High Performance Electrical Motors for Automotive Applications – Status and Future of Motors with Low Cost Permanent Magnets

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Summary

The Permanent Magnet technology offers a good compromise of high specific torque and low losses, which justifies its choice in most electric motors for automotive applications. 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. As a consequence, alternative technologies that include rare-earth free machines or reduced rare-earth PM machines, are of high interest.
Several types of motors have been under study for propulsion applications, including low-cost PM, induction, switched reluctance and synchronous reluctance motors.
In this paper, different types of low-cost PM or rare-earth free motors for automotive applications are reviewed and discussed highlighting the advantages and drawbacks and the design of synchronous reluctance motor for a pure electric vehicles is presented.

Introduction

The impact of internal combustion engine on the environment has led to efforts to replace it by alternative propulsion systems, among which the electric machine has become the primary candidate [1, 2].
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 advantages of high quality materials, power electronics, and microcontrollers have contributed to new energy efficient and high performance electric drives that use new electric motor technologies.
In general, electric motors in powertrain applications need to meet several requirements that can be summarized as follows:

1) high torque and power density;
2) high torque at low and high power at high speed;
3) wide Constant Power Speed range;

4) fast dynamic response;
5) high efficiency;
6) reliability and robustness;
7) reasonable cost.

The vast majority of motor solutions rely on permanent magnet (PM) technology using rare-earth magnets [3,4,5]. They offer a good compromise of high specific torque and low losses, which justifies its choice in most applications.
Table 1 summarizes the existing electric vehicles in the European & US markets, specifying the technological solution for the traction motors.

Table 1 – Traction motors

Vehicle	Motor type	Specifics
BMW i3	Interior PM	Rare-earth
Chevrolet Volt	Interior PM	Ferrite/ Rare-earth
Hyunday Sonata	Surface PM	Rare-earth
Mitsubishi PHEV	Interior PM	Rare-earth
Nissan Leaf	Interior PM	Rare-earth
Porsche Panamera	Surface PM	Rare-earth
Tesla S	Induction motor	Copper cage
Toyota Prius	Interior PM	Rare-earth

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. Also, permanent magnet technology presents a number of technical drawbacks that limit the capability of the motor, notably the demagnetization effect if the temperature of the motor exceeds a certain limit.
Therefore, it has become mandatory to find alternative solutions, that include rare-earth free machines or reduced rare-earth PM machines [6].
Several types of motors have been under study for propulsion applications, including low-cost PM, induction, switched reluctance and synchronous reluctance motors.
The induction motor (IM) is potentially the lowest cost, and it is able to operate over a wide speed range. However, it is a lower torque density, power factor and efficiency compared to permanent magnet machine [7].
The switched reluctance motor (SWR) is another possible solution. There are several advantages in SWR such as a simple structure, low cost, rotor robustness, and possible operation in high temperatures or high speed. However, there are a few major problems such as the low torque for its volume, low efficiency, noise, vibration, and torque ripple.
The synchronous reluctance machine (SyR) is also a candidate for a rare-earth-free machine, but its torque density, power density, power factor and efficiency are inferior compared to PM motors. By adding the proper amount of low-cost permanent magnets in the rotor, the torque density and power density can be improved.

The design of these new traction motors requires accurate sizing procedures [8,9] that differ from the process of a traditional industrial machine, where it is designed to mostly operate at a nominal speed and torque. In traction motor, high performance and high efficiency are required in a wide speed range and specific tools and optimization procedures [10,11] should be used for the design refinement, in order to satisfy the hard requirements without oversizing the machine.
In this paper, different types of low-cost PM or rare-earth free motors for automotive applications are reviewed and discussed highlighting the advantages and drawbacks and the design of synchronous reluctance motor for a pure electric vehicles is presented.

Electric motor technologies

Table 2 presents a comparison among the different tecnologies [12]. The PM solution points out good benefit in terms of power density and efficiency but the high cost of rare-earth magnets represents an heavy drawback.
The IM and SyR present a resonable costs and a good manufacturability but a moderate power density.

