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High Performance Synchronous Reluctance Motor for Electric Vehicles – Comparison between NGO e GO Electrical Steels

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Summary

The electric car market is booming and in the next twenty years a surge electric vehicles sales is expected which should exceed that of traditional ICE cars.
The adopting motor solutions are mainly based on high performance permanent magnets but the high and volatile cost of raw materials for magnets makes uncertain their long-term availability, especially since the electric vehicle technology is going to be manufactured in mass production. Therefore, there is a growing attention in alternative solutions that include rare-earth free machines and the Synchronous Reluctance motor represent a valid alternative for electric and hybrid vehicles due to their simple and rugged construction.
In this paper, a case study is presented and particularly a high speed Synchronous Reluctance motor for "premium" full-electric vehicle with focus on the comparison between low-thickness NGO and GO electrical steels.

Introduction

The new technologies for energy storage and powertrains play a critical role in the development of the electric vehicle market. At motor level, key components and innovative materials must be integrated in the current motor designs. Recent advances in materials, power electronics, control systems have contribuited to new energy efficient and performant powertrains adopting innovative motor technologies.

The requirements of the electric motors for EVs are different from the conventional ones used in the industrial applications and the most challenging specifications are a reduced size and high efficiency in an extended speed range.
The adopting motor solutions are mainly based on high performance permanent magnets (PM) manufactured with rare-earth materials [1,2,3,4].
Table 1 summarizes the main existing electric vehicles in the European & US markets, specifying the technological solution for the traction motors and their maximum operating speed [5].

The high and volatile cost of raw materials for magnets makes uncertain their long-term availability, especially since the electric vehicle technology is going to be manufactured in mass production. Therefore, there is a growing attention in alternative solutions that include rare-earth (RE) free machines or reduced RE PM machines [6,7,8].
The Synchronous Reluctance (SynRel) motors are becoming of great interest in the recent years and represent a valid alternative for electric and hybrid vehicles due to their simple and rugged construction [5,9,10,11]. The main advantage of the SynRel relies on the absence of the rotor cage losses or PM losses, allowing a continuous torque higher than the torque of an induction motor of the same size.
With respect to PM motors, conventional SynRels are known for their lower specific (peak) power and specific (peak) torque, higher noise and lower power factor. Despite these drawbacks, it is possible to obtain high torque density and high efficiency motors through an optimized rotor design.

Table 1 – Traction motors for electric vehicles (2018-2019) [5]

Vehicle Model	Motor type Front/Rear	Max Power (kW) Front / Rear	Battery energy (kWh)
Audi e-tron 55	IM / IM	125 / 140	95
Audi Q4 e-tron	IM / PMSM	75 / 150	82
BMW i3S 42	- / PMASynRel	- / 135	42.2
BMW i3S 33	- / PMASynRel	- / 135	33.2
Chevrolet Bolt	PMSM / -	150 /-	60
FIAT 500e	PMSM / -	83 /-	24
Hyundai e-Kona 64	PMSM / -	150 /-	64
Jaguar I-Pace	PMSM / PMSM	147 / 147	90
KIA Soul EV	PMSM / -	81 / -	31.8
KIA e-Niro 39	PMSM / -	100/ -	39.2
KIA e-Niro 64	PMSM / -	150 / -	64
Nissan Leaf SL Plus	PMSM / -	160 / -	62
Nissan Leaf SL	PMSM / -	110 / -	40
Renault Zoe R110	WRSM / -	80 / -	45.6
Renault Zoe Q90	WRSM / -	65 / -	45.6
Tesla Model X	IM / IM	193 / 375	100
Tesla Model X SR	PMASynRel / IM	193 / 375	100
Tesla Model 3	IM / PMASynRel	147 / 211	79.5

Tesla Model S P100D	IM / IM	193 / 375	100
Volkswagen e-Golf	PMSM / -	100 / -	35.8
Volkswagen e-up!	PMSM / -	60 / -	18.7

The paper presents a high speed liquid-cooled Synchronous Reluctance motor for “premium“ full-electric vehicle with focus on the comparison between low-thickness NGO and GO electrical steels: this study is part of the H2020 European Project ReFreeDrive (Rare-earth Free e-Drives) that aims on reducing the use of rare-earth materials in the next generation of electric drivetrains, facilitating the industrial feasibility for mass production at low manufacturing costs [12].

