HEFT

Highly Efficient Recyclable Motor

HEFT

D1.3 Validation Plan

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GLOSSARY

Abbreviation/ acronym	Description
CA	Consortium Agreement
DoA	Description of the Action – Annex I to the Grant Agreement
CD	Communication and Dissemination
EC	European Commission
EMC	Electromagnetic Compatibility
GA	Grant Agreement
IP(R)	Intellectual Property (Rights)
WPL	Work Package Leaders
WP	Work Package
CPD	Continuing Professional Development
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
SAE	SAE (Society of Automotive Engineers) International
MGEP	Mondragon Goi Eskola Politeknikoa Jose Maria Arizmendiarrieta S Coop
GKN	GKN Driveline Zumaia Sa
GKN AIC	GKN Hybrid Power ltd
MAG	Magneti Ljubljana Podjetje Za Proizvodnjo Magnetnih Materialov Dd
VYN	Vyncolit
IKE	Ikerlan Coop
KUL	Katholieke Universiteit Leuven
UNIBO	University of Bologna

1 EXECUTIVE SUMMARY

Climate change has created an increased need for innovation in various sectors, including the automotive industry. Many corporations are striving to fulfil this need by developing and producing electric cars. However, the production process remains inefficient and environmentally harmful. The EU-funded HEFT project will reverse this trend by introducing a revolutionary synchronous motor for electric cars, which will be recyclable, cost-efficient and require fewer materials while producing fewer emissions and creating novel European circular economies.

HEFT Project proposes a set of innovation challenges on electric synchronous motor configuration based on SiC inverters (direct cooling of rotor and stator, advance insulation for high voltage, multibarrier rotor topology, wave windings) and advanced materials (advanced GBD magnets, epoxy for magnet fixation, composite for motor housing, insulation resin). These innovations will result in a high-efficient and low-cost solution that will be validated on 2 motor topologies.

- Motor topology type C: Motors for C-D-E segments.
- Motor topology type A: Motors for A-B segments.

In this document, a validation plan is defined to assess the compliance of the concept with the requirements defined in Task 1.2 of HEFT project. A test matrix is created, describing the necessary tests to be performed. This test matrix should identify the responsible partner, the equipment and measurement conditions to use, as well as specify the criteria for performance assessment and validation.

In this document the following issues will be covered:

1. A general review of set of requirements to be fulfil for each motor type.
2. Main magnitudes to be tested to verified emotor performances.
3. General description of testbenches to be used to validate the defined requirements.
4. Overall view of test matrix.
5. Detailed testing plan.

2 GENERAL OVERVIEW FOR MOTOR SPECIFICATIONS

The HEFT project will be focusing on offering electric motors for mass production vehicles in the EU. For this, HEFT will be offering two motor topologies for the main vehicle's segments produced in the EU, vehicles segment A+B and vehicle segments C+D+E, which together comprise more than the 50% of the vehicles sold in EU (data from 2020)[1].

- Vehicle segment A+B motor (Motor A): The eMotor Fiat 500e has been chosen as a benchmark for the small vehicle segment A+B. This motor has been developed by GKN and it has been in mass production since August 2020.
- Vehicle segment C+D+E motor (Motor C): For the family size segment (C+D+E), eMotor VW ID.4 has been the chosen as a benchmark. This motor has been in mass production since September 2020.

The baseline vehicles are going to be the reference to develop the set of specifications for each motor topology.

2.1 Specifications for Motor A: A+B segment

Specifications starts from vehicle specifications, shown in Table 1.

Table 1. Specifications of FIAT 500e

Vehicle FIAT 500e			
Max vehicle speed	kph	160	
Vehicle weight - kerb	kg	1365	Kerb Vehicle Weight - used for WLTC & ADAC cycles
Vehicle weight - gross	kg	1750	Gross Vehicle Weight - worst case for hill-climbing
Tire circumference	m	1,80	Typical 195/65R14
Aerodynamic drag area (Af*CD)	m2	0,6624	
Predicted 0-100kph Acceleration	secs	7,5	Simulation prediction

In order to fulfill the vehicle driving performance, the following requirements (Table 2) have been defined for the output power of the traction axle:

Table 2. Specifications for traction axle for A+B segment

Motor A: Traction axle (torque and Power)			
Max axle torque	Nm	2200	Between 5 -30s
Max axle power	kW	80	Between 5 -30s
Continuous torque	Nm	1513	30 min
Continuous power	kW	55	30 min

[1]https://www.acea.auto/figure/new-passenger-cars-by-segment-in-eu/

Taking these values and other vehicle driving performances, the Torque VS speed curve is defined for the traction axle, as it is shown in Figure 1.

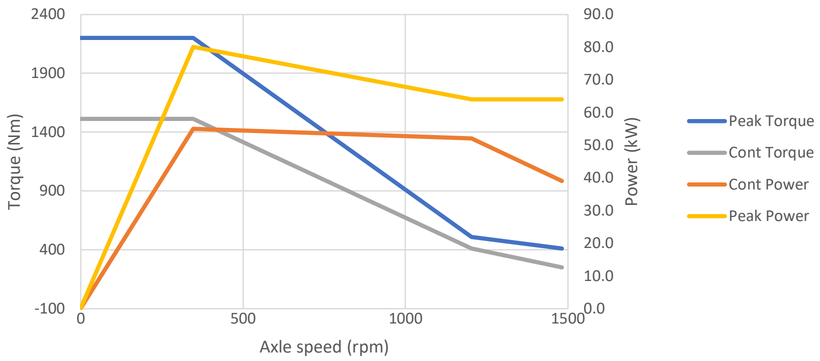


Figure 1. Torque VS speed & Power VS speed (axle)

System level specifications:

- DC-link 800V (LV123 standard)
- Max gear ratio - NVH constraint. x:1=16. Do not exceed: NVH limit for 2-stage offset design.

