Rare Earth Free e-Drives Featuring Low Cost Manufacturing

ReFreeDrive

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Abbreviations

CAN: Controller Area Network

GA: Grant Agreement

HV: High Voltage

IM: Induction Motor

LV: Low Voltage

NVH: Noise, Vibration and Harshness

PE: Power Electronics

SiC: Silicon Carbide

SynRel: Synchronous Reluctance motor

UAQ: University of L'Aquila

IFPEN: IFP Energies Nouvelles

WLTC: Worldwide Harmonized Lightweight Testing Cycle

WP: Work Package

1 Executive Summary

This report D7.2 details the activities carried out in Task 7.2 of ReFreeDrive's Work Package 7 (WP7), contributing to the overall objective of the WP, which is to test and gather experimental evidence of the powertrains performance following an incremental approach, starting from the testing of the motors and Power Electronics (PE) designed in WP3, WP4 and WP5 and manufactured in WP6, up to the full vehicle integration.

According to the ReFreeDrive's Grant Agreement (GA), Task 7.2 is focused on the integration of the powertrain and various vehicle systems in a test bench at CIDAUT, in order to characterize and to validate the vehicle functioning conditions in a controlled and measurable environment. To this end, CIDAUT carried out a series of integration tests on powertrain components, such as accelerator pedal and CAN communication, with the support of IFP Energies Nouvelles (IFPEN), PRIVÉ, University of L'Aquila (UAQ) and R13.

Taking advantage of the capabilities available at CIDAUT and the suggestions of some project partners, additional actions not included in the GA were carried out, namely:

- Functional testing on Medium Power Silicon Carbide (SiC) PE, which supplemented the laboratory characterization activities carried out by R13 within WP5.
- Acoustic characterization.

The experimental facility used for testing the 75kW powertrains was equipped with: High Voltage (HV) power supply, Low Voltage (LV) power supply, test bench (load motor), water cooling circuit, accelerator pedal, Controller Area Network (CAN) bus and motor control software, and data acquisition systems. It is presented in Figure 1.

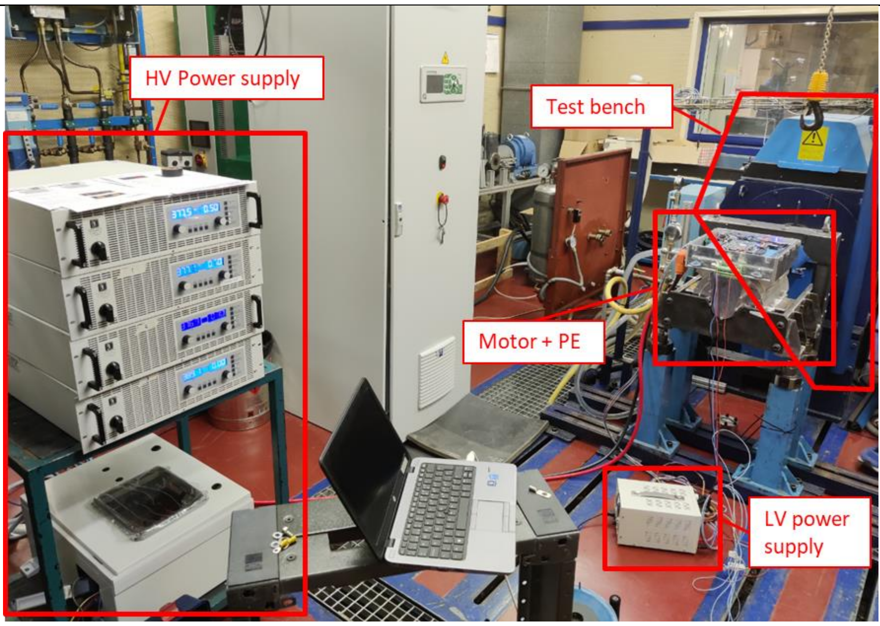

Figure 1. Experimental facility

Prior to evaluating the performances of the powertrain in real-world based scenarios, a tuning stage was carried out with a double objective:

- Optimize the control firmware of the motor and the motor response to the accelerator pedal inputs.
- Check that all systems were operating and communicating properly. Concretely the focus was put on ensuring, through a series of functional tests supervised by UAQ and R13, that the medium power PE behaved as expected. Main efforts were dedicated to enhancing the firmware that controls the motor.

Once the setup was properly adjusted, a series of tests were performed to evaluate the behavior of the powertrains in real-world based driving scenarios, focusing on the low efficiency regions of the system (motor + powertrain) efficiency maps, such as the following ones:

- Constant speed tests. Efficiencies ranged from 57% (at 20 km/h) to 91% (at 60 km/h).
- Acceleration steps on flat terrain (efficiency 84%) and on a 10% slope (efficiency 87%).
- Low speed driving cycle. Efficiency measured: 84%.

All efficiencies measured were in line with the expectations. These tests allowed completing the characterization carried out within Task 7.1 by IFPEN. Finally, noise emitted by the pure Synchronous Reluctance (SynRel) motor was measured, obtaining values of 88 dB and 82 dB(A), what emphasizes the importance of addressing this aspect as part of the in-vehicle integration activities.

The impact of Covid-19 on Task 7.2 and accordingly on D7.2 was severe and caused some deviations both in content and in time. In terms of time, lockdowns, national and international travel restrictions and freight traffic inconveniences that happened throughout 2020 and the beginning of 2021 affected the development of the project and specifically of WP7 tasks. The greatest impact was on WP6 (Prototypes manufacturing) activities. The manufacturing of components and the assembly of the prototypes, including the sub-contracting of some activities underwent significant challenges and delays. Delays in WP6 implied that the beginning of Task 7.2 had to be postponed, therefore coinciding in time with Task 7.3. In terms of content, Task 7.3 was considered of higher priority; hence some powertrain components such as battery pack and gearbox were kept at PRIVÉ and were not included in the tests carried out in Task 7.2.

To mitigate the negative impacts and make possible the completion of both affected Tasks, actions and countermeasures were defined in agreement with the partners involved in WP7, mainly IFPEN, R13, UAQ and PRIVÉ.

Despite the deviations, it is considered that D7.2 fully fulfils its objectives, bridging the gap between the component testing and the full in-vehicle testing.

2 Introduction

Task 7.2 is devoted to the integrated powertrain testing of the 75kW motor prototypes designed and built in previous WPs of ReFreeDrive project. As stated in the GA, in this Task other powertrain systems apart from the motor and the PE were included incrementally in a test bench at CIDAUT facilities, which is equipped with an electric motor that replicates the energy demand of the auxiliaries, the energy losses during the vehicle rolling and, in general, the vehicle functioning conditions in a controlled and measurable environment. For the integration of the different systems and controls, CIDAUT counted with the active support of PRIVÉ, UAQ and R13.

Apart from the aforementioned scope of the Task, additional actions not included in the GA were carried out, namely:

- Functional testing on Medium Power SiC PE, which supplement the laboratory characterization activities carried out by R13 within WP5.
- Acoustic characterization

The impact of Covid-19 on this subtask was severe. Lockdowns, national and international travel restrictions and freight traffic inconveniences that happened throughout 2020 and the beginning of 2021 affected the development of the project and specifically of WP7 tasks. The biggest impact was on WP6 (Prototypes manufacturing) activities. The manufacturing of components and the assembly of the prototypes, including the sub-contracting of some activities underwent significant challenges and delays. Consequently, the beginning of Task 7.2 had to be postponed, therefore coinciding in time with Task 7.3. To mitigate the negative impacts, actions and countermeasures were defined in agreement with the partners involved in WP7, mainly IFPEN, R13, UAQ and PRIVÉ. All of them will be detailed in the following sections. Section 3 describes the experimental facility used for the testing. Section 4 covers all activities carried out in relation with the setup of the different subsystems involved, for instance the functional tests performed on the medium power PE. Section 5 reports the integration tests (constant speed, acceleration and driving cycle), from which efficiency calculations have been made. Section 6 deals with the acoustic characterization of the powertrain. Finally, Section 7 summarizes the main conclusions obtained in Task 7.2.

3 Experimental facility and testing setup

3.1 Setting up the integrated powertrain testing facility

The first step of Task 7.2 consisted on preparing the testing facility at CIDAUT in order to carry out the powertrain integration tests for the ReFreeDrive 75kW motors. This included not only the testing of the full motor and inverter system together (step forward compared with the partial standalone testing carried out within Task 7.1), but also the installation of the accelerator, the batteries or the reduction gearbox, among others. Two power supplies were needed: on the one hand, the battery pack would act as the High Voltage (HV) power supply that fed the motor; and on the other hand a 12V Low Voltage (LV) power supply was used to make the electronics run. The schematic concept of the testing facility is shown in Figure 2.

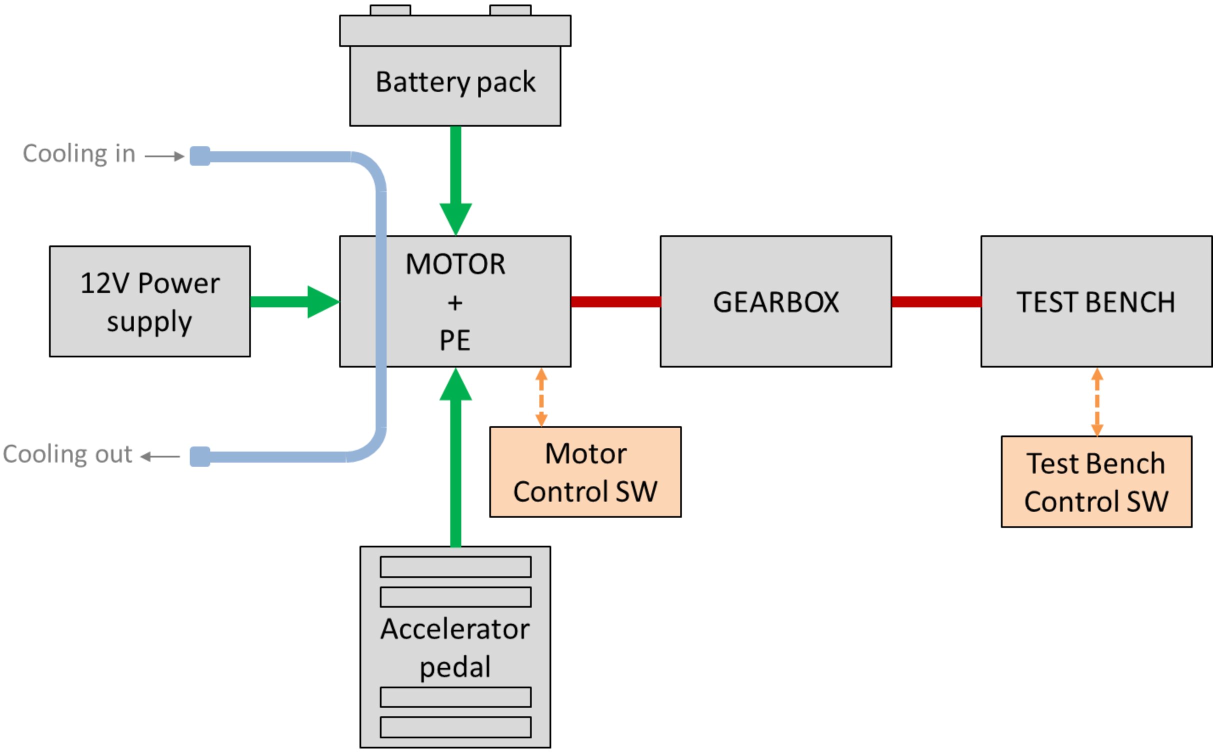

Figure 2. Experimental facility concept layout.

