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Horizon2020 ReFreeDrive Project: Rare Earth Free e-Drives featuring low cost manufacturing

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Abstract

EU-Horizon2020 funded project ReFreeDrive focuses on innovative electric motor designs for automotive industry completely free of rare earth magnets. Compared with the benchmark motors and manufacturers within the electric vehicles industry, ReFreeDrive motors are expected to improve specific torque and specific power by 30%, with a 50% increase in maximum operating speed and power density in power electronics, while halving motor losses. Two technologies, fabricated and die cast induction motor, and synchronous reluctance motor with and without ferrite permanent magnets assistance were analyzed for 200kW and 75kW power levels. Electromagnetic, thermal and mechanical performances of each motor have been optimized for each case, in order to fulfill industry requirements. Low manufacturing cost and reduction of the use of materials have been considered during the design stage, which allowed achieving 15% lower production cost. Prototypes of each kind of motor will be manufactured and tested before the end of the project.

Keywords: Horizon2020; rare earth elements; induction motor; synchronous reluctance motor; power electronics; efficiency

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1.1.1. Nomenclature

CR-IM	Copper Rotor-Induction Motor
EGVI	European Green Vehicles Initiative
EV	Electrical Vehicle
IGBT	Insulated Gate Bipolar Transistor
IM	Induction Motor
KPI	Key Performance Indicator
LSC	Laminar Squeeze Casting
PM	Permanent Magnets
REE	Rare Earth Elements

2. Introduction

ReFreeDrive project is an EU-funded project under the European Green Vehicles Initiative (EGVI) looking at societal challenges for Smart, Green and Integrated Transport (grant agreement nº 770143). The ReFreeDrive project is focused on avoiding the use of Rare Earth Elements (REE) based magnets. This objective will be addressed through the development of a next generation of innovative electric drivetrains, ensuring the industrial feasibility for mass production while considering the low cost of the manufacturing technologies. With respect to the current state-of-the-art motors (benchmark Tesla S60), the main objectives of ReFreeDrive project are:

- Increase specific motor torque by 30%.
- Reduce motor losses by 50%.
- 15% cost reduction against similar solutions.
- Increase power density in power electronics by 50%.

The importance of reducing the dependence of REE in the electric drivetrain industry is based on the fact that these elements are considered critical raw materials due to both economic and environmental reasons. In Figure 1(a) a REE matrix created by the US Department of Energy (2011) is shown, which classifies them according to their importance to clean energy and supply risk. It can be seen that some of the elements that are currently been used in electric motors' magnets, such as Dysprosium (Dy) or Neodymium (Nd), are among the most pernicious elements in terms of environmental impact and supply risk. Besides, it is important to highlight that most of these REE are relatively sparse and are usually found out of Europe, which causes a dependence on external suppliers. Derived from the latter, these materials are subjected to high prices (permanent rare earth magnets are a high share of the powertrain cost) and high price volatility, as stated by Rowlatt (2014), Figure 1(b).

