Rare Earth Free e-Drives Featuring Low Cost Manufacturing

ReFreeDrive

Collaborative Project
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Lead contractor for this deliverable:	**Motor Design Ltd. (MDL)**
Author(s):	**Popescu, Mircea (MDL), Riviere, Nicolas (MDL)**
Participant(s):	**Villani, Marco (UAQ), Fabri, Giuseppe (UAQ)**
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Executive Summary

The present report covers the electro-magnetic design analysis for Copper-Rotor Induction Motors (CR-IM) for inner and outer rotor for traction systems in Electric Drive Technologies (EDT). This is one of the technical solutions investigated by ReFreeDrive project.

The overall objectives of the entire WP3 are according to the ReFreeDrive GA:

- To identify the key factors in copper alloy cage rotor Induction Motor (IM) design that lead to an increase in power/torque density and lower cost.
- To select the materials –copper alloy electrical steels laminations- for IM high speed applications eliminating rare earth materials content and lowering costs.
- To achieve an electro-magnetic design of an IM with internal rotor fulfilling the requirements specified in WP2.
- To achieve the Electro-magnetic design of an IM with outer rotor 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.
- To design the Cooling system and analyze the selected IM inner and outer rotor topologies based
- To ensure the mechanical design of the selected topologies (i.e., mechanical strength to centrifugal forces, etc)

The objective of this deliverable is to report the work done in Task 3.2.

The degree of fulfilment required by the GA has been achieved. No deviation on content or time have occurred in the degree of fulfilment.

In WP3, Inner Rotor (IR) and Outer Rotor (OR) induction motors configurations with cage built using die-casted or fabricated rotor technologies are proposed. When IR topology is used in combination with high rotational speed, i.e. $\geq$ 20000rpm, the torque density and the specific power are increased. Similarly, an OR topology can be used at lower rotational speed, i.e. $\leq$ 18000rpm, the increase in torque density and specific power is guaranteed due to the inherent higher diameter in the motor airgap.

Task 3.2 (*Electro-magnetic CR-IM Design*) aims at designing an optimised and cost-effective solution for a CR-IM with inner or outer rotor topology. Even though it is technologically possible to use the same stator assembly in an IM and SynRel machine (the latter topology being subject of WP4), due to performance/cost estimations, CR-IM designs presented in this report are innovative and unrelated to the SynRel design. The only common point between technologies is the power supply unit.

The objectives of Task 3.2 are:

- Task 3.2.1, Selection of materials for IM applications: the active components of IM are modelled considering various electrical steel grades for stator/rotor laminations and die-cast and fabricated copper alloys for the rotor cage.
- *NOTE: This section was originally planned to be covered in Task 3.1. However, due to difficulties and delays in procuring various electrical steel samples, the analysis of the CR-IM designs with different electrical steel grades is covered in this report*
- Task 3.2.2, Analysis of performances when using various rotor cage alloys and comparison between die-cast and fabricated rotor cage
- Task 3.2.3, Scalability of the CR-IM and design that ensures similar motor assembly units can be used for various power levels and various EVs, based only on different power supply units
- Task 3.2.4, Mechanical analysis for the CR-IM using the selected materials from Task 3.2.1 and 3.2.2
- Task 3.2.5, Optimisation of the inner and outer rotor CR-IM, by using advanced mathematical algorithms along with technical constraints, so that the best motor configuration and minimum weight for imposed performance, is carried forward

This report is divided in five main sections.

- Section 1 (*Introduction*), it is presented the justification in selecting certain electrical steel grades and rotor cage alloys. The role of scalability in getting the most favourable design, optimisation principles are also briefly discussed.
- Section 2 (*Material Selection*) describes the performance in a comparison of the designs detailed in Task 3.1, when 4 (four) electrical grades are considered and between 3 (three) material solutions for the rotor cage. The design analysis is based on a hybrid 2D Finite-Element Analysis (FEA) method and analytical magnetic equivalent circuit.
- Section 3 (*Scalability*) describes the performance of the candidate design from Task 3.1 with materials selected in section 1 and 2 for 200kW and 70kW EVs.
- Section 4 (*Mechanical Analysis*) describes the dimensions and speed limits from the mechanical stress and modal analysis point of view. The analysis makes use of 2D/3D FEA models and analytical expressions.
- Section 5 (*Optimisation*) describes the optimisation results for inner rotor CR-IM and sensitivity analysis for outer rotor CR-IM. The optimisation process uses as constraints radial dimensions and axial length of the motors, while keeping the same stator OD and winding pattern. More than 10,000 candidate designs are considered in this process.

The optimum IR and OR topologies are configured with 36 stator slots and 50 rotor bars, with hairpin winding type as presented in report D3.1.