Table 2 – Motor technology comparison

	PM motor	IM	SyR
Cost	highest	moderate	low
Power density	highest	moderate	moderate
Efficiency	good	good	moderate
Noise & vibration	good	good	challenging
Manufacturability	difficult	mature	easy

Whatever the price of rare earth magnets, it is generally recognised that their elimination from electrical machines will lead to a reduction in costs [6,13]. However caution must be taken in this respect; it is possible that the use of other motor technologies may result in increased costs in other elements of the electric vehicle drivetrain (power electronics or batteries). If not carefully managed this could offset or even exceed any cost benefits linked to the removal of rare earth magnets from the electrical machine.
Table 3 summarises the differences between technologies: the ferrite magnet and switched reluctance motors may offer the lowest cost in volume manufacture, though care must be taken not to increase system costs (power electronic converter and battery) and neither technology is yet fully proven in this application. However rare earth PM motors are likely to continue to have a place in very high performance applications, for example where individual electric motors are placed in each vehicle wheel, and torque density is therefore the critical requirement.

Table 3 Comparison of electric motor technologies which reduce or eliminate rare-earth magnets

Motor technology		Reduced NdFeB	Ferrite PM	Switched Reluctance
Peak power	kW	80	80	75
Peak efficiency	%	98	96	97
Active material cost	$	223	154	118
Active material costs per kW		2.78	1.93	1.57

Materials

The strong demand of high performance electric motors for automotive applications requires the use of innovative design procedures [4,8,9] and an accurate choice of the materials, in order to satisfy the hard requirements and constraints in terms of encumbrance, weight, efficiency, reliability and cost.

a) Electrical steel

The SiFe sheets are currently the most used material in the realization of electric motors, because they offer a relatively low cost and excellent magnetic properties (low loss, high permeability, high saturation induction, low coercive field). In addition, this material has a good punchability and relatively high thickness (0.50 and 0.65 mm). In high-frequency applications to limit the power losses, SiFe sheets with a reduced thickness (0.2 mm and 0.3 mm) are used. Typically for the production of electric motors cores non grain oriented SiFe sheet, the Si content is in the range 1% to 3.2%. In this respect it has to be noticed that as the Si content increases the electrical resistance of the material increases as well, decreasing the power lost due to the magnetization of the material. At the same time, however, the increase of silicon content decreases the magnetic saturation induction and consequently tends to lower the torque. To achieve high performance it is therefore necessary to carefully balance these effects, balancing the percentage of silicon in the alloy and other materials production processing conditions.
In the last years high permeability material have been developed, which at same silicon content have higher magnetic induction respect conventional materials. Such materials are particularly suitable for high torque motors.[14] From this point of view "semi-finished" non grain oriented electrical steel are quite interesting, which are annealed by the motor core manufacturer after punching, completely relieving the stress of the tension caused by the mechanical displacement of punching. The relieving of the stress improves the magnetic characteristic of the material, which at same power losses values reaches better magnetic induction [15].
Having the electric traction motors the need to be used at high rotational speed, and being, as a consequence, the outer part of the rotor subjected to strong centrifugal forces, in the last years some "high strength" electrical steel have been developed, in order to act against the tendency to deform the rotor in"high speed" conditions [16].
Figure 1 schematically illustrates the performances required to an electric motor used for electric traction in relation to the characteristics of the sheet [17].
The electric motor has to have a high torque for starting, a high maximum speed, and high efficiency in the most frequently used drive range. In addition, since an EV

traction motor is mounted in a limited space of a vehicle it is expected to have a compact design, light weight and high efficiency compared to the motors for other applications. The electrical steel sheet used for the motor is required to have higher magnetic flux density under given field strength, namely higher magnetic permeability.
In addition, to minimize the airgap between the rotor and stator, good stamping workability is required of an electrical steel sheet as well. For compact design, a high maximum speed is advantageous, but since a high frequency is required for this, the electrical steel should have low iron loss under high frequency excitation. At high speed, the rotor is subjected to large centrifugal force, and the electrical steel sheet must withstand the force. Low iron loss and excellent magnetizing properties in the most frequently used drive range is important for reducing losses.

