Rare Earth Free e-Drives Featuring Low Cost Manufacturing

Collaborative Project
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Abbreviations

GA: Grant Agreement

IM: Induction Machine

KPI: Key Performance Indicator

PM: Permanent Magnet

PMa-SYNREL: Permanent-Magnet assisted Synchronous Reluctance Motor

RPM: Rounds Per Minute

SYNREL: Synchronous Reluctance

WLTP: Worldwide harmonized Light vehicles Test Procedures

WP: Work Package

Executive Summary

The main objective of Work Package 4 (WP4) is to design low cost rare earth free Synchronous Reluctance (SynRel) motors fulfilling the requirements defined within the WP2 for the 200kW and 75kW motor applications. This document reports on the electro-magnetic design of the Permanent Magnet (PM) assisted Synchronous Reluctance (PMa SynRel) motors performed within the ReFreeDrive project Task 4.2.

According to the ReFreeDrive Grant Agreement (GA) document the main objective of Task 4.2 is "*To achieve an electro-magnetic design of a PM SynRel motor with low cost ferrite permanent magnets fulfilling the requirements specified in WP2. A comparison of different stator-rotor configurations will be done for evaluating the best trade-off between performance and cost.*"

With respect to the list of the task 4.2 items provided in the GA WP4 description, the work carried out during the project included (with no deviation from the WP4 timeline):

- a specific rotor geometry optimization (flux barriers) for PM SynRel
- a specific stator design for PM SynRel using the winding distribution selected in task 4.1.1
- the investigation on the demagnetization of the selected PM
- the investigation on scalability aspects (to derive the 75 kW motor design)

<u>and did not include</u>:

- The comparison of different configurations (hair-pin stator / PM SynRel stator + SynRel rotor / PM SynRel rotor) motor design selection with respect to the criteria listed in WP2
- the analysis of performances when using the same stator technology as for the induction machine (IM) avenue
- analysis of performances when using the same rotor geometry as for the pure SynRel avenue in task 4.2.1

This was mainly due to the following reasons:

- the rotor geometry (flux barriers shape) derived for the pure SynRel motor was not compatible with the industrial constraints of the PMa SynRel motor manufacturing
- the optimal pole number found for the pure SynRel motor (6) was not the same as for the PMa SynRel motor (10)
- it was established at the beginning of the project that the hairpin winding technology would have been exploited by WP3 only, then the configuration using the IM stator has not been considered.

The 200 kW and 75 kW motor electro-magnetic designs for the PMa SynRel technology carried out in task 4.2 will be exploited in WP6 to manufacture the active parts of the prototypes. On the basis of theses designs a common mechanical design (cooling system and housing) for both motors will be derived in task 4.3.

This report is organized as follows:

- Section 1 gives a brief introduction to the PMa SynRel motor electro-magnetic design methodology used in task 4.2.
- 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 description of the electro-magnetic-design for both 200 kW and 75 kW
- Section 4 presents the mechanical stress analysis for the 200 kW PMa SynRel motor design. As the 75 kW motor design is obtained by scalability (same stator and rotor geometry as for the 200 kW design), the same conclusions can be directly derived.
- Section 5 presents the thermal analysis (both continuous and transient operation) for both 200 kW and 75 kW.

Electromagnetic Design

The main objectives of the electromagnetic design are:

- To match the torque and power requirements specified by the end users according to the Key Performance Indictors (KPI) specified in WP2 (see Table ES.1)
- To limit the torque ripple
- To limit the demagnetization of the permanent magnets
- To optimize the motor efficiency (peak value and average value over a reference driving cycle)

Table ES.1 KPIs for PMa SynRel Motors

Parameter	Unit	75 kW	200 kW
Specific Power	kW/kg	>1.8	>3.0
Specific Torque	Nm/kg	>2.8	>5.7
Total weight	kg	45	60
Maximum speed	rpm	15000-18000	
Peak efficiency	%	>95%	

200kW Pma SynRel Motor Design

In Task 4.2 the electromagnetic design of the 200 kW has been carried out on the basis of the 10 pole design with distributed round wire winding presented in the deliverable D4.1. The major difference with respect to the previous design consists in the stator outer diameter reduction following the guidelines provided by JLR. Updated Key Performance Indicators (KPIs) defined in WP2 have been used, and additional vehicle performances, as acceleration time and average efficiency over the Worldwide harmonized Light vehicles Test Procedures (WLTP) cycle, provided by JLR have been also taken into account.

The main performances obtained for the 200 kW PMa SynRel motor are summarized in Table ES.2. Note that the peak power (223 kW) exceeds the required value (200 kW): that was necessary in order to limit the power drop in the speed region corresponding to the 80-120 kph vehicle speed and therefore ensure the vehicle acceleration performances specified by the end user (JLR).

The efficiency map is showed in Figure ES.1. The peak value is about 95.5% and above 92% for a large region of the map. An evaluation of average efficiency and energy loss over the WLTP cycle has also been computed, the results are presented in

Table ES.3.