The Synchronous Reluctance motor

The Synchronous Reluctance (SynRel) motor is considered a competitor to the induction motor and permanent magnet machines for traction applications, owing to the fact that it allows for elimination of the expensive rare-earth permanent and of the rotor cage.
The main advantages of the SynRel motor are:

- the rotor is potentially less expensive than both PM and induction machines due to cancelling cage, winding, and magnets from its structure;
- the torque per ampere is acceptable and unlike the PM and induction machines it does not depend on the rotor temperature;
- the control system is simpler than that of the field oriented induction motor drives.

The torque generated by SynRel motor is due to the magnetic saliency of the rotor that is constructed by barriers and segments which make this motor a simple and robust electric machine.
The “flud-shaped” type rotor (Fg.1) is preferable due to its simple manufacturing and lower iron losses: the laminations are identical and punched or cut in the traditional way. Some thin connections which are called “rib” connect the ends of the segments to each other axially and transversally. These connections maintain enough mechanical integrity in the rotor structure against rotational forces in high-speed operations.

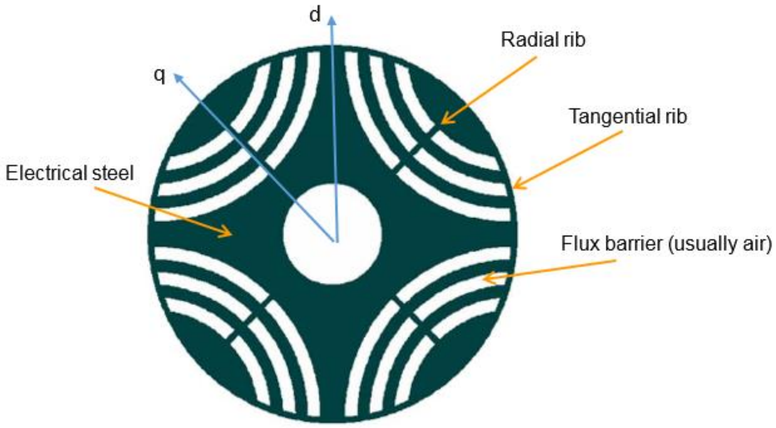

Fig.1 - Typical rotor with fluid-shaped barriers

The steady-state torque in the rotor reference frame is:

$$T = 3/2\ p\ [(L_d - L_q)\ I_d\ I_q)] \quad (1)$$

where I_d and I_q are the axis currents.

The d and q-axis inductances (L_d and L_q) vary with saturation, and the d-axis inductance is more sensitive to saturation than the q-axis inductance due to the low reluctance path of d-axis flux [13,14,15].
The reluctance torque is proportional to the difference of the inductances corresponding to the d-q axis. To maximize the output torque, the ratio of (L_d/L_q) that is called "saliency ratio" needs to be maximized.
The anisotropic nature of the rotor in the synchronous reluctance machine eliminates the expensive rare earth permanent magnet as well as the copper or aluminum cages from the rotor structure. These results in a less expensive motor drive compared to the permanent magnet and a more efficient alternative compared to the induction machine and can be considered a strong potential for electrified powertrains.

The electrical steels

Electrical machines, especially those with high speed and high-performance requirements, are often designed with non-grain oriented silicon-iron steel that should be carefully selected. Magnetic performances, core losses, mechanical strength and cost are the main criteria used to evaluate these materials [16,17,18,19,20].

Three commercial fully-finished NGO electrical steels with different thickness have been selected in order to evaluate their effects on the SynRel motor performance. Particularly:

- M235-35A - thickness 0.35 mm;

- NO30-15 - thickness 0.30 mm;
- NO20HS - thickness 0.20 mm.