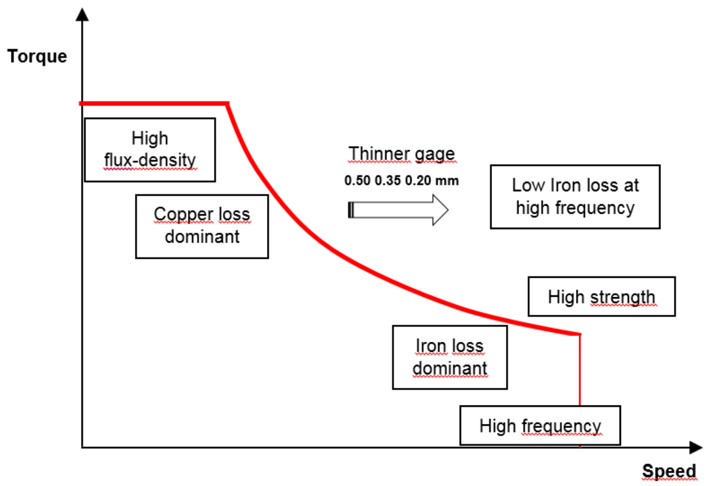


Fig. 1 – Required performance of electric motor and electric characteristics of the steel

For high power density motors, cobalt iron (CoFe) is generally the most expensive alloy. If alloyed with iron, cobalt reaches the highest maximum saturation magnetization of all materials. With the large maximum flux density, the size and weight of electrical machine cores can be decreased significantly. This allows the design of electrical machines with very high power densities. By varying the ratio between the cobalt and iron content in the material, lower iron losses or a higher mechanical strength can be achieved.
CoFe materials are mainly used in machine for aerospace applications and electric sport cars where the lighter weight compensates for the higher price [18,19].

Table 4 presents a comparison of different electrcal steels for EV motors..

To help choose the best material, the ″loss-to-squared-flux-density″ factor can be used, which is the specific iron-loss density (W/kg) over the square of the flux density, yielding (W/kgT^2). This also helps to identify the specific loss range of the different diagrams for different frequencies. A visual comparison between materials is possible and gives an objective material grading to select the most suitable material for a certain machine application in terms of magnetic saturation, material utilization, and iron losses [20].

Table 4 – Electrical steels for EV motors

Material type	Composition	Thickness (mm)	Flux density @ 0.8 kA/m (T)	Flux density @ 2.5 kA/m (T)
CoFe	49% cobalt 49% iron 2% V	0.2÷0.5	2.1	2.23
NiFe	40% nickel 60% iron	0.1÷0.5	1.4	1.48
High-Silicon content SiFe	6.5% silicon iron balanced	0.1÷0.2	1.3	1.40
Thin NO SiFe	3% silicon 0.4% aluminum iron balanced	0.1÷0.3	1.2	1.63

b) Alternative to rare-earth PM

It is interesting to consider the alternatives to the use of rare-earth PMs, aim to reduce the amount of rare earth material. Whilst not allowing the complete elimination of rare-earth magnet materials, much work has focussed on reducing the quantity of magnet used in traction applications. Efforts in this area have tended to focus on two alternative approaches.

Firstly magnet manufacturers are seeking to reduce the rare earth content of magnets whilst maintaining or increasing their performance. An example is Hitachi Metals [21] who have developed magnets which reduce Dysprosium content when compared to conventional NdFeB materials, without a reduction in their high temperature coercivity. These magnets are manufactured using a new process which involves the diffusion of Dysprosium into the magnet material in place of direct alloying.

Others [22] are seeking to reduce the grain size in the magnets to nanoscale with the expectation that this will significantly increase the Maximum Energy Product of the material.

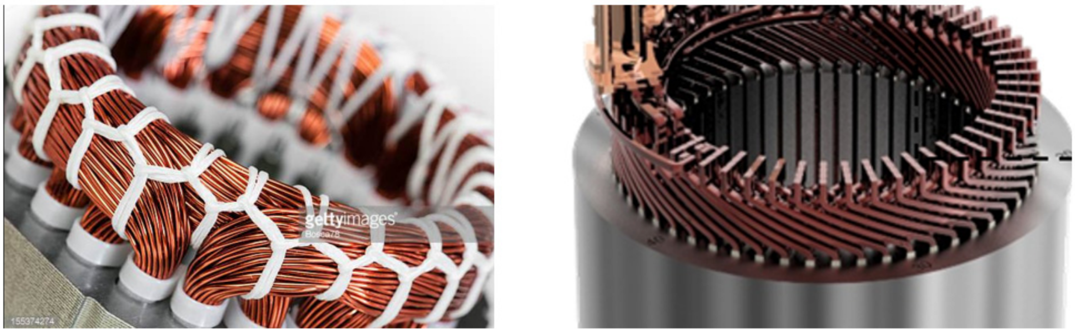
There has been much work reported in the development of magnetic materials not using Neodymium and Dysprosium. There have been reports of new, very high performance magnetic materials such as Iron Nitride [23], Manganese based compounds [24] and others [25]. However it is not clear how practical or close to market these materials are and it can be argued that commercialisation is likely to take several years, even once significant improvements have been achieved.

