# Rare Earth Free e-Drives Featuring Low Cost Manufacturing

ReFreeDrive

Collaborative Project
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| V07 | 14.05.2019 | Error with Figure 2 reference in text fixed |

# Table of Contents

# Abbreviations

| | |
|---|---|
| CR-IM | Copper rotor induction motor |
| CST | Customized sequence tests |
| DoA | Document of Actions |
| EM | Electro magnetic |
| FEA | Finite element analysis |
| FEM | Finite element method |
| IM | Induction motor |
| IPR | Intellectual property rights |
| IR-IM | Inner rotor induction motor |
| KPI | Key performance indicator |
| MEPT | Maximum efficiency per torque |
| MTPA | Maximum torque per ampere |
| OD | Outer rotor |
| OEM | Original Equipment Manufacturer |
| PMa | Permanent magnet assisted |
| PMaSynRel | Permanent magnet assisted synchronuous reluctance |
| SDC | Standard driving cycle |
| SynRel | Synchronuous reluctance |
| WP | Work Package |

# Executive Summary

This document reports the project progress during the period from the project kick off meeting (October 2017, M1) to M9 (June 2018). It reviews each of the work packages (WPs), the work carried out and the coming activities for the next period. The next progress report will be carried out in M18 (March 2018). The main objective of this deliverable is to provide a summary of the work done so far and reflect the project current status from a global perspective:

- WP1 Management has overseen the work flow, organizing meetings and web conferences when needed and working with the Work Package Leaders to ensure activities are carried out according to schedule. A quality management procedure has been set in place and followed for the deliverables sent during this period. Project milestones have been reviewed, achieving the first of them (related to the boundary conditions definition).
- WP2 has established the boundary conditions at different levels, defining the driving cycles, and setting the basis for the design work packages (WP3, WP4) and the integration work package (WP5) to work with.
- WP3 and WP4 have researched preliminary designs of their respective technologies, induction machines (IM, WP3) and synchronous reluctance machines (SynRel, WP4). After the first mechanical and thermal analysis of different design options, the obtained results will be optimized in the next period. . Four non-oriented electrical steels, silicon-iron type, and one grain oriented steel have been selected in the project. The preliminary magnetic characterization on the selected materials has been carried out by RINA-CSM.
- WP5 has been kicked off in advance to follow the progress of the motor designs. The first technologies and integration analysis is reported in this deliverable
- WP9 has led the dissemination and communication planning and already undertaken several actions to raise the awareness of different target audiences towards the project objectives and its research.

This D1.1 deliverable has fully met its objectives. No deviations have been found in the deliverable or in the project progress in content, time or impacts, as set out in the Grant Agreement.

# 1 Project Objectives 1st year review

The main aim of this project is to develop rare earth-free traction technologies beyond their current state-of-art, with a strong focus on industrial feasibility for mass production, targeting lower costs with higher specific torque and power density.

The vision is to contribute to a greener European transport, by offering new solutions non dependant on critical sources and making use of the vast electric motor manufacturing capabilities in Europe.

In order to reach this challenging objective, several scientific and technological objectives have been defined:

- To explore, optimize and compare motor designs in two rare earth-free motor technologies: copper rotor induction machines and synchronous reluctance machines. In the case of the induction machines two sub-avenues will be explored for comparison and optimization purposes: fabricated and die casted copper rotors. In the case of synchronous reluctance machines also two sub-avenues will be explored: pure and ferrite permanent magnet. As a result, four designs will be obtained for each of the two power range settings under study in this project: 75kW (some candidates are Iveco Daily, Mercedes Sprinter, Isuzu, Ford Transit and Nissan Cabstar, or a Land Rover Defender) and 200kW (Jaguar Land Rover vehicle).

  ☞ During this first year preliminary designs of both technologies have been carried out. The analysis of the induction machine has already been reported in D3.1, whereas the preliminary analysis of the synchronous machines is reported in D4.1 (also handed out in September 2018). Both work packages have included preliminary designs for 75kW and 200kW using the requirements outlined in WP2

- To design, prototype and test four high speed (maximum speed of 45.000 rpm) motors (one for each technology) that increase the specific torque by 30%, and reduce the motor losses by 50%, compared to the project benchmark (Tesla S60 motor). To achieve these ambitious targets the project will tackle a number of innovations that are further defined later in this document.

  ☞ During this period the work has been focused on preliminary designs and sensibility analyses, influences of different material studies, and on the interaction with other WPs

- To achieve a ambitious cost objective. ReFreeDrive electric powertrain can reach a cost reduction foreseen in at least 15%, against solutions with equal performance characteristics, such as is forward justified in Impact section, due to exhaustive work on optimized designs of motor and power electronic, proper selection of materials, implementation of better mass-manufacturing process and advanced motor control solutions and cooling system. This conclusion was achieved after a deep benchmark carried out against the Tesla S60 electric traction system.

  ☞ Currently the cost objective has not been considered as a design driver, though certainly evaluated when assessing different materials and to rule out certain specific designs (such as outer rotor technologies in induction machines)

- To develop the power electronics needed for each power setting, increasing the power density by 50% compared to current system which are been using in the electric vehicles, by means of adoption of wide bandgap semiconductor technology, increasing efficiency and reducing the weight of the cooling system, but also, adopting of advanced gate driver and efficiency optimizer control strategies. To reach this objective a key work is to achieve an integrated design of the power electronic together the different motors topologies within the project.

  ☞ During this year, actually in the 6M General Assembly it was unanimously agreed that the integration and power electronics design should start earlier than initially planned and run in parallel to the electric machine designs in order to inform on the integration point of view when taking design decisions and optimize both design flows. Preliminary analysis of systems and simulations made in WP5 are reported in this document.
- To define, prototype and test a cooling system that complies with the performance targets set above, based on a novel technology, which will use an internal oil spray cooling method.
- To validate the motor technologies by obtaining an integrated powertrain, including all the powertrain systems (batteries, gear box, etc.) that will be tested in real driving conditions in the full electric vehicles customized by PRIVÉ (e.g. Iveco Daily, Mercedes Sprinter)

  ☞ These last two objectives have not been addressed during this period
- To present the obtained results and boost their commercial exploitation to encourage the use of rare earth free motor technologies in Europe, demonstrating their feasibility with mass production industrial manufacturing support.

  ☞ In this period dissemination and communication actions have been planned and done in order to pave the way and raise the awareness needed on the project results, which will later enable a wide audience for the demonstration of the feasibility of the project results.

# 2 Explanation of the work carried out per WP

In the following sections the technical progress done by each of the work packages (WPs) is reviewed. For Dissemination and Communication actions, please see D9.4 Dissemination Plan.

## *2.1 WP2 Boundary Conditions*

WP2 has defined the boundary conditions for the motor development and tests:

- Identifying measurable Motors' Key Performance Indicators (KPI) to correspond with the vehicles performances and main equipment's requirements (Driving Cycle definition) necessary for the development and layout definition of powertrain per application to correspond with the State of the Art.

- Listing vehicle-system's and all the functional subsystems' components needed to design and realize the appropriate powertrains to be integrated in the vehicles in order to respond to initial KPI and requirements.

Task 2.1 (*Key Performance Indicators (KPIs) to be identified and compared with PM motors or other engine types*) aimed at a joint definition of the motor KPIs to allow a comparison of the ReFreeDrive results with the current State of the Art.

WP2 partners carried out (D2.1 *KPI Key Performance Document*) a market research oriented to find the most relevant applications of the two power size motors (75kW and 200kW) in order to obtain a ranking list of vehicles. The vehicles have been sorted by category considering the different modes of use to carry out KPI families (Table 1).

**Table 1: ReFreeDrive vehicle categories and classes**

| CATEGORY | |
|---|---|
| **A** | **CITY CARS** |
| **B** | **SMALL CARS** |
| **C** | **MEDIUM CARS** |
| **D** | **LARGE CARS** |
| **E** | **EXECUTIVE CARS** |
| **F** | **LUXURY CARS** |
| **S** | **SPORT COUPES** |
| **J** | **SPORT UTILITY CARS (SUV)** |
| **M** | **MULTI PURPOSE CARS (MPV)** |

| CLASS |
|---|
| **Economy** |
| **Standard** |
| **High End** |
| **Premium** |
| **Luxury** |

Besides for each category the driving habit and the KPI at vehicle level have been also identified. Finally, through the vehicle level KPI and the kinematic chains the components KPI have also been identified (see Deliverable D2.1).

Task 2.2 (*Target performances of ReFreeDrive testing vehicles: Driving Cycle definition)* aimed at setting a driving cycle in order to test and analyse the vehicle's and motor's performances.

Driving cycles have been produced to assess the performance of vehicles in various ways, also in vehicle simulations. More specifically, they will be used in propulsion system simulations to predict performance of motors, transmissions, electric drive systems, batteries, and other components.

Some driving cycles have been derived theoretically, whereas others are direct measurements of a driving pattern deemed representative.

D2.2 (*ReFreeDrive testing vehicles: Driving Cycle*) was divided in two main sections. Section 1 (Driving cycles quantity and type) summarized the State of the Art of all available driving cycles to test and compare vehicle performances in real operational profiles. Section 2 showed the designed Driving Cycles planned for the bench and on road tests. **The bench test is needed to**

**perform vehicle operations under reproducible conditions and the on-road/on-track test as the closest representation of the real conditions.** For the bench tests two different kind of tests were scheduled: one based on standard driving cycle (SDC), and the other based on customized sequence tests (CST).