Moreover, the following GO steel has also been tested:

- HGO M85-23P - thickness 0.23 mm.

The electrical steels have been characterized by RINA-Centro Sviluppo Materiali at 50, 400, 800 and 1000Hz to provide accurate data (magnetization curve and core losses) for the sizing step of the SynRel motor.

The magnetic characterization of the NGO materials at 50Hz are listed in the following Table 2 and Table 3.

Table 2 - Characterization at 50 Hz of NGO materials

Material	Thickness [mm]	P10 [W/kg]	P15 [W/kg]	J2500 [T]	J5000 [T]	J10000 [T]
NO20HS	0.20	1.30	2.88	1.498	1.597	1.721
NO30-15	0.30	1.31	2.61	1.552	1.646	1.766
M235-35A	0.35	1.33	2.70	1.537	1.630	1.746

Table 3 - Characterization at 50 Hz of GO material

Material	Thickness [mm]	P15 [W/kg]	P17 [W/kg]	J800 [T]
M85-23P	0.23	0.79	1.07	1.880

Fig.2 shows a comparison of the magnetization curve and core losses at 400 Hz.
From the results obtained in the material characterization of the NGO materials can be inferred that the low thickness material NO20HS and NO30-15 show the highest induction values and the lowest core losses values (at high frequency) so they are the best candidates for the realization of the high speed motors for automotive. However, in the framework of the better choice of the motor design it has to be considered that they also are the materials with the highest anisotropy.
The cost of NO30-15 is approximately 30÷40% higher than the material M235-35A and the NO20HS 2÷3 time the cost of the M235-35A.

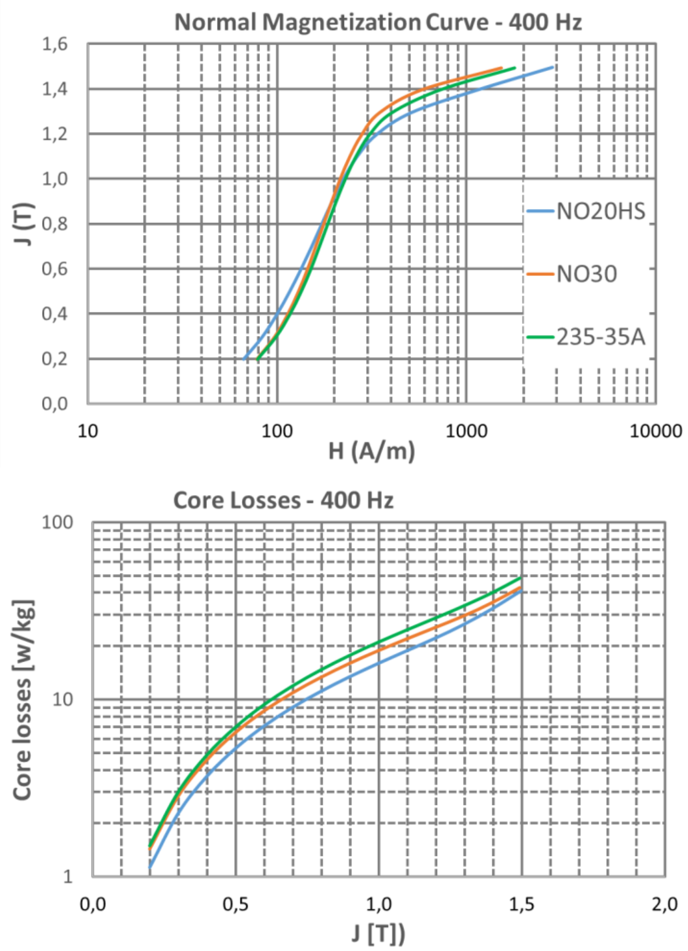

Fig. 2 - NGO electrical steels: Magnetization curves and Core losses at 400 Hz

Fig. 3 shows the magnetization curves and core losses of GO material M85-23P. For each selected direction of magnetization (0°,45° and 90° with respect RD) a comparison of curves obtained at 50, 400, 800 and 1000 Hz are reported. As expected this material shows a marked magnetic anisotropy behaviour that can be observed in both magnetization curves and core losses.

