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Innovative E-Drive solutions for battery electric vehicles avoiding rare earths

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Summary

The EU Commission funded Horizon2020 project „ReFreeDrive" is focused on contributing to avoid the use of rare earth magnets through the development of a next generation of electric drivetrains, ensuring the industrial feasibility for mass production while focusing on the low cost of the manufacturing technologies.
This project will study and develop simultaneously two rare earth magnet free solutions for the power traction system of electrical vehicles: induction machine with fabricated and copper die-cast rotor and synchronous reluctance machine. The project will develop the new machines for a testing validation campaign and a final in-vehicle validation for two use cases (75kW medium power range, and 200kW high power range).

1. Intro

This from the European Commission under Grant Agreement nº 770143 funded project is part of the Horizon 2020 programme looking at societal challenges for Smart, Green and Integrated Transport. The ReFreeDrive project, started in October 2017 and running over three years, is focused on contributing to avoid the use of rare earth magnets through the development of a next generation of electric drivetrains, ensuring the industrial feasibility for mass production while focusing on the low cost of the manufacturing technologies.

Project consortium is composed by 13 partners with focus on different tasks:

a) Project Coordinator: Fundacion Cidaut (ES)
b) Electrical Machine Design & Manufacturing:
   - University of Aquila (IT)
   - Motor Design LTD (UK)
   - IFP Energies Nouvelles (FR)
   - Mavel SRL (IT)
   - Technomatic (IT)
c) Power Electronics: R13 Technology SRL (IT)
d) Copper:
   - European Copper Institute (BE)
   - Metallgießerei Breuckmann (DE)
   - Aurubis(BE)
e) (Magnetic) Steel: Rina-Centro Sviluppo Materiali (IT)
f) Vehicle Integration: PRIVE SRL (IT)
g) OEM Validation: Jaguar Land Rover (UK)

See more: http://www.refreedrive.eu/

2. Why rare earth free?

The expansion of the electric vehicle (EV) market will impact the socio-economic dimension of the transport sector. The introduction of new technologies for energy storage and powertrains plays a critical role in the

development of the EV market. At motor level, key components and innovative materials must be integrated in the current motor designs.
Today, the vast majority of motor solutions rely on permanent magnet technology using rare earth magnets. Permanent magnet technology offers a good compromise of high specific torque and low losses, which justifies its choice in most of the cases. However, the high and volatile cost of raw materials for magnets makes uncertain their long-term availability, especially since the electric traction technology is called to be deployed at large scale in the future transportation system.
With critical materials like heavy rare earths, the EU is vulnerable to supply bottlenecks of several key materials needed in wind, photovoltaic and electric vehicles technologies and EU resilience to potential supply issues will deteriorate if mitigation measures are not taken.
Permanent Magnets for electric motors rely on Neodymium and Dysprosium, for which supply is critical. Dysprosium demand expected to exceed supply, mainly driven by electric and hybrid vehicles. Insufficient supply of heavy rare earths may lead to dramatic price surges, as already occurred in 2011, but also, it may lead to slower market adoption of EV & Hybrids if no alternatives are available. Hence it appears that substitution is the most effective measure to improve the EU resilience to anticipated supply bottlenecks.