The other tests planned were for the powertrain integrated on the vehicle and performed on a real road or on track. Standard driving cycle is not applicable for the on-road tests and only the CST will be performed.

Task 2.3 (*Powertrain subsystems and powertrain integration level definition: Technical Specifications*) aimed at setting a full technical specification of the powertrain per Track application (75 kW and 200 kW) in order to define each powertrain subsystem to be developed/integrated.

For each functional subsystem, each OEM, final user and design partner defined the technical specifications concerning the subsystem it is responsible of, and considering the KPIs resulted in Task 2.1.

D2.3 (*Functional subsystems Full Technical Specifications*) was divided in three main sections. In section 1 (*Vehicle Model selection*) the vehicle model for each targeted power (75 and 200 kW) was selected (Table 1). To take the best choice the different features were considered, such as, the dimensional study for new components housing and integration, new components weights and distribution, chassis characteristics, drivetrain characteristics, accessibility, etc. Taking into consideration D2.1 and D.2.2 PRI have selected the Mercedes Sprinter 311 CDI as the 75-KW vehicle, seen in Figure 1. The 200-kW vehicle proposed by JLR was the Jaguar XJ.


**Figure 1: Selected vehicle model for each trargeted power**

Section 2 (*In vehicle integration level*) described the procedure to carry out during the in-vehicle integration phase of the project, in order to define the framework for the definition of the subsystems technical specifications.

Finally, section 3 (*Subsystem technical specifications*) defined all the technical specifications for each subsystem to achieve the expected vehicle performance level (**ReFreeDrive Boundary Conditions – MS1**).

## 2.2 WP3 Induction machine design

Work package 3 (WP3) has four tasks to address with ReFreeDrive project.

Task 3.1 – Preliminary CR-IM design is completed.

Current work and progress are within the planned schedule for Task 3.2 – Electromagnetic design of CR-IM. The status for Task 3.2 is described in this section for each objective in part.

**Selection of materials**

*A. Copper Alloys*

Two options are considered for the rotor cage of CR-IM: die-casted and fabricated copper alloys. Figure 2 illustrates the rotor cage assembly for CR-IM design.

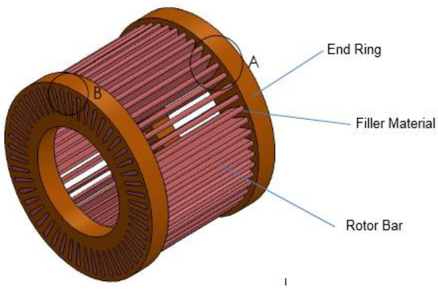



Figure 2: Illustrative for rotor cage assembly

Table 2 shows the possible options for fabricated copper alloys and the methods that can be used to connect the rotor bars with the end-rings. Based on the properties, a copper-silver alloy (CuAg0.04) has been selected. The decision on soldering and welding will be analyzed during the next period. This information was provided by Aurubis (AUR) – partner in ReFreeDrive project.

Table 2: Fabricated rotor materials

| | Material | Tensile Strength (MPa) | Shear Strength (MPa) | Resistivity (Ohms.mm²/m) | Conductivity (%IACS) | Thermal Conductivity (W/m.K) |
|---|---|---|---|---|---|---|
| Rotor Bar | CuAg0.04 | <250 | No data | 0,01702 | 101,3 | 388 |
| End Ring | CuAg0.04 | <250 | No data | 0,01702 | 101,3 | 388 |
| Soldered | SAC305 | 29,7 | 27@20°C, 17@100°C | 0,104 | 16,6 | 58,7 |
| Welded | Bercoweld K5 | 220 | No data | 0,05-0,0667 | 25,8-34,5 | 120-145 |

For die-cast copper solution, the alloy Cu-ETP is selected. The comparison with other alloys is given in Figure 3. Information was provided by Breuckmann (BREU) – partner in ReFreeDrive project.

| Legierung | Zugfestigkeit $R_m$ (MPa) | | 0,2% Dehngrenze $R_{p0,2}$ (MPa) | | El. Leitfähigkeit σ (MS/m) | |
|---|---|---|---|---|---|---|
| | M | SD | M | SD | M | SD |
| *Cu-ETP* | 270,03 | 61,00 | 150,35 | 41,66 | 54,50 | 2,62 |
| *CuAg0,1* | 259,54 | 40,14 | 135,40 | 17,27 | 48,46 | 5,03 |
| *CuSn0,15* | 250,18 | 47,64 | 142,24 | 44,49 | 50,17 | 1,21 |
| *CuSn0,3* | 241,48 | 28,93 | 117,15 | 17,43 | 55,91 | 1,15 |
| *CuSnTe* | 107,76 | 29,72 | - | - | 48,93 | 1,41 |
| *CuZr0,15* | 261,22 | 27,39 | 126,58 | 32,53 | 51,22 | 0,86 |
| *CuCr1Zr* | 455,00 | 3,63 | 376,00 | 12,73 | 44,22 | 0,04 |

M = mean, SD = standard deviation

**Figure 3:Die-cast copper alloys properties**

The difference between various solutions for the cage rotor material is related to the rotor equivalent resistance. Table 3 summarizes the values for the analysed cases.

**Table 3: Equivalent rotor resistance for various copper alloys**

| Copper cage type | Material | Referred rotor resistance @ 120C |
|---|---|---|
| Die-cast | Cu ETP | 0.01973 |
| Fabricated/ soldered end-ring | CuAg 0.04 | 0.0205 |
| Fabricated/ welded end-ring | CuAg 0.04 | 0.01902 |

### B. *Electric Steels*

Four non-oriented electrical steel, silicon-iron type, have been considered for CR-IM. Tests on the steel samples have been performed by RINA – CSM (see further details in WP4 description and D4.1)

- Material 1: NO-020HS (Non-Oriented, fully-processed, thickness 0.20 mm)
- Material 2: NO-30-15 (Non-Oriented, fully-processed, thickness 0.30 mm)
- Material 3: HP 290-50K (Non-Oriented, semi-processed, thickness 0.50 mm)
- Material 4: M235-35 A (Non-Oriented, fully-processed, thickness 0.35 mm)
- Frequencies used in tests: 50Hz, 400Hz, 800Hz, 1000Hz
- Induction up to 1.6T – extrapolated by MDL to 2.1T in modelling CR-IM

The analysis performed for the designs selected at Task 3.1 for inner CR-IM and outer CR-IM lead to the following conclusions:

- BH curve values effect:
  - 50Hz would estimate 370Nm peak torque vs 400Hz would estimate 350Nm; small drop in magnetizing current
- Inner CR-IM:

- Very little impact on performance, as most of losses are in stator winding and copper cage
- Best choice will be M235-35A considering cost/performance ratio

- Outer CR-IM:
  - With NO20 and NO30, can reach 95% efficiency in a small area
  - M290-50HKE is clearly leading to poor performance
  - Best choice will be M235-35A considering cost/performance ratio

**Scaling**

The selected designs for both inner and outer rotor configurations, can be scaled and used for various power levels, by just changing the power and control unit, as seen in Table 4. This means, that the same motor can be used as an electro-mechanical converter for power levels between 75kW and 200kW. An alternative option was investigated, i.e. using shorter axial length for the stator/rotor laminated packs, shown in Table 5. However, this solution is leading to significant peak torque and possibly suitable for vehicles with less demanding drive cycle.

Table 4: Scaling results for inner CR-IM

| Rated Peak Power (kW) | Peak torque (Nm) | Max. eff (%) | DC voltage (V) | Line Current (Arms) | Max speed (rpm) |
|---|---|---|---|---|---|
| 200 | 372 | 96 | 720 | 500 | 18000 |
| 75 | 192 | 95 | 350 | 275 | 13000 |

Table 5: Scaling options for outer CR-IM

| Rated Peak Power (kW) | Peak torque (Nm) | Max. eff (%) | DC voltage (V) | Line Current (Arms) | Max speed (rpm) |
|---|---|---|---|---|---|
| 200 | 353 | 94 | 720 | 500 | 15000 |
| 75 | 157 | 94 | 350 | 250 | 10000 |

**3D FEA modelling**

The validation of the initial 2D FEA model designs is done using also 3D FEA models. This work was performed by University of Aquila (UAQ). Table 6 and Table 7 summarize the comparison between 2D and 3D FEA models for inner rotor design operating at 6000rpm and 20000rpm respectively. The two models agree with sufficient accuracy in all cases.

**Table 6: Comparative results 2D/3D FEA for 6000rpm**

| | 2D | 3D | % |
|---|---|---|---|
| **Phase current [Amax]** | 589 | | |
| **Frequency [Hz]** | 200 | | |
| **Speed [rpm]** | 6000 | | |
| **Slip** | 0.0339 | | |
| **Induced voltage [Vmax]** | 327 | 333 | **1.8** |
| **Flux linkage [Wb]** | 0.2725 | 0.274 | **0.5** |
| **Average Torque (steady-state) [Nm]** | 346 | 281 | **-23** |

**Table 7: Comparative results 2D/3D FEA for 20000rpm**

| | 2D | 3D | % |
|---|---|---|---|
| Phase current [Amax] | 589 | | |
| Frequency [Hz] | 200 | | |
| Speed [rpm] | 6000 | | |
| Slip | 0.0339 | | |
| Induced voltage [Vmax] | 327 | 333 | 1.8 |
| Flux linkage [Wb] | 0.2725 | 0.274 | 0.5 |
| Average Torque (steady-state) [Nm] | 346 | 281 | -23 |

**Mechanical**

A modal analysis was performed on the new IR-IM design to ensure the first rotor natural frequency is still below the maximum operating frequency. The shaft length (bearing to bearing distance), the shaft diameter at ends and the bearing stiffness were varied to know assess their impact on the natural frequency. This parametric analysis is important for two reasons: first to know how much space can be allocated to end-windings and secondly to select the right bearing for the ReFreeDrive application. A simplified model was used for the analysis to reduce the computation time. As shown Figure 4 the rotor bars were replaced by an equivalent copper layer with the same volume.