c) Stator winding

A large part of the windings for electrical machines are composed by stranded enameled copper conductors, generally arranged in coils and placed in the stator slots, which can be rectangular or trapezoidal and lined with special insulation paper. Recent developments in electrical machines include the use of enameled flat wires instead of round wire in a wide range of applications and especially in automotive. Flat wire conductors have many advantages over round wires (Fig.2): slot fill factor up to 80% and more, reduction of Joule losses, winding overhead more compact, and improved heat dissipation.

The possibility to fit more copper in a given slot permits to reduce the overall stator size, leading to a considerably more compact design and material saving. Beside the aforementioned features, others like low losses, optimized shape of the lamination stack and highly efficient manufacturing process represent the distinguishing features over round wires stators. The innovative process includes a special forming process of the flat wire, arranged into hairpins and inserted into the stator to form the coil.

The bar-wound construction, due to higher cross-sectional area of the individual conductors, has significant skin and proximity effects and this increases the resistance at higher motor speeds.



Stranded winding Hairpin winding

Fig.2 Stator winding

Rare-earth free motors

a) Copper cage Induction motor

The induction machines are versatile, robust and simple to control. Although induction machines are very common in industrial automation, they are less frequently used in automotive traction application (Table 1).
The most common form of induction motors utilize a squirrel-cage rotor, which comprises a series of longitudinal conductor bars (usually made of aluminum) inserted into slots located towards the periphery of a stack of steel laminations. The conductor bars are connected at both ends by shorting “end” rings, producing what is known as a “squirrel cage” structure.
These machines can produce high levels of performance using vector control or direct torque control techniques. For conventional IMs, the “constant power speed range” (CPSR) typically extends to 2-3 times the base speed. By appropriate choice of supply voltage and frequency, the starting torque can be almost as high as the maximum torque, while a high efficiency can be achieved by minimum slip control.
Induction machines incur losses in their rotor conductors, which can result in total rotor losses typically two to three times higher than in a permanent magnet based motor.
High rotor losses are not desirable as the rotating rotor is much more difficult to cool than the stationary stator. In practice these high losses mean not just that this type of electrical machine may be less efficient than other options [8], but also that in operation it may quickly become overheated.

New solutions have been proposed to develop more economic processes for making the squirrel cage from a highly conductive material such as copper. The squirrel cages for induction motors are typically produced from either aluminum or copper, and rotors can be manufactured by either casting or a fabrication approach, where the squirrel cage is brazed together from a large number of machined pieces
The lowest cost approach for producing rotors is by die casting aluminum in the squirrel cage, but as the electrical conductivity of pure copper is more than 60% greater than that of aluminum, die-cast copper rotor (Fig.3) generally gives significant efficiency improvements [26]. However, the cost of manufacture of these copper rotors is higher; this is because of the high cost of copper, when compared to aluminum, and due to its higher melting temperature, which makes process control more difficult and more costly than for aluminum.
An alternative to the die-casting avenue is the fabricated cage (with copper bars).

Nowadays the technology is well developed and available. In various studies it was illustrated how the induction machines compare to the highest torque density motor types, i.e. synchronous PM machines.
Induction machines result however cheaper in investment than permanent magnet ones and operational costs remain almost identical. Motor design, high density wiring and material optimization can address the above mentioned drawbacks.
In order to increase the efficiency of rotors, the reduction of the slot width and an associated increase in the number of rotor slots are interesting focus of development.

