Rare Earth Free e-Drives Featuring Low Cost Manufacturing

ReFreeDrive

Collaborative Project
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Executive Summary

The present report covers the thermal design analysis for Copper Rotor Induction Motors (CR-IM) with Inner Rotor (IR) 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 Work Package 3 (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 (OR) 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 analyse 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) and investigate the noise, vibration and harshness (NVH)
- One of the alternative technical solution, CR-IM with outer rotor for traction systems in EDT, was determined to have lower technological potential as described in detail within deliverable 3.2. Accordingly, this solution is discarded for further thermal analysis or NVH and not included in this deliverable.

The objective of this deliverable is to report the work done in Task 3.3.

The degree of fulfilment required by the GA has been achieved. The deviation on content is related to the exclusion of CR-IM outer rotor from thermal analysis due to the technical limitations of the solution. No deviation on time has occurred in the degree of fulfilment. There are no impacts on the overall project implementation.

In WP3, inner and outer rotor 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 3.3 (*Thermal Analysis and Cooling System Optimisation*) aims at designing an optimised and cost-effective cooling system solution for a CR-IM. Only inner rotor topology is analysed, as results from Task 3.2 showed that this solution is clearly superior to the outer rotor topology for traction systems in EDT. Even though it is technologically possible to use the same cooling system in an IM and Synchronous Reluctance (SynRel) machine (the latter topology being subject of WP4), due to performance/cost estimations, CR-IM cooling system 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 overall housing dimensions and mechanical connections to the system.

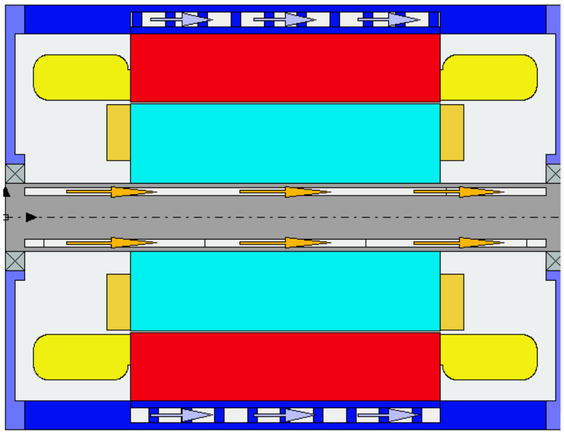
The objectives of Task 3.3 are:

- Task 3.3.1 Final 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 selected.
- *NOTE: This section was started to be covered in Task 3.2. However, due to the complexity and number of parameters that can vary, this task is completed and covered also in this report*
- Task 3.3.2 Analysis of CR-IM cooling system performances when using various liquid cooling systems:
    - housing water jacket
    - slot water jacket – is discarded due to the technical difficulties in implementing this system as a low-cost solution
    - oil spray cooling
- Task 3.3.3 Analysis of CR-IM cooling system performances when using various cooling fluids:
    - mixtures water – ethylene glycol
    - automotive transmission fluid
    - water – is discarded due to the technical difficulties in having this fluid available in the vehicle
- *Note: The analysis of the CR-IM cooling system performance considering forced air cooling systems is discarded due to the technical complexity and addition of a component: air-compressor or cooling fan that would increase the cost of the solution.*
- Task 3.3.4 Study of the manufacturing uncertainties on motor performance
- Task 3.3.5 Iterations with the electromagnetic design from Task 3.2 for convergence in electromagnetic and thermal designs: same losses and temperature values

This report is divided in four main sections.

- Section 1 (*Introduction*), it is presented the justification in selecting liquid cooling systems for heat extraction. The optimisation principles are also briefly discussed.
- Section 2 (*Electromagnetic Design*) describes the Key Performance Indicators (KPIs) and the boundary conditions. A comparison between the reference CR-IM inner rotor electromagnetic design and final optimised design is presented. The design analysis is based on a hybrid 2D Finite-Element Analysis (FEA) method and analytical magnetic equivalent circuit. A validation using 3D FEA and mechanical stress analysis completes this section.
- Section 4 (*Mechanical Design*) contains the stress and modal analysis results, that demonstrate the feasibility of the CR-IM inner rotor topology.
- Section 3 (*Thermal Design*) describes the performance of the CR-IM inner rotor optimised design using two cooling systems using water-ethylene glycol mixture of automotive transmission fluid as heat extraction fluids. The optimisation of the housing dimensions, fluid flow rate and manufacturing uncertainties are investigated in this section.

