirit test bench, adapted for electric motor testing, is used to test the motor. The motor cooling system is a direct oil system, so an oil station is integrated into the test rig to cool and circulate the oil within the motor circuit. The oil station and inverter are cooled by the test bench's cooling system, which uses a mixture of water and glycol.

The test bench enables the reproduction of shaft speed with high accuracy, simulating the vehicle's wheel speed and measuring the torque on the motor for analysis of the IWM's performance.

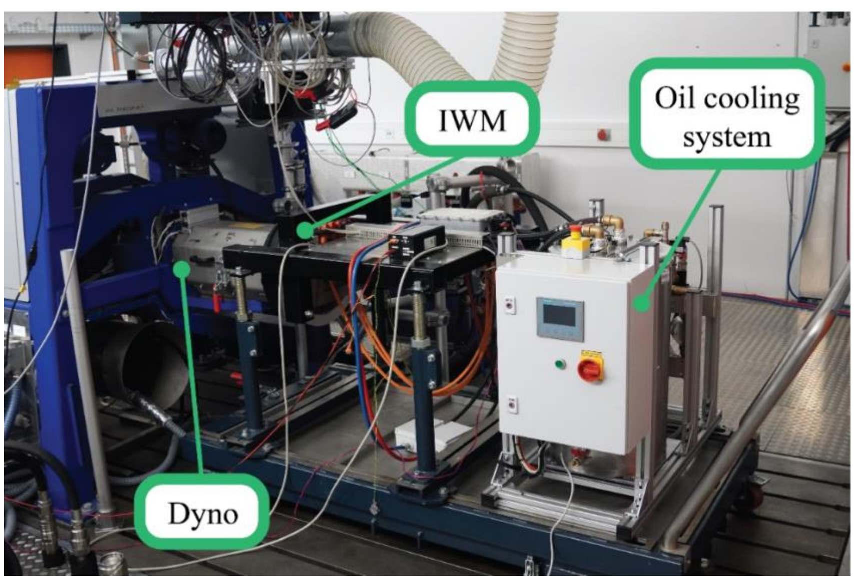


Figure 6.1 E-corner test setup at TUIL

The electric motor developed in the project can adjust the configuration of the motor windings to enhance energy efficiency and expand the operating range of torque and speed. The E-Gear is integrated into the IWM. In other words, IWM + e-Gear as a whole is capable of adjusting the motor winding configuration.

The E-Gear control strategy requires the coordinated operation of the power electronics, controlled by the electric motor and the contactor that switches the winding configuration. To test and evaluate the system, an inverter for the electric motor must be created that can work with such a device. To simplify concept validation, E-gear has its controller, and the synchronisation of the inverter and the mechanical part of the contactor is performed on a rapid prototyping device. Therefore, the test setup includes a test bench controller that controls the dynamometer, an inverter that controls the motor, and an E-gear controller, Figure 6.2. The mechanical part of the E-gear is connected to the phase wires of the motor.

