Rare Earth Free e-Drives Featuring Low Cost Manufacturing

ReFreeDrive

Collaborative Project
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V2	31.08.2018	Update of the Techno economic evaluation section
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V6	20.09.2018	Update of the Electrical Steel Characterization and SynRel sections
V7	22.09.2018	Update of Executive Summary, Section 5 and 6
V8	27.09.2018	Update of Executive Summary

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Abbreviations

FEM: Finite Element Model

GO: Grain Oriented

IM: Induction Motor

KPI: Key Performance Indicator

NGO: Non-Grain Oriented

PM: Permanent Magnet

PMa-SYNREL: Permanent-Magnet assisted Synchronous Reluctance Motor

RPM: Round Per Minute

SYNREL: Synchronous Reluctance

WP: Work Package

Executive Summary

This document reports on the preliminary design of Synchronous Reluctance (SynRel) motors performed within the ReFreeDrive project Task 4.1. The main objective of Work Package 4 (WP4) is to design low cost rare earth free SynRel motors fulfilling the requirements defined within the WP2 for the 200kW and 75kW motor applications. Two configurations are considered: pure and Permanent Magnet assisted Synchronous Reluctance motors (SynRel and PMa SynRel in this report).

According to the ReFreeDrive Grant Agreement document the objectives of Task 4.1 are:

- *to identify the key factors in SynRel motor design that lead to an increase in power/torque density and lower cost*. This objective is fulfilled within subtask 4.1.1 with no deviation on content or time. Several stator/rotor configurations have been investigated in order to find the best trade-off between performances and costs. For the thermal analysis, conventional water jacket cooling has been considered.
- *to select the materials for SynRel high speed motor applications avoiding rare earth content and lowering costs*. This objective is fulfilled within subtask 4.1.2 with no deviation on time and the following limitations:
    - o the electrical steel characterization was limited to commercially available products. It was not possible to test high strength electrical steels for high speed rotors due to unavailability of samples. As a consequence, especially for the PMa SynRel motor design (Task 4.2 and Task 4.3), several iterations between the electro-magnetic design and mechanical analysis will be required in order to comply with the mechanical strength limit at high speed without impacting the performances.
    - o only commercially available ferrites have been considered as rare earth free permanent magnets as their characteristics are well known.

The cost aspect has been taken into account carrying out a techno economic evaluation of the proposed solutions: the best configurations will be chosen for the design to be carried on during the optimization phases (Tasks 4.2 and 4.3).

This report is organized as follows:

- Section 1 gives a brief introduction to the SynRel technology.
- Section 2 sums up the motor specifications used for the design of the 200 kW and 75 kW motors.
- Section 3 is dedicated to the material selection for SynRel motor applications, with a special focus on the electrical steel and rare earth free permanent magnets.
- Section 4 presents several PMa SynRel preliminary designs for the 200 kW application. The electro-magnetic performances are presented in details together with a preliminary mechanical and thermal analysis. The design of the 75 kW application obtained by scalability (same stator and rotor geometry as for the 200 kW design) is also presented.

- Section 5 presents several SynRel preliminary designs for the 200 kW application and the design of the 75 kW application obtained by scalability. As for the PMa SynRel motor design, a preliminary mechanical analysis is presented.
- Section 6 provides a techno-economic evaluation of the available designs, based on the cost to power ratio.

In Task 4.1 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 Key Performance Indicators (KPIs) defined in WP2. For the given case study, the analysis of the impact of different technological solutions on performances and costs for PMa and pure SynRel motor design has been performed.

This analysis covered the following aspects:

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

Scalability has been also investigated by designing a 75kW motor using the same stator/rotor geometry as the 200kW motor.

Materials selection

The influence of different types of magnets has been studied: the reference 200kW motor design has been used with low cost ferrites (Hitachi NMF™ series) and, for comparison purposes, dysprosium free rare earth magnets. As expected, the quality of the selected magnets has an important impact on the performances. With respect to the given reference, that is the NMF-15G (Ferrite), with NMF-6G magnets the performances are reduced of 50%, while with the N35SHDF (dysprosium 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 rare earth free PMa SynRel motor design.

Electrical steels to be used for the motor active parts design should be carefully selected, especially for high speed (frequency) applications. Magnetic performances (BH curve), core losses, mechanical strength and cost are the main criteria used to evaluate these materials. Four Non-Grain-Oriented (NGO) materials with different thickness have been characterized by RINA-CSM to provide accurate data to the motor designers (magnetization curve and core losses):

- NO-20HS (0.20 mm)
- NO-30-15 (0.30 mm)
- HP 290-50K (0.50 mm)
- M235-35 A (0.35 mm)

A fifth material (Grain Oriented electrical steel, thickness 0.23 mm) has been selected for characterization to be used in the Finite Element Model (FEM) simulations for the 2 pole SynRel rotor design.