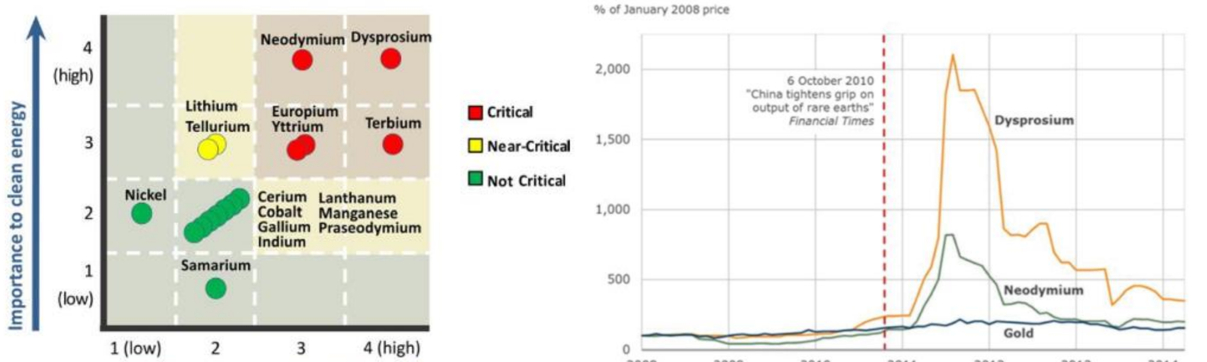

Fig. 1 (a) Critical rare earth metals matrix; (b) REE price volatility

Although electric vehicle adoption and benefits have not reached most emerging markets yet, European cities are developing innovative ways to support the electric vehicle market. Moreover, strong regulatory and fiscal policy will be implemented in the following years, accelerating the transition to electric mobility. Thus, it is expected that the global electric vehicle market will significantly grow in the following years, and this trend will also be observed in Europe, where electric vehicles are expected to increase remarkably their current market share. In this scenario, the risk of dependence on rare earth metals becomes critical.

3. ReFreeDrive's approach to electric motor design

Two technologies for the power traction system of electrical vehicles are analyzed and developed within the scope of ReFreeDrive project: induction motor with fabricated and copper die-cast rotor and synchronous reluctance motor, without permanent magnets and with the assistance of ferrite based permanent magnets. The considered solutions are not only rare earth magnet free, but also share common features that can be exploited during the design and manufacturing steps, allowing a reduction in the total motor development cost. All these motors will be manufactured for a testing validation campaign and a final in-vehicle validation for two use cases, 75kW-medium power range and 200kW-high power range. So, in total, there are 8 motors investigated. The medium power range motor is scaled from the high power motor to fit the targeted vehicle requirements, thus optimizing the design stage and minimizing manufacturing costs. This approach demonstrates that the proposed motor solutions are scalable in the power range from 75kW to 200kW, as the designed prototypes are in the extreme points of the considered power range, therefore validating the scalability of the proposed solution. The geometry and dimensions of the housings are the same, only the power supply levels change, following the method used by motor manufacturers such as Tesla. One of the key avenues for further cost reduction is the size reduction through different design techniques (outer/inner rotor geometry, higher rotational speed, compact hairpin winding, etc.). Figure 2 depicts an overview of the project scope.

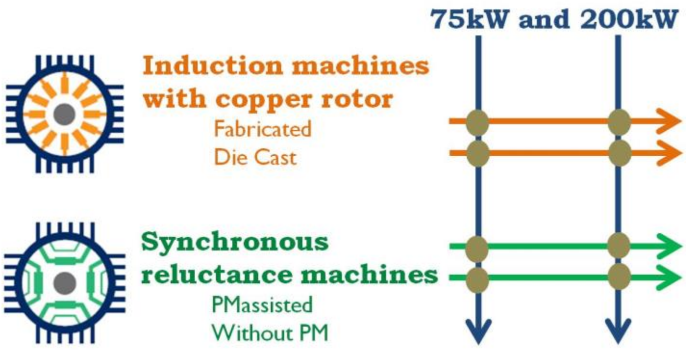

Fig. 2 Motor technologies and use cases considered in ReFreeDrive project

Regarding cooling systems, which are crucial in order to allow the operation at high speed, even though it is technologically possible to use the same cooling system in both motor solutions, due to performance/cost estimations, it was decided to develop innovative and unrelated designs tailored to each motor technology requirements and constraints. The only common points between both technologies are the power supply unit, the overall housing dimensions and the mechanical connections to the system. Related to this, stator hairpin winding is also important to increase the slot filling factor and to improve the heat distribution.

4. Induction motor

For the Induction Motor (IM), the developed motors should achieve more power per unit of volume compared with commercially available motors and reach 96% peak efficiency. The inner rotor topology turned out to be clearly superior to the outer rotor topology, when used for traction systems in electric drivetrains. Thus, this topology was selected for further analysis. When inner rotor topology is used in combination with high rotational speed (i.e. 20000rpm), the torque density and the specific power are increased. For this topology, the optimum cooling system uses water ethylene-glycol mixture as heat extraction fluid.