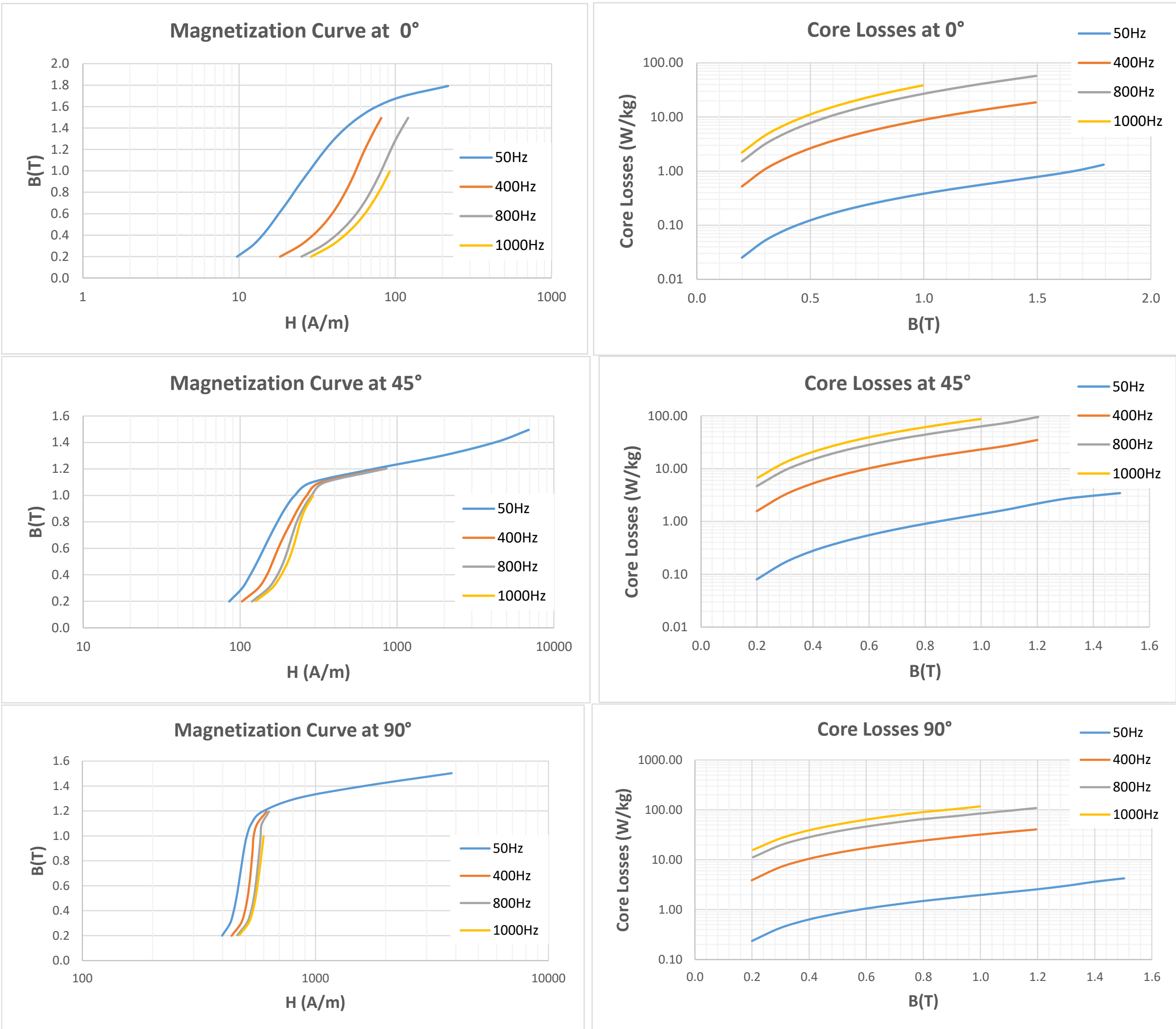

Fig. 3: GO electrical steel: Magnetization curves and Core losses at 50,400,800 and 1000 Hz

Design of the SynRel motor: a case study

The design of the SynRel motor for electric vehicle requires accurate sizing procedures [13,14,15] that differ from the process of a traditional industrial machine, where it is designed to mostly operate at a nominal speed and torque.