Table ES.2 200 kW PMa SynRel Motor Performances

Parameter	Unit	Value
DC link Voltage	[Vdc]	800
Max Phase Current	[Arms]	416
Maximum speed	[rpm]	17500
Maximum torque	[Nm]	430
Peak Power	[kW]	223
Continuous Power	[kW]	70
Peak efficiency	%	95.5%

Table ES.3 200 kW PMa SynRel Motor results over the WLTP Cycle

Parameter	Unit	Value
Efficiency (average)	[%]	93.1
Energy Losses	[Wh/km]	18.3

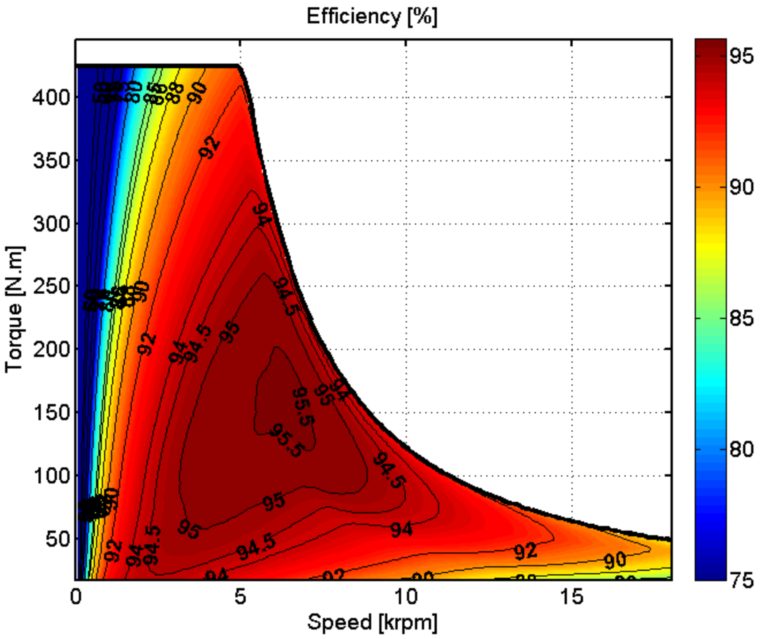

Figure ES.1 200 kW PMa-SynRel Motor – Efficiency map

75 kW PMa SynRel Motor Design

The design of the 75 kW motor has been carried out using the same stator/rotor geometry as the 200 kW motor, reducing the active length and the maximum phase current. The main performances obtained for the 75 kW PMa SynRel motor are summarized in Table ES.4. The theoretical maximum speed of the motor is close to 17500 rounds per minute (rpm) but it will be limited to 12000 rpm to be compatible with the integration in the vehicle demonstrator.

Table ES.4 75 kW PMa SynRel Motor Performances

Parameter	Unit	Value
DC link Voltage	[Vdc]	350
Max Phase Current	[Arms]	353
Maximum speed	[rpm]	12000
Maximum torque	[Nm]	144
Peak Power	[kW]	83
Continuous Power	[kW]	30
Peak efficiency	%	95.5%

The efficiency map is showed in Figure ES.2. The peak value is about 95% and for a large region of the map the value is above 92%.

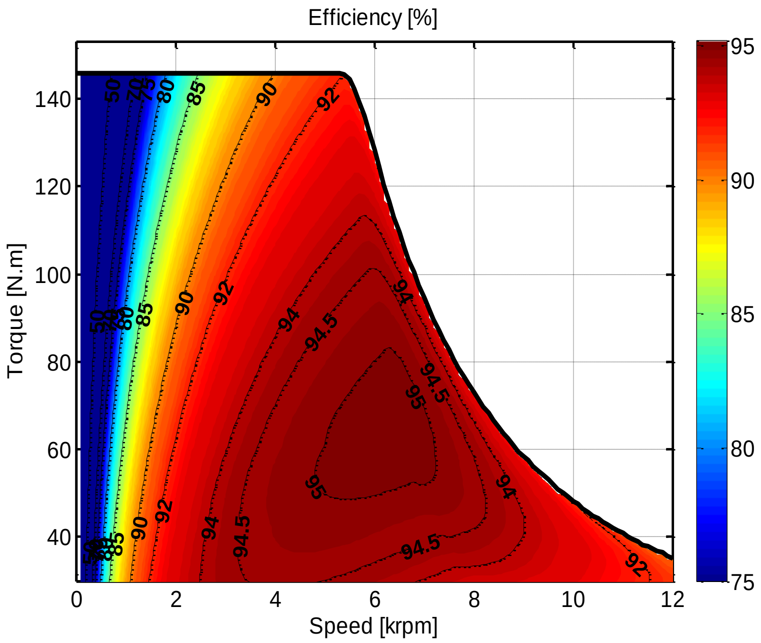

Figure ES.2 75 kW PMa-SynRel Motor – Efficiency map

Mechanical Analysis

In order to ensure the mechanical strength of the motor, an extensive mechanical analysis of the final design at 100°C has been carried out. The mechanical stress due to the centrifugal force at maximum speed (17500 rpm) and over speed (21000 rpm) are below the limits defined, therefore the rotor geometry that has is proposed is suited for high speed motor applications.

Thermal Analysis

For both 200 kW and 75 kW motor designs a thermal analysis using a preliminary water cooling system has been performed. Continuous and peak power operating points have been simulated: in the first case hot spot temperature can be kept below the limits using potting, for the maximum phase current case it will be necessary to improve (in task 4.3) the water jacket design in order to respect the temperature winding limit for at least 30s.