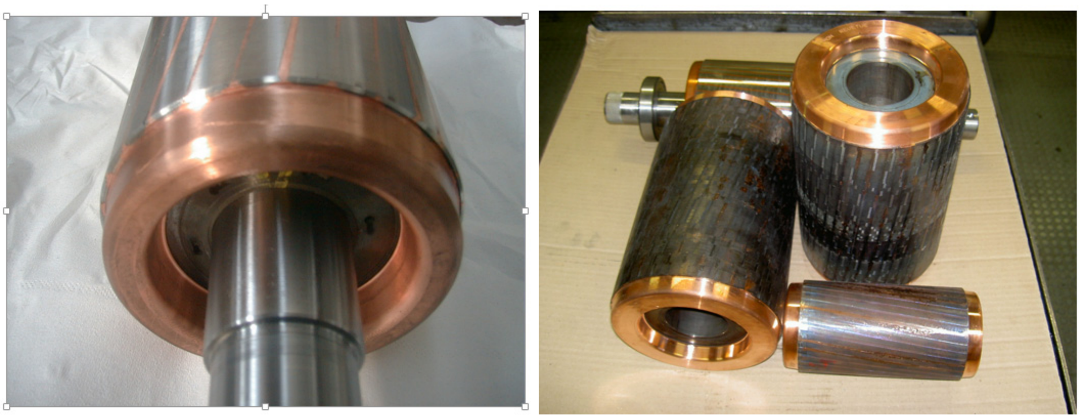


Fig.3 Die-cast copper rotors

In [7] a 50 kW copper rotor induction motor has been compared with a PM motor for hybrid electric car: this comparison has pointed out that the induction motor has a weight 40% higher respect the PM solution with a reduction of torque density of about 25%. However, IM represents a good alternative because the absence of magnets gives a significant reduction of the total motor and inverter unit cost.
The use of the aluminum instead of copper in the rotor of the 50 kW induction motor gives an increase of the losses of about 4% and lower torque density (about 5%).

b) Switched Reluctance motor

The Switched Reluctance motor has several advantages including a simple structure, mechanical robustness and low cost. It has neither a permanent magnet nor a

second winding in the rotor. Only silicon steel and stator winding are needed in an SWR. The copper can be reduced by having concentrated winding which provide short end-windings. Fig.4 shows a view of the motor.
The simple and robust structure of the rotor in particular makes the SWM good choice for high speed applications.
The main disadvantages relative to permanent magnet and induction machines are a high torque ripple, increased acoustic noise and vibration. All the problems could be solved by an accurate design.

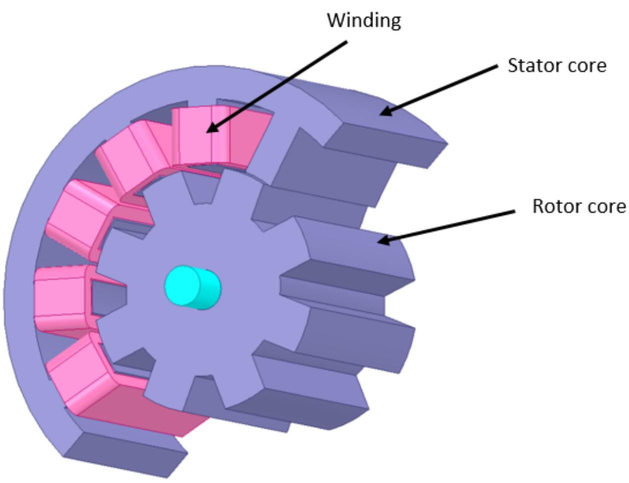


Fig.4 3D view of Switched Reluctance motor

Torque is directly dependent on the current and the rate of change of the inductance with respect to rotor position.
The number of rotor and stator poles is important for improving torque density. When the number of stator poles is increased, then coil end lengths are decreased. Then, the stack length of the stator can be increased; and the torque can be improved. In addition, the width of the stator yoke can be narrow at a high number of poles.
In ordert to improve the efficiency, better iron core is needed in the SWR to be competitive.
Several solutions of SWRs have been proposed [27, 28] with high torque and efficiency as well as compactness with respect to PM synchronous motors in hybrid electric vehicles.

c) Synchronous reluctance motor

The synchronous reluctance motor represents a possible alternative to ac drives [29, 30].
In principle, this machine is similar to the traditional salient pole synchronous motor but does not have an excitation winding in the rotor. In this machine only the rotor is constructed by flux-barriers (Fig. 5).
The main advantage of the SyR relies on the absence of rotor copper losses that permits continuous torque that can be higher than an IM of the same size. The other important features of the SyR are:

1) the rotor is potentially less expensive than both PM and IM motors due to cancelling cage, winding, and magnets from ist structures:
2) the torque per ampere is acceptable and unlike the PM and IM motors it does not depend on the rotor temperature;
3) the control system is simpler than that of the field oriented IM drives. However, rotor position information is necessary.
With respect to PM, conventional SyRs are known for their lower power and torque densities, higher noise and also for their lower power factor. Despite these disadvantages, through an optimized motor design, it is still possible to obtain high torque density and high efficiency motors adapted to automotive applications.