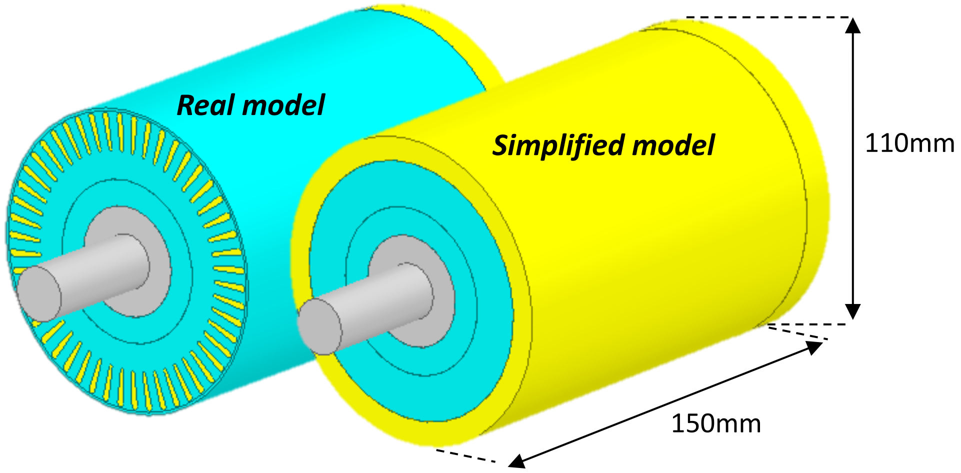



Figure 4. Simplified model fore the modal analysis

Results are shown Figure 5. The shading applies to the natural frequency and for all graphs the feasible designs are on the right side of the bold red line that corresponds to the frequency limit. The results show that the given rotor OD and active length:

- the higher the bearing stiffness, the lower the first critical speed,
- the bigger the bearing diameter, the higher the first critical speed,
- the longer the shaft, the lower the first critical speed.

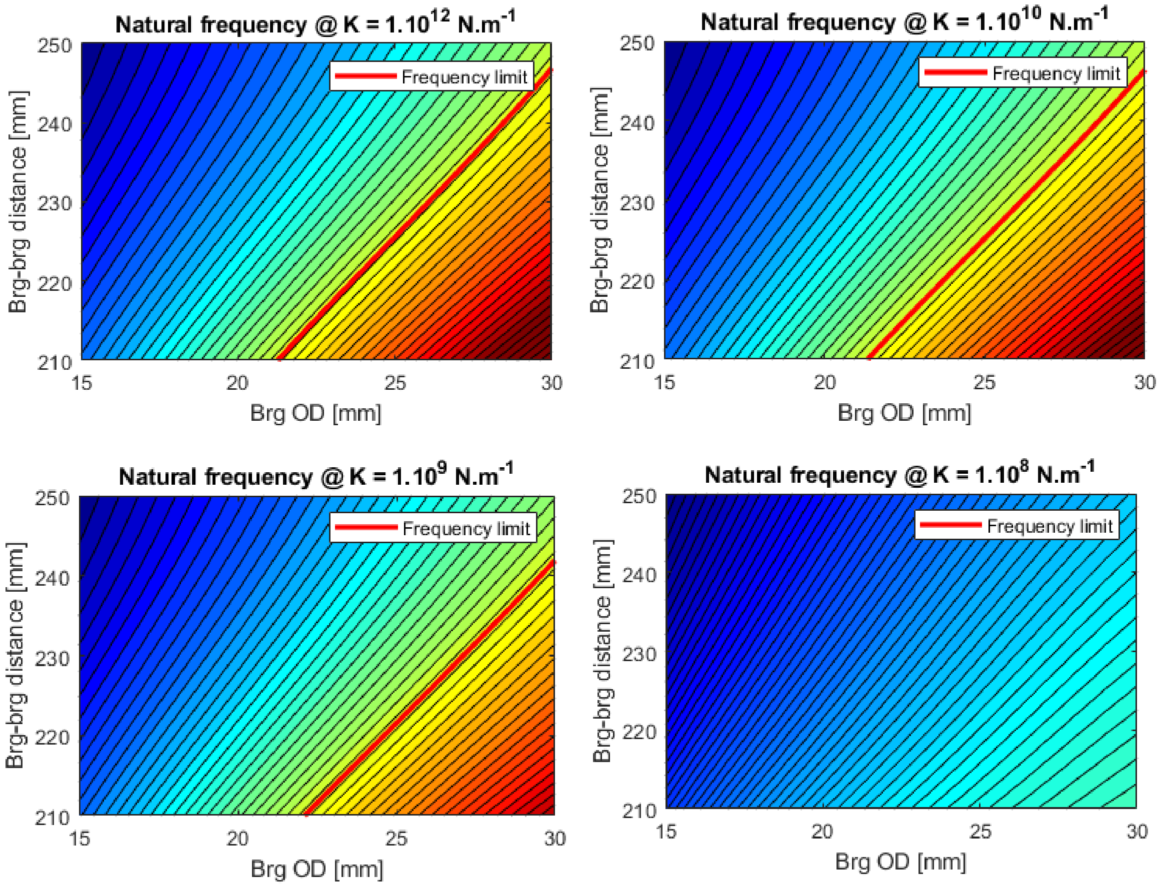



**Figure 5. Parametric results from the modal analysis**

The results show that the given rotor OD and active length:

- the higher the bearing stiffness, the lower the first critical speed,
- the bigger the bearing diameter, the higher the first critical speed,
- the longer the shaft, the lower the first critical speed.

It seems that the bearing should be stiff enough and with an outer diameter at least higher than 20mm in case the minimum space for the end-winding is required. Also this parameter has to be selected accordingly with the maximum speed to reduce costs.

Note: *If the active length or the rotor outer diameter are changed following the optimisation of the machine, the shaft diameter to rotor diameter ratio and the active length to machine length ratio must be used as scaling factors. Hower to get more accurate results the study must be conducted again for the new active geometry.*

**Optimisation**

An optimisation process was setup for the IR-IM in optiSLang, a software developped by Dynardo. Motor-CAD is called via the so called ActiveX connection. As presented in Figure 6 it is possible to use the 'custom integration', allowing for setting up the parameters and responses to be extracted from Motor-CAD with a simple drag and drop. Self-made python script can also be used for more flexibility.

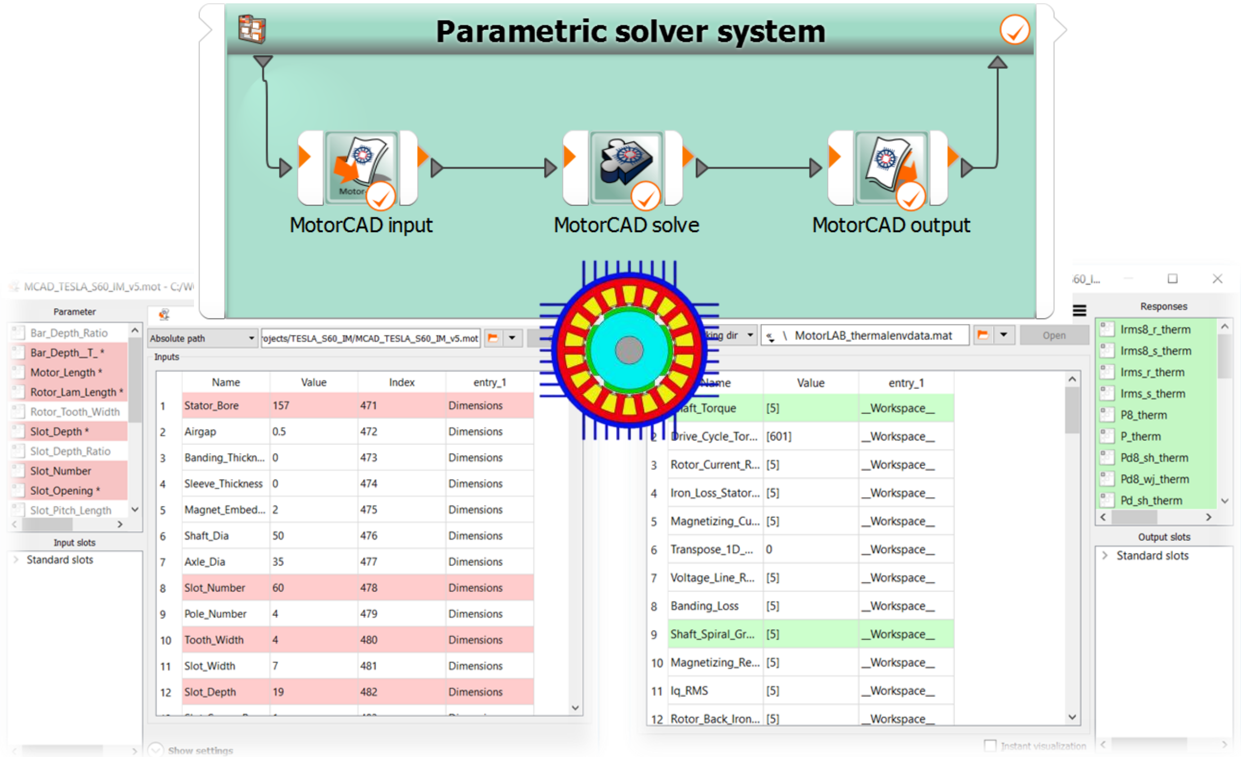



Figure 6. Integration workflow in optiSLang

A number of parameters were fixed for the optimisation based on the preliminary design, including the maximum dimensions (stator OD, active length), the winding configuration (turns per coil, coil pitch, slot fill factor), the slot/pole/bar combination, the cooling system, the materials, the drive settings (maximum current and voltage levels) and the temperatures limits for the rotor and the stator. The varied parameters with their bounds are reported in Table 8. Note that most of them are geometrical ratios. This makes the problem setup easier and allows for better understanding of the results.