Motor A level specifications:

Taking vehicle requirements and system level specifications, full eDrive specifications (emotor, inverter, gearbox) will be define. An optimal global sizing will be applied.

External inputs:

- Gearbox ratio
- Maximum inverter current (Arms)

Main Motor specifications to be tested:

- Maximum stator phase current: I_{s_max} (Arms)
- Peak Torque: T_{peak} (Nm). Between 5 -30s. According to Peak Torque VS Speed (Figure 1).
- Continuous Torque: T_{cont} (Nm). 30min. According to Cont. Torque VS Speed (Figure 1).
- Peak Power. P_{peak}(kW). Between 5 -30s. According to Peak Power VS Speed (Figure 1).
- Continuous Power. P_{cont} (kW). 30min. According to Cont. Torque VS Speed (Figure 1).
- Motor losses. M_{loss} (Wh/km). Mean value over WLTP. > 20% reduction over baseline Fiat 500e eMotor.
- Maximum temperature on winding. T_{cu_max} (ºC) According to the designed insulation class.
- Maximum magnet temperature. T_{pm_max} (ºC). According to the temperature grade of the magnets and the rotor robustness face to demagnetization risks.

2.2 Specifications for Motor C+D+E segment

Specifications starts from vehicle specifications, shown in Table 3.

Table 3. Specifications of VW ID.4

VW ID.4			
Max vehicle speed	kph	180	
Vehicle weight - kerb	kg	2068	Kerb Vehicle Weight - used for WLTC & ADAC cycles
Vehicle weight - gross	kg	2560	Gross Vehicle Weight - worst case for hill-climbing
Tire circumference	m	2,32	Typical 255/45R20
Aerodynamic drag area (Af*CD)	m^2	0,8372	
Predicted 0-100kph Acceleration	secs	6,4	Simulation prediction

In order to fulfill the vehicle driving performance, the requirements have been defined for the output power of the traction axle, as it is shown in Table 4:

Table 4. Specifications of traction axle for C+D+E segment

Motor A: Traction axle (torque and Power)			
Max axle torque	Nm	4000	Between 5 -30s
Max axle power	kW	170	Between 5 -30s
Continuous torque	Nm	2600	30 min
Continuous power	kW	110,5	30 min

Taking these values and other vehicle driving performances, the Torque VS speed curve is defined for the traction axle, as it is shown in Figure 2.

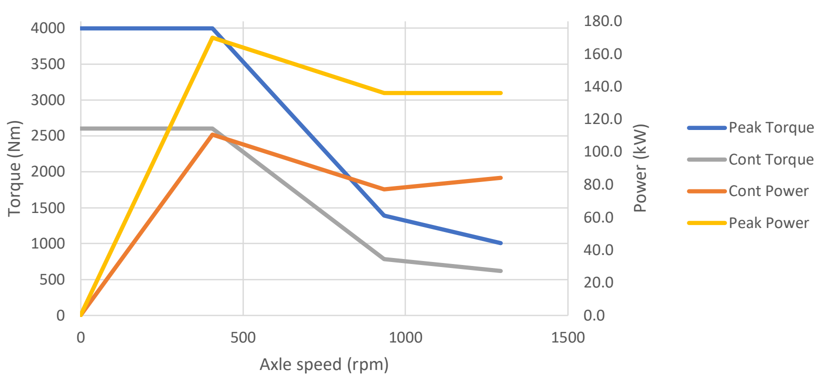


Figure 2. Torque VS speed & Power VS speed (axle)

System level specifications:

- DC-link 800V (LV123 standard).
- Max gear ratio - NVH constraint. x:1=16. Do not exceed: NVH limit for 2-stage offset design.

Motor C level specifications:

Taking vehicle requirements and system level specifications, full eDrive specifications (emotor, inverter, gearbox) will be defined. An optimal global sizing will be applied.

External inputs:

- Gearbox ratio.
- Maximum inverter current (Arms).

Main Motor specifications to be tested:

- Maximum stator phase current: I_{s_max} (Arms)
- Peak Torque: T_{peak} (Nm). Between 5 -30s. According to Peak Torque VS Speed (Figure 2).
- Continuous Torque: T_{cont} (Nm). 30min. According to Cont. Torque VS Speed (Figure 2).
- Peak Power. P_{peak}(kW). Between 5 -30s. According to Peak Power VS Speed (Figure 2).
- Continuous Power. P_{cont} (kW). 30min. According to Cont. Torque VS Speed (Figure 2).
- Motor losses. M_{loss} (Wh/km). Mean value over WLTP. > 20% reduction over baseline VW ID.4 eMotor.
- Maximum temperature on winding. T_{cu_max} (ºC) According to the designed insulation class.
- Maximum magnet temperature. T_{pm_max} (ºC). According to the temperature grade of the magnets and the rotor robustness face to demagnetization risks.

3 MAIN PARAMETERS TO BE TESTED TO VERIFY EMOTOR PERFORMANCES

In this section the main tests to carry out are described.

3.1 Test ID1_Thermal: Continuous thermal tests

ID: Test ID1_Thermal

Short Name: Thermal test

Full Name: Continuous thermal test

Several representative points of the Continuous curve Torque VS speed will be selected and tested in a testbed. To validate the continuous driving performances each selected working point will be tested continuously during 30min period.

Working conditions: A constant torque and speed working point for 30min.

Output variables:

- Motor torque along time. $T_{out}(t)$ (Nm). Measured using a high precision torque transduced.
- Speed along time. $w_{mech}(t)$ (rad/s) rotor speed measured using a high precision resolver.
- Stator winding temperatures: $T_{cux}(t)$ (ºC), several temperature sensors at the endwindings.
- Cooling inlet and outlet temperatures: T_{cool_in} and T_{cool_out} (temperature sensors).

