Rare Earth Free e-Drives Featuring Low Cost Manufacturing

ReFreeDrive

Collaborative Project
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Abbreviations

FE: Finite Element

GO: Grain Oriented

KPI: Key Performance Indicator

MTPA: Maximum Torque Per Ampere

OD: Outer Stator Diameter

SYNREL: Synchronous Reluctance

WLTP: Worldwide Light Vehicle Test Procedure

WP: Work Package

Executive Summary

This document covers the electromagnetic design of the pure Synchronous Reluctance (SynRel) motor: the goal is to design an optimal and cost effective solution without permanent magnets by imposing the external dimensions and the maximum speed of the motor, coherently with the Key Performance Indicators (KPIs) defined in Work Package WP2.

This task includes:

- different design strategies for the rotor geometry shape;
- optimization of stator and rotor cores by a specific algorithm linked with the Finite Element (FE) software;
- comparison of several stator/rotor configurations in order to find the best solution.

The avenues indicated above require a complex optimization process for matching the desired motor performances whilst respecting the target components cost.

This report is organized as follows:

- Section 1 gives a brief introduction to the Task 4.2 and the main goal.
- Section 2 presents the design optimization of the 200 kW SynRel motor: in this section the design of the 2-pole motor with Grain Oriented (GO) electrical steel is also presented.
- Section 3 is dedicated to the electro-magnetic performance of the optimized design at peak and continuous power and with Worldwide Light Vehicle Test Procedure (WLTP Class_3) driving-cycle (torque, torque ripple, losses and efficiency maps).
- Section 4 presents the design of the 75 kW using the same stator/rotor geometry as the 200 kW motor (scalability).
- Section 5 describes the mechanical analysis of the optimized design and particularly the mechanical strength of the rotor structure by the 2D/3D Ansys software. Focus is given on high speed impact on mechanical stress.
- Section 6 presents the thermal behavior of the liquid cooled SynRel motor considering the water jacket designed and proposed by Mavel partner in ReFreeDrive consortium; for this analysis, two software are used to determine the temperatures in the stator winding and stator/rotor core at different operating conditions and the temperature and velocity of the fluid.
- Section 7: comments and conclusions.

Electromagnetic Design

The main objectives of the electromagnetic design are:

- To satisfy the requirements by the end users according to the KPI specified in WP2 (see Table Table ES-1)

- To refine the rotor shape by an optimization procedure in order to improve the Torque/Ampere ratio and smooth the torque profile.

Table ES-1 KPIs for Pure SynRel Motors

Parameter	Unit	Value
Specific Peak Power	kW/kg	> 4.3
Peak Power Density	kW/lit	> 8.0
Specific Peak Torque	Nm /kg	> 8.2
Peak Torque Density	Nm/lit	> 15.4
Maximum speed	rpm	15000 ÷ 18000
Peak efficiency	%	> 96
Active parts weight	kg	< 47
Motor dimensions (ODxL housing included)	mm	250 x 310

200kW Pure SynRel Motor Design

Two design strategies have been chosen and particularly:

1) SynRel motor with radial ribs in the rotor core;
2) SynRel motor without radial ribs.

The aim was to verify which of the two solutions could guarantee better motor performance in terms of efficiency, torque and ripple.

The final design with 6pole-54slots presents a rotor with “fluid shaped” flux barriers without radial ribs in order to improve the motor performance: as this choice is very critical for the mechanical strength of the rotor core, it was decided to fill the flux barriers with epoxy adhesive resin.
The SynRel motor has been tested at peak and continuous power and with Worldwide Light Vehicle Test Procedure (WLTP Class_3) driving-cycle, in order to evaluate the motor performance and the efficiency maps over the full speed range with a Maximum Torque Per Ampere (MTPA) control strategy.
The performance of the final design at peak and continuous power are summarized in Table ES-2: Fig. ES-1 and Fig. ES-2 show the efficiency maps (for the motor operating mode) and the operating points of the WLTP driving cycle where the peak efficiency is about 96%: the high torque value guarantees good performance during the acceleration step.

75kW Pure SynRel Motor Design

The lower power machine has been scaled from the 6-pole 200 kW design by only changing the stator winding and stack length: good power levels can be obtained with the same material quality (M235-35A) and radial dimensions. The DC voltage for this size is 350 V.

The motor performance at rated power are listed in Table ES-3.