The sizing process has to be referred to electric, magnetic, and thermal aspects. In traction applications, to develop the required torque in critical times such as startup and maximum power demand at maximum speed, the machine needs to be designed for high current density and high frequency operations.

Therefore, it is necessary to perform the whole procedure of sizing with taking into account the maximum output power, torque-speed profile, initial data, and assigned parameters. The use of specific Finite Element Analysis (FEA) tools is necessary to verify and evaluate the machine's performances toward different modes of operation.

The design of the SynRel motor should be focused on:
- advanced rotor shape solutions;
- investigation on the adoption of high performance NGO and GO electrical steels;
- analysis on the mechanical stress with focus on the rotor ribs at high speed;
- investigation on low cost rotor.

The avenues indicated above for SynRel motor design require a complex optimization process for matching the desired motor performances whilst respecting the target components cost.

In this paper, a liquid-cooled SynRel motor for full-electric "premium" vehicles is presented: Table 4 reports the requirements of the motor.
It is worth to highlight the high value of the peak power requested at base speed (6000 rpm) for a short time and the significant value of the power at maximum speed (14000 rpm), where the SynRel motor operates in a deep flux weakening condition.

Two different designs have been carried out:

a) SynRel motor with NGO electrical steel;
b) SynRel motor with GO electrical steel.

Table 4 - Motor requirements

DC Voltage	V	700
Peak Torque density	Nm/lit	> 15
Peak Power density	kW/lit	> 8
Base speed	rpm	6000
Peak Power @ base speed	kW	200
Rated Power @ base speed	kW	125
Max speed	rpm	14000
Rated Power @ max speed	kW	125
Outer stator diameter	mm	≤ 280
Stack length	mm	≤ 200
Cooling		liquid

a) SynRel motor designs with NGO electrical steels

A 6-poles solution has been chosen that presents a good performace allowing the highest power density and the highest power at maximum speed [11]. Fig. 4 shows the cross section and the design parameters of the SynRel motor. The stator has a distributed single layer winding with 54 slots, while the rotor has 8 barriers per poles with radial and tangential ribs to improve the mechanical robustness.

The SynRel motor performance have been evaluated (by FEA) using the NGO electrical steels presented in the previous Section and the magnetization curves and core losses (at different frequencies) provided by RINA-Centro Sviluppo Materiali.
The comparison has been carried out at the same peak power and rated power: the performance are listed in Table 5. A temperature of 120°C has been imposed fo the stator winding.

The copper losses do not significantly change since both machines have identical windings and the same number of conductors; the only expected difference is related to the phase current amplitude. The design with NO20HS has the lower core losses.
The solutions with NO20HS and NO30-15 present slight efficiency increase compared to the motor with M235-35A. However, these slight differences do not justify the use of the expensive low-thickness electrical steels: to justify this choice, it should be necessary to have significant improvements in motor performance.
Based on these considerations, the best choice is the M235-35A considering the cost/performance ratio.
Fig.5 shows the efficiency map of the SynRel motor with M235-32A steel and the map of core losses in the torque-speed plane: the peak efficiency is higher than 95% in a wide speed range.