The figures ES.1 and ES.2 show the two topologies:

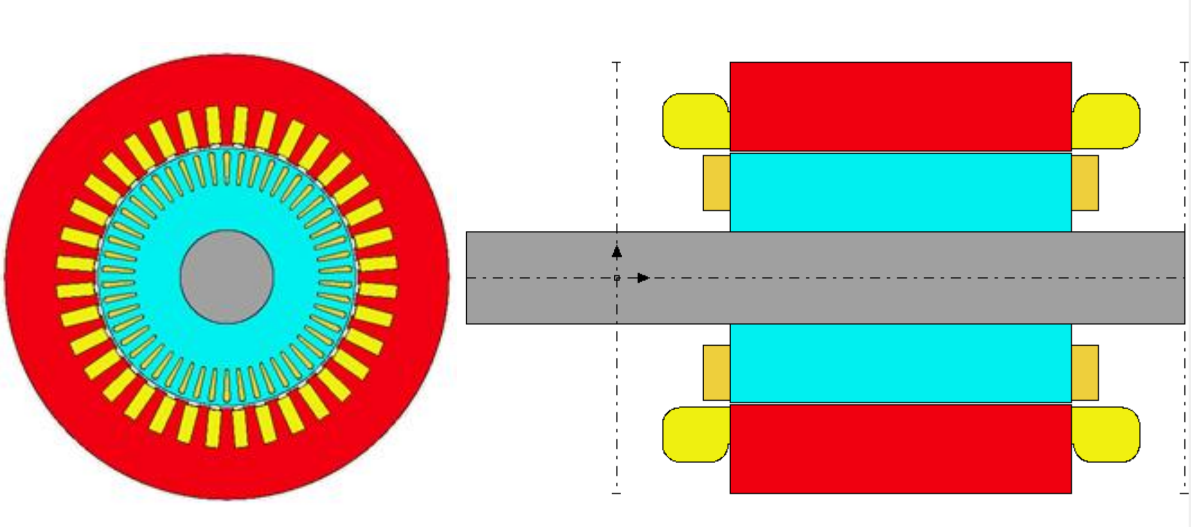

Figure ES 1 Inner CR-IM selected topology

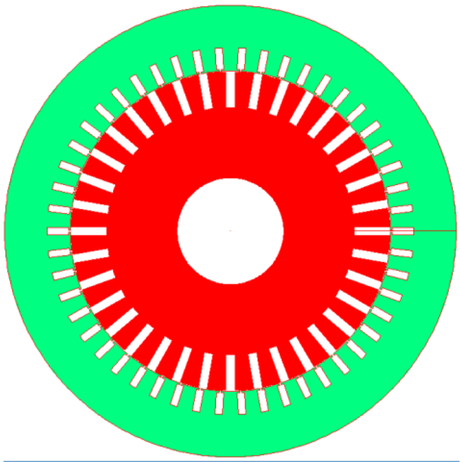

Figure ES 2 Outer CR-IM selected topology

The mechanical analysis confirmed that the proposed IR and OR designs are within the maximum acceptable limits for the mechanical stress and natural frequencies that may occur.

The outcome of this report provides clear guidelines on the CR-IM solutions for EDTs and identifies the optimum candidates design solutions for IR and OR topologies.

The IR topology outperforms the OR topology for the selected KPI values given in Table ES 1

Therefore, the IR design is selected as best candidates design and will be further analysed in Task 3.3 for the following tasks:

- Investigation of non-sinusoidal supply losses
- Investigation of three cooling systems: stator water jacket with water/oil as cooling liquid, oil spray cooling and combined stator jacket and spray cooling using oil as cooling system
- Optimisation of the housing dimensions

Table ES 1 summarizes the KPI values for the high power range application. The specified specific torque and specific power targets are peak values and relate to active weight, including housing.

Table ES 1 - KPI values

KPI	Unit	Reference (TESLA 60S)	ReFreeDrive Goals	Comment
Specific power	kW/kg	3.31	4.3	30% increase
Specific torque	N.m/kg	8.2	8.2	30% increase
Efficiency	%	92%	96%	> 94%

Table ES 2 summarizes the main boundary conditions (BC). All quantities include the housing. The maximum speed will be determined later on during the optimisation phase so as to find the best performance to cost ration for the powertrain.

Table ES 2 - BC values

Bondary Conditions (BC)	Unit	Value
Machine length	mm	250
Machine OD	mm	250
Maximum speed	krpm	18..22
Active weight	kg	47

The low power range motor will be scaled from the high power motor to fit the targetted vehicle requirements. The dimensions will remain the same, only the power supply levels will change (method used by TESLA motors.