Two manufacturing avenues are considered for the copper rotor: fabricated and die cast. The main technical issue regarding die cast rotors is porosity, more specifically porosity generated by residual air trapped has to be avoided, as it worsens the electrical conductivity, therefore lowering motor efficiency and power density. Furthermore, it can cause balancing problems at high speed operation too. This issue was solved by using the advanced technique of Laminar Squeeze Casting (LSC) with a vertical casting machine. LSC allows parallel filling of all slots, this way the entrapped air is pressed out by the liquid metal itself, achieving almost zero porosity.

4.1. Machine topology

Even if induction machines present a lower efficiency and torque density than Permanent Magnets (PM) motors, the technology is well established in the automotive industry (e.g. Tesla Motors) and it still represents an attractive and feasible solution for Electric Vehicles (EVs), due to its simplicity, robustness, versatility, cost-effective manufacturing aspects and fault tolerant capability. In addition, the IM does not use rare-earth materials, ensuring mass production feasibility at lower cost [Burwell et al. (2013)]. The copper is usually preferred to the aluminium due to its higher electrical conductivity, higher mechanical strength and better thermal properties. The rotor can be either die-casted or fabricated and both methods are now industry proven [Tiwari and Bhardwaj (2009)].

A hairpin winding is used on the stator side. The proposed designs for the IM use exceptional performance of the proprietary hairpin stator winding**.** In contrast to conventional round wire windings, the hairpin stator winding uses precision-formed rectangular wires. Multiple layers of interlocking “hairpins” produce a superior slot fill (up to 73% vs. 40% for typical round-wire windings) [Jurkovic et al. (2015)].

The adopted design is outlined in Figure 3. A Copper Rotor-Induction Motor (CR-IM) topology is employed: stator with 36 slots and rotor with 50 bars topology, inner rotor configuration. The number of magnetic poles is 4-pole.

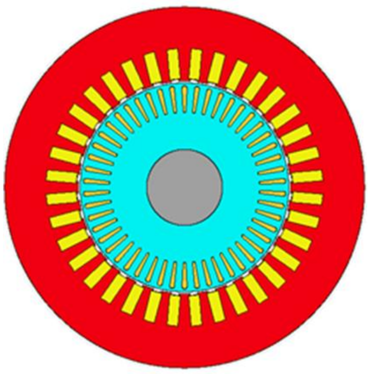

Fig. 3 Radial cross sections of proposed induction motor design

4.2. Materials selection

The specific materials suitable for the CR-IM design in traction applications include electrical steels and copper alloys. Considering the rotational speed, it is possible to select optimum materials for the CR-IM from a mechanical point of view.

Several non-oriented electrical steel, silicon-iron type, have been considered for CR-IM. Tests on steel samples have been performed at different frequency values (50Hz, 400Hz, 800Hz and 1000Hz) and induction levels (up to 1.8T, extrapolated to 2.1T in modelling). Electrical steel M235-35A was selected for prototyping.

Regarding copper alloys selection, two options are considered for the rotor cage of CR-IM: die-casted and fabricated copper alloys. A copper-silver alloy (CuAg0.04) was selected for fabricated rotor solution, showing a good trade-off between electrical and mechanical properties at high temperatures (200°C and higher). For die-cast rotor solution, alloy Cu-Electrolytic Tough Pitch was selected.

4.3. Electromechanical performance

The performance of inner rotor topology was investigated, considering the following operation parameters: maximum current = 500Arms; maximum speed = 20krpm; DC bus voltage = 720V; control strategy = maximum torque per ampere; motor temperature = 120°C. For the analysis, losses are taken into account in the following components: DC and AC stator copper, rotor copper, stator/rotor core, windage and stray load.

Figure 4 shows the efficiency map in motoring mode. The electromagnetic performance analysis proves the potential for inner rotor topology at high speed operation, i.e. up to and above 20,000rpm.