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 Task 4.2, and one of these materials will be chosen for the realization of the SynRel prototypes active parts.

PMa SynRel motor design

IFPEN predesigned a 200kW PMa SynRel 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 (Figure ES.1).

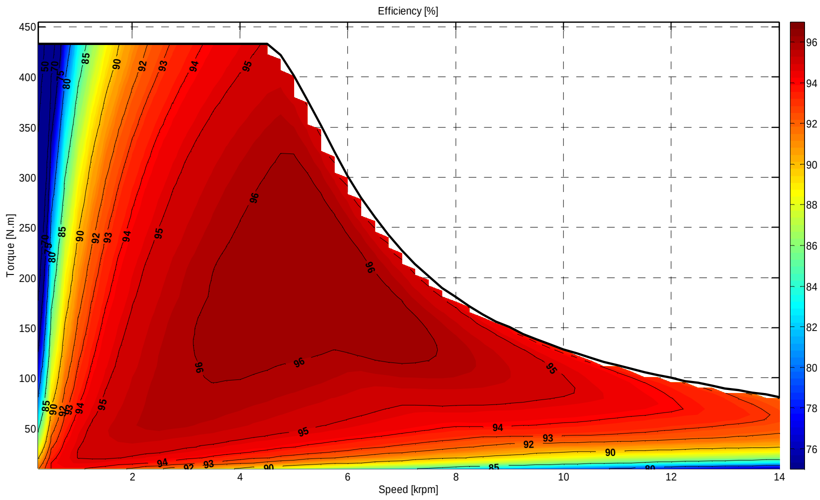

Figure ES.1 PMa-SynRel - Efficiency for the reference design (10-pole)

For all designs 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 14000 rpm potentially affects the electro-magnetic 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

For the pure SynRel motor design, 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% (Figure ES.2); at peak power the 8-pole only does not satisfy this constraint;
- 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 also 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.

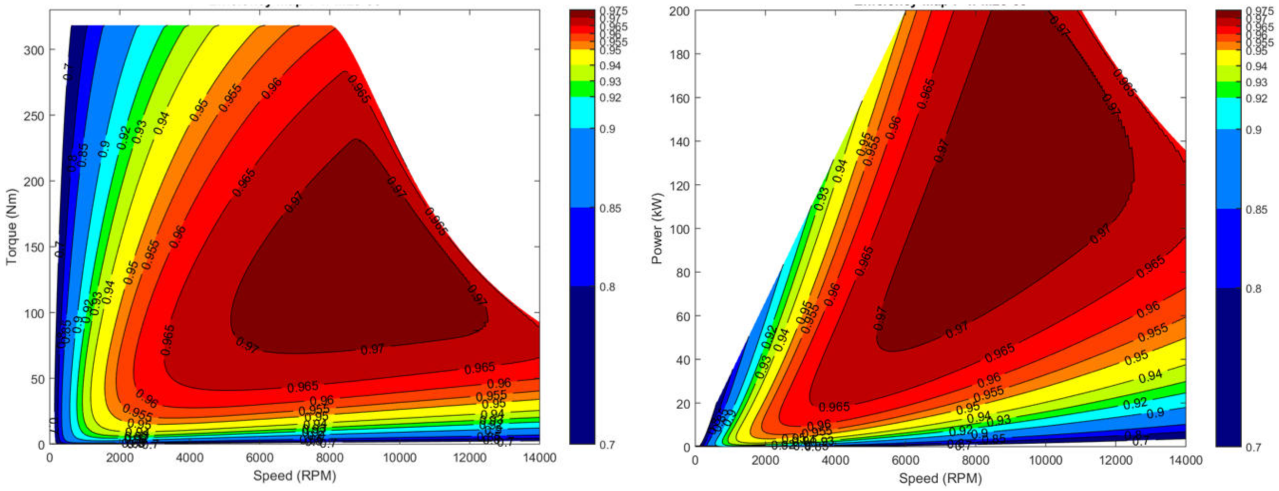

Figure ES.2 SynRel Preliminary design 6-pole – Efficiency maps

Mechanical integration

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 ES.3) 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.