Validation criteria for the test:

- Electrical measurements are below maximum limits.
- Dynamic evolution of $T_{cux}(t)<T_{cu\_max}$. According to the designed insulation class
- Average stator winding temperature at 30min. $T_{cu\_avg}< T_{cu\_max}$ (calculated using measuring stator winding electrical resistance when emotor stopped).
- Average permanent magnet temperature at 30min $T_{pm}< T_{pm\_max}$ (calculated using calibrated EMF test measuring when the test is finished).

Motor performances and KPIs:

The verified measured values of continuous thermal test will be used to calculate.

- The maximum temperatures in the stator windings and permanents magnets at continuous working conditions.
- To confirm that the continuous Torque VS speed curve allows a 30min continuous working mode.

3.2 Test ID2_ContinuousLoad: Continuous Torque/Power VS speed curves

ID: Test ID2_ContinuousLoad

Short Name: Continuous load test

Full Name: Maximum Continuous Torque/Power VS speed curves

Several representative points of the Continuous curve Torque VS speed will be selected and tested in a testbed.

Working conditions: Continuous mode 30 min

Output variables:

- Motor continuous torque. T_{cont} (Nm). Measured using a high precision torque transducer.
- Motor continuous output power. P_{cont} (kW). Calculated as $P_{cont}=T_{cont}*w_{mech}$ (w_{mech} rotor speed measured using a high precision resolver)

Validation criteria for the test:

- Inverter currents during the tests below maximum current ratings of the inverter
- Temperatures remain below the continuous ratings values (T_{cu_max}, T_{pm_max}, output cooling temperatures).

Motor performances and KPIs:

The verified measured values of T_{cont} (Nm) and P_{cont} (kW) will be used to calculate.

- Continuous motor torque and power performances.
- Continuous torque density: T_{cont}/mass (Nm/kg) and P_{cont}/volume = (kW/l)
- Continuous power density: P_{cont}/mass (kW/kg) and P_{cont}/volume = (kW/l)

3.3 Test ID3_PeakLoad: Peak Torque/Power VS speed curves

ID: Test ID3_PeakLoad

Short Name: Peak load test

Full Name: Maximum Peak Torque/Power VS speed curves

Several representative points of the Peak curve Torque VS speed will be selected and tested in a testbed.

Working conditions: Peak mode between 5 -30s

Output variables:

- Motor peak torque. T_{peak} (Nm). Measured using a high precision torque transducer.
- Motor peak output power. P_{peak} (kW). Calculated as $P_{cont}=T_{cont}*w_{mech}$ (w_{mech} rotor speed measured using a high precision resolver)

Validation criteria for the test:

- Inverter currents during the tests below maximum current ratings of the inverter
- Temperatures remain below the maximum peak ratings values (T_{cu_max}, T_{pm_max}, output cooling temperatures).

Motor performances and KPIs:

The verified measured values of T_{peak} (Nm) and P_{peak} (kW) will be used to calculate.

- Peak motor torque and power performances (30 s).
- Peak torque density: T_{peak}/mass (Nm/kg) and P_{peak}/volume = (kW/l)
- Peak power density: P_{peak}/mass (kW/kg) and P_{peak}/volume = (kW/l)

3.4 Test ID4_Efficiency: Efficiency Maps

ID: Test ID4_Efficiency

Short Name: Efficiency Maps test

Full Name: Efficiency Maps inside Torque VS Speed curves

Motor efficiency during all the working points will be measured and compared with a minimum efficiency map defined in the design stage. Motor efficiency will be measured at several representative points inside of the area below Torque VS Speed curve.

Working conditions: In a steady-state thermal mode (at different reference temperatures).

Output variables:

- Motor Efficiency $\eta\ (\%) = \frac{P_{in}}{P_{out}} \cdot 100$ at each testing point (T_{out} and speed)
  Where:
  - P_{out}=T_{mech}*w_{mech}. T_{mech} will be measured using a high precision torque transducer. w_{mech} rotor speed measured using a high precision resolver.
  - P_s (kW). Input power at the three-phase stator windings. Measured using a high precision power analyser

Validation criteria for the test:

- All electrical and mechanical measurements at steady state. Electrical and thermal measurements remain below maximum limits.

Motor performances and KPIs:

The verified measured values of $\eta\ (\%) = \frac{P_{in}}{P_{out}} \cdot 100$ will be used to calculate.

- To calculate the efficiency map at any point below the Torque VS speed curve.
- To obtain a first evaluation of Motor Losses (Wh/km) at any driving cycle (WLTP, NEDC…).

3.5 Test ID5_WLTP: WLTP test

ID: Test ID5_WLTP

Short Name: WLTP test

Full Name: Driving WLTO cycles.

Motor losses will be measured during the driving cycle defined by the WLTP test. For that, Torque and Speed instantaneous references will be used to emulate the emotor real performances during the vehicle at WLTP cycle.

Working conditions: Driving cycle defined by WLTP test.

Output variables:

- Motor Losses(t). Loss(t)=P_{in}-P_{out} (w) at each instantaneous point along the time.
- M_{loss} (Wh/km) =$(\int Loss(t)dt)$/(equivalent distance traveled by the vehicle: km).

Validation criteria for the test:

- Measured torque and speed dynamic evolution near the same as dynamic torque and speed setpoints. Electrical and thermal measurements remain below maximum limits.

Motor performances and KPIs:

The verified measured values of Losses(t). Loss(t)=P_{in}-P_{out} will be used to calculate.

- Detailed experimental evaluation of Motor Losses (Wh/km) at WLTP driving cycle.
- Thermal dissipation performances at each working point.

4 RELIABILITY TESTS

The robustness of HEFT motors prototypes will be validated through a research program of reliability tests. It should be noticed that every OEM has their own ideas on which is the best way to ensure the electrical motor is robust. The objective of these tests is not to validate the robustness of a final commercial motor, but to detect critical design problems that would affect the HEFT motors.