Firstly, in order to place the motor, the gearbox and the test bench axles in their correct position, a steel frame was designed and manufactured (Figure 3). The frame counted with shock absorbers (grey parts in Figure 3, left image) to reduce the mechanical and acoustic impact of potential motor vibrations.

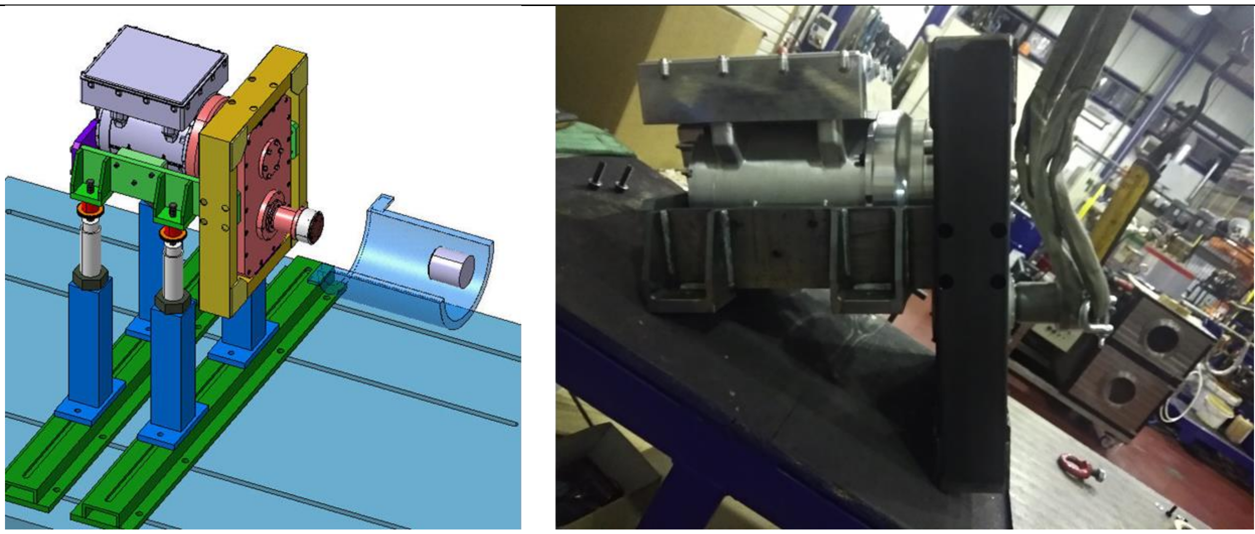

Figure 3. Motor and gearbox frame. Left: design concept. Right: final assembly.

The simultaneity of T7.2 and T7.3 tasks meant that the battery pack and the gearbox had to be from a certain date at the same time in CIDAUT and PRIVÉ (from a schedule point of view). After agreement, considering that it was not possible to receive in-person support from PRIVÉ and the higher flexibility of CIDAUT's testing campaign, higher priority was given to in-vehicle integration and testing, therefore the test facility concept as conceived (Figure 2) was redesigned according to the new scenario. Hence, the gearbox was dismounted and sent back to PRIVÉ's facilities, and the motor frame was redesigned.

To adapt the motor axle to the test bench axle, it was necessary to move the motor down. IFPEN did not report any major vibrational issues during Task 7.1 tests, therefore it was decided to get by without the shock absorbers so as to meet the new constraints. The modified design, also suitable to carry out the testing program, is shown in Figure 4.

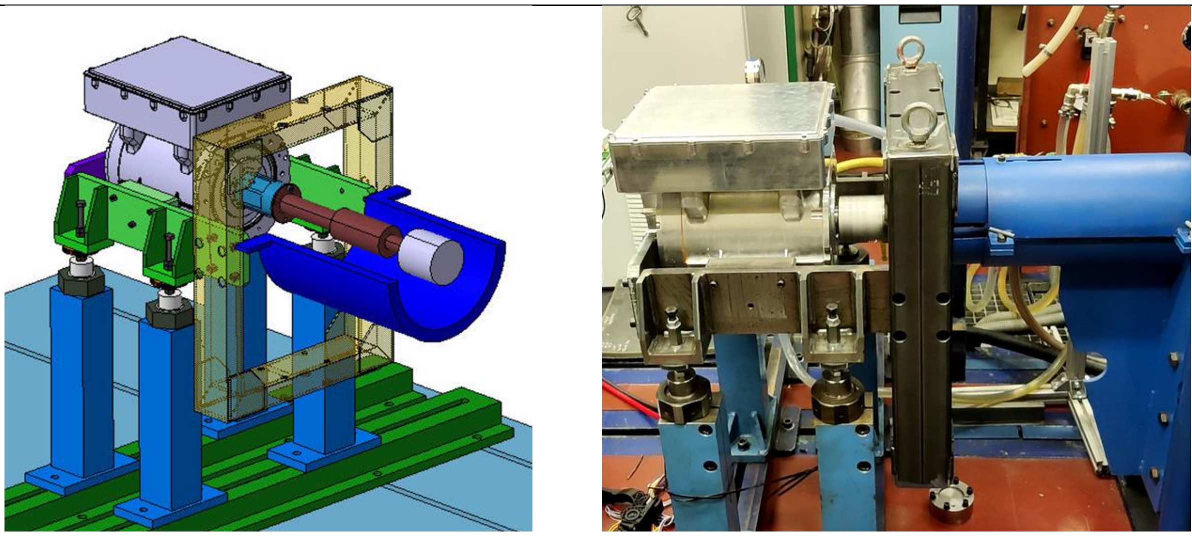

Figure 4. Motor modified frame. Left: design concept. Right: final assembly.

The adaptation described above also implied some changes on the flange, as in the initial configuration the output of the motor was connected to the input of the gearbox, while in the final configuration it is connected directly to the test bench's axle. The initial and final design of this part is shown in Figure 5.

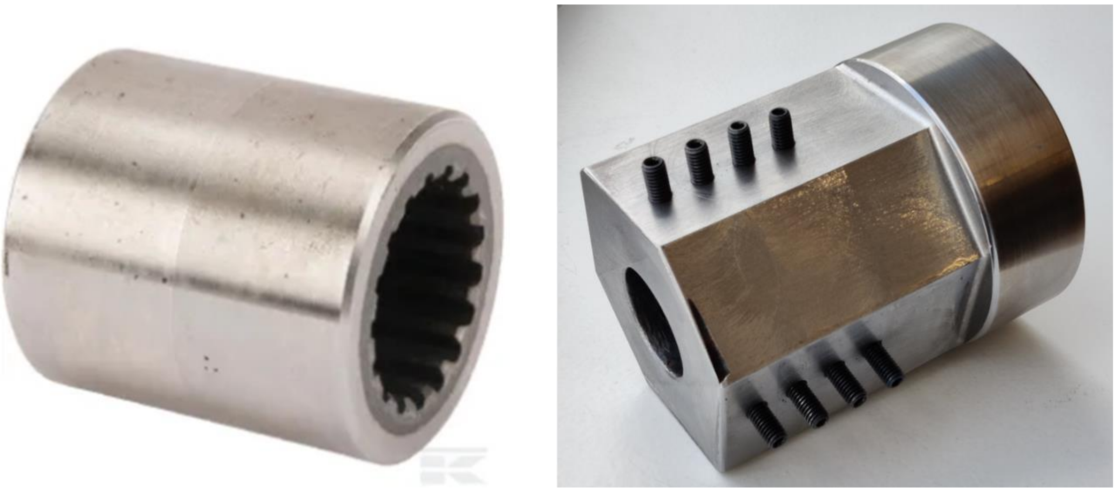

Figure 5. Initial (left) and final (right) design of the flange.

Adaptations from the original layout were also needed concerning the HV power supply, identified initially with the battery pack designed and built by PRIVÉ to be used in the real vehicle. As the installation of the battery pack was not critical to achieve Task 7.2 results but was an essential part of the vehicle integration activities, CIDAUT and PRIVÉ agreed to retain the battery pack at PRIVÉ's facilities, looking for alternative power sources for the tests at CIDAUT.

In first place a single power supply, presented in Figure 6, already available at CIDAUT's facilities was installed.

Figure 6. Initial power supply installed in the experimental facility.

By using this power source it was possible to start the motors and make them run, but after a few seconds the Power Electronics (PE) entered in safe operation mode and the motor stopped. After thorough analysis from UAQ, R13 and CIDAUT, issues in the PE design and control were discarded. Specific tests carried out by CIDAUT under the guidance of UAQ and R13 indicated that voltage drops in the power source were the most likely cause of the PE entering in safe operation mode. To try to improve the behaviour of the power source, a capacitors bank made up from two 15 µF (680 V) capacitors was designed, built and installed between the power source and the motor to compensate the voltage drops and ensure a continuous power supply. Some of the components used for its construction can be seen in Figure 7.

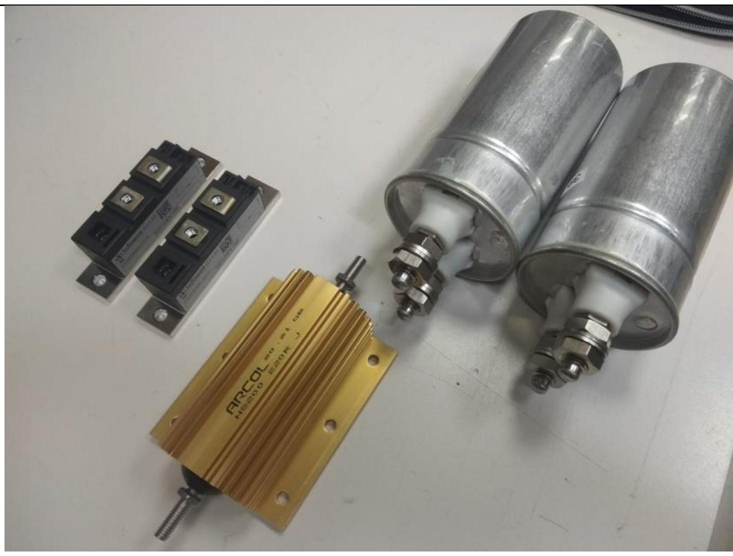

Figure 7. Components of the capacitors bank.

After this modification, the motor was able to run for a longer time, reaching higher speed and torque values, however in the end the PE always forced the test to end too early. Due to the tight deadlines, developments in this direction were stopped and CIDAUT opted to looking for another solution. Hence a set of four 15kW power sources connected in parallel was installed, shown in Figure 8, being able to provide up to 60kW, which was more than enough for validating the correct operation of the drivetrain. Using this power supply concept the PE was able to work as expected.

Figure 8. Final power supply (4 x 15kW connected in parallel)

Finally, all other hardware (accelerator, cooling circuits, Controller Area Network (CAN) bus) and software (motor control firmware) was added to the setup. The full testing setup used for the powertrain integration tests is briefly described in the following Section 3.2, and its scheme is presented in the following Figure 9.