The optimum cooling systems for CR-IM inner rotor topology are shown in the figures ES.1 and ES.2:



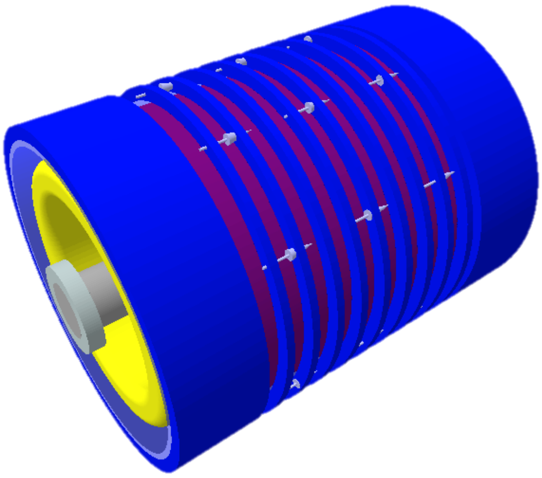
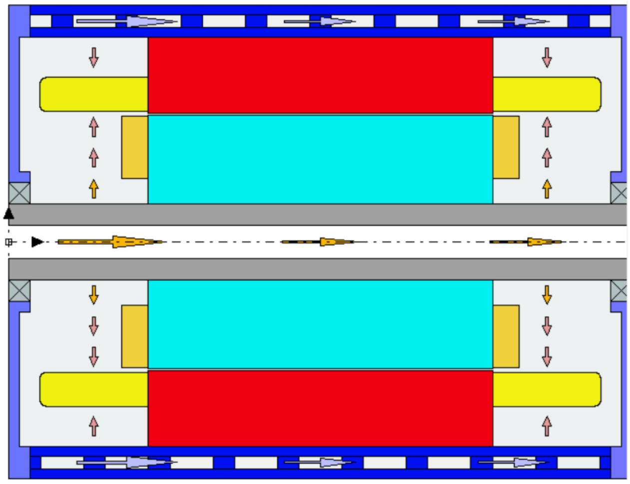


Figure ES 1 Inner CR-IM water jacket cooling topology



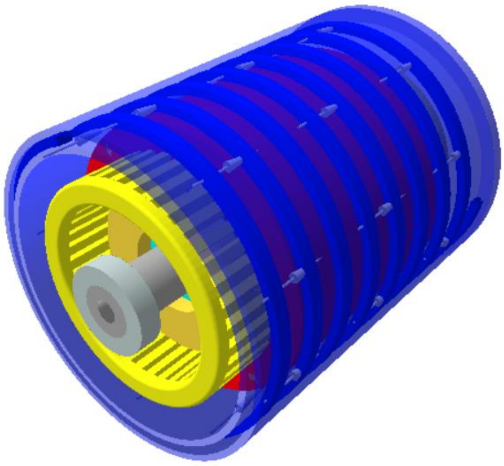


Figure ES 2 Inner CR-IM oil spray cooling topology

The thermal analysis confirmed that the both cooling systems ensure that CR-IM design can deliver continuous power and torque as specified by Jaguar Land Rover (JLR), consortium partner in ReFreeDrive.

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

The IR topology respects all the selected KPI values given in Table ES 1

Consequently, the optimum IR design with cooling system using water ethylene-glycol mixture as heat extraction fluid is selected as best candidates design and will be further analysed in Task 3.4 for the following tasks:

- Noise, vibration and harshness analysis
- Investigation of non-sinusoidal supply losses
- Final CAD drawings for prototyping stage (WP6)

Table ES 1 summarizes the KPI values for the high power range application (200kW). The specified specific torque and specific power targets are peak values and relate to active weight, including housing.

Table ES 2 summarizes the main volume boundary conditions (BC). All quantities include the housing.

The low power range motor is 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). Detailed BC are given in Section 2 of this report, Electromechanical Design.

Table ES 1 - KPI values

KPI	Unit	Reference (TESLA 60S)	ReFreeDrive Goals	Comment
Specific power	kW/kg	3.31	> 4.3	Peak value, active parts only
Specific torque	N.m/kg	6.32	> 8.2	Peak value, active parts only
Efficiency	%	92%	96%	Peak value

Table ES 2 – Main Volume, Weight and Speed BC values

Bondary Conditions (BC)	Unit	Value
Machine total length	mm	310
Machine total OD	mm	250
Maximum speed	rpm	20,000
Active weight	kg	< 44.6