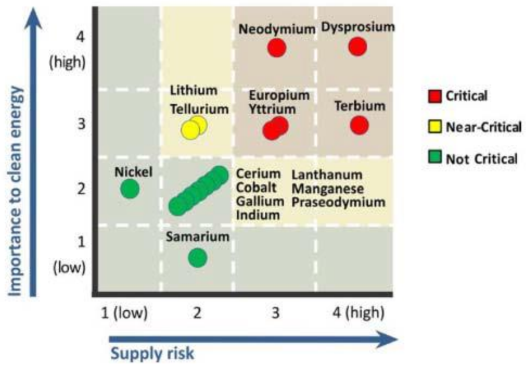


Figure 1: Critical materials matrix, source: DOE, 2015

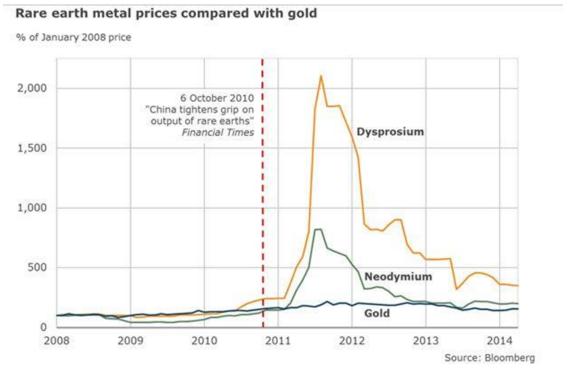


Figure 2: Rare earth (Nd and Dy) price volatility, source: Bloomberg, 2014

3. Electric Motor Design Objectives

The design of the ReFreeDrive motors will take as a premise the reduction of use of materials, as more than half of the final price is formed by raw materials cost. Also, a minimization of manufacturing costs will be ensured by an early involvement of manufacturers, from the design stage. ReFreeDrive motor topologies have good room for cost reduction by off-setting permanent magnet use. Through their configurations these machines are not only are rare-earth magnet free, but also share common features that can be exploited during the design step, as well in the manufacturing process. In addition, one of the key avenues for cost reduction is the reduction of size through different techniques (higher rotational speed, compact hairpin winding, etc).

This project will study and develop simultaneously two solutions for the power traction system of electrical vehicles:

1) induction machine (IM) with a) fabricated and b) copper die-cast rotor, and
2) two types of synchronous reluctance (SynRel) machine, a) pure SynRel without any permanent magnets and b) with the assistance of ferrite based permanent magnets.

The project will develop the new machines for a final in-vehicle validation for two use cases (75kW, medium power range, and 200kW high power range). Hence the project will evaluate 8 electrical motor use cases in total as highlighted in the following figure.

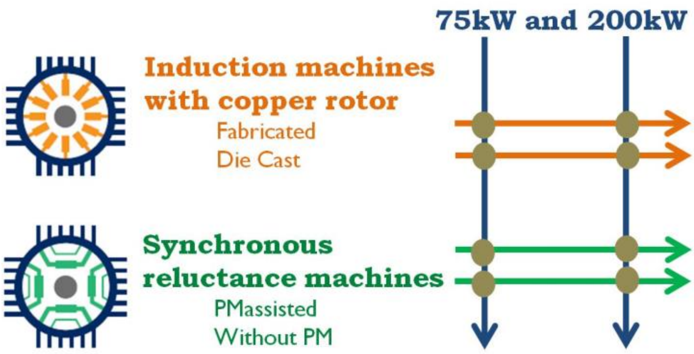


Figure 3: ReFreeDrive electrical motor use cases overview

The initial motor designs for both topologies have been optimized for the 200kW high power range and then for the lower 75kW power range scaled down to meet the vehicle performance requirements and minimize manufacturing costs.

For both motor topologies analysed within our project, we set quite challenging objective to be achieved compared to existing solutions (e.g. Tesla S60) in this power classes:

- 30% more specific torque
- 50% less direct motor losses
- 50% more power density in the power electronics
- and ultimately approx. 15% lower production costs in mass production.

4. Electrical Motor Performance according to final design optimization

Both IM and SynRel machine are nowadays under evaluation as alternative solutions for mass production in automotive applications, as both show good performance associated with low cost materials and eliminate the supply risks associated with heavy rare earths.
In a recent paper, the adoption of advanced design strategies coupled with innovative manufacturing techniques (hairpin winding, rotor copper die-cast or automatized processes for fabricated rotors) and cooling methods for IM are discussed as providing new possibilities for design improvements [1] to use IM for traction in electric vehicles. Another recent comparison between IM and SynRel technology shows interesting advantages but also some challenges and drawbacks to be considered in the proper design of rare earth-free motor approaches [2].