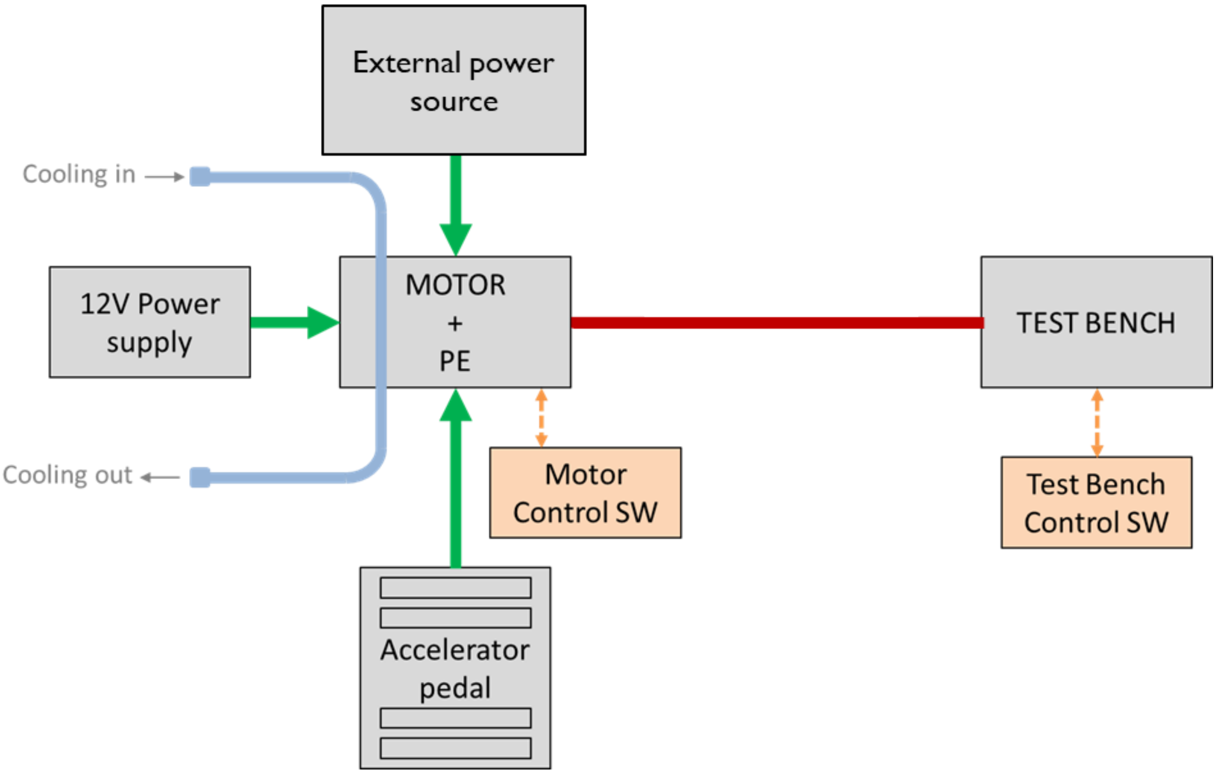

Figure 9. Final experimental layout

3.2 Experimental facility description

The experimental facility used for testing the 75kW powertrains, displayed in Figure 10, was equipped with:

- HV power supply (60kW)
- LV power supply (12V)
- Water cooling circuit, inlet and outlet visible at the left part of the e-drive in Figure 10.
- Test bench (load motor)
- Accelerator pedal (see red ellipse in Figure 11)
- CAN bus and motor control software
- Data acquisition systems

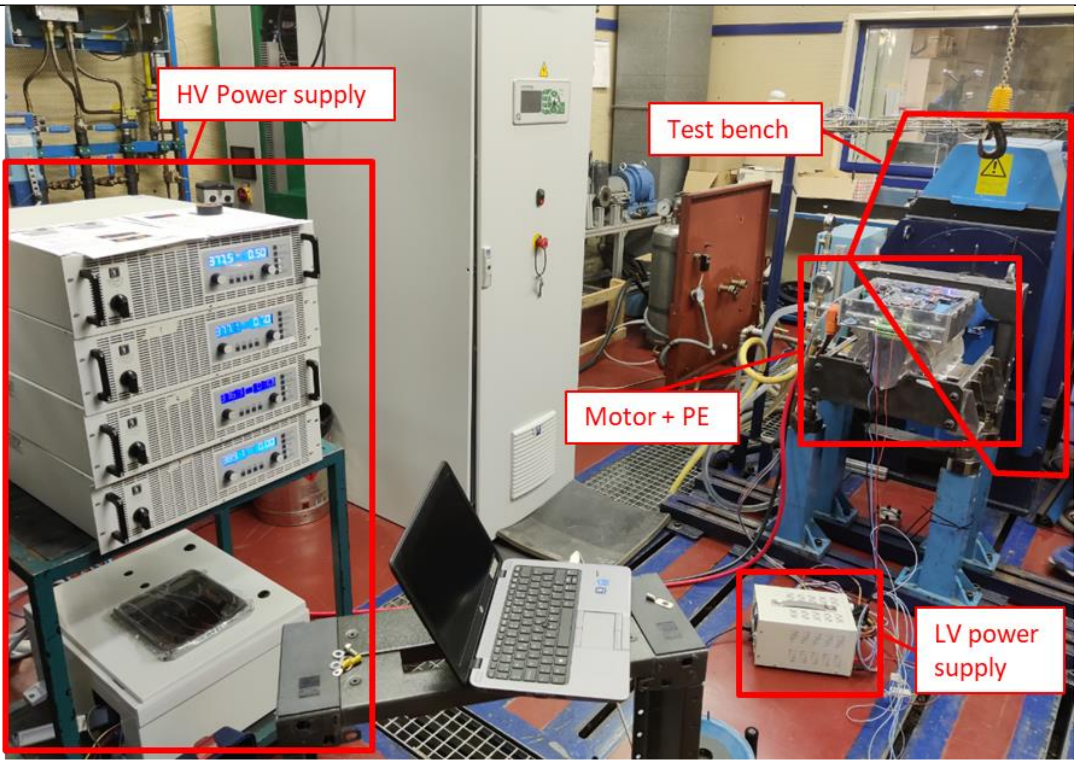

Figure 10. Experimental facility

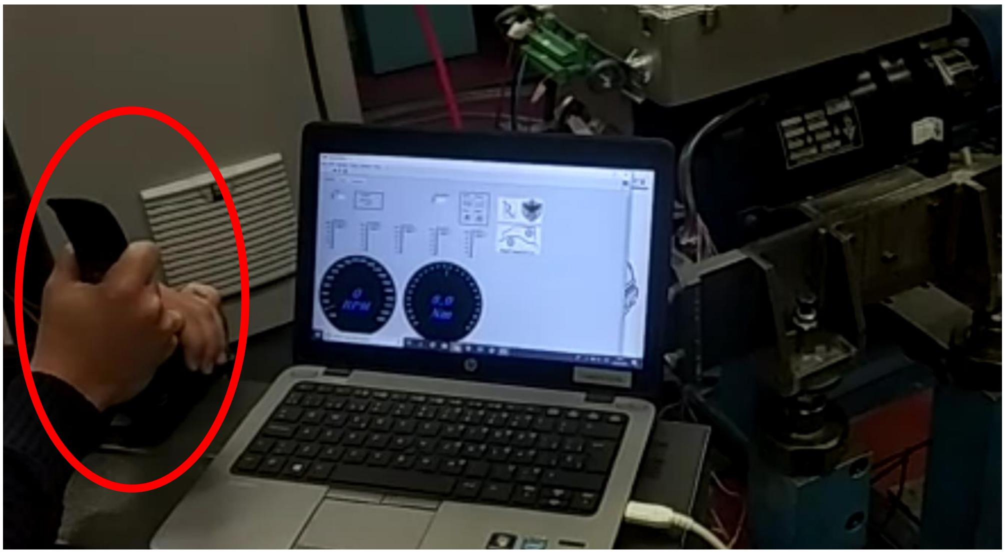

Figure 11. Accelerator pedal

4 Systems integration and tuning

Prior to evaluating the capabilities and the performances of the powertrain in real-world based scenarios, a tuning stage was carried out with a double objective:

- Optimize the control firmware of the motor and the motor response to the accelerator pedal inputs.
- Check that all systems were operating and communicating properly. Concretely the focus was put on ensuring, through a series of functional tests supervised by UAQ and R13, that the medium power PE behaved as expected.

Main efforts were devoted to enhance the firmware that controls the motor. The first step consisted on checking the motor and inverter operation as a whole system, without introducing any load through the test bench (no load tests). The input torque was provided directly via keyboard, in order to have full control on the input signal. Since the completion of these trials was independent on the torque level requested to the motor, motor capabilities (namely torque output) were limited through PE software to avoid damaging any component.

Once the CAN protocols were properly adjusted and the motor responded as expected to the input signals, the next step consisted on switching the input to the accelerator pedal, example shown in Figure 12. First trials were partially satisfactory: high speeds could be achieved through the accelerator with a fast response from the motor if the pedal was pushed quite smoothly, but the system stopped if an abrupt behavior of the pedal was simulated. This issue was reported to UAQ and R13 and the firmware version was updated accordingly.

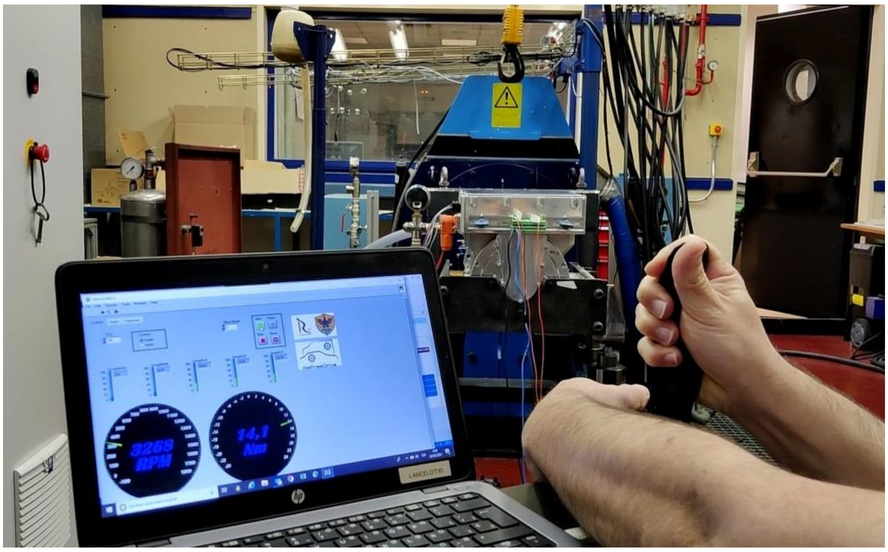

Figure 12. Acceleration pedal tuning tests.

Subsequent versions of the firmware progressively unlocked motor capabilities until being able to use the full power of the motor through the pedal in a safe manner for the motor and PE components while providing a realistic behavior. During the process, additional minor software issues that arose were also fixed, for instance having a real-time monitoring of motor and SiC temperatures. Under request of CIDAUT, UAQ and R13 added the possibility of recording the monitored variables at 10Hz acquisition frequency (Figure 13), which are mainly:

- SiC modules temperature
- Motor temperature
- Motor speed
- Motor torque
- Motor voltage
- Motor current

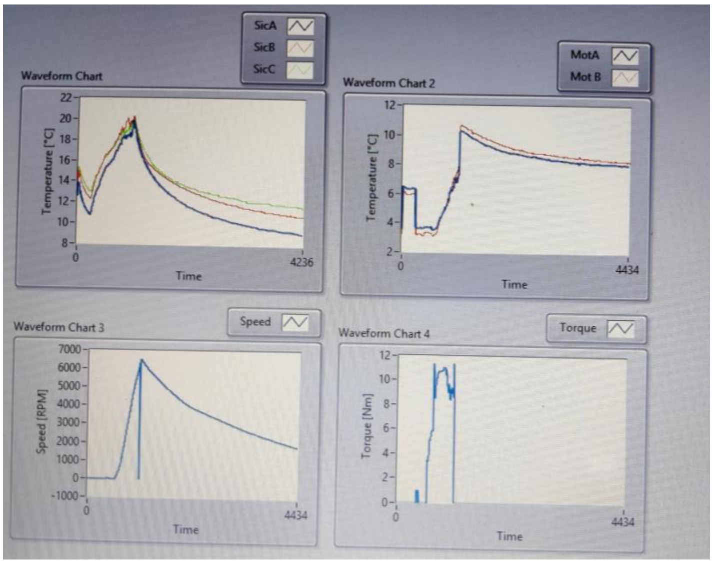

Figure 13. Example of monitored motor and power electronics variables

Another key finding that appeared during this tuning stage, on the pure Synchronous Reluctance (SynRel) motor, was related to the cooling. In the first trials with pressurized water (cooling circuit pressure ranging between 0.5 - 0.9 bar), some leakage issues appeared, similar to the ones reported by PRIVÉ during the in-vehicle tests, where they used the second prototype of the pure SynRel motor. Just after the first drops were detected going out of the housing, test were stopped to avoid damaging the PE. The area of the motor where leakage was found is marked by the yellow arrow in Figure 14.