Table 8. Optimisation variables and bounds

| Variable | Bounds |
|---|---|
| **Slot width/Slot pitch** | [0.45; 0.75] |
| **Active length** | [100; 150] mm |
| **Bar opening depth** | [0.5; 2] mm |
| **Stator ID/Stator OD** | [0.5; 0.75] |
| **Slot depth/(Slot depth + Stator yoke)** | [0.25; 0.7] |
| **Bar depth/(Bar depth + Rotor Yoke)** | [0.3; 0.6] |
| **Slot opening width/Slot width** | [0.2; 0.8] |
| **Bottom bar width/Bar pitch** | [0.2; 0.6] |
| **Top bar width/Bar pitch** | [0.3; 0.65] |

Two scenarios were investigated so far (see Figure 7). The first one consists in maximising the peak torque at low speed respectiv the power requirements and without deteriorating continuous performance. The second scenario aims at minimising the length of the machine with constraints on the nominal and peak powers and on the peak torque at low speed. Finally a pareto front was computed to find the best compromise between length reduction and continuous performance while reaching the target in terms of power.

**Scenario 1** $$\begin{cases} \max(T_{peak}@LS) \\ T_{cont}@6krpm > 130N.m \\ P_{peak}@MP > 200kW \\ P_{cont}@MP > 120kW \end{cases}$$

**Scenario 2** $$\begin{cases} \min(L) \\ T_{peak}@LS > 280N.m \\ P_{peak}@MP > 200kW \\ P_{cont}@MP > 120kW \end{cases}$$

**Figure 7. Scenarios for the optimisation**

The results for scenario 1 are presented Figure 8 and Figure 9. The red points relate to the preliminary design values. Therefore both continuous and peak performances are increased over the full speed range for the given maximum dimensions.

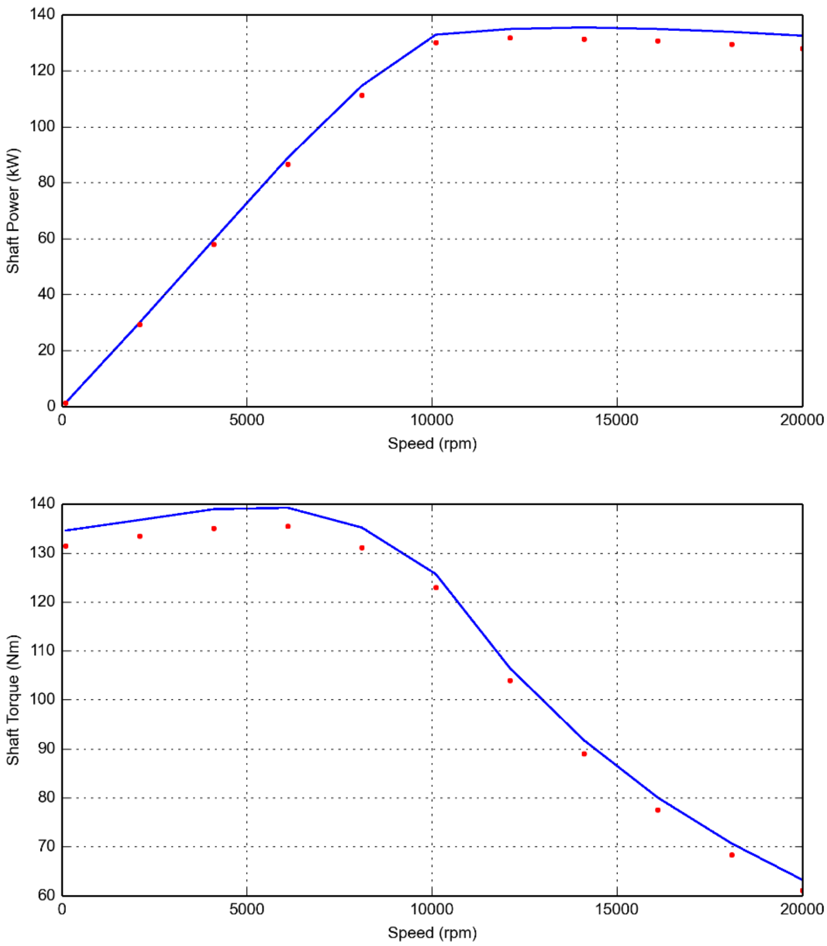
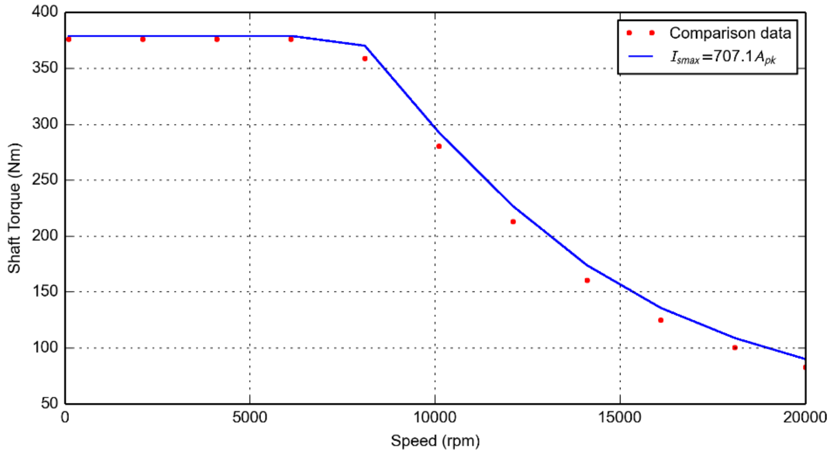



**Figure 8. Continuous performance of the optimised design - Scenario 1**



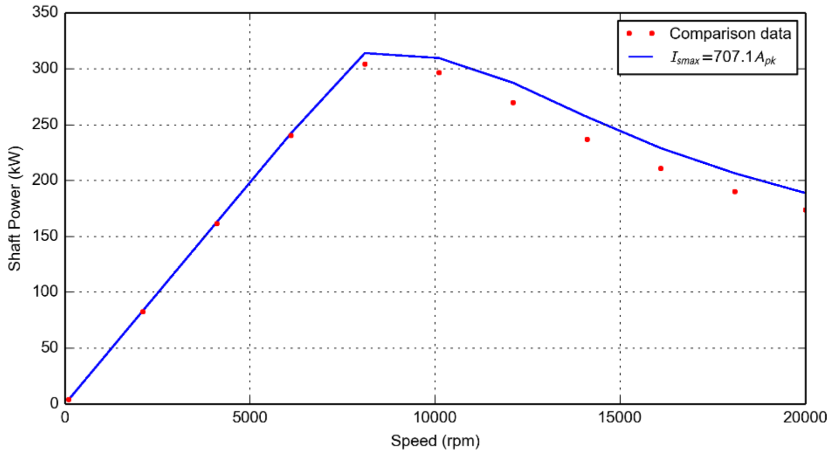




Figure 9. Peak performance for the optimized design - Scenario 1

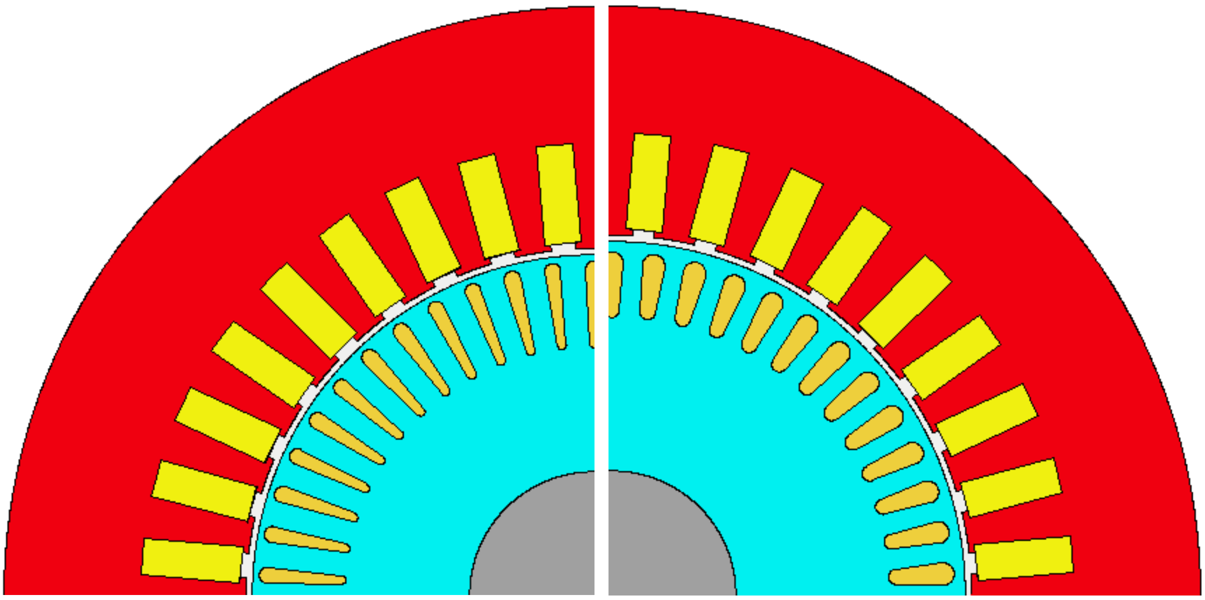


Figure 10. Radial cross section of the reference (left) and optimised design (right) - Scenario 1