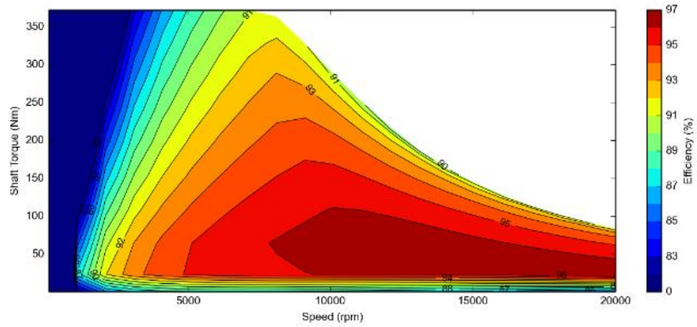

Fig. 4 Efficiency map for inner rotor CR-IM, with M235-35A steel

4.4. Thermal performance

In IMs, most of the loss components are of Joule type and are located in the stator winding and rotor cage. Iron losses may represent a more significant heat source only at high speed operation. Also, the mechanical losses must be considered. Regarding the temperature levels, the critical points to be considered are described below.

For the thermal cooling system of IM, two possible solutions have been considered [Jurkovic et al. (2015), Rosu et al. (2018), Popescu et al. (2016)]):

(1) Housing water jacket and shaft spiral groove cooling systems coupled in parallel, using ethylene-water-glycol mixture as a coolant. This type of cooling is used in the Tesla 60S and the Audi e-tron traction motors. This cooling system was optimized focusing on the continuous torque maximization at low speed. The variables include the housing thickness, the water jacket channel dimensions (width and height), the shaft channel thickness and the flow rate distribution between the two flow paths. The main constraints regard the continuous power at maximum speed (≥ 70kW) and the maximum pressure drop in the water jacket housing (≤ 10kPa).

(2) Housing jacket and hollow shaft cooling systems coupled in parallel, with oil spray through nozzles placed on the shaft and the housing, using automatic transmission fluid as a coolant. For comparison purposes the second option with oil spray was designed using the same external envelope as the first cooling design.

The machine's thermal behaviour was evaluated in transient operation for 30 seconds, without any potting material for end-windings. The estimated winding maximum temperature is 120°C for cooling system (1) where a value of 195°C was found for cooling system (2).

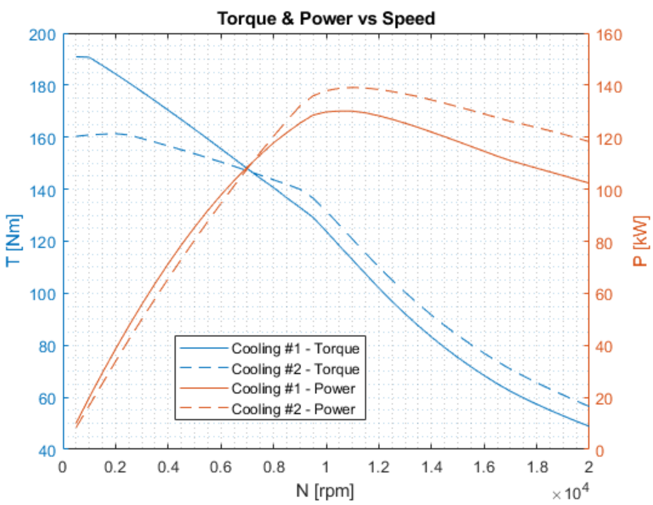

Fig. 5 Comparison between continous performance of cooling system (1) and (2)

Figure 5 shows the comparison between continuous performance of the inner rotor topology using the cooling systems. It was assumed that maximum acceptable temperatures are 180°C for both the stator winding and rotor cage. Note the advantages of cooling system (1) at low speed, high torque operation, while cooling system (2) is a preferred solution in case of operating points at high speed. The explanation for the latter is given by the more efficient heat extraction of the AC copper losses in system (2) due to oil splash and spray technique.

5. Synchronous reluctance motor

The best in class electric motors use rare earth PM. However, the reduction or complete replacement of rare earth PM is one of the main topics for the future electric vehicle drivetrain developments. Synchronous reluctance motor topology appears to be relevant when rare earth magnets removal is concerned. Actually, pure synchronous reluctance motors do not require magnets of any kind in order to operate, and are able to give high power densities at low cost. In synchronous reluctance motors, the principle of torque and power generation is based on the coupling of the magnetic field generated by the stator windings with the rotor iron core. Hence, the rotor core needs to be properly shaped to maximize performance, namely torque and power, and the optimal geometry of the rotor core is usually not effective with respect to the mechanical strength when subjected to high centrifugal forces. For this reason, the maximum speed is usually limited to contain the mechanical stress, with effect on the achievable power density. To withstand very high rotational speeds and to decrease the ripple at low speeds, a new design strategy has been developed to take into account the mechanical stress related to the centrifugal forces in the optimization steps. On the other hand, these motors can be assisted by rare earth free PM as low cost ferrites in order to increase the torque and keep the ripple low.