Figure 14. Area of the pure SynRel motor where leakage was found.

Looking the causes of the leakage, it was found that during disassembly drops stopped falling, hence the root cause could likely be an increase of the clearance between the exterior and interior housings due to the assembly process, that allow water escaping from the cooling circuit when the pressure is above 0.5 bar. The leakage mechanism, shown schematically in Figure 15, is the following: when the powertrain is installed in the test bench, the motor has to be somehow fixed to the rigid test bench. The total pre-existing clearance between the tooling and the exterior housing of the motor (Figure 15, left image) is 0.35 mm. Once everything is fixed, there is no clearance between the exterior housing and the tooling anymore, which implies that a gap of the same magnitude (0.35 mm) has to appear between the exterior and interior housing (Figure 15, right image). Experiments showed that this tiny gap was enough to allow water escaping from the cooling circuit under certain circuit pressure conditions.

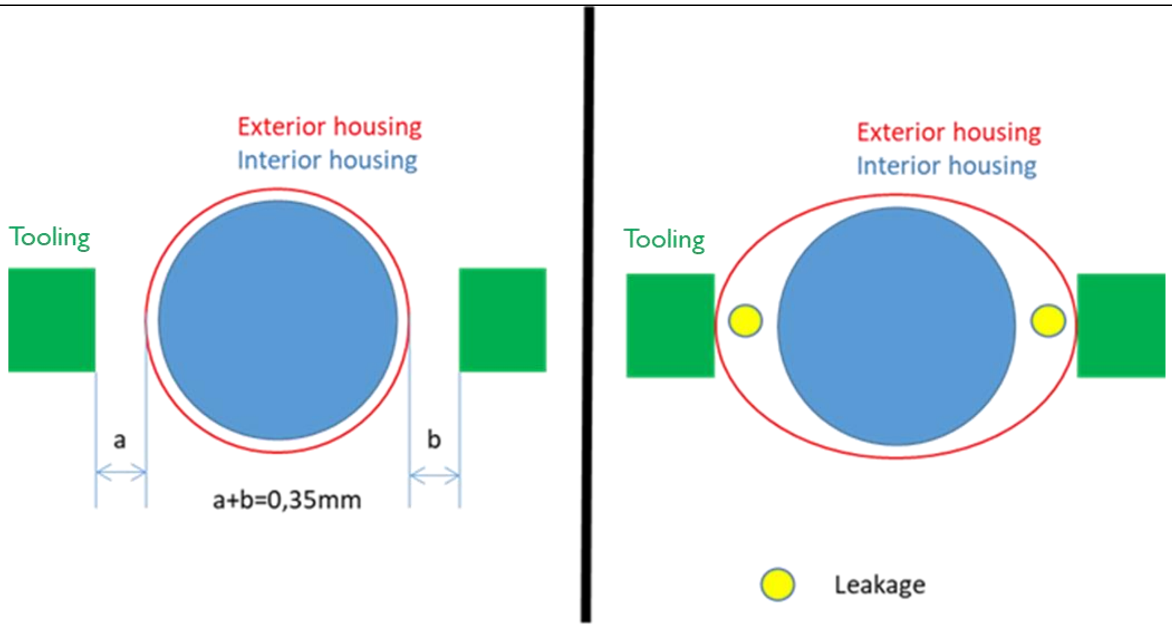

Figure 15. Leakage found in the pure SynRel motor during the powertrain tests.

To fix the leakage, the motor was disassembled, the cover removed and an additional sealant cord was introduced. Besides, for safety reasons, a conservative cooling approach was followed by carrying out the tests with limited water pressure.

Considering the even more complex cooling concept introduced in the Induction Motors (IM), and considering the feedback from IFPEN regarding the coolant flow issues found on the die-cast IM (see Deliverable 7.1 for further details), the same approach was followed in the die-cast IM.

5 e-Drive integration test results

This section presents an overview of the tests performed on the 75kW pure SynRel and die-cast IM motors. The objective of the tests is to validate that the developed prototypes provide expected performance in real-world based driving scenarios. All motors were tested on 375V source voltage.

5.1 Pure SynRel 75kW

Figure 16 presents an overview of the Pure SynRel 75kW motor installed at CIDAUT's experimental facility.

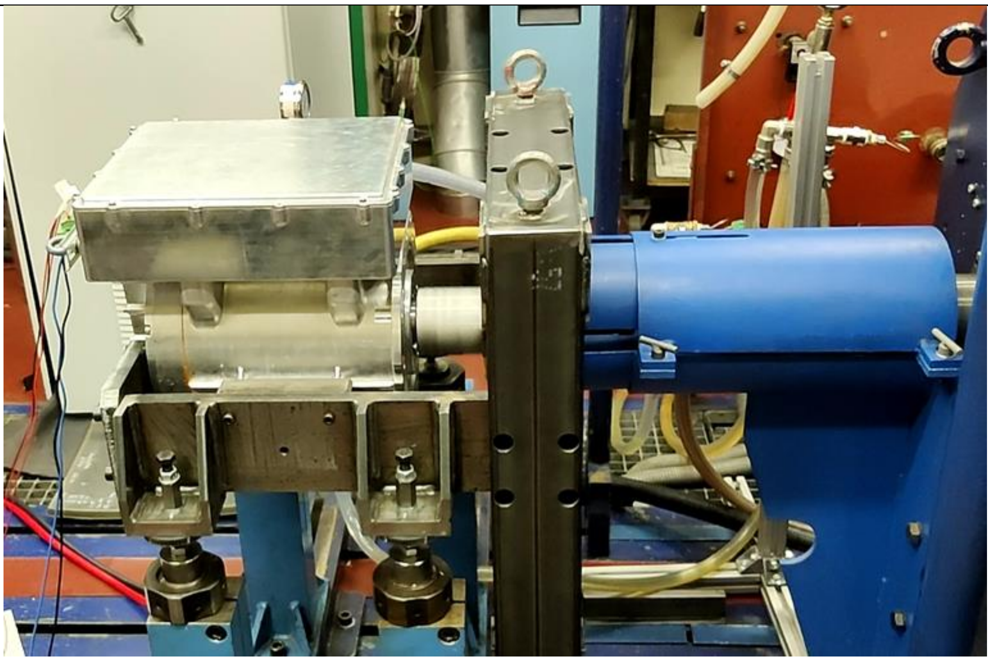

Figure 16. Pure SynRel motor overview

5.1.1 Constant speed tests

Constant speed tests intend to characterize the performance of the powertrain when driving at constant speeds. As this tests are conceptually quite similar to the ones carried out within Task 7.1 at IFPEN, the focus here has been put into the low torque – low speed – low efficiency areas of the torque-speed map that are difficult to measure experimentally, in order to complement their characterization (see Figure 26 and Figure 27 in D7.1). Therefore in this tests speed range was considered from 20 km/h to 60 km/h, which means torque values under 20 Nm.

In order to calculate the motor rotational speed (in rpms) that equals the target lineal speeds (in km/h), the complete powertrain architecture, such as reduction gear, differential or wheels have to be taken into account. For the purpose of these tests the main vehicle (Mercedes Sprinter) features taken into account are gathered in Table 1.

Table 1. Main vehicle parameters considered in the tests.

Parameter	Value
Reduction box ratio, $i_{gearbox}$ (-)	3.5
Differential (final group) ratio, i_{diff} (-)	3.923
Wheel radius, r_{wheel} (m)	0.356
Dynamic correction coefficient, $C_{dynamic}$ (-)	0.9

To make the conversion from rotational speed (rpm) of the motor to linear speed (km/h) of the wheels, the following relation is used:

$$V_{wheel} = N_{motor} \frac{3.6\pi r_{wheel}}{30} \frac{1}{i_{gearbox} i_{diff}} C_{dynamic}$$

where V_{wheel} represents the lineal wheel speed and N_{motor} represents the motor speed. The following relationship is obtained: 1000 rpm correspond to 8.8 km/h. From that, the equivalence for the target speeds is detailed in Table 2.

Table 2. Relationship between rotational and linear target speeds.

Linear speed	Rotational speed
20 km/h	2273 rpm
30 km/h	3409 rpm
40 km/h	4545 rpm
50 km/h	5682 rpm
60 km/h	6818 rpm

The constant velocity test was carried out by reaching a steady state between the torques provided by the motor and requested by the test bench respectively. It is important to highlight here that the vehicle parameters have been used in the bench software in order to simulate the rolling resistance and the aerodynamic resistance as function of vehicle speed. Once this mechanical equilibrium was reached for a certain speed (initially the lowest one, 20 km/h), the motor operated at this speed for some seconds for data logging purposes. It is important to note that temperatures were tracked, although thermal equilibrium was not sought in this test. Then speed was increased to the next level. This process is repeated until all target speeds were tested. The test results in terms of speed, torque and power registered in the test bench are represented in Figure 17 and Figure 18.