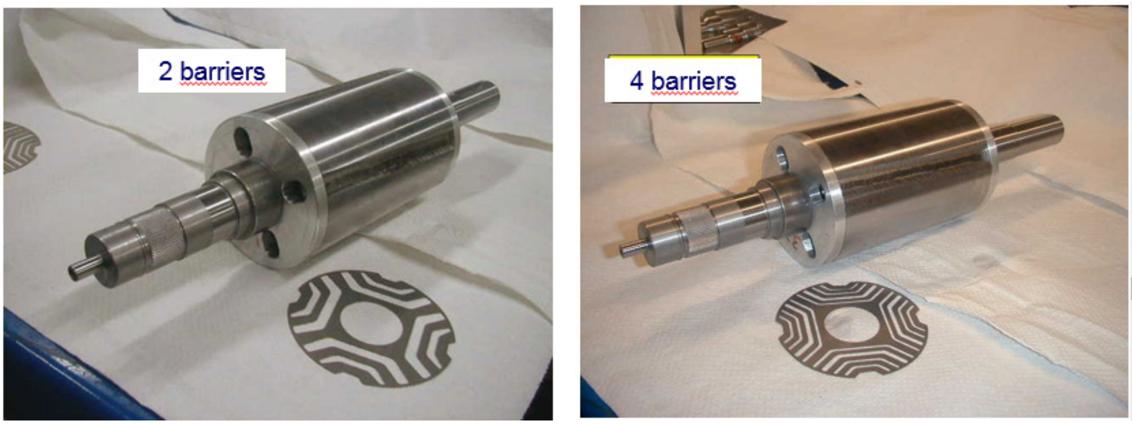


Fig.5 Rotors with flux-barriers for synchronous reluctance motors

By adding a proper amount of cheaper PMs (Ferrite) in the rotor flux barriers of SyR motor (Fig.6), similarly to internal permanent magnet motors configurations, performances close to those of PM motors can be obtained at a lower cost [19]. This topology is referred to as permanent magnet assisted synchronous reluctance motor (PMa-SyR), and the available torque is obtained thanks to the contribution of both reluctance torque and synchronous torque. This gives rise a torque improvement of about 20% respect to the SyR without PM.

Fig.6 Rotor of PM-assisted synchronous reluctance motor (in Ferrite)

The advantage of this family of motors is the increase of the inherent low power factor, resulting into a large constant power speed range, and also of the motor

efficiency. However, further developments are required to make this technology competitive in terms of performance/cost trade-off for electric vehicles traction.
The use of ferrite magnets seems to be a good compromise for using permanent magnets without drastically increasing the motor cost.
Irreversible demagnetization is the major aspect to take into account, and a robust design of rotor and stator geometry is mandatory to respect the maximum electrical loading limit for extreme conditions, as short circuit at very low temperature [31].