Following table shows the goals for the 200kW electrical motors in the ReFreeDrive project:

KPI	Unit	Reference TESLA 60S	ReFreeDrive Goals	Comment
			200kW	
Specific power	kW/kg	3.31	> 4.3	Peak value, active parts only
Power density	kW/l	-	> 8.0	Peak value, active parts only
Specific torque	Nm/kg	6.3	> 8.2	Peak value, active parts only
Torque density	Nm/l	-	> 15.4	Peak value, active parts only
Weight	kg	68	< 44.6	Active parts only
Efficiency	%	92%	96%	Peak value

Table 1: ReFreeDrive goals for 200kW electrical motors

4.1 Induction Machine Performance

After several steps of design optimization itineration, in the ReFreeDrive project the IM prototypes will be based on inner rotor topology in combination with high rotational speed (up to 20.000rpm) to increase the torque density and the specific power and to achieve a high efficiency.

The main performances obtained for the 200kW IM design with 4 poles are summarized in following table:

Parameter	Unit	Value
DC link Voltage	[Vdc]	720
Max Phase Current	[Arms]	<500
Maximum speed	[rpm]	20.000
Peak Torque	[Nm]	370
Peak Power	[kW]	200
Continuous Torque	[Nm]	152
Continuous Power	[kW]	70
Peak efficiency	%	>95%

Table 2: IM key performance parameters

The efficiency map of the final IM design shows a large area of >95% efficiency (nb: mechanical losses like windage losses in the airgap and friction losses due to bearings are NOT considered here):

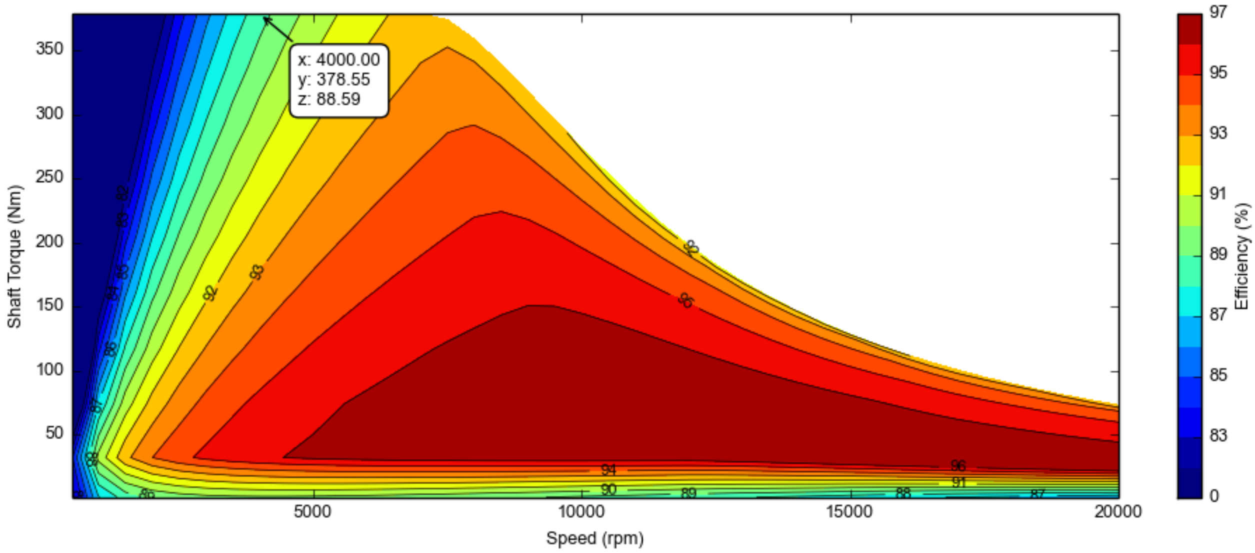
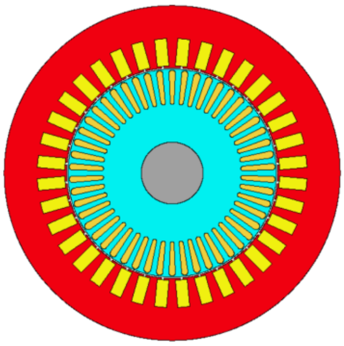


Figure 4: Torque vs Speed efficiency map of 200kW IM

Following figure and table show the key IM design parameters:



Parameter	Value
Stator Slots	36
Poles	4
Rotor Bars	50
Max Speed	20.000rpm

Figure 5: IM radial cross-section view

Table 3: IM key parameters

4.2 Permanent Magnet Assisted Synchronous Reluctance Machine Performance

The final design of the PMA SynRel machine will use low-cost ferrite magnets to replace Neodymium based permanent magnets for high power applications. In the permanent magnet assisted motor, the main issue is the demagnetization of ferrite magnets, which has been limited to 1% through a complete design and optimization of both the rotor (mainly flux barriers) and the rest of the machine (specific stator design) to improve performances and high efficiency over a large region of the torque/speed map. The final PMA SynRel design is scalable to possible use one stator/rotor geometry for a large range of output power applications later.

The main performances obtained for the 200kW PMA SynRel motor design with 10 poles are summarized in following table:

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 4: PMA SynRel key performance parameters

The peak efficiency value of the final PMA SynRel design is about 95.5% and above 92% for a large region of the map as shown in following figure:

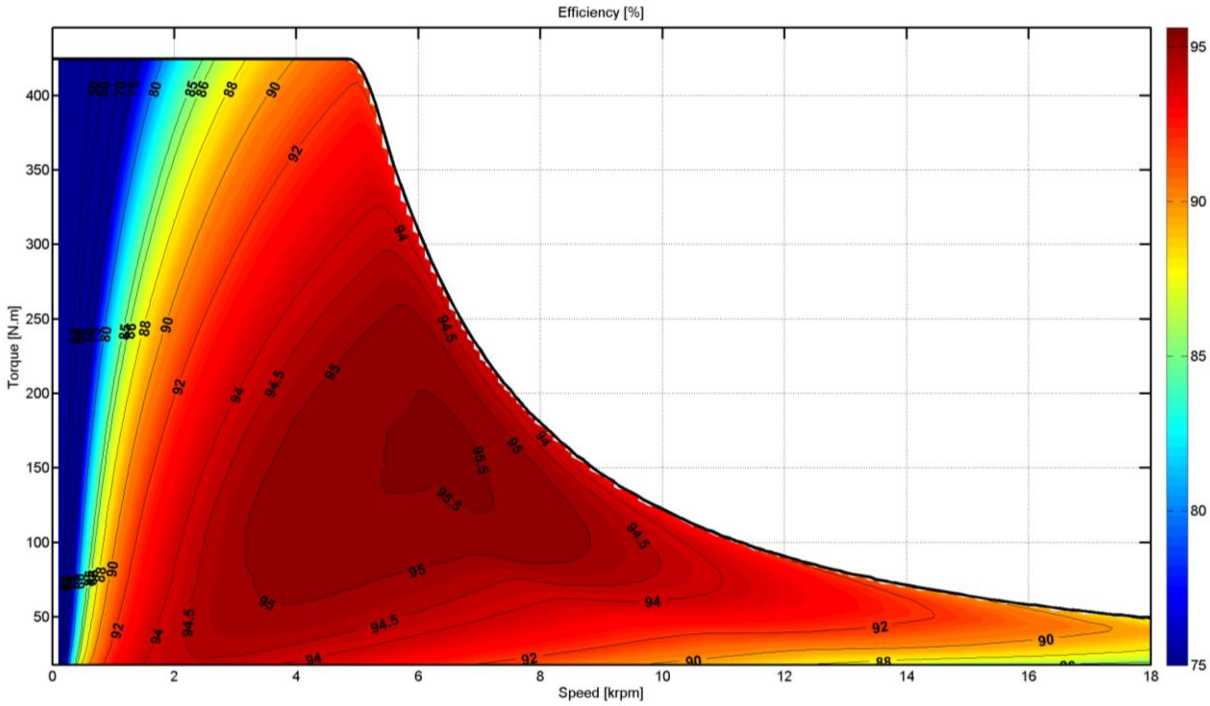


Figure 6: Torque vs Speed efficiency map of 200kW PMA-SynRel Motor

4.3 Pure Synchronous Reluctance Machine Performance

The pure synchronous motor, without permanent magnets, as rather simple solution seems to offer interesting advantages for its use in electric vehicle motors: compactness, low temperature rise, acceptable performance at rated and peak power, reliability and specifically its lower costs compared to other motor technologies.
The final design of the pure SynRel machine will have 6 poles and 54 slots with flux barriers without radial ribs in order to improve the motor performance. In order to meet the mechanical strength requirements of the rotor core, it was decided to fill the flux barriers with epoxy adhesive resin.