Table ES-2 Performance of the SynRel optimized design

Parameter	Unit	Peak Power (30 sec.)	Contin. Power (S1)
DC Voltage	V	800	
Phase current	Amax	700	231
Phase voltage	Vmax	346	395
Speed	rpm	4800	18000
Output Power	kW	201	69.7
Joule losses	W	22810	2480
Iron losses	W	903	1350
Torque ripple (*)	%	10	12

(*) no-skewed rotor

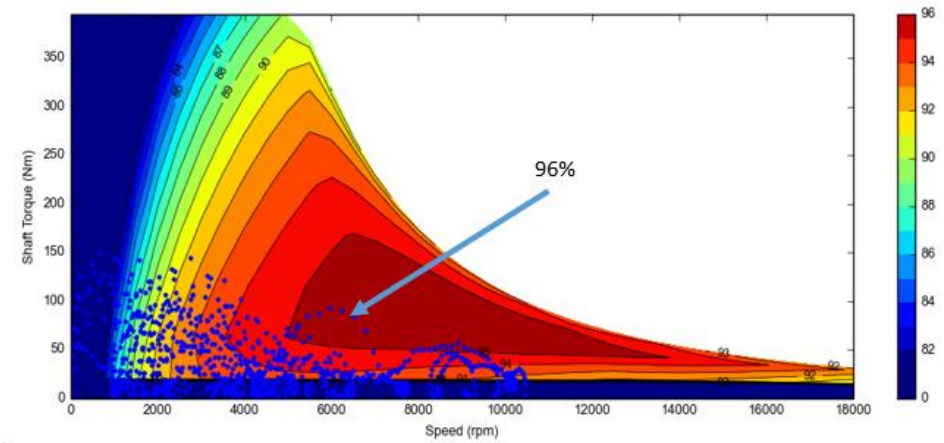

Fig. ES-1 - Torque vs. Speed and efficiency maps

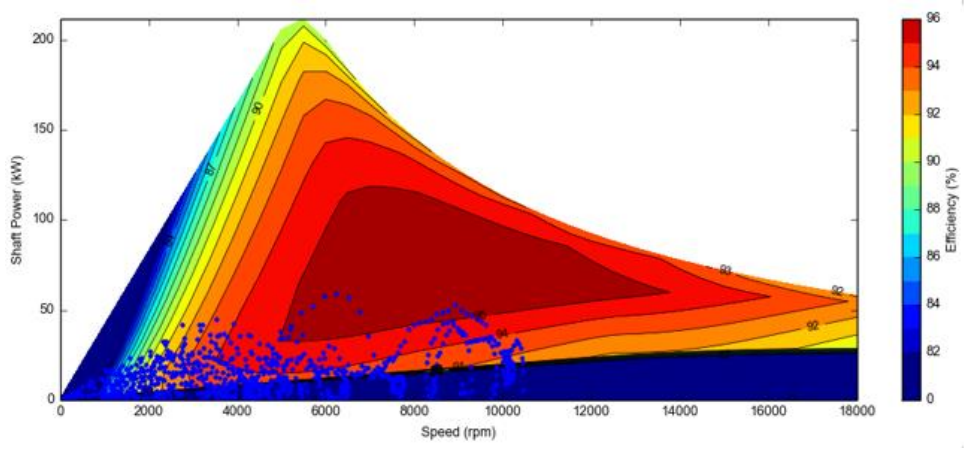

Fig. ES-2 - Power vs. Speed and efficiency maps

Table ES-3 Scaled 6-pole SynRel motor – Performance @ rated Power

Parameter	Unit	Performance @ 4800 rpm	Performance @ 18000 rpm
Torque	Nm	150	18
Rated Power	kW	75	34
Phase current	Amax	350	200
Phase voltage	Vmax	200	200
Efficiency	%	94.40	93
Current density	A/mm^2	16.6	9.5

Thermal Analysis

The thermal behavior of the liquid cooled SynRel motor has been analyzed considering the water jacket designed and proposed by Mavel partner in RefreeDrive consortium.
The analysis has pointed out that the maximum winding temperature during in the WLTP Class 3 driving cycle is lower than 100°C; at continuous power (70 kW) the steady-state temperatures after 1 hour are quite reasonable. In the peak power operation (200 kW) the hotspot temperature in the stator winding, after 30 sec., is slightly higher than the limit for the class H: the average value is about 160°C.

Mechanical Analysis

The proposed SynRel motor presents an unusual rotor shape compared to those typically reported in literature and then a deep mechanical analysis has been carried out at high speed operation. For this study, the 2D Mechanical FE software has been used and the rotor core has been modelled taking into account the material properties of the electrical steel and the epoxy adhesive resin.
The results point out that the rotor structure with resin, is able to withstand mechanical stress at high speeds even if some critical points are highlighted inside the flux barriers that could cause the resin to detach from the wall with consequent weakening of the rotor structure. Therefore, design measure are being studied to reduce the critical issues and this could result in a slight change of the rotor shape respect to the solution proposed in this report.