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). The final design, based on a 10 pole rotor with distributed round wire winding, provides peak efficiency of about 97% and above 92% for a large region of the efficiency map.

The pure synchronous reluctance motor, without permanent magnets, is a very simple and cheap solution that has not been used in electric vehicle motors for traction until now. Some of the advantages of this technology are: compactness, low temperature rise in the rotor core, good performance at rated and peak power, good efficiency, simplicity, reliability and cost. To overcome mechanical stress limitations, two design strategies were studied: with and without radial ribs in the rotor core. Both of them were analyzed in terms of efficiency, torque and ripple. The best performance was obtained using a rotor without radial ribs. As this design is critical for the mechanical strength of the rotor core, it was decided to fill the flux barriers with epoxy adhesive resin. Peak efficiency of 96% is reached with this technology and the high torque value achieved at high speed (i.e: 18000rpm) guarantees good performance during the acceleration stage.

Those two synchronous reluctance motor technologies development within ReFreeDrive project are described in the following.

5.1. Machine topology

First, the motor topologies were investigated from the techno-economic point of view in order to compare several designs, to evaluate the impact of different solutions and to establish the most promising active parts design to optimize considering cost to power ratio. Both motor topologies will be using the same standard cost effective electrical steel for all power ranges. Same, both motor technologies stators will have distributed windings. The motor development was mainly focused on the 200kW application, while 75kW motors were derived from the initial design through scalability of the active parts. Essentially, 75kW motor is a shorter version of the 200kW motor obtained by reduced number of rotor and stator stack assembly. As the lower power range motors operate under 350V while 200kW motor under 800V, stator winding is replaced with a more suitable version.

5.1.1. Pure synchronous reluctance motor

Based on the preliminary conclusions the 800V, 200 kW and 6-pole design has been optimized using specific algorithms interfaced with Finite Elements tools. Two different design strategies have been chosen for the rotor geometry shape with the aim to verify the effects on the motor performance in terms of efficiency, torque and ripple. The first rotor design has radial ribs in the rotor core while the second one has radial ribs replaced by flux barriers filled with epoxy adhesive resin [Credo et al. (2019)].

The optimized design, shown in Figure 6, consists of a 6 pole-54 slot stator with an asymmetric shape rotor with multiple ribs. This configuration has also been tested through thermal and mechanical analysis in order to evaluate the motor behavior in the critical operating conditions. The rotor with radial ribs replaced by flux barriers filled with epoxy adhesive resin brings very high electromagnetic performance potential.

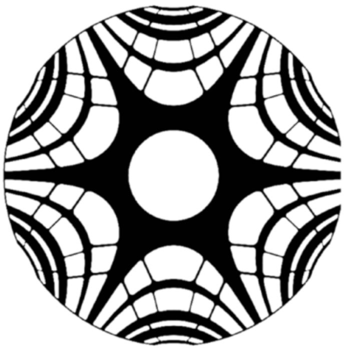

Fig. 6 Rotor shape of the 6-poles machine

The estimated performances of this motor considering mechanical losses are depicted in Figure 7, showing respectively max torque and power peak values of 387Nm, 243kW and 53kW at 18000rpm under 800V for less than 47kg of active parts.