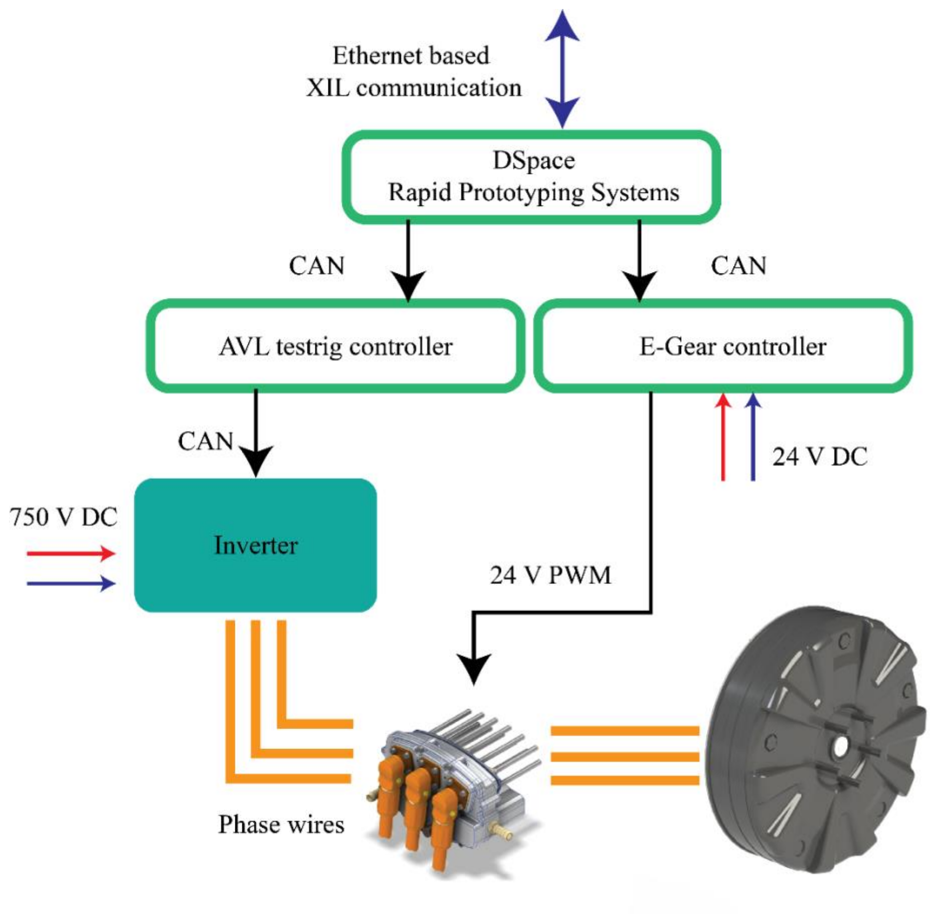


Figure 6.2 Component diagram of the test bench

The primary control element in the E-corner is the dSpace rapid prototyping device, which is responsible for distributed simulation with the XIL vehicle model and simultaneously controls the test dynamometer and the E-Gear motor configuration change device. A CAN interface is used to control the test bench, which contains information about the required shaft speed and the torque requested from the motor. The controller receives measured values from the motor, such as torque and temperature, via the same channel.

Additional information is also transmitted between the devices to ensure correct operation, such as operating mode, direction of rotation, and other enabling signals. The AVL test bench independently controls the inverters by relaying the required signals to the inverter's CAN control channel. The inverter is connected to a 750 V DC power supply.

The second CAN channel of the dSpace device exchanges data with the E-Gear controller and is responsible for optimal and timely switching of contacts. The E-Gear controller receives a command for the required contact configuration and reports on the completion of the mechanical switching. A 24V PWM signal controls the mechanical actuator. The dSpace controller needs to determine when switching is complete to prevent a torque request from the motor when the contacts are open. A current request in an open circuit can cause a spark that will damage the contacts, or an error in the control electronics.

The high-voltage part consists of phase wires that emerge from the inverter, which are connected to the E-Gear, and then connected to the motor windings. A photo of this system is shown in Figure 6.3.

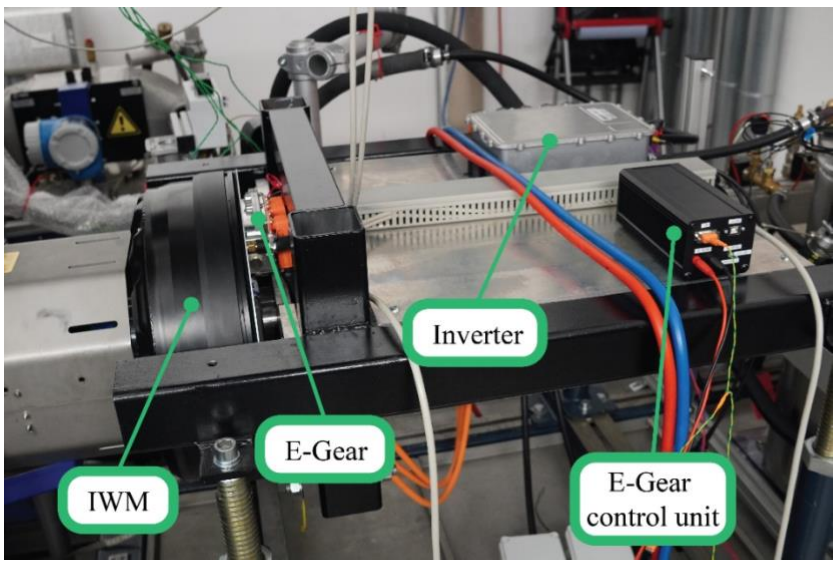


Figure 6.3 Close-up photo of the control electronics

6.1.1 Test bench control panel

Outside the test room, behind a safety partition, is the operator's station. The workstation contains a computer that controls the AVL test bench, a dSpace controller, and a computer running the dSpace controller program interface. The workstation is shown in Figure 6.4.