Different reliability tests will be carried out according to the critical points detected in the motor's designs. At least the following tests will be carried out using advanced Test Beds:

4.1 Mechanical Fatigue

ID: Test ID6_Fatigue

The purpose of this test is to validate the structural integrity of a permanent-magnet synchronous motor under conditions of alternating loads (fatigue). The conditions of this test will simulate driving a vehicle with high acceleration and regeneration torques.

4.2 Bearing and Seal Lifetime

ID: Test ID7_Bearings

The purpose of this test is to validate the bearings and seals lifetime during high acceleration and regeneration torques with thermal ramps.

4.3 Overspeed

ID: Test ID8_Overspeed

The purpose of this test is to validate that the motor does not break when at overspeed is achieved (10% above from maximum speed).

5 TEST BEDS: GENERAL DESCRIPTION

Validation procedures will be implemented using the nowadays-existing automotive Test Beds in GKN and MGEP, composed of a mechanical torque sensor, electrical machine acting as controllable load, advanced laboratory instruments to measure and register the electrical, thermal and mechanical magnitudes.

5.1 Test Bed at MGEP

Test Bed available at MGEP is specially designed to carry out research, functional & type tests (automotive standards) for automotive e-motors.

Motors will be controlled with the laboratory open SiC inverter platform to have a highly flexible voltage and power range, with the capacity to perform different research tests at very hard-working conditions. EMC tests will also be performed.

Figure 3 shows the existing Test Bed at MGEP, including the following components:

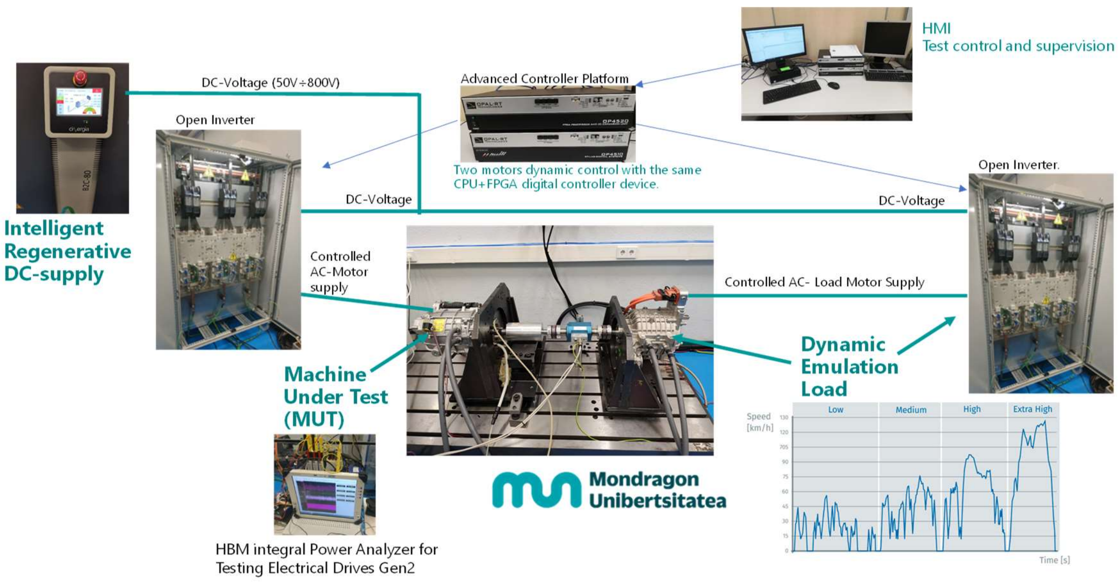


Figure 3: General Lay-Out of emotor testing Test Bed (MGEP facilities)

Intelligent Regenerative DC-Supply

This intelligent DC supply will control the voltage value at DC link where two three-phase SiC inverters will be connected. The defined testing DC link voltage range will be from 450V_{DC} to 800$V_{DC.}$ This range corresponds to the motor specifications. Intelligent DC supply can emulate DC voltage behaviour in the battery, allowing to test the eDrive performance variations due to discharging cycles (driving) or charging (regenerative brake) of the battery.

Open SiC Inverter for Motor Under Test (MUT) control

A three-phase SiC Inverter will be used to dynamically control the MUT. This inverter is developed for laboratory purposes, and it has a flexible and large power and frequency range. The SiC power modules have their own embedded safety protections. Dynamic control of this Inverter is carried out by an external very high-performance Controlled Platform.

Open SiC Inverter for Load Motor control

A three-phase SiC Inverter will be used to dynamically control the Load Motor. This inverter is equal to the SiC Inverter for MUT. Then, the voltage, power and frequency range of two inverters are fully compatibles. Dynamic control of this Inverter will be carried out by an external very high-performance Controlled Platform.

Advanced Controlled Platform

The dynamic controls of the MUT and the Load Motor will be implemented in the same Advanced Controlled Platform (high performance CPU+FPGA controller device). In addition, in the same Controlled Platform a dynamic load profile will be implemented in order to emulate any desired driving cycle or any specific working condition of the vehicles in route.

In WP 3, an improved drive control will be developed maximizing the possibilities of the SiC devices to reduce powertrain losses and improve EV range. The proposed drive control improvements will be developed using Matlab/Simulink simulation tool. Model-Based-Design methodology with automatic code generation tools will be used to easily transfer the developed control improvements to the drive SW. The Advanced Controlled Platform available in this Test Bed is 100% compatible with Matlab/Simulink automatic code generation tools, allowing to a fully implementation of a Model-Based-Design methodology for control SW development.

Torque transducer and Power Analyser

Dynamic performances of the MUT will be measured using high precision voltage, current, speed and torque sensors. Instantaneous values of all electrical measurements (voltage, current, power), all mechanical measurements (speed and torque) and all thermal measurements will be acquired, computed and registered by a high speed Power Analyser. All high resolution synchronized measurements will allow to determinate motor performances at any instant during the testing profile.