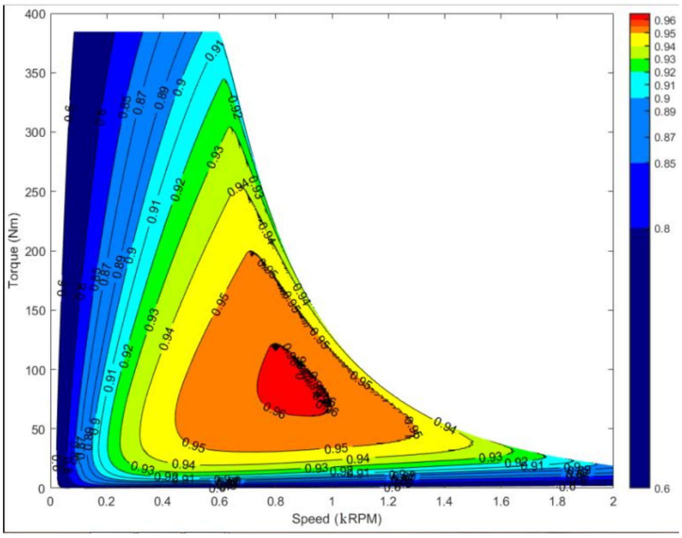

Fig. 7 200kW pure synchronous reluctance motor efficiency map

5.1.2. PM assisted synchronous reluctance motor

Based on the preliminary investigation about number of pole pairs and stator architecture, an optimization of the 800V, 200kW PM assisted synchronous reluctance motor topology was accomplished in terms of torque ripple, ferrite demagnetization and power at very high speed [Abdelli et al. (2019)].

As the coercivity value for ferrite magnets is much lower than the one of the Nd magnet (around 2 to 3 times lower at 20°C), the risk of demagnetization due to high flux-weakening angle or short-circuit is more important in this case than for synchronous motors with REE. Motor design was mechanically optimized in order to minimize the risk of ferrite damage at highly loaded operation. Also, low cost ferrites minimal size appears to be larger in comparison with Nd magnets, which is another challenge when ripple optimization is concerned.

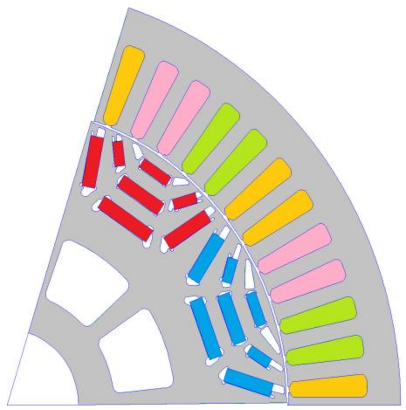

Fig. 8 PM assisted synchronous reluctance motor design

Mechanical rotor stress was another optimization target for this motor. Mechanical validation at maximal speed, at over speed (21000 rpm) as well as the air gap variation impact was accomplished in order to ensure safe motor operation during motor testing on the bench. The design that will be prototyped in ReFreeDrive is a 10 pole, 60 slot stator with distributed windings and an asymmetrical rotor having 7 magnets per pole, shown schematically in Figure 8.

The estimated performances of this motor considering mechanical losses are depicted in Figure 9 and show respectively max torque and power peak values of 405Nm, 226kW and 91kW at 17500rpm under 800V for less than 47kg of active parts.

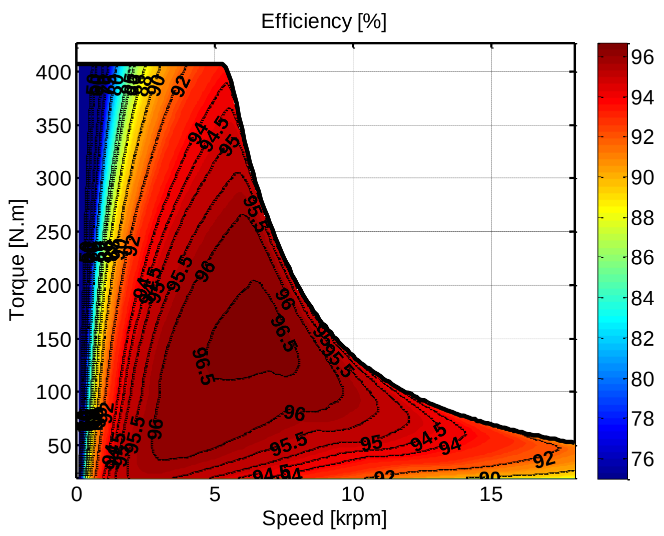

Fig. 9 200kW PM assisted synchronous reluctance motor efficiency map

6. Power electronics

Taking into account that efficiency and weight of the power electronics affect the efficiency and range of EVs, power electronic design within ReFreeDrive project aimed to enhance specific power, power density and efficiency for all motor technologies. The project goal is to use off-the-shelf components and not to develop new power electronics; therefore project activities are focused on the selection of the most suitable power electronics components and architectures available in the market.