The main performances at peak power vs. continuous power obtained for the 200kW pure SynRel motor design with 6 poles are summarized in following table:

Parameter	Peak Power	Cont. Power
Phase Current [Amax]	700	231
Speed [rpm]	4.800	18.000
average Torque [Nm]	400	37
Output Power [kW]	201	69,7
Peak efficiency [%]	> 95%	

Table 4: pure SynRel key performance parameters

The peak efficiency value of the final pure SynRel design is about 96% and above 92% for a large region of the map as shown in following figure:

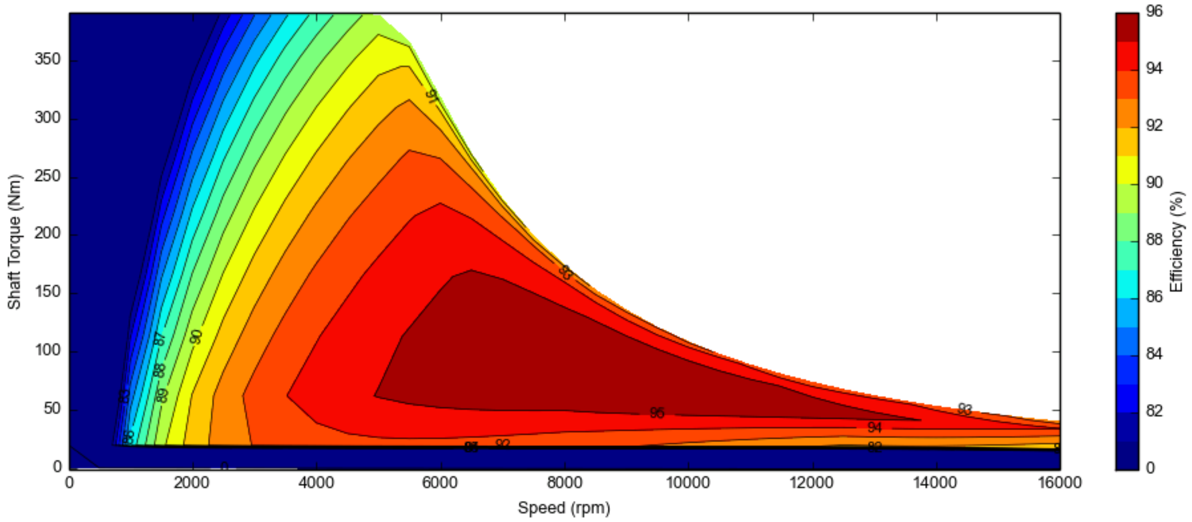


Figure 7: Torque vs Speed efficiency map of 200kW pure SynRel Motor

5. Outlook

After the final design optimization, the manufacturing of the 8 electrical machine prototypes will start in summer 2019 and testing is scheduled for early 2020. Later at least two 75kW motors will also be integrated into a light-duty vehicle and tested according to modified WLPT drive cycle on the road

6. References

[1] M. Popescu, J. Goss, D. A. Staton, D. Hawkins, A. Boglietti, Y. Chuan Chong; "Electrical Vehicles - Practical Solutions for Power Traction Motor Systems" *IEEE Transaction on Industry Applications*, Vol: PP, Issue 99, 2018.

[2] M. Villani, M. Tursini, M. Popescu, G. Fabri, A. Credo, L. Di Leonardo "Experimental Comparison between Induction and Synchronous Reluctance Motor-Drives", *XIII International Conference on Electrical Machines (ICEM)*, September 2018.

List of abbreviations:

- DOE = US Department of Energy
- EU = European Union
- EV = electrical vehicle
- IM = induction machine
- PMA SynRel = permanent magnet assisted synchronous reluctance machine
- SynRel = synchronous reluctance machine
- WLPT = Worldwide harmonized Light vehicles Test Procedure