5.2 Test Bed at GKN

Test Bed available at GKN AIC is specially designed to carry out type, combined and reliability tests of full eDrives, following automotive standards.

An automotive 800V SiC inverter will be used to test all components under the same mechanical frame allowing to evaluate the thermal performances of the full e-drive system.

Figure 4 and Figure 5 show the existing Test Bed at GKN.

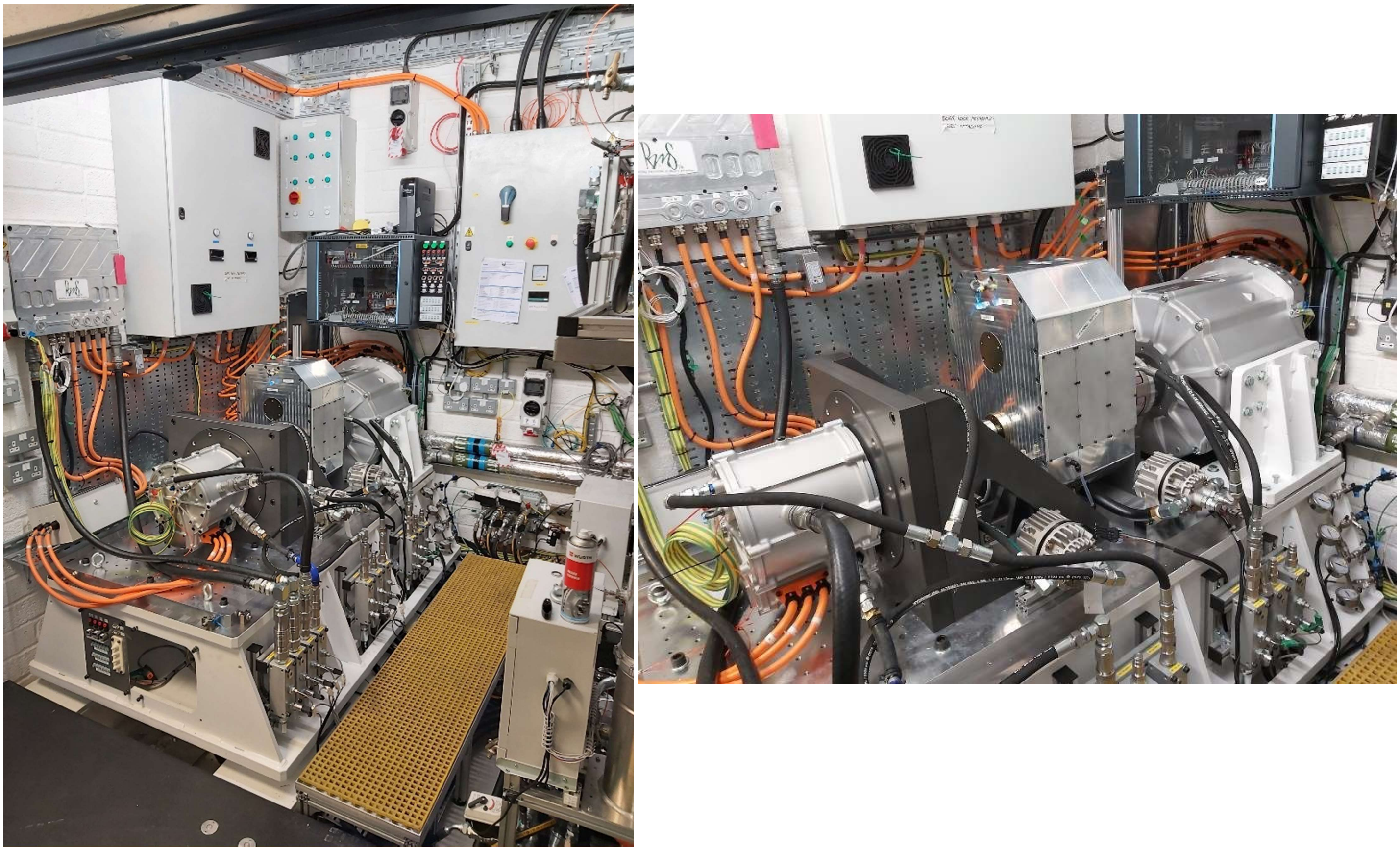


Figure 4: General Lay-Out of emotor testing Test Bed (GKN facilities)