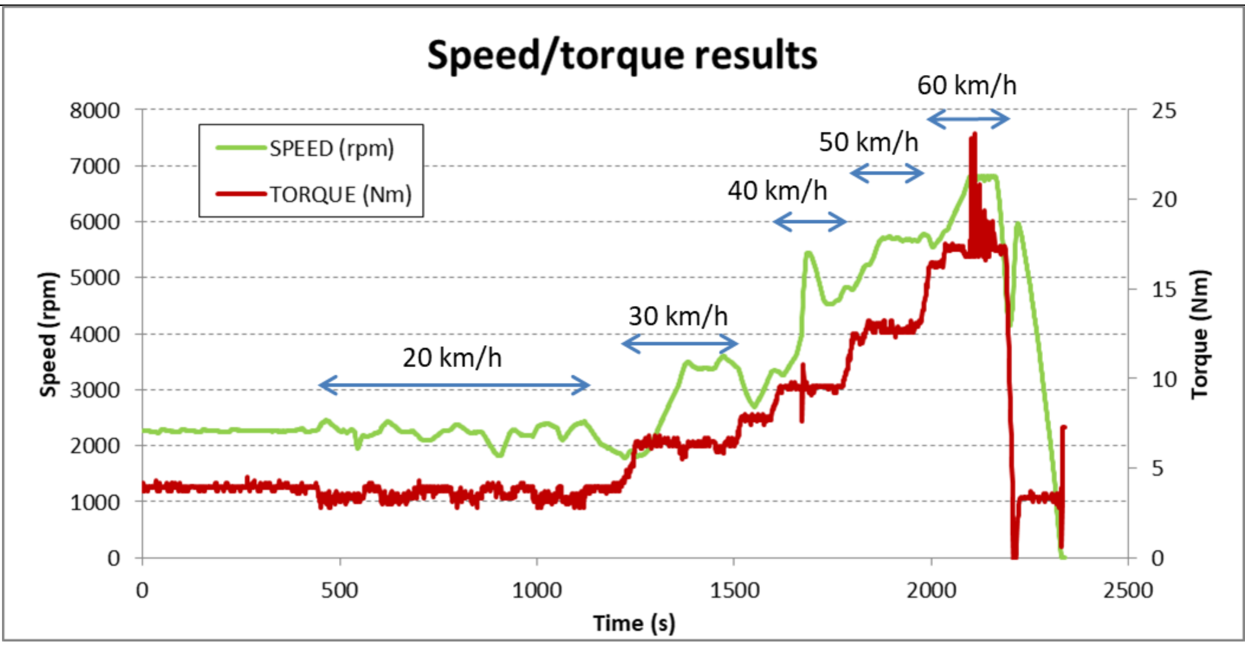

Figure 17. Constant speed tests: speed and torque results

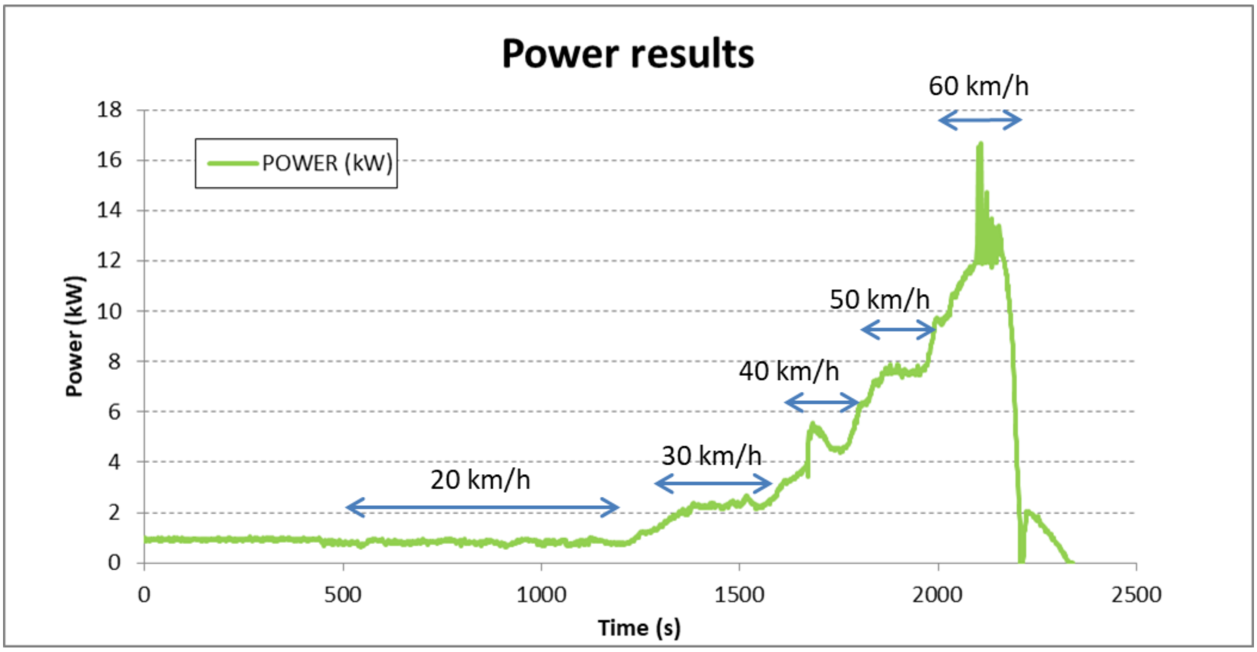

Figure 18. Constant speed tests: power results

As can be seen in the previous figures, synchronization for 40 km/h and 60km/h was quite tricky, and therefore there is some noise in the data (especially at 60km/h). Nevertheless, this does not represent a limitation from the point of view of validation, which was the aim of these tests. The motor was able to respond to the inputs in a fast and precise manner, even if the input was abruptly introduced. Besides, as shown in Figure 19, temperatures remained well below the limit values.

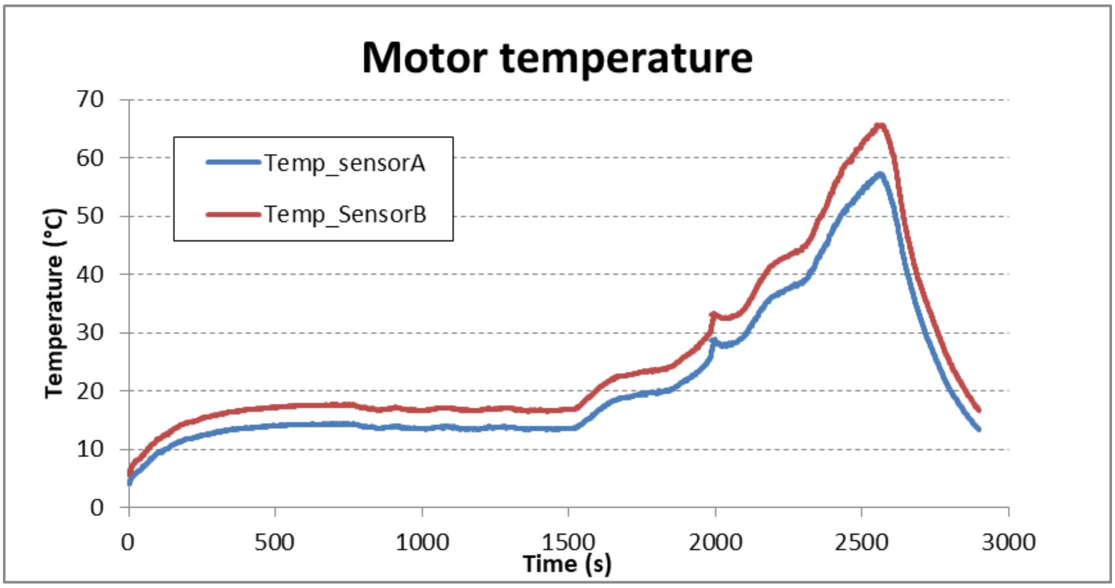

Figure 19. Temperature evolution during constant speed tests.

DC power was also measured at the exit of the power supply. Table 3 summarizes these measurements for each target speed.

Table 3. Summary of parameters registered at the power supply

Linear speed (km/h)	Voltage (V)	Current (A)	Power (kW)
20	375	4.49	1.68
30	375	9.64	3.62
40	375	16.22	6.08
50	375	25.39	9.52
60	375	41.53	15.57

From the previous Figure 18 and Table 3, some efficiency calculations can be made. Results are gathered in the following Table 4.

Table 4. Efficiency calculations.

Linear speed (km/h)	Measured efficiency (-)
20	0.57
30	0.69
40	0.80
50	0.88
60	0.91

As expected, efficiency is quite low at the lowest speeds (20 km/h and 30 km/h) and becomes higher as speed increases. If the obtained values are compared against the full torque-speed motor map calculated in the design stage within WP4 (Figure 20, test points shown in grey color), test values are below the expected performance, especially for the low speed points. This first comparison is indeed affected by the fact the calculated map only spans motor efficiency with sinusoidal currents, hence it might be at some point misleading if only figures are compared. However, the comparison from a qualitative point of view is useful, in the sense that it allows a quick check on the efficiency regions where the motor is operating for each speed.

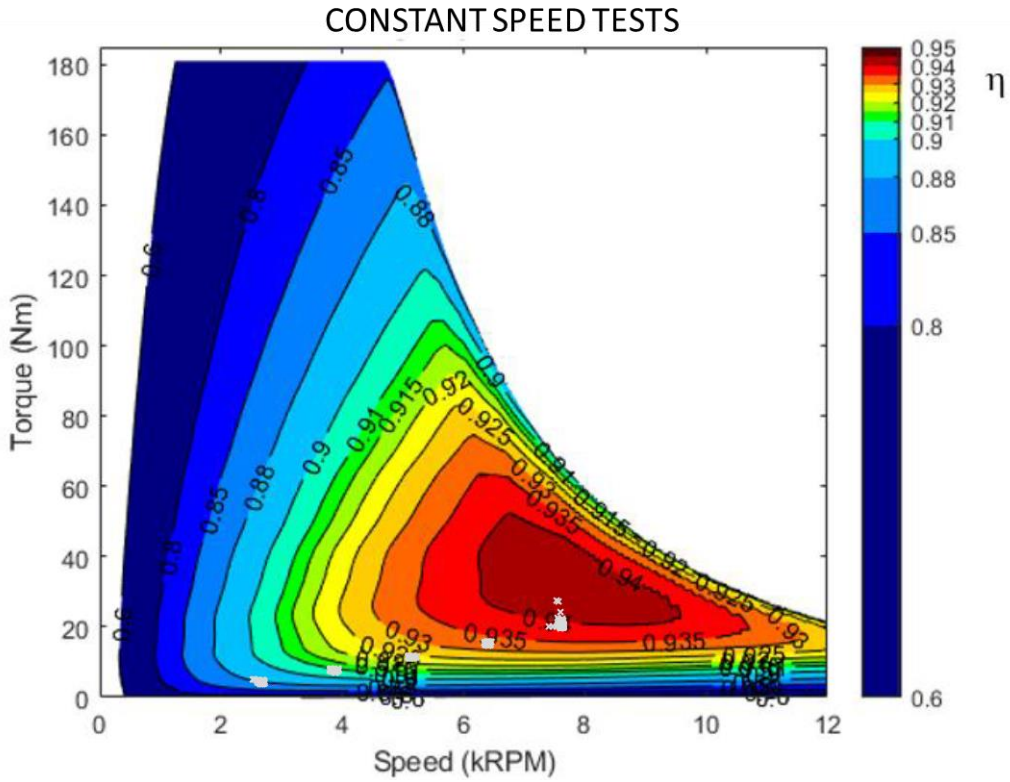

Figure 20. Comparison between measured motor efficiency and expected efficiency of the constant speed tests.

Nevertheless, if the comparison is made against the system efficiency map obtained experimentally within Task 7.1, shown in Figure 21 below, it can be seen that the 60 km/h efficiency (torque values around 20 Nm and speeds close to 8 krpm) is quite close to the values obtained at IFPEN. By making some data extrapolations to the system efficiency map, 50 km/h results are also in line with what is expected to obtain. Hence, efficiencies measured at lower speeds are considered valid and representative of the powertrain performance.