A case study

In this section, a synchronous reluctance motor for pure electric vehicles is proposed in order to demonstrate how a low-cost solution without PMs is able to meet the hard requirements typical of an electric car.
Table 5 present the main requirements: the motor is liquid cooled, and could be installed on a medium car model.
In ordert to reduce the maximum supply frequency and thus the iron losses, the number of poles has been selected to 4: on the other hand low pole rotors provide higher anisotropy than high pole number machines. As a consequence, an integral slot distributed winding has been considered with flat wires conductors.
The motor has been designed by an optimization procedure linked to FE code [10,11,29] and the commercial SiFe 0.35 mm electrical steel M235-35A has been chosen whose main data are shown in Table 6.
Fig. 7 shows the cross section of the final design. The stator has a distributed single layer winding, with hairpin technology, with 36 rectangular slots, while the rotor has 4 layers of flux barriers and radial ribs to improve the mechanical robustness.
The main dimensions and performance of the motor are listed in Table 7: a temperature of 120°C has been imposed fo the stator winding. Moreover, in order to reduce de AC resistance due to the skin and proximity effects, more conductors in parallel have been considered (Fig. 7).
The motor performance fully satisfy the imposed requirents. Fig.8 shows the calculated torque-vs-speed and output power-vs-speed characteristics by FE analyses in the continuous and peak mode. These curves point out an excellent field-weakening performance of the SyR with a wide constant-power speed range: this is an important requirement for the electric vehicle. Fig.9 shows the flux density at base and maximum speed with reference to the continuos operation.
The mechanical robustness of the rotor structure has been analyzed with regards to the effects of the rotational forces that cause deformation in critical points such as tangential and radial ribs. This may occur in high speed operations where the rotational forces are dominant. Since, the SyR is regularly designed with small air gap, the rotor structural deformation is an important challenge at high speed.
In the high speed mode (14000 rpm), the displacement of the rotor structure at radial ribs near the air gap area is about 0.15 mm (Fig.10) that can be tolerable compared to the 0.7 mm airgap. This confirms that the maximum deformation in the rotor structure is not a concern for the machines at maximum desired speed.

The study has been completed by considering the effect of CoFe electrical steel (0.35 mm), without changing the motor dimensions and stator winding. This solution has allowed a reduction of the phase current of about 20%, at the rated power, respect to the design with SiFe.

Table 5 – Motor requirements

DC Voltage	V	600
Rated power	kW	90
Peak power	kW	150
Base speed	rpm	5000
Rated torque @ base speed	Nm	172
Maximum speed	rpm	14000
Efficiency	%	> 94
Stack length	mm	200
Outer stator diameter	mm	250
Cooling		liquid

Table 6 – Electrical steel M235-35A

Magnetic polarization @ 50Hz:		
H=2500 A/m	T	1.53
H=5000 A/m		1.64
H=10000 A/m		1.76
Loss @ 1.5 T:		
50 Hz	W/kg	2.25
100 Hz		5.54
400 Hz		41.2
Yeld strength	MPa	460
Tensile strength	MPa	580

Table 7 – Main data and performance

N.pole		4
N.stator slots		36
Stack length	mm	200
Outer stator diameter	mm	250
Inner stator diameter	mm	170
Air-gap	mm	0.70
Turns per phase		12
Electrical steel		M235-35A
Continuos mode:		
Phase current	Arms	300
Base speed	rpm	5000
Rated torque	Nm	172
Rated power	kW	90
Efficiency	%	96.4
Maximum speed	rpm	14000
Torque @ max speed	Nm	61
Peak mode:		
Phase current	Arms	460
Base speed	rpm	5000
Torque	Nm	290
Power	kW	152