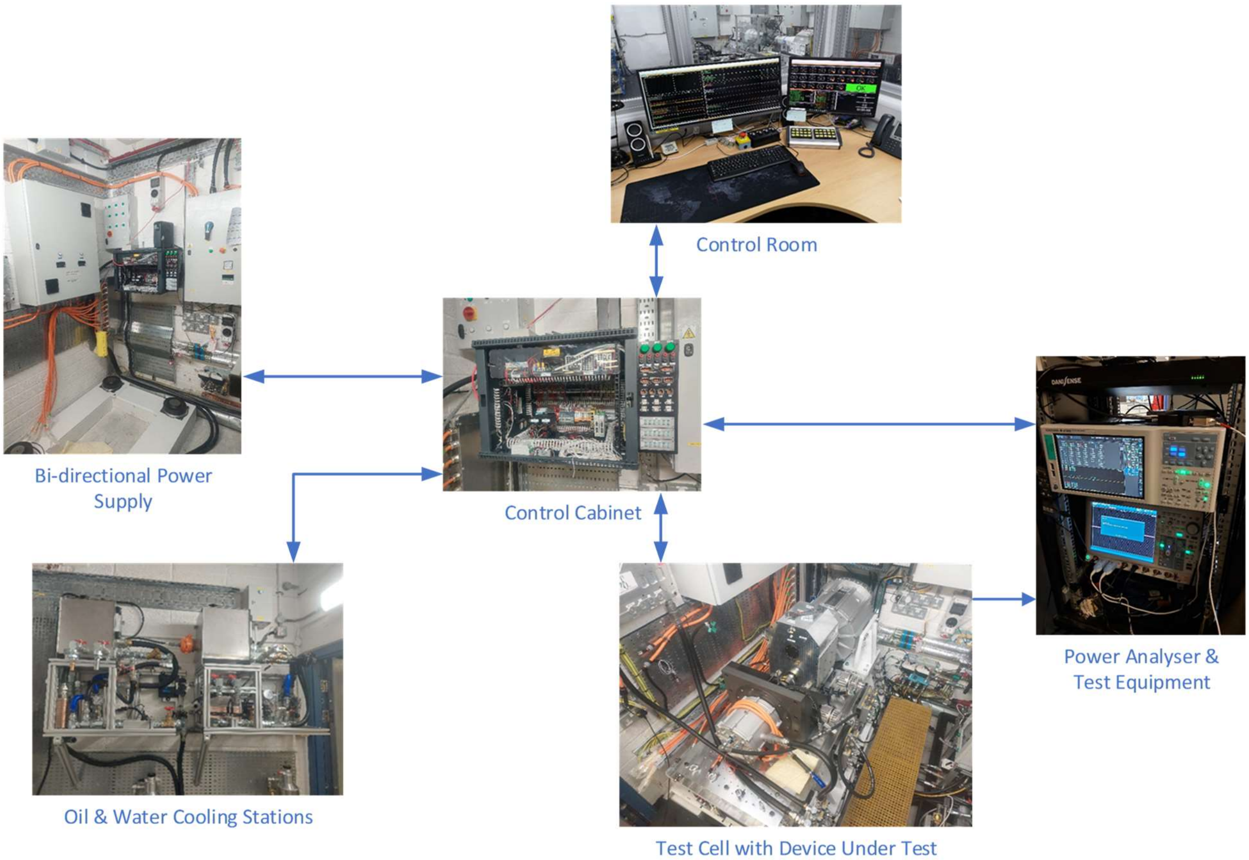
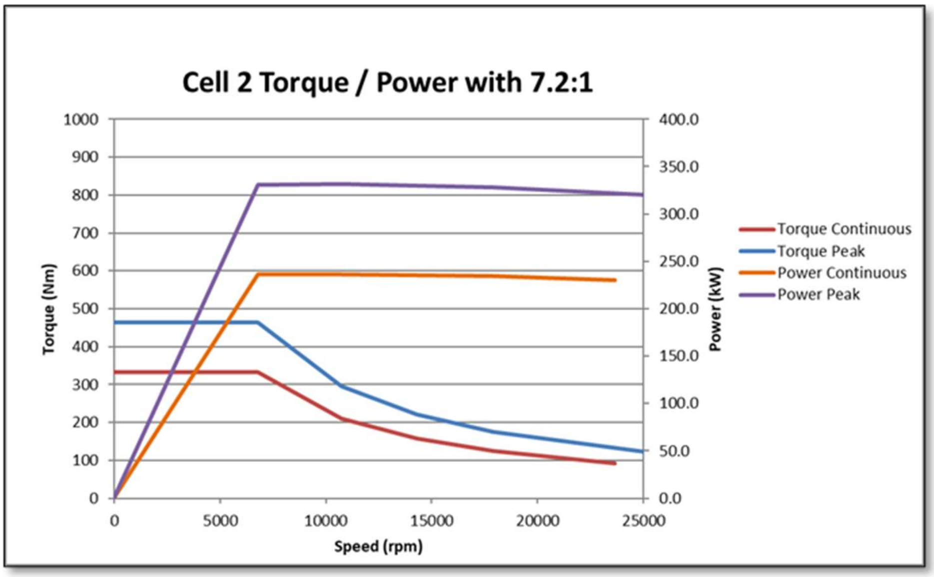


Figure 5: General Lay-Out of emotor testing Test Bed (GKN facilities)

The test bed main characteristics are:

- Configuration: 1M high-speed rig.
- DC Source: 800V, 400A, recirculating in cell (600A per device).
- Specs: 2 gearbox options; 700Nm and 24krpm peak. Depending on the gearbox, different performances are presented in Figure 6.
- Cooling Configuration: Standard cooling modules, 40kW$_{th}$ cooling total:
    - Water (12 < 80°C), 4kW heating.
    - Oil (12 < 100°C, 8 bar), 5kW heating.
- Specific Capabilities: Motor development / cooling.



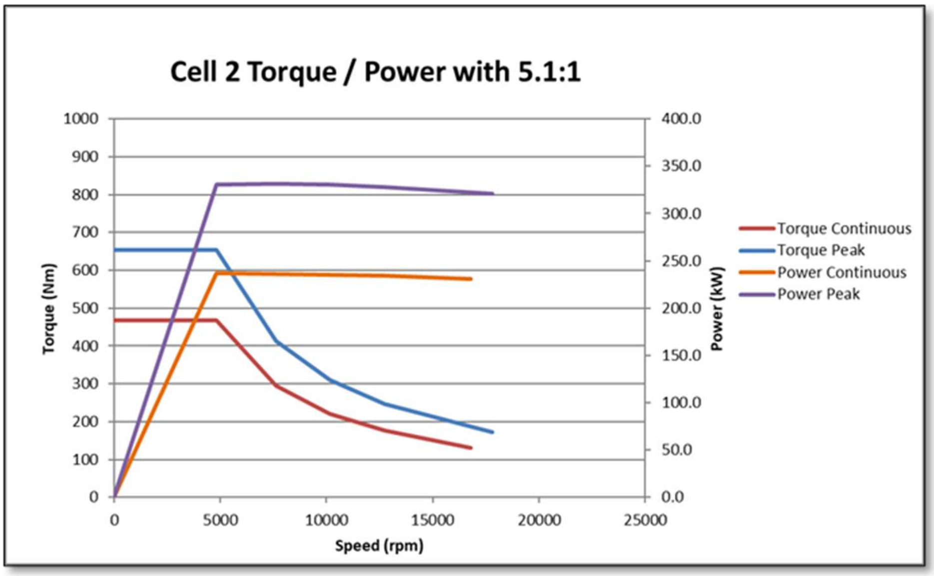


Figure 6. Test bed performance depending on gearbox option.