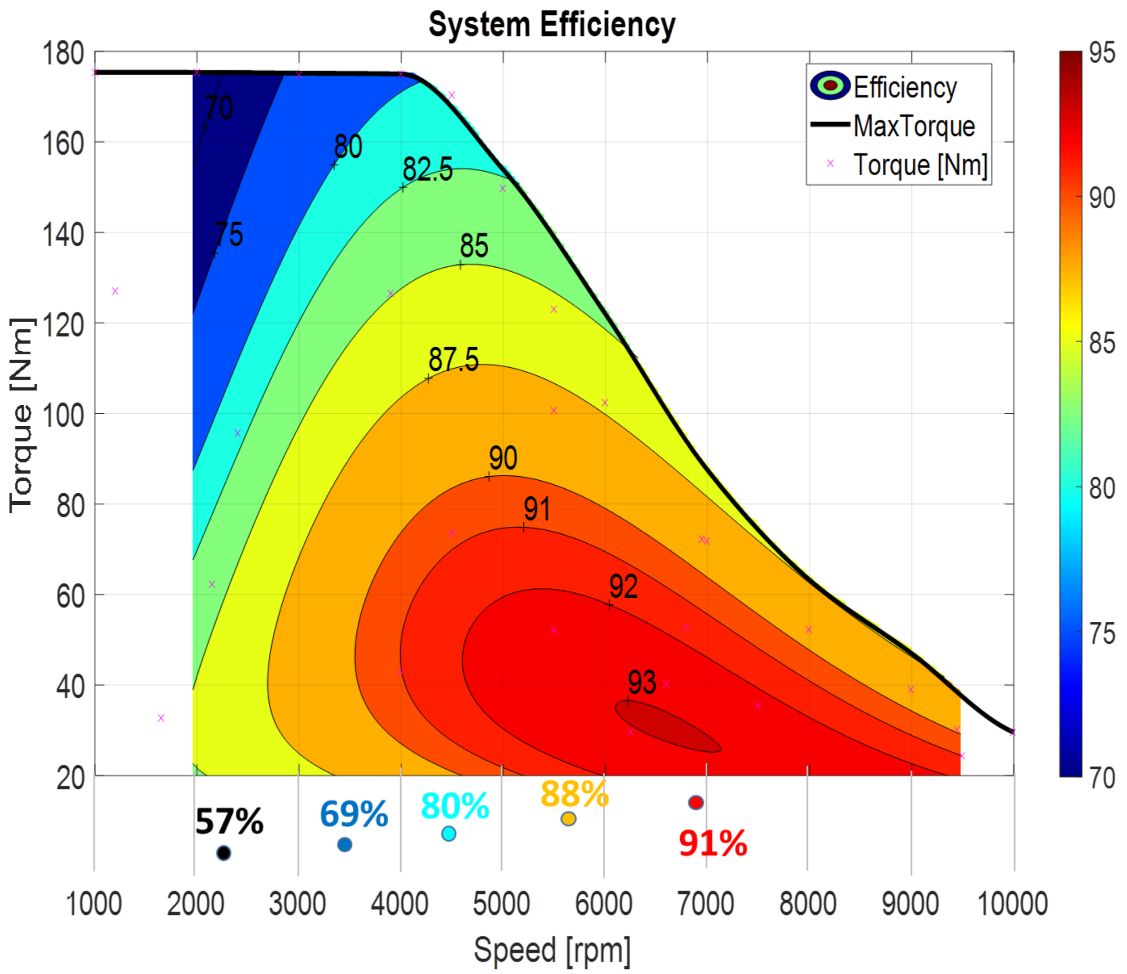

Figure 21. Constant speed points vs system efficiency map (from D7.1) comparison

It is concluded that, from a validation point of view, the performance of the powertrain is satisfactory, considering that it is able to meet the requirements fastly and without any mechanical (vibrations, temperature) or control (e.g. PE forcing to stop prematurely the test for safety reasons) issues.

5.1.2 Acceleration tests

In the acceleration tests, the objective was to find out how the powertrain behaves when it has to accelerate while overcoming a resistant torque, representing for example a driving scenario where the driver needs to increase the vehicle speed in a slope (here the resistant torque would represent the steepness of the slope). For the sake of comparison, in this stage two driving scenarios are designed: a strong acceleration on flat terrain, and a smoother acceleration on a 10% slope.

The tests were carried out as follows: firstly the test bench and the motor were balanced at 20 km/h, that is, 2272 rpm. Next, the torque requested by the test bench was increased to the setpoint in 5 seconds and, at the same time, the accelerator pedal was fully pushed so that speed is increased as fast as possible (maximum acceleration) until the motor reaches a target speed, in particular 6000 rpm for the flat terrain scenario and 4500 rpm for the 10% slope scenario. A new equilibrium was established for a few seconds at these target speeds, and after that the resistant torque is released and the test finished.

Figure 22 and Figure 23 present the speed and torque values registered for the flat and slope acceleration tests respectively.

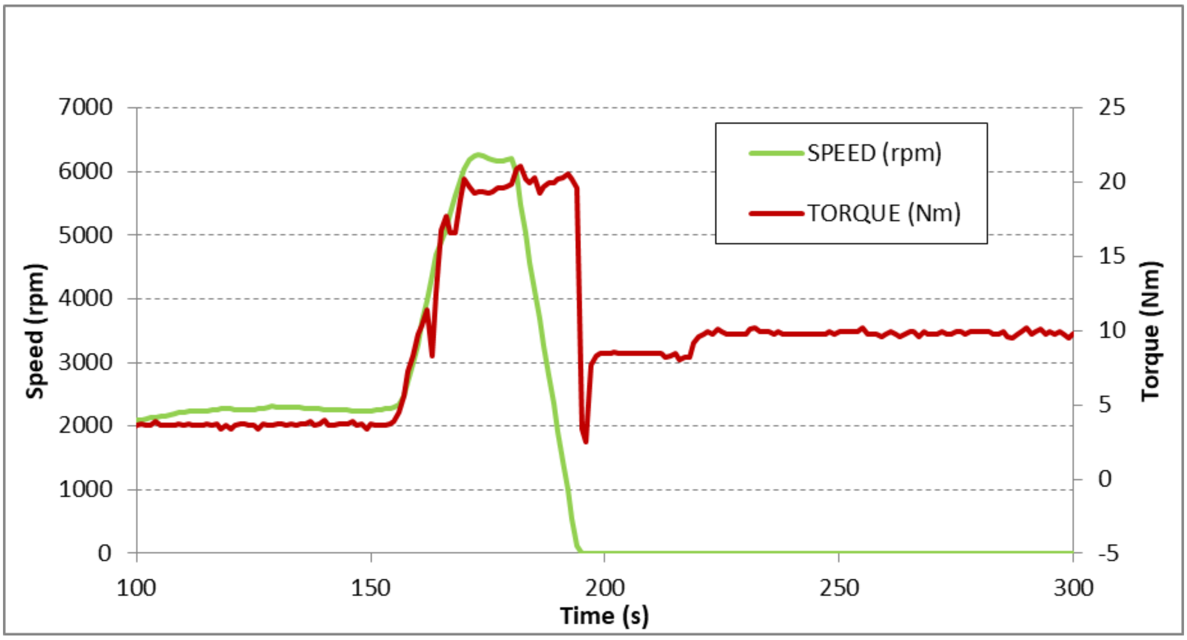

Figure 22. Torque and speed values for the flat terrain acceleration scenario

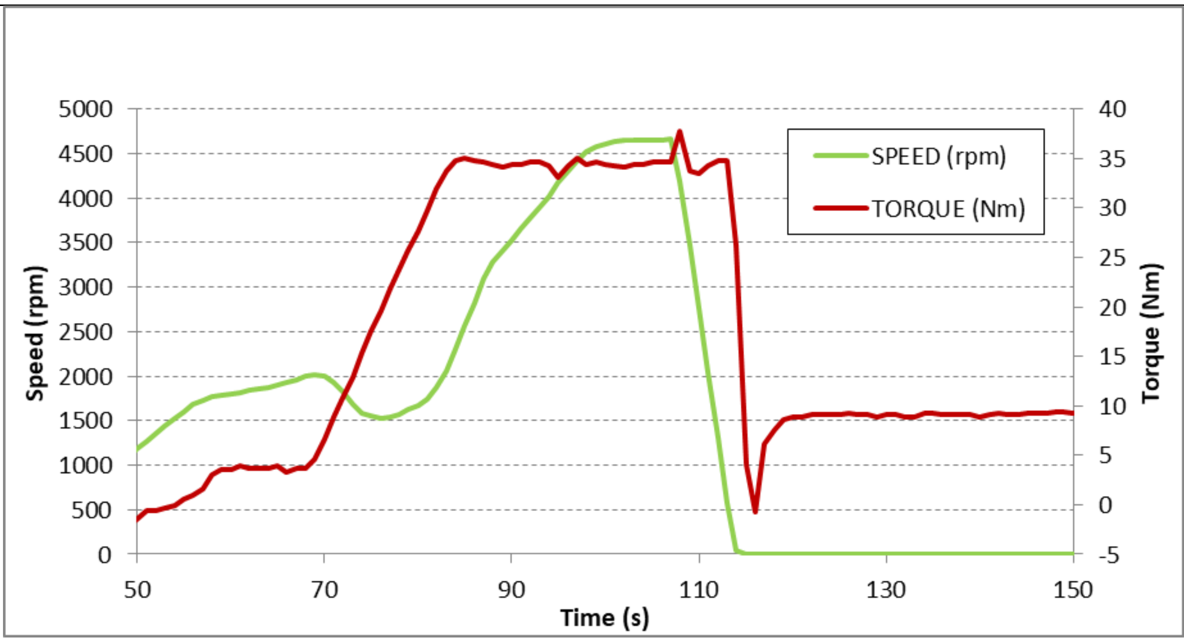

Figure 23. Torque and speed values for the slope acceleration scenario

It is interesting to note here that in Figure 22 speed follows quite closely torque variations (in time), as would be expected in accelerations on flat terrain. However, in Figure 23, due to the existence of a slope, firstly a certain decrease of speed is experienced when the vehicle enters the slope, which is reverted after some seconds to start the acceleration itself.

Due to the short duration of these tests, temperature was well below the acceptable limits at any moment. Power was also measured during the tests. Figure 24 and Figure 25 present the power measurements for each acceleration scenario.

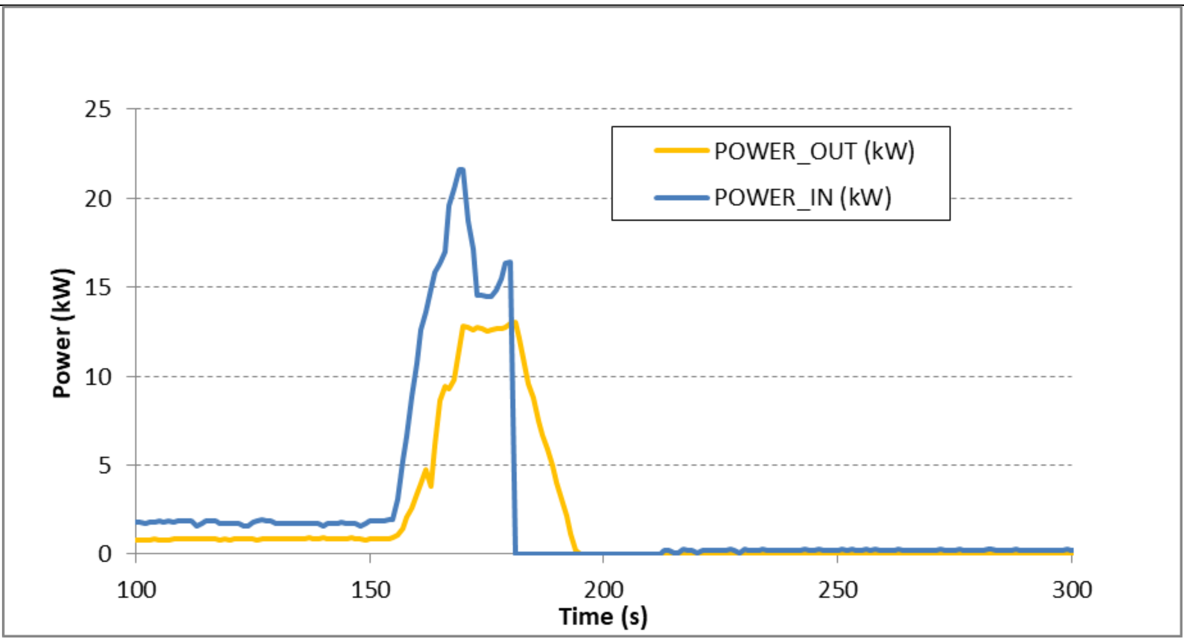

Figure 24. Measured power values for the flat terrain acceleration scenario.