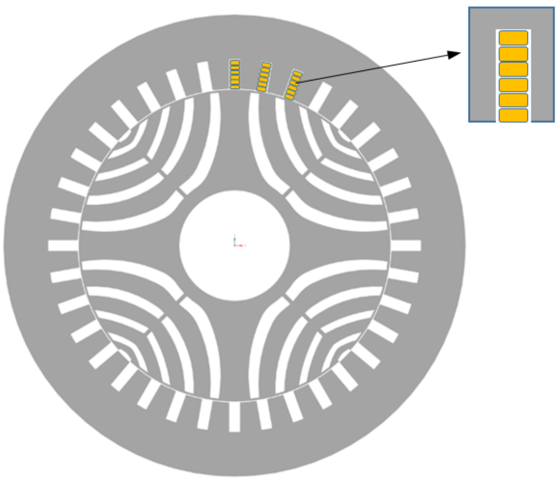


Fig.7 Cross section of synchronous reluctance motor with hairpin winding

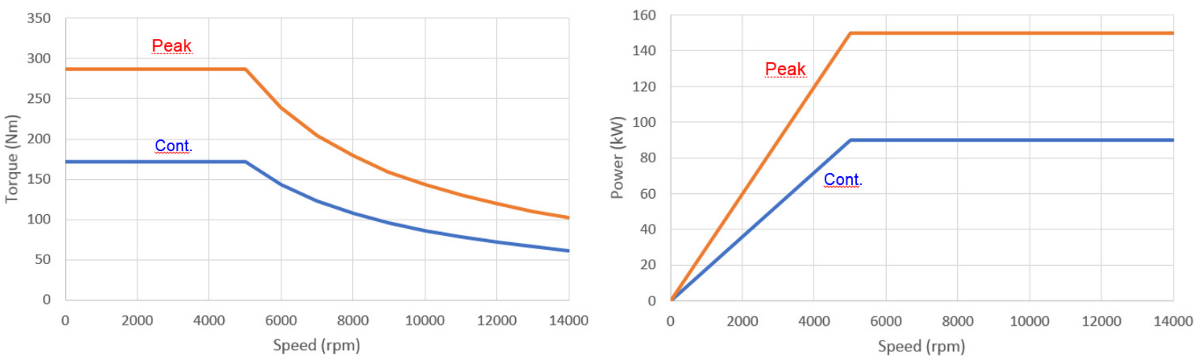
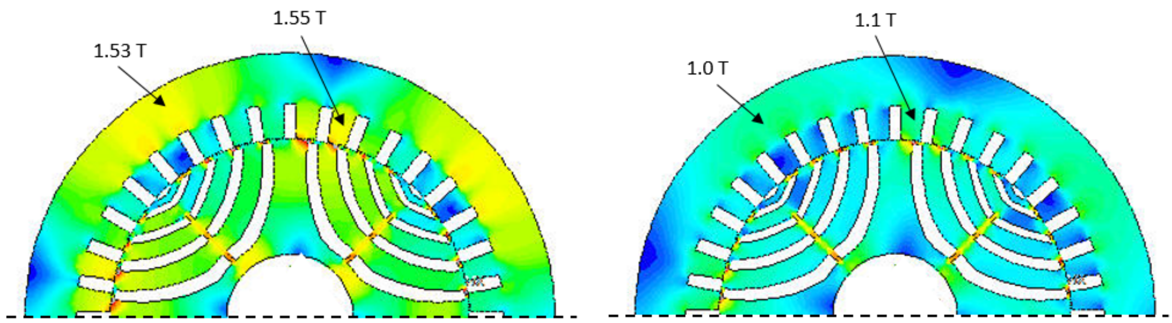


Fig.8 Torque and Power vs. Speed



Base speed Max speed

Fig.9 Flux density @ rated power

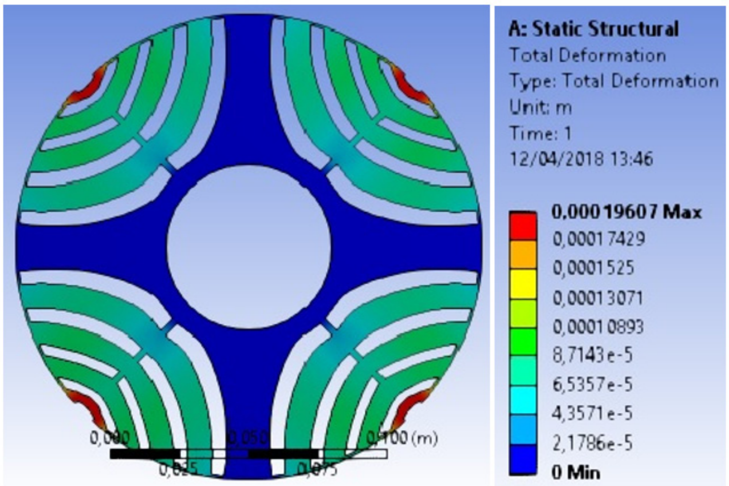


Fig.10 Rotor deformation @ 14000 rpm

Conclusion

The vast majority of motor solutions rely on permanent magnet technology using rare-earth magnets. They offer a good compromise of high specific torque and low losses, which justifies its choice in most applications.
The key problem is the relatively high cost due to PM materials: this technology may not offer the best long-term solution for use in the electric vehicle. Therefore, it has become mandatory to find alternative solutions, that include rare-earth free machines or reduced rare-earth PM machines.
The induction motors, switched reluctance motors, ferrite magnet and synchronous reluctance motors represent valid alternatives, though care must be taken during the motor sizing and selection of electrical steel in order to satisfy the hard requirements and avoid an increasing on the system costs.
The development of rare-earth free traction technologies allows to contribute to a greener transport, by offering new solutions non dependant on critical sources and making use of vast electric motor manufacturing capabilities.

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