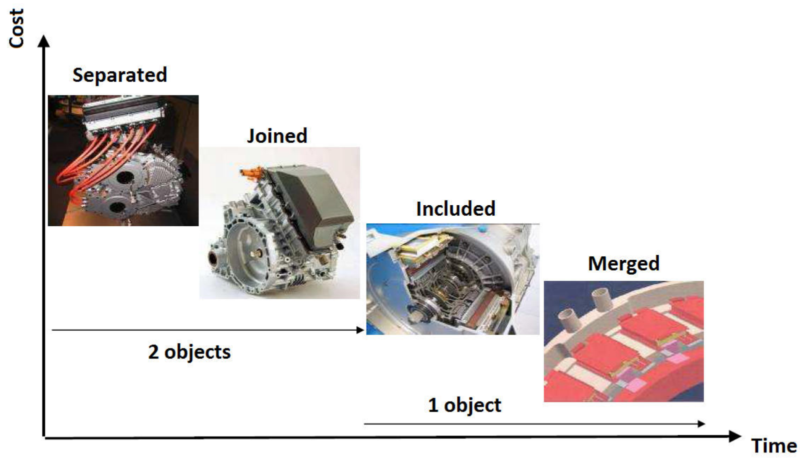

Figure ES.3 Levels of Power Electronics Integration

Techno-economic evaluation

The techno-economic evaluation for the studied motors configurations is based on the cost to power ratio (Figure ES.4) which provides a direct overview of the advantages of one design choice with respect to another. Two type of ratio are extrapolated, one which refers to the overall motor cost to the power value, at the maximum efficiency point, and the other which refers to the overall motor cost to its peak power value.

From the data provided by the motor designers, based on the cost to power ratio, the best configurations for both PM SynRel than Pure SynRel are: 10P-EM-FRACT (10 pole PMa SynRel with fractional slot winding and 0.35 NGO electrical steel), 10P-FM-M235 (10 pole PMa SynRel with 0.35 NGO electrical steel and extra permanent magnet content), 8P-EM-M235-35A (pure 8 pole SynRel with 0.35 NGO electrical steel) and 8P-EM-NO30 (pure 8 pole SynRel with 0.30 NGO electrical steel). The configurations which seem less advantageous from a cost to power point of view are the low poles PM SynRel.

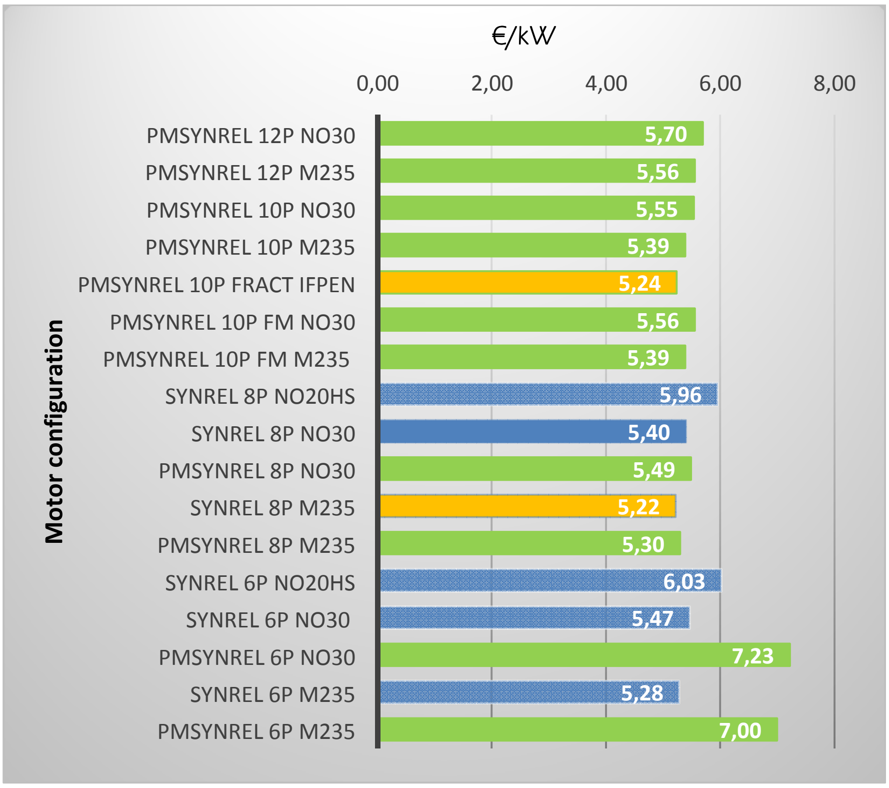

Figure ES.4 Cost to Power ratio, at the max efficiency condition, for all analysed PM and Pure SynRel motors configurations: Pma SynRel and SynRel best motor configurations (orange) vs other studied PMa SynRel and SynRel configurations (green and blue, respectively)