In commercial EVs, the power converter is usually designed in a different housing with respect to the electric motor. It means that one additional housing and cooling system are needed, increasing the material use, the weight and the size of the full powertrain; moreover three power cables are needed to connect the power converter with the motor. The classical adopted architecture is based on voltage source inverter. As for the power electronics components, Insulated Gate Bipolar Transistors (IGBT) are the dominant technology for traction in electric vehicles. The technology and the packaging have been improved in the last years and have reached good levels of specific power and efficiency, respectively of 10kW/kg and 95% [Burress (2014)].

The main strategy to increase the specific power of the power converter is to reduce the losses the cooling system needs to dissipate and to optimize the cooling system itself and the converter housing. Power modules are off-the-shelf components and their specific power does not change significantly in the range of power 75kW-200kW and in the range of voltages 400V-800V. This is due to the fact that available packages are very close in terms of dimension and weight due to the needs of power dissipation and voltage insulation. Losses produced by the power modules are due to conduction of current and commutation.

Following the above considerations, the design strategy adopted in ReFreeDrive had the following main guidelines:

- Housing and cooling integration between motor and power electronics.
- Adoption of more efficient technologies for power modules, working at higher frequencies.

The integration of the motor and the power converter’s respective housings can potentially save weight and material, reducing greatly the amount of cabling needed as well. Moreover, the design of a shared cooling system becomes possible and gives the possibility to optimize the overall powertrain cooling needs.

New technologies based on Wide Band Gap semiconductors (Silicon Carbide (SiC) or Gallium Nitride (GaN)) are becoming very interesting for traction application in EVs due to the higher efficiency they can guarantee. While GaN devices are becoming popular in the low power and low voltage range, SiC are currently adopted in traction application for Formula E and Formula 1 vehicles.

SiC technology allows a strong reduction of the commutation losses, allowing the power modules to work at higher commutation frequencies. Higher commutation frequencies allow capacitor reduction, while lower losses reduce the requirements for the cooling system, thus easing integration with the motor. Nevertheless, when costs are taken into account, SiC components are not competitive compared with IGBT yet, mainly due to the lack of mass production [Sarlioglu et al. (2015)]. Nonetheless, this trend is expected to change in the following years, as vehicle manufacturers are looking with interest this kind of devices. For example, Tesla model 3 is accounted to use SiC components in their powertrain and the challenge on the vehicle range versus the costs of the batteries will push other early adopters. In fact, some SiC manufacturers have already released a full scalable portfolio of SiC power modules using the same package, which allows reducing costs for the middle power range.

The consideration about the power module losses and the little differences in power densities of the power modules analyzed led ReFreeDrive to adopt the same SiC power converter in the full range of 75kW/200kW operations. The available SiC technology seems to be adequate for the 200kW power range and up to 400kVA, thus being cost reduction the main target.

7. Conclusions

In this project Tesla model S60 is the benchmark for both induction and synchronous reluctance motors. The Key Performance Indicators (KPIs) for the higher power range application (200kW) of each motor technology and the performance achieved with ReFreeDrive induction and synchronous reluctance motors are showed in Table 1 and Table 2 respectively. All KPIs have been successfully accomplished at the end of the design stage.

Table 1. KPIs of Induction Motor for 200 kW application.

Parameter (unit)	Reference (Tesla S60)	KPI	ReFreeDrive
Specific power (kW/kg)	3.31	> 4.3	5.1
Specific torque (Nm/kg)	8.2	> 8.2	9.5
Efficiency (%)	92	96	96
Power density (kW/lit)	-	>8.0	27
Weight (kg)	-	<47	39 (Active parts only)

Table 2. KPIs of Pure (left) and Permanent Magnet Assisted (right) Synchronous Reluctance Motor for 200kW application.