The rapid prototyping device is connected to the LAN network for communication with the vehicle model, allowing for the remote control of multiple test stands simultaneously using the XIL methodology. However, an operator must always be present at the stand during the operation to ensure that all systems are functioning correctly and to be able to shut down the system in the event of a simulation error. The operator's task is also to ensure that the stand is switched on in the correct sequence and that the communication is set up before the test begins.

Figure 6.4 Test bench operator's workstation at TUIL

7 Distributed HiL testing between USR and TUIL: Integration of real AFM motor and full vehicle simulation

A distributed XiL testing framework has been established between USR and TUIL to enable real-time testing of electric powertrain systems. To facilitate seamless and secure data exchange between the two geographically separated sites, the VPN architecture has been implemented. Cisco RV340 routers are deployed at both locations to provide encrypted and reliable Ethernet-based communication channels.

Within this XiL environment, the simulation and physical test rigs operate in synchronization, with dSpace Scalexio utilized at TUIL and dSpace MicroAutoBox II at USR. The VPN ensures low-latency, high-integrity transmission of control and measurement signals, enabling HiL integration across institutional boundaries. This setup supports the development and validation of distributed powertrain architectures under realistic testing conditions. It serves as a secure gateway for encrypted Ethernet communication within the distributed XiL testing framework, enabling real-time data exchange with the TUIL counterpart. The router ensures reliable and secure connectivity, which is critical for maintaining synchronization between physical and simulated subsystems during cross-site testing.

This collaborative setup integrates a physical AFM, installed on a test bench at USR, with a comprehensive vehicle dynamics model at TUIL. The aim of this integration is to allow both real-world motor testing and full-vehicle simulation to be conducted in synchrony across geographically separate test rigs.

Figure 7.1 shows the distributed XiL testing architecture between USR and TUIL.

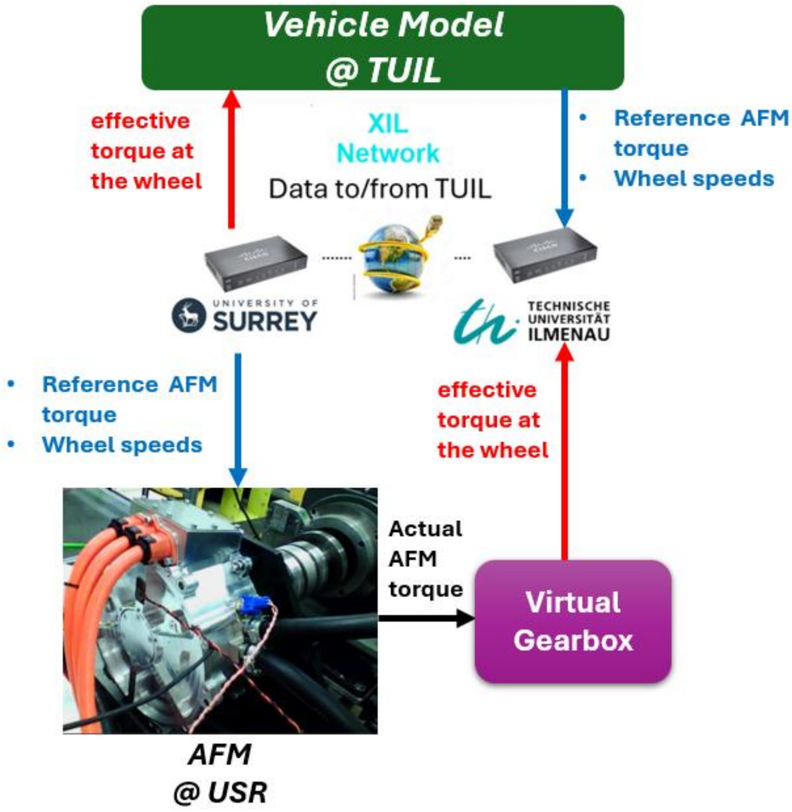


Figure 7.1 Distributed XiL setup showing real AFM motor and virtual gearbox at USR exchanging torque and wheel speed data with TUIL's full vehicle model via VPN.

Figure 7.1 illustrates the distributed XiL testing framework where the real AFM motor is hosted at USR and a virtual gearbox model is integrated in the Simulink model within USR test rig model. TUIL runs a full vehicle simulation including wheel dynamics. The AFM motor torque is physically generated and measured at USR, then passed through a local virtual gearbox to compute the effective torque at the wheels. This simulated wheel torque is sent over Ethernet VPN to TUIL, where it is used as the input driving torque for their vehicle model in the wheel dynamics block. TUIL computes vehicle response and wheel speeds, which are then sent back to USR. These wheel speeds serve as reference inputs for controlling the dynamometer and closing the loop with the real motor under realistic virtual vehicle testing.