Only the radial cross section of the optimised design is shown Figure 10 as the length reached its maximum bound corresponding to the reference design length. The main differences lie in a higher split ratio and bigger cross sectional area for the copper bars.

The results for the scenario 2 are presented Figure 11 and Figure 12. The optimised design is 114mm long and satisfy all the constraints. However the continous performance are considerably reduced and a mutli-objective optimisation with a Pareto front is therefore well suited to find the best compromise performance to cost ratio.

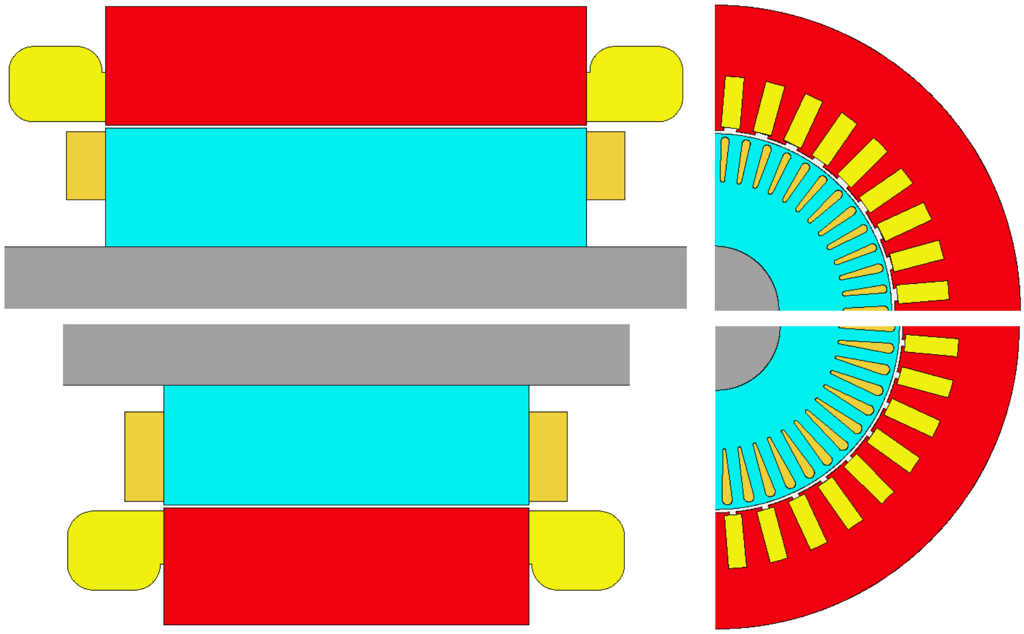


Figure 11. Radial and axial cross sections of the optimised design - Scenario 2

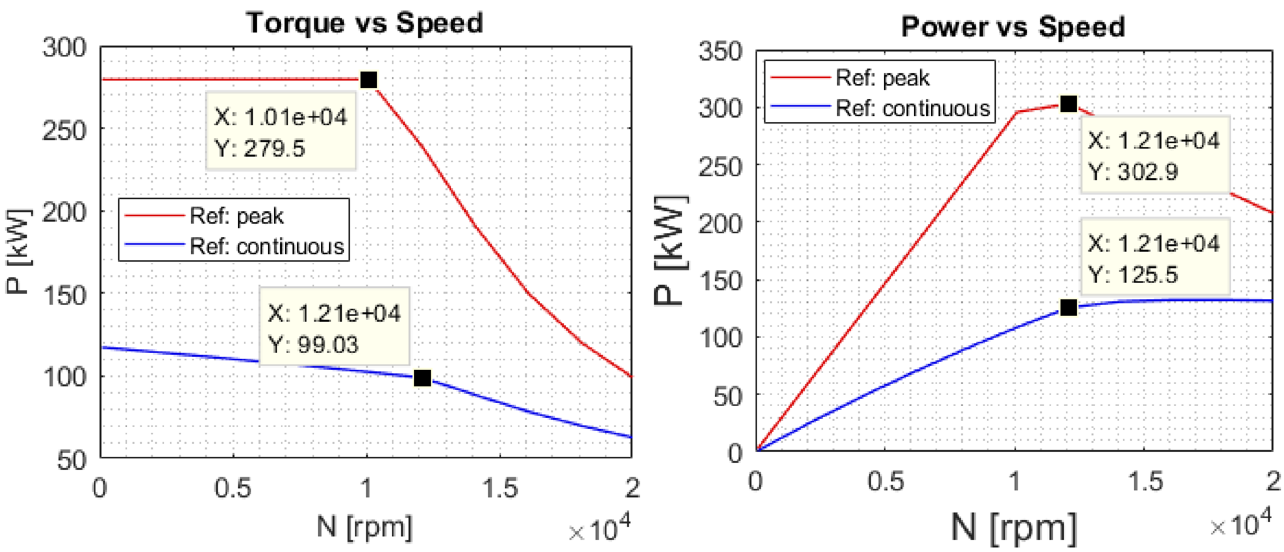



Figure 12. Peak and continuous performance of the optimised design - Scenario 2

Results from the multi-goals optimisation are presented in Figure 13 and Figure 14.

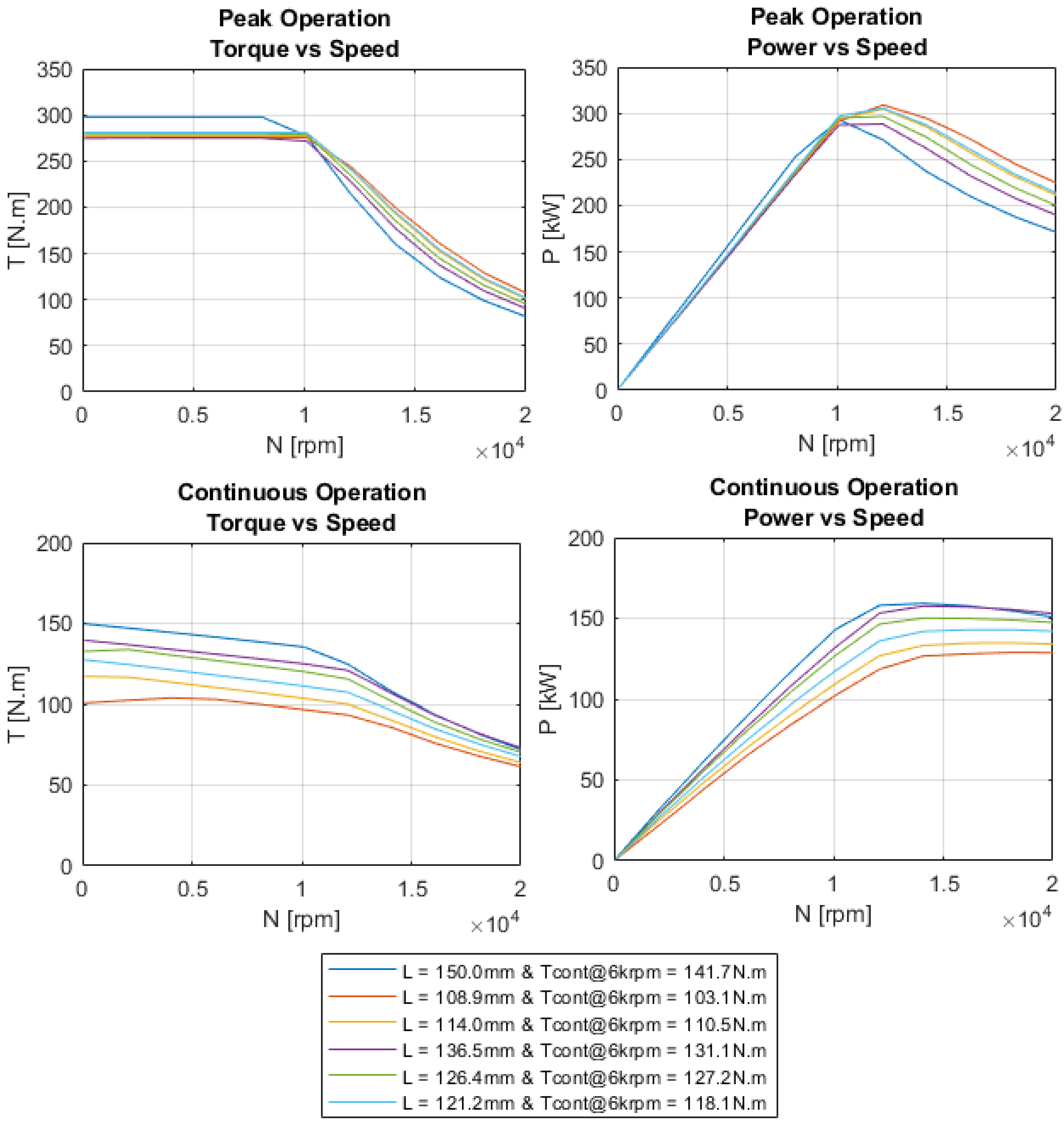



**Figure 13. Peak and continuous performance for different optimised designs on the Pareto front**

These results show that a compromise can be found between the reduction of the length (that directly impact the cost of the machine) and the continuous performance while satisfying the constraints (maximum temperatures, nomial power, peak power...).