N.pole		6
N.slots		54
N.barriers x pole		8
Stack length	mm	200
Outer stator diameter	mm	260
Inner stator diameter	mm	180
Airgap	mm	0.70
N.turns x phase		15
Volume (active parts)	lit	14

Fig.4 – Cross-section of the 6-pole 54-slots SynRel motor (1 pole) and design parameters

Table 5 - SynRel motor 6-pole: comparison of NGO electrical steels

Parameters		M235-35A	NO30-15	NO20HS
Rated Power				
Power @ 6000 rpm	kW	125	125	125
Phase current	Amax	486	484	490
Phase voltage	Vmax	250	250	250
Core losses	W	800	775	685
Efficiency	%	96.7	96.7	96.7
Power @ 14000 rpm	kW	125	125	125
Phase current	Amax	355	353	352
Phase voltage	Vmax	360	360	360
Core losses	W	800	640	500
Efficiency	%	96.6	96.7	96.8
Peak Power				
Power @ 6000 rpm	kW	200	200	200
Phase current	Amax	820	810	820
Phase voltage	Vmax	280	280	280
Core losses	W	630	530	500
Efficiency	%	94.9	95.0	95.0
Power @ 14000 rpm	kW	136	136	136
Phase current	Amax	445	455	455
Phase voltage	Vmax	360	360	360
Core losses	W	825	650	525
Efficiency	%	96.2	96.3	96.4

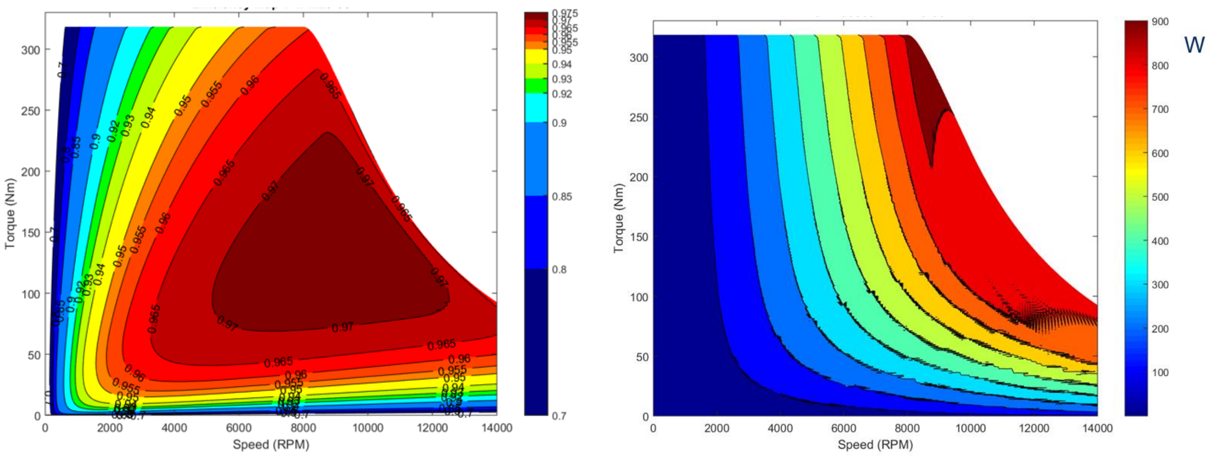

Fig. 5 - Efficiency map and Core losses (M235-35A)

A mechanical FEA has been carried out in order to evaluate the deformation in the rotor at worst mechanical stress operating conditions and high speed (14000 rpm).

The aim was to evaluate the mechanical robustness of the rotor core (above all in the radial and tangential ribs) and verify the rotor deformation close to the airgap. For this analysis, the experimental mechanical properties of the M235-32A material (Table 6) have been used. The stress distributions are shown in Fig.6 and the rotor deformation in Fig.7: no critical values have been reached and there are safety margin at maximum speed, with a maximal deformation close to airgap of about 46 µm (7% of the airgap).
In order to improve the mechanical strength of the rotor core and enhance the mechanical integrity of the rotor at vey high speed, the flux barriers could be filled with adhesive epoxy resin as proposed in [11].