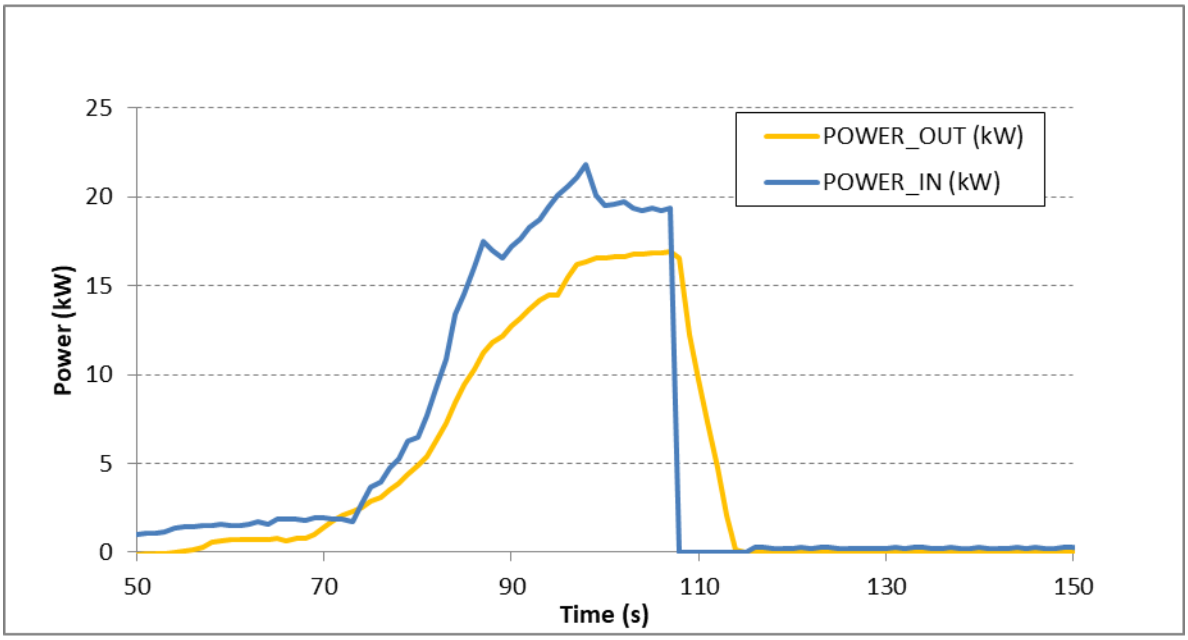

Figure 25. Measured power values for the slope acceleration scenario.

From the power introduced to the system and the power extracted at the test bench, it is possible to calculate the efficiency of each scenario. Calculated efficiencies are shown in Table 5. It can be seen that the trends observed in the constant speed test, as well as in WP4 simulations and Task 7.1 test, are maintained, in the sense that the efficiency increases as the motor works in more demanding (torque and speed, and consequently power) conditions which are closer to the optimal efficiencies of the powertrain operation.

Table 5. Results summary of acceleration tests

Acceleration scenario	Resistant torque (Nm)	Target speed (rpm)	Efficiency (-)
Flat	20	6000	0.84
Slope	35	4500	0.87

5.1.3 Driving cycle simulation test

In line with the constant velocity test, driving cycle simulation test is conceived as an exercise to provide a more comprehensive understanding of the behavior of the powertrain when operating in the low efficiency region of the efficiency map. It allows assessing the dynamic behavior of the whole system (motor, PE, actuators and sensors) in real driving conditions as well. Hence, the last validation test consisted on performing a series of accelerations and decelerations at low levels of speed and torque, to check that the powertrain is able to respond quickly and effectively to changing demands, as could occur in real driving conditions (i.e. urban driving).

The proposed driving cycle shown in Figure 27, is envisioned as a simplification of the low speed region of the Worldwide Harmonized Lightweight Testing Cycle (WLTC) class 3 driving cycle, highlighted in orange in Figure 26.

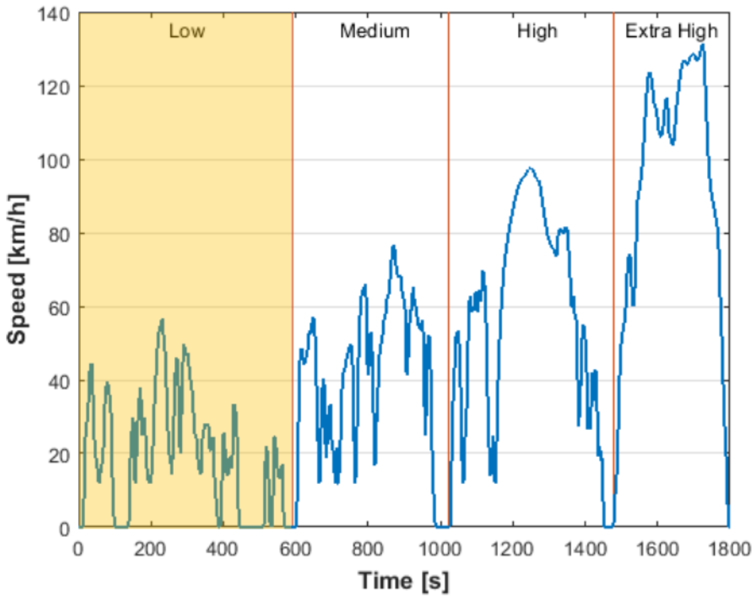

Figure 26. WLTC Class 3 driving cycle, low speed region emphasized.

The proposed driving cycle can be divided in three different sections:

- Acceleration from around 2300 rpm up to 4500 rpm against a resistant torque of 20 Nm in 15 s, then 15 s at equilibrium and deceleration to 2300 rpm in 15 s.

- Acceleration from around 2300 rpm up to 3000 rpm against a resistant torque of 15 Nm in 15 s, then 15 s at equilibrium and deceleration to 1000 rpm in 15 s.
- Acceleration from around 1000 rpm up to 3500 rpm against a resistant torque of 18 Nm in 30 s, then 30 s at equilibrium and final deceleration.

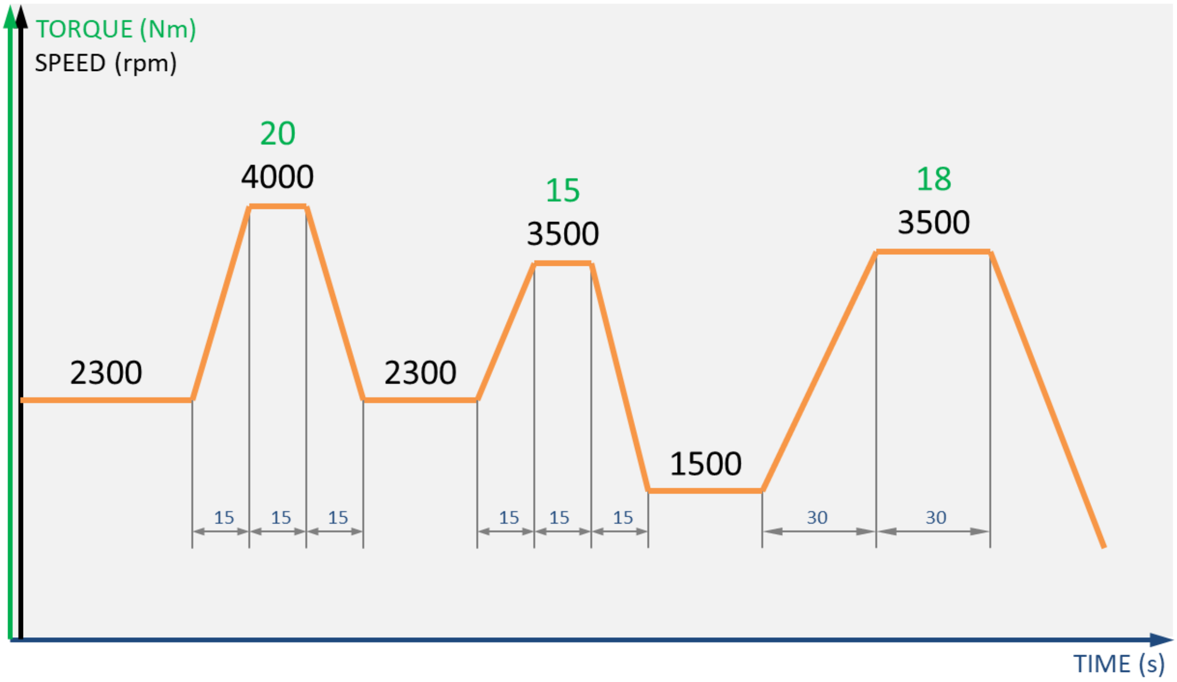

Figure 27. Proposed driving cycle test

Figure 28 and Figure 29 below present the measured cycle parameters: speed, torque and power. In these tests accelerations were adjusted so that the motor provided a sufficient but smooth response to the resistant torque introduced, but not full power as in the previous acceleration tests. No thermal or control issues were experienced during this test.