8 Conclusion

This deliverable has presented the integration of two electric drivetrain systems: a smart e-corner developed and tested at TUIL, and a smart e-axle implemented at USR. The work was carried out within a distributed XiL framework, which enabled real-time co-simulation and system-level validation across geographically separated sites. Using a secure VPN connection and dSpace platforms—Scalexio at TUIL and MicroAutoBox II at USR—the test environments were synchronized, allowing for remote hardware testing within a shared virtual vehicle model.

At USR, the e-axle system featured a baseline AFM provided by TRX, an inverter from I&M, and a virtual gear transmission developed by AVL. This system was integrated into a powertrain test bench designed to capture detailed electrical, mechanical and thermal data. A custom-designed cooling system ensured safe and stable operation of the AFM under varying test conditions. Section 3 through Section 5 of the report detail the HiL facility, the integration of hardware and models, and the supporting infrastructure.

In parallel, TUIL implemented IWM supplied by ELA within the existing smart e-corner platform which is discussed in section 6. The test rig emulated a quarter-vehicle setup, enabling evaluation of the motor's performance, including dynamic torque response and E-Gear switching under realistic operating scenarios. The system was coordinated through a dSpace rapid prototyping device and supported by robust CAN-based communication with the test bench and E-Gear controller. It further elaborated on the TUIL test bench configuration, highlighting the control system, cooling integration, and safety protocols in place for reliable operation.

Section 7 of the report outlined the XiL communication architecture, describing the Ethernet-based signal exchange over VPN and the specific control and feedback signals required for synchronizing the two test environments.

Overall, this work demonstrates the viability and effectiveness of distributed XiL methodologies for the remote testing of physical electric drivetrain components. The approach not only supports modular development but also enhances flexibility, scalability, and collaboration between research and development sites. The insights and validation results gained from this setup will inform the future design and testing of integrated electric powertrains in next-generation mobility platforms.

8.1 Deviations, Impact and Recovery Actions

The deliverable is delayed by a few months due to technical issues for the integration of the components on both test benches. The issues have been solved, and no further delay is expected.

Bibliography

[1] ATESTEO. (n.d.). F-Series Torquemeters – Data Sheet F1xS. Retrieved from F series torque transducers and torque sensors | ATESTEO
[2] HEIDENHAIN. (n.d.). Rotary Encoders – 349529-2H. Retrieved from https://www.heidenhain.us/wp-content/uploads/349529-2H_Rotary_Encoders_en.pdf
[3] EP Solutions. (n.d.). 5000/5020 Series Power Supplies – Datasheet. Retrieved from https://www.ep-solutions.rs/uploads/documents/5000-5020-en3.pdf
[4] dSPACE. (n.d.). Homepage. Retrieved from https://www.dspace.com/en/pub/home.cfm
[5] Davies Craig. (n.d.). Electric Water Pumps. Retrieved from https://daviescraig.com.au/electric-water-pumps
[6] Technical Services UK. (n.d.). EMP OP80 Electric Oil Pump. Retrieved from https://www.technical-services.co.uk/emp-op80-electric-oil-pump/
[7] Tilton Engineering. (n.d.). Oil Cooler Pumps – Product Guide [PDF]. Retrieved from https://tiltonracing.com/wp-content/uploads/2013/07/Oil-Cooler-Pumps.pdf
[8] SPAL Automotive. (n.d.). Axial Fans. Retrieved from https://www.spalautomotive.com/en/axial-fans
[9] Bosch Motorsport. (n.d.). Fluid Temperature Sensor – Product Sheet. Retrieved from https://www.bosch-motorsport.com/content/downloads/Raceparts/en-GB/54249355.html#/Tabs=9007199309005067/
[10]IFM. (n.d.). SBY432 – Flow Sensor Product Page. Retrieved from https://www.ifm.com/na/en/product/SBY432
[11]Analog Devices. (n.d.). ADXL330 – 3-Axis Accelerometer Datasheet [PDF]. Retrieved from https://www.analog.com/media/en/technical-documentation/data-sheets/adxl330.pdf
[12]] FLIR Systems. (n.d.). FLIR Ex-Series – User Manual [PDF]. Retrieved from https://www.flir.com/globalassets/imported-assets/document/flir-ex-series-user-manual.pdf