Table 6 - Mechanical properties of the M235-35A electrical steel

	Yield strength R_{p02} [MPa]	Ultimate strength R_m [MPa]	Elongation A_{50} [%]	Specimen orientation
M235-35A	444-444	572-577	23.6-22.7	TRASV
	423-424	551-550	20.5-21.6	LONG

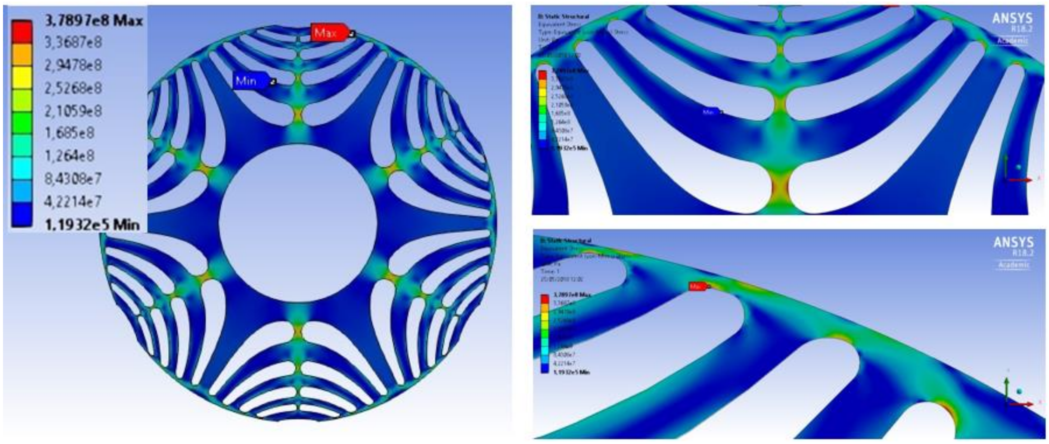

Fig.6- Mechanical stress analysis @ 14000 rpm

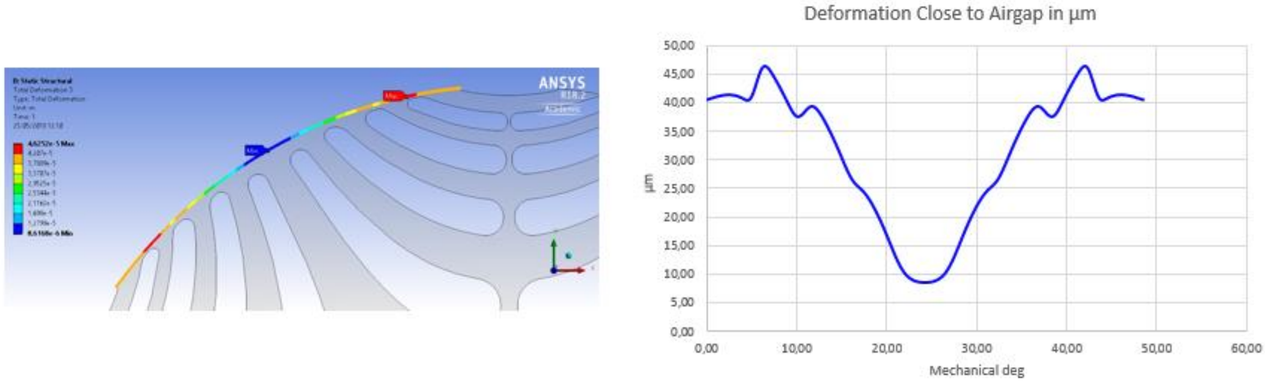

Fig.7 - Deformation @ 14000 rpm

b) SynRel motor design with GO electrical steel

The design of a high performance SynRel motor requires maximizing the anisotropic property of the rotor geometry and for this an innovative rotor lamination design using grain oriented electrical steels has been tested.

The design has been carried out using the HGO M85-23P electrical steel and the magnetization curves and core losses (at different frequencies) provided by RINA-Centro Sviluppo Materiali.

The GO electrical steel shows improved magnetic properties in the rolling direction and can be used in the rotor core. Particularly, the rotor poles may be segmented to obtain individual one-pole rotor laminations which are cut from GO steel sheet. The one-pole rotor laminations may be aligned with the rolling direction such that the direction of the q-axis (Fig.1) of each one-pole is perpendicular to the rolling direction.