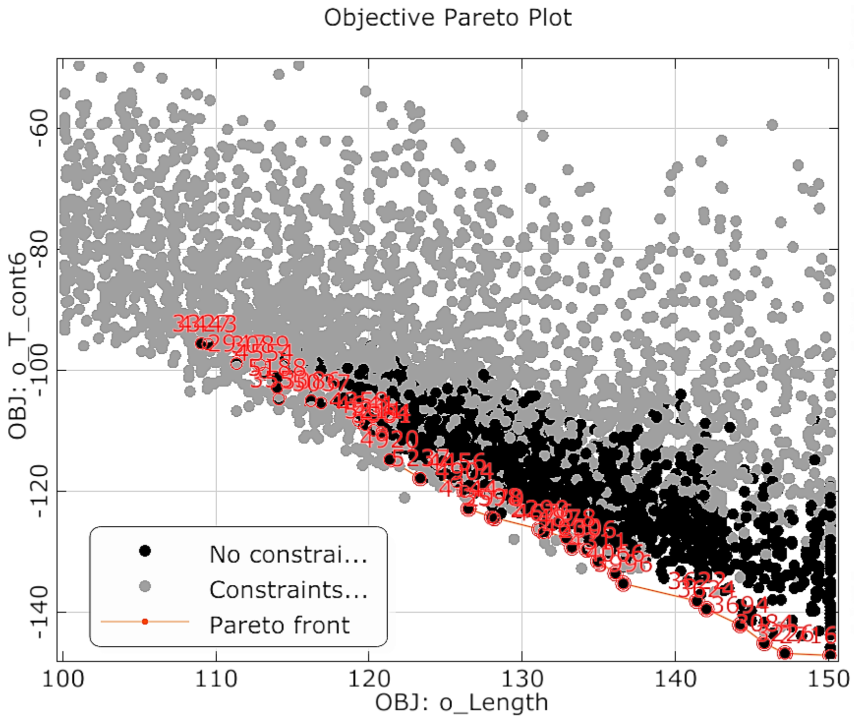



**Figure 14. Multi-objective optimisation - Pareto front**

## 2.3 WP4 Synchronous reluctance machine design

The list of WP4 objectives is seen in Table 9:

**Table 9: List of WP4 objectives**

| Objectives from DoA | Work carried out during the reported period | Achievements/Results |
|---|---|---|
| To identify the key factors in SynRel motor design that lead to an increase in power/torque density and lower cost. | Electro-magnetic FEM simulations for the design of several 200 kW SynRel and PMaSynRel motors | Results of the electro-magnetic performances, mechanical and thermal assessment when using different stator and rotor configurations |
| To select the materials for SynRel high speed motor applications avoiding rare earth content and lowering costs. | Evaluation of the performances when using different magnet technologies for the PMaSynRel technology (200kW)<br>Magnetic characterization of 4 standard NGO electrical steels | Comparison of the electro-magnetic performances of a reference 200kW PMaSynRel motor design using different magnet technologies (ferrites and low rare earth content magnets)<br>Detailed data and characteristic curves of each |

| | | |
|---|---|---|
| | | type of electrical steel sheet. |
| To achieve an electro-magnetic design of a SynRel motor without permanent magnets fulfilling the requirements specified in WP2. The design may use the same technology for the stator designed for IM in WP3 based on hair-pin configuration. A comparison of different stator-rotor configurations will be done in order to improve the power density. | Not applicable | Not applicable |
| To ensure the mechanical design and advanced thermal analysis of the selected SynRel and PM SynRel motors topologies. | Not applicable | Not applicable |

The main objective of WP4 is to design low cost rare earth free SynRel motors (pure and PM assisted) fulfilling the requirements defined within the WP2 for the 200kW and 75kW motor applications. According to the WP4 planning, seen in Figure 15. WP4 Planning the work carried out within the WP4 during the period M1-M9 has been focused on the task 4.1 (Preliminary SynRel Motor Design), started in M4. The full results will be reported in the deliverable D4.1, due in M12 (30/09/2018).

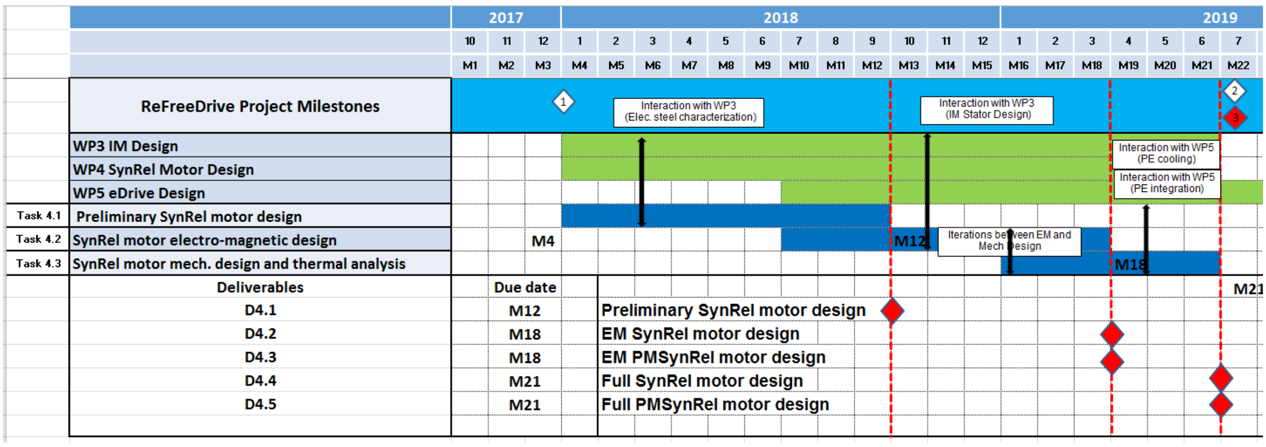



Figure 15. WP4 Planning

### *Task 4.1 Preliminary SynRel Motor Design*

The objective of this task is to identify the key factors for the design of low cost rare earth free SynRel motors. Two main aspects have been considered: the selection of the materials to be used in order to improve the motor performances whilst lowering the costs, and the choice of the stator/rotor/cooling configuration that offers the best trade-off between performances and costs. Following a techno economic evaluation of the proposed solutions, the best configuration will be chosen for the design carried on during the optimization phases (tasks 4.2 and 4.3).

### *SubTask 4.1.1 Preliminary analysis of SynRel motor technology*

In this subtask the used approach is to consider the high power range application (200 kW) as case study by imposing the external dimensions and the maximum speed of the motor, coherently with the KPIs defined in WP2. For the given case study, the analysis of the impact of different technological solutions on performances and costs for PMaSynRel and pure SynRel motor design has been performed.

This analysis covered the following aspects:

- Electro-magnetic performances (Maximum Torque, Torque Ripple)
- Demagnetization (for the PMaSynRel design)
- Losses distribution
- Mechanical stress on rotor
- Thermal analysis

From the point of view of the mechanical integration of the power electronics and the motor in the same housing, benefits and disadvantages of different levels of integration have been evaluated. The partners of the ReFreeDrive consortium agreed to use a "joined" type approach (see Figure 16) as this will enable to share the same cooling circuit for both motor and power modules, without imposing a too strong constraint (in terms of volume and cost) on the power electronics design.

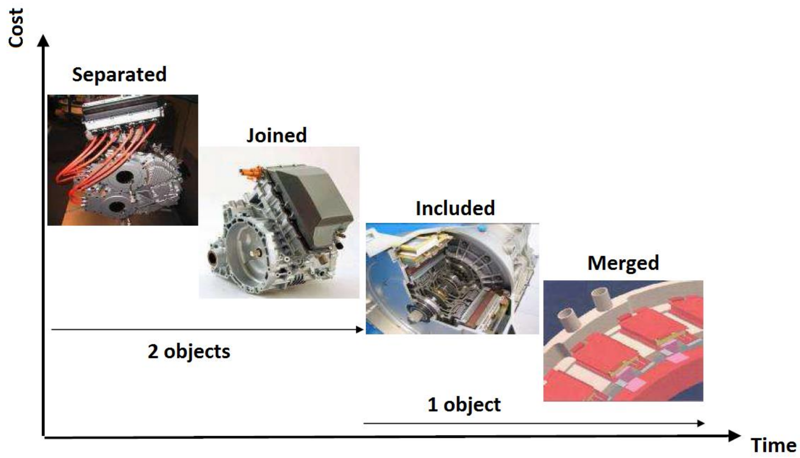



Figure 16 Levels of Power Electronics Integration

In order to select the best technological solution, the results obtained during the M1-M9 period will be exploited in M10-M12 to carry on a techno-economic evaluation mainly based on the material and manufacturing costs estimated from the designs proposed by IFPEN and UAQ.