6 TEST MATRIX

Table 5 shows a test matrix describing the test to be performed to assess the predefined requirements:

Table 5. Matrix of the test to carry out

Motor Specification	Variables	Tests to be performed
Continuous Torque/Power	T_{cont}(Nm) P_{cont} (kW)	1. Test ID1_Thermal 2. Test ID2_ContinuousLoad
Peak Torque/Power & Maximum stator phase current	T_{peak}(Nm) P_{peak} (kW) I_{s_max} (Arms)	✓ Test ID3_PeakLoad
Maximum temperature on windings and magnets	T_{cu_max} (ºC) T_{pm_max} (ºC).	1. Test ID1_Thermal 2. Test ID3_PeakLoad
Motor losses	M_{loss} (Wh/km)	✓ Test ID4_Efficiency + ✓ Test ID5_WLTP
Reliability face to mechanical fatigue	$T_{fatigue}$ (h)	✓ Test ID6_Fatigue
Bearing and seal life	$T_{bearings}$ (h)	✓ Test ID7_Bearings
Reliability face to overspeed	$N_{overspeed}$ (rpm)	✓ Test ID8_Overspeed

7 DETAILED TESTING PLAN

The previously defined testing program is based on a combination of the following fundamental tests: no-load, load, thermal and driving tests, running at different working points and thermal conditions.

Next, a detailed testing plan is included for each fundamental test:

7.1 No-load tests

No-load test in a Test Bed is done with the MUT without electrical feeding and controlling the load Machine at the testing speed.

Testing goals

This test can be useful for the following goals:

- Stator magnetic flux linkage due to permanent magnets Ψ_{pm} (Wb rms) (fundamental harmonic)
- Back EMF (V) waveform and harmonic spectrum
- Iron losses (W) due to rotor magnetic field

Working conditions

- MUT with stator terminals disconnected from any electrical feed.
- Load Machine controlled in a speed control mode by an inverter.

Magnitudes to be measured

- MUT
  - Line voltage: V_{uv}, V_{uw}, V_{vw}: Vrms & waveform.
  - Output axle: Torque (Nm), Speed(rpm).

Testing plan

1. Fix several accelerometer sensors along MUT housing
2. Setting the Load Machine in speed control mode.
3. Increase speed setpoint with a slope rate limitation.
   Note: If one accelerometer value increases above maximum predefined levels, test is immediately stopped.
4. Once speed is in steady-state -> Register all measurements.

Acceptation criteria for the test

1. Accelerometer levels are below maximum predefined levels.
2. Axle speed is in steady state with a low harmonic content.
3. MUT: Line voltages: V_{uv}, V_{uw}, V_{vw} are balanced.

7.2 Load tests

Load test in a Test Bed is done with the MUT in a torque control mode and the load Machine in a speed control mode.

Testing goals

This test can be useful for the following goals:

- Output performances measurement: Average torque (Nm) and torque ripple (Nm).
- Electrical magnitudes measurement: Stator voltages (V), Stator currents (A), Input Power (W).
- Efficiency Measurement.

Working conditions

- MUT is controlled in a torque control mode by a three-phase inverter.
- Load Machine controlled in a speed control mode by a three-phase inverter.

Magnitudes to be measured

- MUT:
  - Line voltage: V_{uv}, V_{uw} $V_{vw,}$: V_{rms} & waveform, I_u, $I_{v,}$ $I_{w,}$: I_{rms} & waveform, Input Power P_s (W).
  - Output axle: Torque (Nm), Speed(rpm).
  - Stator winding temperatures: T_{cux}(t) (ºC), several temperature sensors at the end-windings.
  - Cooling inlet and outlet temperatures: T_{cool_in} and T_{cool_out} (temperature sensors).

Testing plan

1. Fix several accelerometer sensors along MUT housing
2. Setting the Load Machine in speed control mode and MUT in torque control mode
3. Set MUT $T_{setpoint}$=0Nm
4. Increase Load Machine speed setpoint with a slope rate limitation.
5. Once speed is in steady-state, apply a torque setpoint $T_{setpoint}$=$T_{thermal}$(Nm) to achieve the desired thermal steady-state.
6. Once the thermal steady-state is achieved, apply the testing setpoint $T_{setpoint}$=T_{ref}(Nm). Once electrical, torque and speed measurements are in steady-state-> Register all measurements

   Note: Protections along the testing->.
   -Maximum currents protections are activated in both inverters
   -If one accelerometer value increases above maximum predefined levels, test is immediately stopped
   -If one thermal sensor measurement is higher than maximum predefined levels, test is immediately stopped.

Acceptation criteria for the test

1. Accelerometer levels are below maximum predefined levels.
2. Axle speed is in steady state with a low harmonic content.
3. MUT
   a. Line voltages and current are balanced.
   b. Harmonic content of the output torque ripples are below predefined levels.
   c. Different temperature levels are below predefined levels.

7.3 Thermal tests

Thermal tests in a Test Bed are done with the MUT in a torque control mode and the load Machine in a speed control mode

Testing goals

This test can be useful for the following goals:

- To verify the ability of the MUT to perform the load conditions along the service time.
- To verify temperatures in the different parts of the MUT are below the design limits.

Working conditions

- MUT is controlled in a torque control mode by a three-phase inverter.
- Load Machine controlled in a speed control mode by a three-phase inverter.