Parameter (unit)	KPI	ReFreeDrive	Parameter (unit)	KPI	ReFreeDrive
Specific peak power (kW/kg)	> 4.3	5.3	Specific peak power (kW/kg)	> 4.3	4.9
Peak power density (kW/lit)	> 8.0	20.8	Peak power density (kW/lit)	> 8.0	22.6
Specific peak torque (Nm/kg)	> 8.2	8.4	Specific peak torque (Nm/kg)	> 8.2	9.5
Peak torque density (Nm/lit)	> 15.4	32.6	Peak torque density (Nm/lit)	> 15.4	46.5
Maximum speed (rpm)	15000÷18000	18000	Maximum speed (rpm)	15000÷20000	17500
Peak efficiency (%)	> 96	96	Peak efficiency (%)	> 96	96
Active parts weight (kg)	< 47	46	Active parts weight (kg)	< 47	45.5

In what concerns power electronics, benchmark EVs are Tesla S60 (200kW application) and Nissan Leaf 2012 (75kW application). KPIs and ReFreeDrive's designs achieved performances are compared in Table 3.

Table 3. Power Electronics KPIs for 75kw and 200kW applications.

Parameter (unit)	Tesla S60	Nissan Leaf 2012	75 kW design	200 kW design
Specific Power (kW/kg)	13,3	4,9	7,5	18-20
Power Density (kW/ lit)	11,7	5,7	9,47	20-22
Efficiency (%)	-	95	98,7	98,5
Power electronics Cost ($/kW)	-	13	6	3

Once all motor designs are finished, ReFreeDrive project activities now focus on the manufacturing, testing and in-vehicle integration of the developed motors.

Acknowledgements

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References

Abdelli A., Chareyron, B., Gaussens, B.Design of a 200 kW PM SynRel Motor without rare-earth earth magnets for electric vehicle. 19-22 May 2019, EVS32.

Burress, T., 2014. Benchmarking State-of-the-Art Technologies. Oak Ridge National Laboratory Annual Progress Report for the Power Electronics and Electric Motors Program, ORNL/SPR-2014/532, Retrieved from https://info.ornl.gov/sites/publications/Files/Pub52422.pdf.

Burwell, M., Goss, J., Popescu, M., 2013. Performance/Cost Comparison of the Induction Motor and Permanent Magnet Motor in a Hybrid Electric Car. TechnoFrontier 2013, Tokyo, Japan.

Credo, A., Fabri, G., Villani, M., Popescu, M. High speed synchronous reluctance motors for electric vehicles: a focus on rotor mechanical design. 12-15 May 2019, IEEE.

Jurkovic, S., Rahman, K., Morgante, J., 2015. Induction Machine Design and Analysis for General Motors e-Assist Electrification Technology, IEEE Transactions on Ind. App., Vol. 51, No. 1.

Popescu, M., Staton, A., Boglietti, A., Cavagnino, A., Hawkins, D., Goss, J., 2016. Modern Heat Extraction Systems for Power Traction Machines—A Review. IEEE Transactions on Industry Applications, vol. 52, no. 3, pp. 2167-2175.

Rosu, M., Zhou, P., Lin, D., Ionel, D., Popescu, M., Blaabjerg, F., Rallabandi, V., Staton, D., 2018. Multiphysics Simulation by Design for Electrical Machines, Power Electronics and Drives, IEEE Press, Wiley

Rowlatt, J., 2014. Rare earths: Neither rare, nor earths. BBC World Service. Retrieved from https://www.bbc.com/news/magazine-26687605.

Sarlioglu, B., Morris, D., Han, D., Li, S., 2015. Benchmarking of electric and hybrid vehicle electric machines, power electronics, and batteries. 2015 Intl Aegean Conference on Electrical Machines & Power Electronics (ACEMP)

Tiwari, R., Bhardwaj, A.K. Analysis of Induction Motor with die-cast rotor. International Journal of Innovative Research in Electrical, Electronics, Instrumentation and Control Engineering, Vol 2, Issue 6.

Tursini, M., Villani, M., Fabri, G., Credo, A., Parasiliti, F., Abdelli, A., 2018. Synchronous Reluctance Motor: Design, Optimization and Validation, 2018 International Symposium on Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM), Amalfi

US Department of Energy, 2011. Critical Materials Strategy. Office of Policy and International Affairs.