In [21] a 4-pole pole SynRel motor with GO material is presented and the method of the rotor assembly using segmented poles.This approach seems too expansive for a large mass production and for this reason a 2-pole solution has been chosen in order to simplify the rotor manufacturing.

The cross section of the SynRel motor is shown in Fig. 8: in this case, no segmented poles are necessary.

The GO electrical steel has been used for the rotor core only: the rolling direction (RD) is along the direct-axis and the transversal direction (TD) along the quadrature axis. For the stator core, the NGO M235-32A material has been used.

The design of the 2-pole has required a significant increase of the stator yoke in order to contain the flux density values. The motor performance are listed in Table 7.

These results clearly indicates that, for this specific application, the 2-pole motor with GO electrical steel in the rotor core does not satisfy the requirements in terms performance at base and high speed.

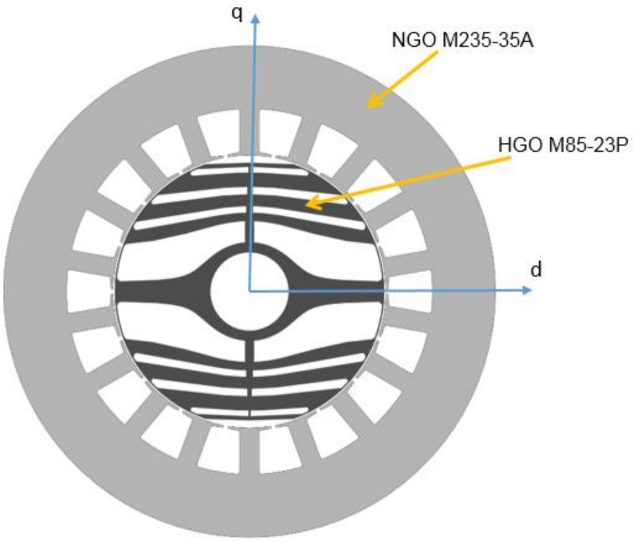

Fig. 8 - 2-pole SynRel with GO electrical steel

Table 7 – Performance of 2-pole SynRel with GO electrical steel

Outer stator diameter	mm	260
Stack length	mm	200
DC Voltage	V	700
Phase current	Amax	800
Base speed	rpm	6000
Peak Power @ base speed	kW	168
Phase current @ base speed	Amax	800
Max speed	rpm	14000
Power @ max speed	kW	103
Phase current @ max speed	Amax	300

Conclusion

The new technologies for energy storage and powertrains play a critical role in the development of the electric vehicle market. At motor level, the rare-earth free solutions are becoming of great interest and the Synchronous Reluctance motor represent a valid alternative for electric and hybrid vehicles due to their simple and rugged construction. The anisotropic nature of the rotor eliminates the expensive rare earth permanent magnet as well as the copper or aluminum cages from the rotor structure. These results in a less expensive motor drive compared to the permanent magnet and a more efficient alternative compared to the induction machine and can be considered a strong potential for electrified powertrains.

In this paper, a case study has been presented and particularly a high speed Synchronous Reluctance motor for “premium“ full-electric vehicle with focus on the effects of commercial NGO and GO electrical steels on the motor performance.

The comparison of the NGO electrical steels does not point out significant differences on the motors performance: the solutions with NO20HS and NO30-15 present slight efficiency increase compared to the motor with standard M235-35A but these improvements do not justify the use of the expensive low-thickness materials.
About the use of the GO electrical steel, a 2-pole SynRel motor has been presented in order to contain the manufacturing cost for the rotor assembly. The performance of the proposed design do not fully satisfy the requirements for this specific application and do not justify the use of this material.

The growth of electric mobility gives to the materials producers the opportunity to develop products with specific characteristics, suitable for the new generation of electric motors at high power density and efficiency in a wide speed range. However, it is strategic that these new materials have reasonable costs especially since the electric vehicle technology is going to be manufactured in large mass production at low manufacturing costs.

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