Magnitudes to be measured

- MUT:
  - Line voltage: V_{uv}, V_{uw} $V_{vw,}$: V_{rms} & waveform, I_u, $I_{v,}$ $I_{w,}$: I_{rms} & waveform, Input Power P_s (W).
  - Output axle: Torque (Nm), Speed(rpm).
  - Stator winding temperatures: $T_{cux}(t)$ (ºC), several temperature sensors at the end-windings.
  - Cooling inlet and outlet temperatures: T_{cool_in} and T_{cool_out} (temperature sensors).
  - Temperatures along the motor housing and in the bearing

Testing plan

1. Fix several accelerometer sensors along MUT housing.
2. Setting the Load Machine in speed control mode and MUT in torque control mode.
3. Set MUT $T_{setpoint}$=0 Nm.
4. Increase Load Machine speed setpoint with a slope rate limitation.
5. Once speed is in steady-state, apply a torque setpoint $T_{setpoint}=T_{thermal}$(Nm) (a constant value or a dynamic torque profile) to achieve the desired thermal steady-state.
6. During the test:
   - Supervise that the measured torque is constant equal to $T_{setpoint}$. Any torque deviation can be adjusted applying some changes to $T_{setpoint}$.
   - Supervise that the dynamic evolution of electrical magnitudes (V, I, P_s) and temperatures follow the predicted waveform. A dynamic abrupt change in any variable will be analysed in detail to check.
7. After the test
   - Set MUT $T_{setpoint}$=0Nm, measure Back EMF -> Compute T_{pm_avg} (ºC).
   - Set $Speed_{setpoint}$=0rpm, once measured speed is zero, switch-off inverters and DC supply.
   - Measurement of average stator winding temperature by the electrical resistance computation method.

Note: Protections along the testing->.
-Maximum currents protections are activated in both inverters
-If one accelerometer value increases above maximum predefined levels, test is immediately stopped
-If one thermal sensor measurement is higher than maximum predefined levels, test is immediately stopped.

Acceptation criteria for the test

1. Accelerometer levels are below maximum predefined levels.
2. Axle speed and measured torque are constants.
3. Electrical measurements below maximum limits.
4. Dynamic evolution of $T_{cux}(t)<T_{cu\_max.}$ According to the designed insulation class.
5. Average stator winding temperature and average permanent magnet temperature when MUT is stopped are below the maximum limits.

7.4 Driving cycle tests

Driving cycle tests in a Test Bed is done with the MUT in a torque control mode and the load Machine in a speed control mode.

Testing goals

This test can be useful for the following goals:

- To verify the ability of the MUT to perform the driving tests.
- To verify that temperatures in the different parts of the MUT are below the design limits.
- Detailed experimental evaluation of Motor Losses (Wh/km) at WLTP driving cycle.

Working conditions

- MUT is controlled in a torque control mode by a three-phase inverter.
- Load Machine controlled in a speed control mode by a three-phase inverter.

Magnitudes to be measured

- MUT:
  - Line voltage: V_{uv}, V_{uw} $V_{vw,}$: V_{rms} & waveform, I_u, $I_{v,}$ $I_{w,}$: I_{rms} & waveform, Input Power P_s (W).
  - Output axle: Torque (Nm), Speed(rpm).
  - Stator winding temperatures: T_{cux}(t) (ºC), several temperature sensors at the end-windings.
  - Cooling inlet and outlet temperatures: T_{cool_in} and T_{cool_out} (temperature sensors).
  - Temperatures along the motor housing and in the bearing

Testing plan

1. Fix several accelerometer sensors along MUT housing.
2. Setting the Load Machine in speed control mode and MUT in torque control mode.
3. Set at the same time $T_{setpoint}$ (t) and $Speed_{setpoint}$(t) profiles.
4. During the test:
   - Supervise the precision of the measured speed dynamic response. Any dynamic variation face to $Speed_{setpoint}$ will invalidate the test, needing to re-adjust speed control regulation parameters.
   - Supervise the precision of the measured torque dynamic response. Any dynamic variation face to $T_{setpoint}$ will invalidate the test, needing to re-adjust torque control regulation parameters.
   - Supervise that the dynamic evolution of electrical magnitudes (V, I, P_s) and temperatures follow the predicted waveform. A dynamic abrupt change in any variable will be analysed in detail to check.
   - Computation of Motor Losses(t). Loss(t)=P_{in}-P_{out} (w) at each instantaneous point along the time.

   Note: Protections along the testing->.
   -Maximum currents protections are activated in both inverters
   -If one accelerometer value increases above maximum predefined levels, test is immediately stopped
   -If one thermal sensor measurement is higher than maximum predefined levels, test is immediately stopped.

Acceptation criteria for the test

1. Accelerometer levels are below maximum predefined levels.
2. Speed and torque dynamic responses have a good precision.
3. Electrical measurements below maximum predefined limits.
4. Dynamic evolution of $T_{cux}(t)<T_{cu\_max}$. According to the designed insulation class.

8 DELIVERY DEVIATIONS FROM THE INITIAL PLANNING

There has been a delay in the delivery of D1.3. Validation plan

Contractual delivery: 2023-03-31

Deliverable Date: 2023-08-07

This delay is due to:

Administrative deviations:

First full version of this document has been checked on 2023-07-10. First draft of the document was uploaded to the TEAMS platform in June, there was a delay in the submission due to doubts and concerns with the motor specifications which have been finally clarified. Furthermore, we have delayed in the review process.

Delay effect on overall project planning:

This report is mainly related to WP5 which has not started yet, so it does not generate any delay in the next tasks.

9 CONCLUSIONS

This document presents the different tests that are going to carry out to validate the new emotors developed in the HEFT project. Two motor topologies will be developed and validated to fulfil the requirements of A-B segment and C-D-E segment respectively.