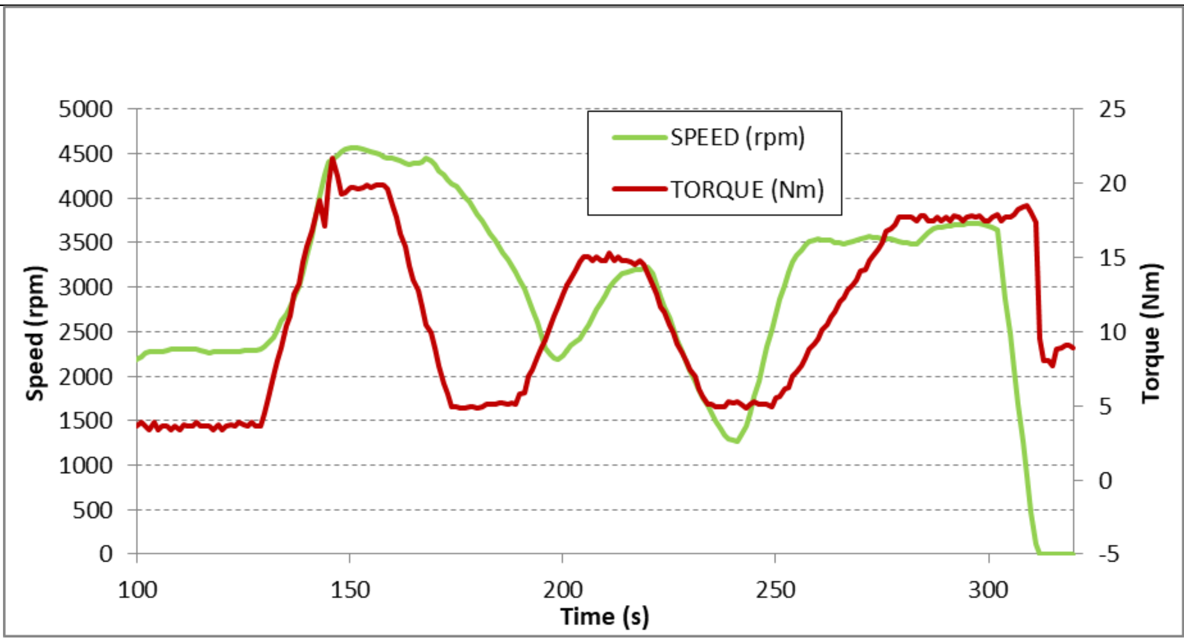

Figure 28. Torque and speed values for the driving cycle scenario

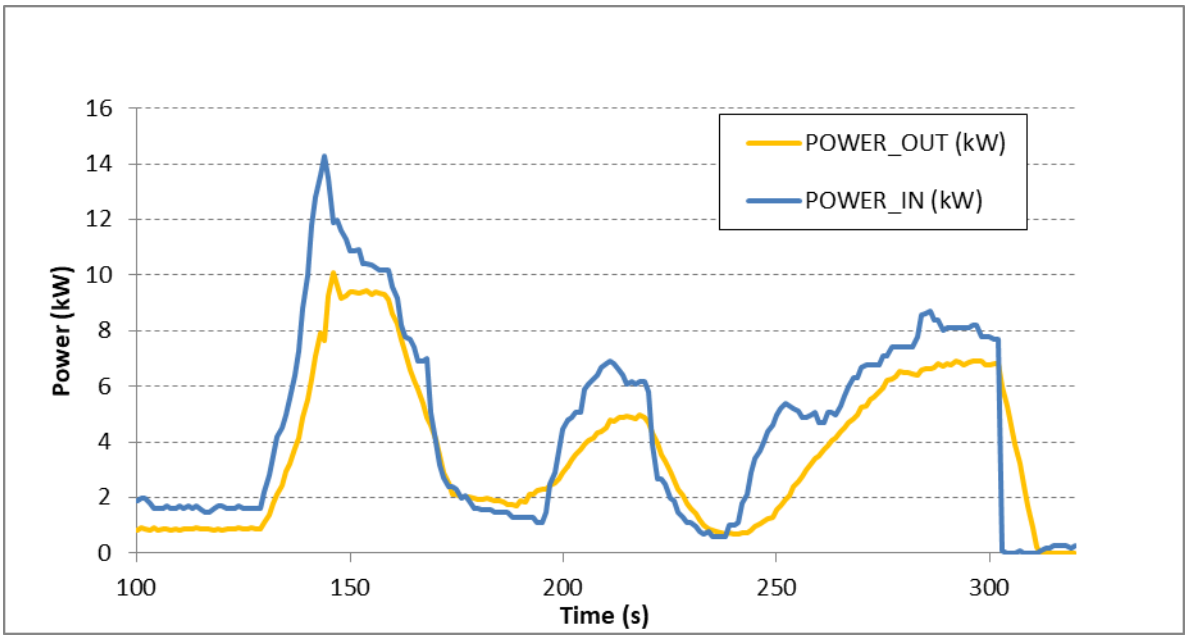

Figure 29. Measured power values for the driving cycle scenario

Looking at Figure 29, it is relevant to note that in the three decelerations the output power is higher than the input power. In fact, this is expected and is due to the system inertia, which allows extracting power from the system while speed is reduced, even if no power is introduced to the system (until the motor stops). From the power data measured in Figure 29, it is possible to calculate some cycle efficiencies. Overall cycle efficiency was 84 %, slightly penalized by the very abrupt initial acceleration requested to the motor. If a smoother behavior was obtained, cycle efficiency would indeed increase. In fact, if efficiency is disaggregated by sections, it can be seen that the first one has the lowest efficiency, 81%, contrarily to what was expected according to the system efficiency map (Figure 21). Anyway, it is a minor deviation that does not affect the overall validation of the powertrain performance in this scenario. Second and third sections present efficiency values of 83% and 86% respectively. Efficiencies obtained seem to be in line the calculations made by JLR on the full WLTC3 driving cycle within WP8 (87.5% efficiency, see further details in D8.1).

5.2 Die-cast IM 75kW

The following Figure 30 presents an overview of the Die-cast IM 75kW motor installed at CIDAUT's experimental facility.

Figure 30. Die-cast IM overview.

Due to time limitations, tests in this motor were exclusively focused on checking that the control software was able to provide a smooth motor control through the accelerator pedal stimuli, which was successfully executed.

It is important to remark here that the iterative firmware updates introduced during the tuning stage (described in Section 4) provided high versatility to the PE and worked nicely on the IM since the very beginning, contributing to speeding up the tests and completing the IM powertrain validation at CIDAUT despite the limited time available.

6 Acoustic characterization

In terms of acoustic characterization of the ReFreeDrive motors, the only precedent within the project is the Noise, Vibration and Harshness (NVH) analysis performed on the IM design as part of Task 3.4 (see Deliverable 3.4 for further details on this topic). There is no NVH simulation data regarding the SynRel motors.

Although it was not included in the Grant Agreement (GA), taking advantage of the fact that CIDAUT counts with the equipment and expertise to perform acoustic assessments, a simple preliminary noise assessment of the pure SynRel motor (75kW) was carried out. Table 6 details briefly the equipment involved in this activity.

Table 6. Equipment used for the acoustic characterization

Equipment	Model
Microphone	B&K 4190
Analyser	LMS Siemens
Software	TEST XPRESS

An overview of the experimental setup is presented in Figure 31.

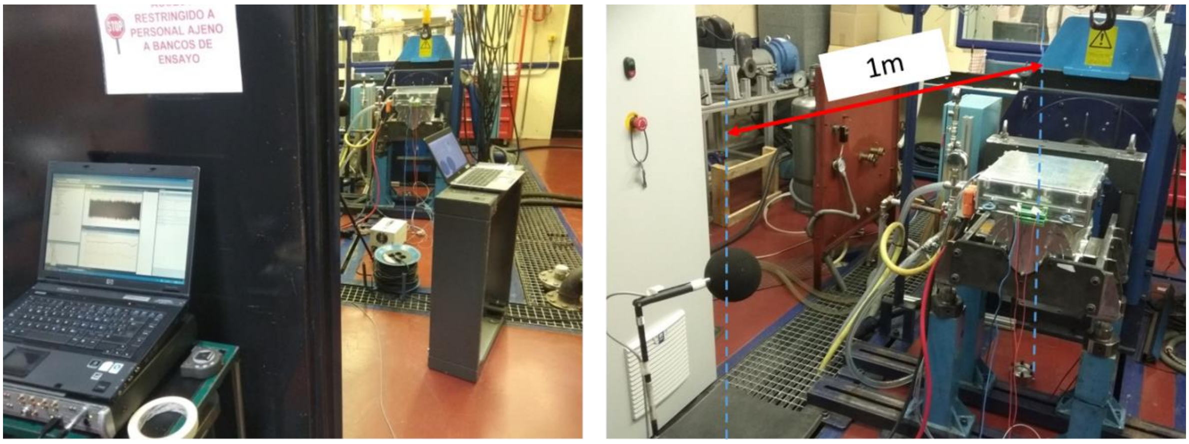

Figure 31. Overview of the noise assessment experimental setup.

The analysis was carried out with the motor running at 6000 rpm (~50km/h) and the microphone placed 1 m away from the motor. Noise was recorded during 60 seconds using a linear, 1 Hz resolution spectrum corresponding to the third octave. A graphic summary of the results is shown in Figure 32.

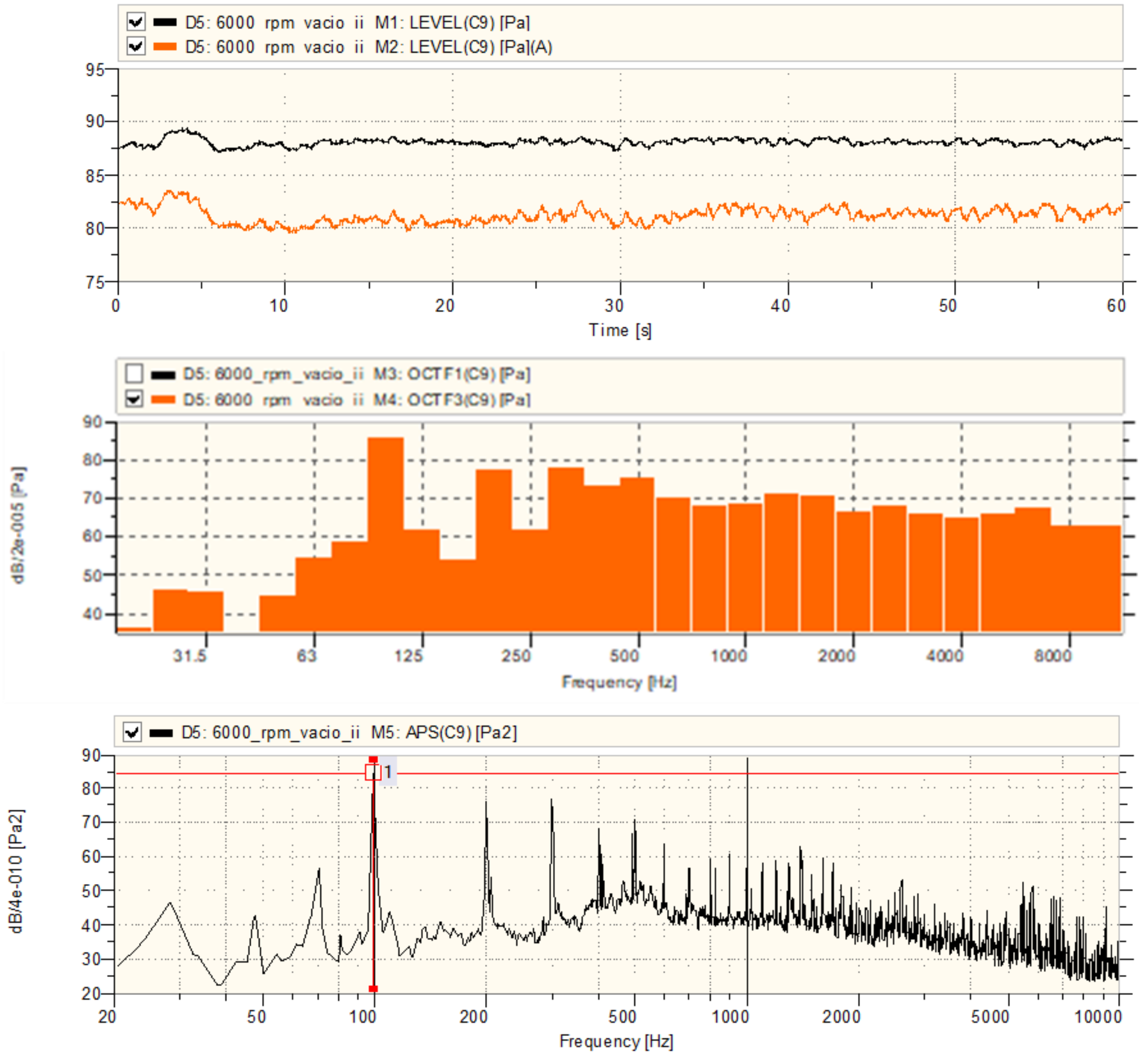

Figure 32. Noise assessment analysis results.

Recorded noise during the test was 88 dB. If the sensitivity of the human ear to the frequency spectrum is cancelled, then noise recorded would be 82 dB(A). As can be seen in the middle and bottom graphs in Figure 32, tonal contribution of 100 Hz (motor rotation frequency) and its harmonics are dominant. Besides, electromagnetic contributions (high frequency noise) are masked by the low frequency components.

Finally, it is interesting to note here that the assembly of the motor in a rigid steel frame could influence to a certain extent the noise levels recorded. Hence, noise has to be taken into account as part of the integration of the motor in a real vehicle so that it can be maintained at acceptable levels for the vehicle occupants.

7 Conclusions

Task 7.2 objectives were accomplished despite deviations in time and content derived from the impact of Covid-19 on prototypes manufacturing activities. The test campaign aimed at complementing the experimental evidence of the developed technologies, which was generated in Task 7.1, providing further understanding of the performance of the powertrains in low efficiency regions of the efficiency maps in several driving scenarios, thanks to the possibility of testing the powertrains in a controlled and measurable environment. Furthermore, some functional tests were carried out on the medium power PE, which allowed optimizing the control firmware and smoothing the response of the system when using the accelerator pedal as input.

For the sake of completeness, an acoustic characterization was made, which highlighted the major influence of the vehicle's motor frame on the noise emitted, and confirmed that noise is mainly due to the motor rotation frequencies.

The experience gained in this Task eased the final in-vehicle integration of the motors and PE in the commercial vehicle. Indeed, Task 7.2 tests allowed early identification of the vehicle environment issues before the real vehicle was ready, leaving only vehicle-specific validations activities to be addressed in Task 7.3. All the experimental results obtained at system level were in line with the expectations coming both from experiments (Task 7.1) and simulations (Task 8.1).

Table 7 summarizes the tests performed and the main results obtained in each test.

Table 7. Main results obtained in the tests performed within Task 7.2

Test	Main result
Constant speed	Efficiency: 57% (20 km/h) – 91% (60 km/h)
Acceleration (flat)	Efficiency: 84%
Acceleration (slope)	Efficiency: 87%
Low speed driving cycle	Overall cycle efficiency: 84%
Noise assessment	Noise levels: 88dB / 82 dB(A) (@100 Hz)