### *PMaSynRel motor design results (IFPEN)*

IFPEN predesigned a 200kW PMaSynRel reference motor using a 10 pole rotor. On the basis of this design several alternatives have been studied by changing the pole pair number (between 6 and 12), the Slot/Pole/Phase ratio (1 and 2) and the amount of ferrite magnets. For each design several performances have been evaluated: maximum torque vs motor speed, torque ripple, efficiency, level of demagnetization when using ferrites. Experimental data provided from the electrical steel characterization have been used to compare the efficiency maps for the reference design. For all design the loss distribution (Joule losses, iron losses, stator and rotor losses,…) has also been investigated.

A preliminary mechanical analysis on the reference design at 100°C showed that the mechanical stress due to the centrifugal force at 14000rpm potentially affects the EM performances due to a non-constant airgap. According to the first thermal analysis results, a conventional cooling system is not sufficient to maintain the rotor temperature below the maximum value admitted when using ferrites. An optimization will be required in task 4.2.

### *SynRel motor design results (UAQ)*

In this pre-design stage, different stator slots and rotor barriers configurations have been considered. In particular, three different preliminary designs have been analyzed and compared:

- 4-pole SynRel motor;
- 6-pole SynRel motor;
- 8-pole SynRel motor.

The stator winding has been selected to be 3-phase, star connection. Standard round wire winding with parallel paths in single-layer coil (easier to implement and with high copper slot fill factor) has been chosen. The proposed designs have been compared in order to select the best solution to be optimized in the task 4.2, leading to the following conclusions:

- the current density values of the preliminary designs are reasonable for the liquid cooled machines;
- the 4-pole design presents the highest outer diameter and this is due to the flux density in the stator yoke: this allows to reduce the phase current but has an impact on the volume of the active parts;
- all the proposed designs have an efficiency at rated power higher than 94%; at peak power the 8-pole only does not satisfy this constraint;
- at rated power the efficiency of the 6-pole is higher than the 4-pole and 8-pole;
- at base speed (6000 rpm), the 6-pole design fully satisfies the requirements with a lower phase voltage than the 4-pole and 8-pole;
- at high speed (14000 rpm), the 8-pole design is not able to reach the required power with the imposed DC voltage;
- at peak power, the 6-pole design presents a wide “constant power speed range” compared to the other solutions.

In terms of performances, the preliminary results indicate that the 6-pole, 54-slots design is the best topology for SynRel motor, with a limited volume and satisfactory performances at rated and peak power. This study has been completed with the analysis of the 6-pole SynRel motor with the other NO electrical steels proposed by RINA-CSM (NO20HS and NO30-15). As no significant improvements on the motors performance have been observed, M235-35A is still the best candidate for the SynRel motor final design.

A preliminary mechanical FE analysis has been carried out in order to evaluate the deformation in the rotor at worst mechanical stress operating conditions and high speed (14000 rpm). The aim was to evaluate the mechanical robustness of the rotor core (above all in the radial and tangential ribs) and verify the rotor deformation close to the airgap. No critical values have been reached for the rotor deformation and mechanical stress.

An extended comparison of the different designs will be done in months M11-M12 and reported in the deliverable D4.1.

### *SubTask 4.1.2 Selection of materials for SynRel motor applications*

#### *Magnets (IFPEN)*

The influence of different types of magnets has been studied: the reference 200kW motor design has been used with both low cost ferrites (NMF) and rare earth magnets without Dysprosium. As expected, the quality of the selected magnets has an important impact on the performances. With respect to the reference that is the NMF-15G (Ferrite), with NMF-6G magnets the performances are reduced of 50%, while with the N35SHDF (Dy Free) magnets an increase of 300% is observed. At this stage of the project the NMF-15G is the best candidate to be used for the PMaSynRel motor design.

#### *Electrical Steel (RINA-CSM)*

Four NGO materials with different thickness have been characterized by RINA-CSM to provide accurate data to the motor designers (magnetization curve and core losses):

- Material 1: NO-20HS (0,20 mm)
- Material 2: NO-30-15 (0.30 mm)
- Material 3: Material 3: HP 290-50K (0.50 mm)
- Material 4: M235-35 A (0.35 mm)

A fifth material (GO electrical steel, thickness 0.23 mm) has been selected for characterization in month M11, to be used by UAQ in the FEM simulations for the 2 pole SynRel Rotor design.

A preliminary magnetic characterization on the four materials has been carried out consisting of the following tests:

- magnetization curves (BH) at different directions, with respect to rolling direction RD, and frequencies (50Hz, 400Hz, 800Hz, 1000Hz)
- core losses at different directions, with respect to rolling direction, and frequencies (50Hz, 400Hz, 800Hz, 1000Hz)

In Figure 17 the setup of Epstein Frame (IEC 60404-2) for the magnetic characterization of all NGO and GO materials is shown. In order to evaluate the magnetic properties of each material with respect to a specific direction of magnetization. 100% of the samples have been cut and tested in the same direction (0, 45, 90° with respect RD – see next figure).

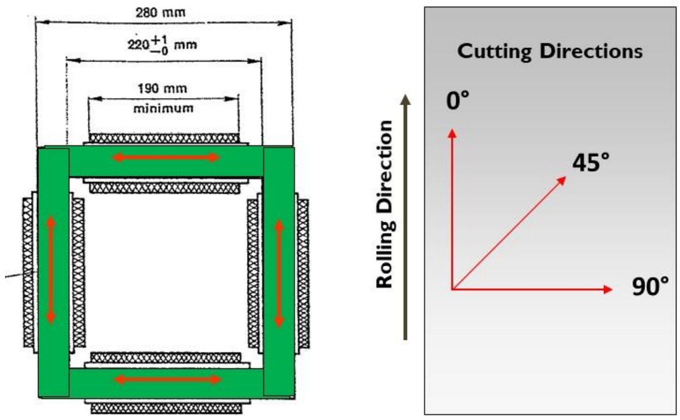



**Figure 17. Setup for the characterization as a function of cutting direction. – 100% of the strip cut in the same direction with respect RD**

As example of the investigation carried out, in the next Figure 18 and Figure 19 are reported the magnetization curves and the core losses at 400 Hz measured for the non-oriented steels (NGO).

The detailed materials characterization is reported in the deliverable D 4.1.

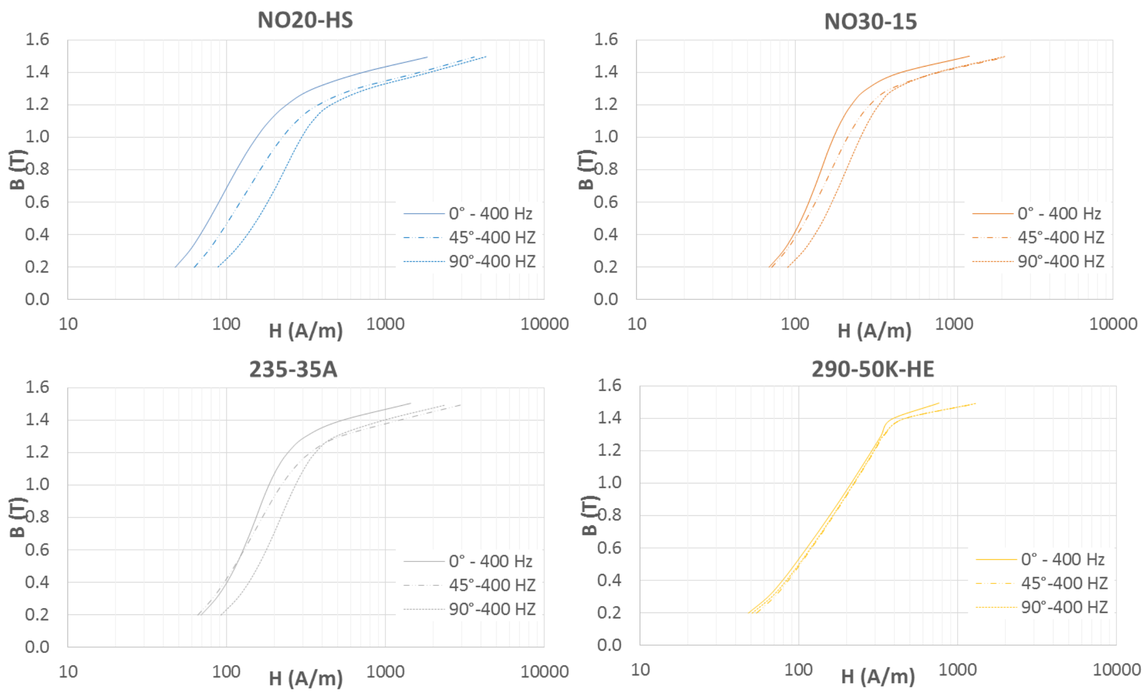



**Figure 18. Magnetization Curves at 400 Hz**

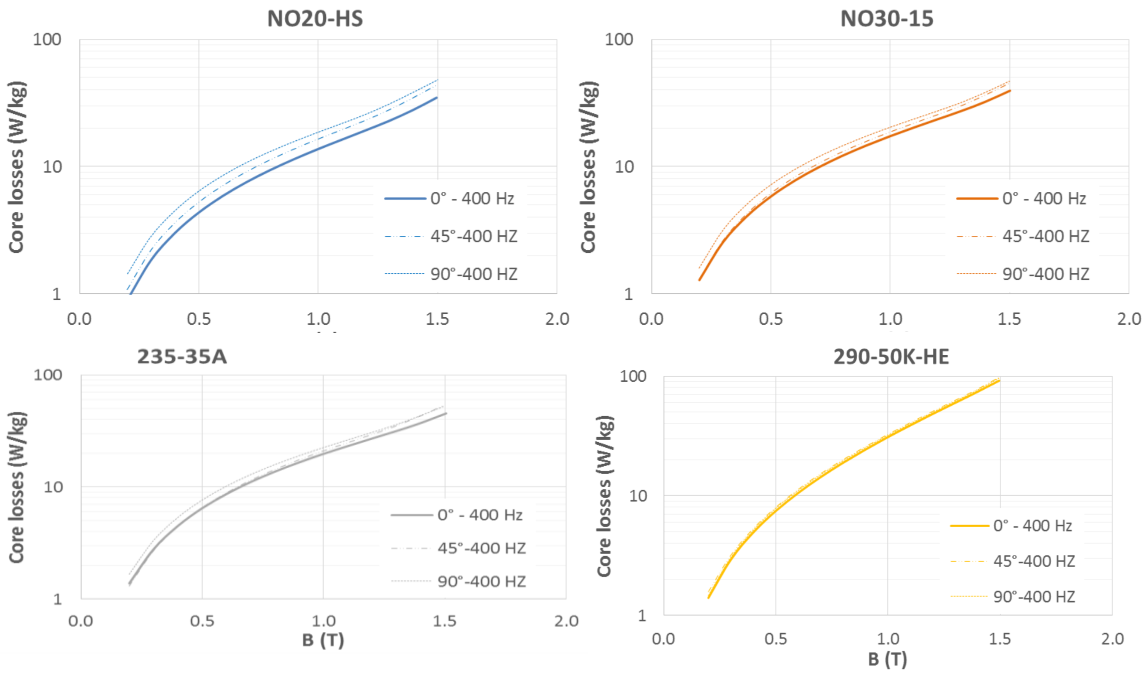



Figure 19. Core Losses at 400 Hz

Based on such characterization, and in cooperation with the motors designers, two materials have been selected for a deeper characterization to be performed in a wide frequency range (50-1000 Hz), and for different angles (0-45°-90°). Among the studied materials, in terms of electro-magnetic performances, NO20 and NO30 materials are the ones which at high frequency have the highest magnetization curve and the lowest losses curve. However, when also taking into account the cost, the standard M235 steel has been considered a better choice than NO20. Therefore M235 and NO30 characterization data will be used during the 4.2 task, and one of these materials will be chosen for the realization of IM and RM prototypes active parts.

## 2.4 WP5 Power Electronics and e-Drive integration design

WP5 intends to research and develop the power electronics and control strategies needed for each power range. This means that both traction technologies will share the same power electronics and control algorithms in each use case (medium power range, high power range). Besides, the WP5 will analyze and select off the shelf solutions for the rest of the powertrain systems needed from an integration point of view, such as batteries, gear box, electric and electronic integration as well as cooling systems and testing systems.

During the 6M GA WP5 partners decided to anticipate the starting dates of all the WP5 tasks from M19 (April 2019) to M7 (April 2018) in order to carry out the following preliminary studies:

- Preliminary selection and analysis of the power electronical components to support the motor design tasks;
- Preliminary design of the motor control strategies to support the motor design tasks;

- Preliminary integration studies;
- Preliminary thermal analysis.

The analyses are still ongoing, preliminary results concern the identification of suitable power modules for the target application:

- Different suitable Power electronics modules are being analysed for the target application (both MOS Silicon Carbide and IGBT Technology);
- Most promising solution are reported in the Table 10.
- The best available solution in the market in terms of power ratings and efficiency is the module BSM600D12P3G001 (Manufactured by ROHM) as seen in Figure 20.
- Thermal analysis (by thermal network) on the BSM600D12P3G001 power module outlined that the module can provide a maximum suitable peak current for the motor phase equal to 780A, precious indication for motor designers.

**Table 10: Main power modules investigated**

| Power module | Manufacturer | Technology | Max voltage | Max Current |
|---|---|---|---|---|
| **BSM600D12P3G001** | Rohm | SIC Mosfet | 1200V | 576Arms |
| **SKM350MB120SCH17** | Semikron | SIC Mosfet | 1200V | 416Arms |
| **FF600R07ME4_B11** | Infineon | IGBT | 1200V | 600Arms |

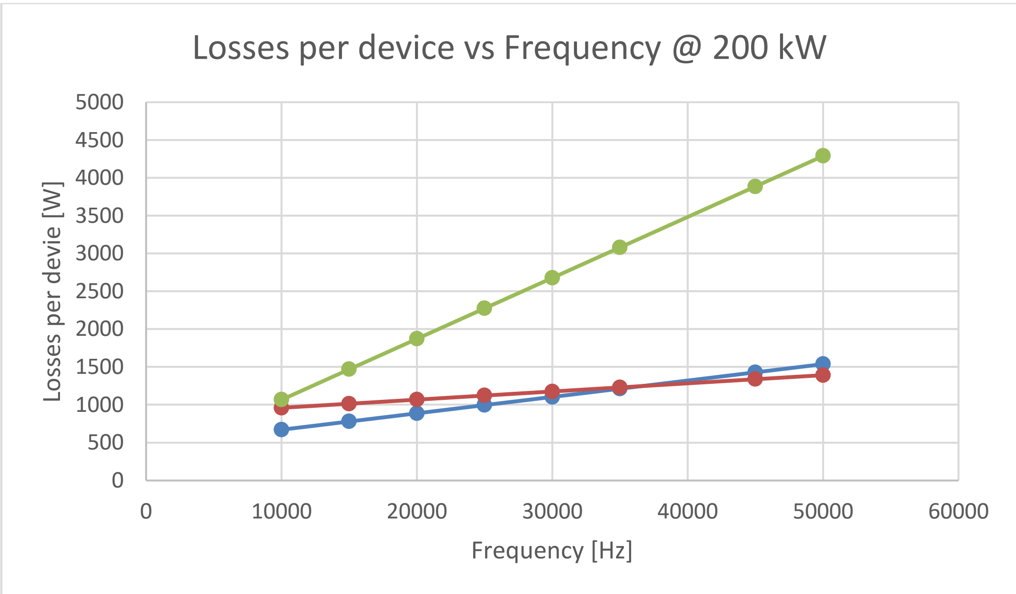



**Figure 20. Losses vs frequency at target maximum power (BSM600D12P3G001, blue; SKM350MB120SCH17, red; FF600R12ME4A_B11, green)**

About the activities on the control strategies, the partners carried out studies on the control strategies of Synchronous and Induction motors aimed to enhance the efficiency at low torque.

The adoption of Maximum efficiency per Torque (MEPT) control strategy with respect to the classical Maximum Torque per Ampere (MTPA) gives advantages in terms of efficiency at low loads, useful to enhance the efficiency of the vehicle at constant speed operations.

Figure 21 reports a comparison between the two control strategies obtained from experimental results on a prototype of Induction motor available in the laboratory.

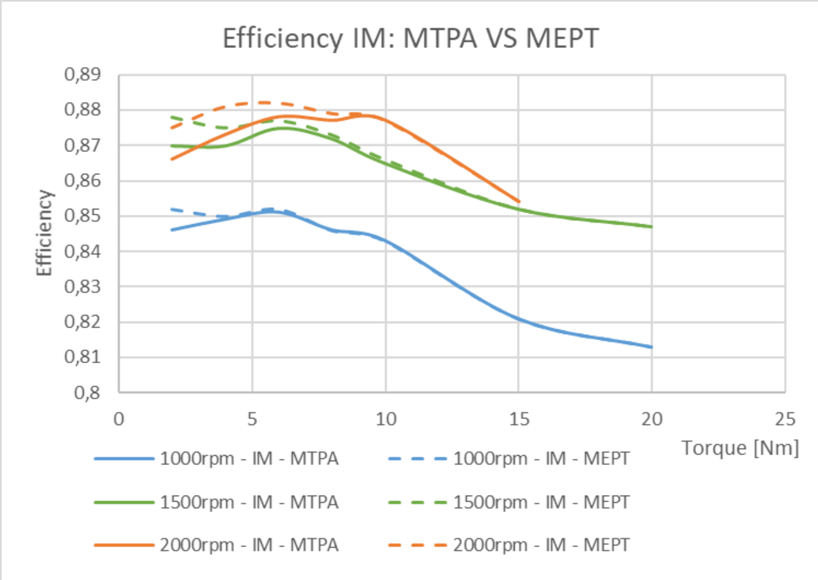



**Figure 21: Efficiency Comparison of METP and MTPA control strategies on a 3kw industrial induction motor**

Preliminary activities have been started concerning the on-vehicle integration of the power units for the demonstrator.

## *2.5 WP8 Techno economic evaluation and exploitation*

WP8 has so far established a procedure to identify new Intellectual Property Rights (IPR) and defined a market analysis and a technology watch to manage the IPR and innovation results. These will be set up in the upcoming period.