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Motor performance improvement via ArcelorMittal's iCARe® electrical steel range for automotive applications

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Abstract

As previously reported [1-3], ArcelorMittal has a specific electrical steel product line for core laminations, which optimises the performance for automotive traction electrical machines. This iCARe® product family consists of Save grades allowing for higher efficiency, Torque grades allowing for higher torque density and Speed grades for high speed rotors. The iCARe® electrical steels now have been developed towards further loss reduction and polarisation increase. This paper shows the improved machine performance achievable by using these new iCARe® grades.

Automotive traction machines require high power density, high efficiency and high torque, to maximise the powertrain's performance and minimise the use of battery power. Permanent magnet synchronous machines (PMSM) are the preferred choice for electric and hybrid vehicles. When searching for cost reduction via eliminating the need for permanent magnets, wound rotor synchronous machines (WRSM) are an alternative. In this paper, a material comparison study is presented for both a PMSM and a WRSM having the same nominal speed and rated mechanical power. The reference case uses M330-35A electrical steel. The impact of switching to either Save or Torque grades of the latest generation is compared numerically: to determine the efficiency of each combination of machine topology and lamination type, the ArcelorMittal loss model is used [4], an extension of Bertotti's loss model [5].

The impact of each grade is checked by varying the stack height whilst keeping the output power level constant. Hence the bill of materials is affected, reflecting the amount of active materials (laminations, magnets, windings) needed within each machine type, depending on the chosen electrical steel grade.

The results show the efficiency benefits when using low loss Save grades and the torque density benefits when using Torque grades. Moreover, the new Torque grades with lower losses present a new potential for further machine performance enhancement: for instance the Torque 27 grade combines outstanding increase of torque density with high efficiency.

Keywords: electric motors & generators, propulsion systems and subsystems, magnetic material, efficiency, torque

1 Introduction

Electrical machines for propulsion of electric, hybrid and fuel cell vehicles need to present high power density, high efficiency and high torque at minimal cost. The "classic" solution has been the use of permanent magnet synchronous machines (PMSM) given its high compactness and good break-away torque. Amongst the alternative designs for cost reduction, the wound rotor synchronous machine (WRSM) has the advantage not to depend on rare earth magnets. This paper presents a case study of both PMSM and WRSM topologies, aiming for a numerical comparison of traction motor performance versus its bill of materials, for different choices of electrical steel.

The above-mentioned machine requirements (high torque density, high efficiency) have to be satisfied in a wide operational speed range. For a given application this translates on the material level into finding the optimal electrical steel having the best compromise between high polarisation and low iron losses. Hence, different electrical steels for the machine's core are analysed within this study. The new ArcelorMittal iCARe® grades are compared to the reference grade M330-35A. The iCARe® Save grades typically enable the machine producer to reduce the active material losses and hence to improve machine efficiency, whereas iCARe® Torque grades assist to produce more air gap flux, allowing the motor to develop more mechanical output for a given motor weight.

A numerical comparison study is carried out, aiming to quantify the effect of electrical steel selection on efficiency, torque production and bill of materials: in other words, the added value in terms of motor performance is quantified for different enhanced electrical steel grades.

2 Machine topologies

Two generic and customer-independent designs of distinct types of traction motors for hybrid electric vehicles are chosen, one with and one without permanent magnets, see Fig. 1.

In this study, both investigated machine topologies share the same stator lamination geometry; hence the air gap diameter and outer machine diameter are identical. Also, both topologies have five pole pairs and have the same nominal speed (4800 rpm), which results in the same electrical frequency at the nominal operational point (400Hz).

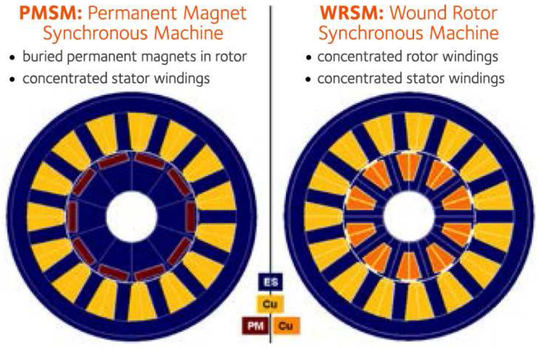

Figure 1: E-machine topologies under study: PMSM (left) and WRSM (right), both having a nominal mechanical power P_{nom} = 31kW at f_{nom} = 400Hz.

Comparing both rotor topologies with fixed stator lamination geometry, the relative contribution of the active materials (= electrical steel, copper conductors and permanent magnets – if any) on efficiency, power density and bill of materials is different. Indeed, as can be derived from Table 1, the torque density of the machine with permanent magnets in the rotor is significantly higher, having an impact on the axial length necessary to achieve the same torque at nominal speed. A different axial length also has an impact on the bill of materials (affecting the amount of steel laminations, permanent magnets and copper conductor length).

M330-35A, @ 400Hz	PMSM	WRSM
Torque per meter axial length	275 Nm/m	232 Nm/m
Axial length	0.224m	0.266m
=> identical torque	61.6Nm	61.6Nm
Active material losses	1200W	1300W
Active material efficiency	96.4%	96.0%
mass	24kg	28kg

Table 1: Compared to PMSM, a WRSM typically needs more axial length in order to produce the same output torque, which has implications on efficiency, mass and power density (comparison for reference material at the nominal speed working point).

3 Methodology

The effect of electrical steel choice is evaluated for the case of equal mechanical power at nominal speed. Such approach implies that the output torque is identical for all investigated machine-lamination combinations. Also the stator phase currents and the 2D design geometry of stator and rotor laminations remain fixed during the entire study.

Since the torque density (torque per meter axial length) will vary for the different materials, such iso-torque condition is achieved by adapting the axial length in such a way that for each machine-material combination the output torque remains equal. Consequently the following properties are varying: machine volume and mass (bill of materials), losses of all active materials (iron losses of electrical steel, Joule losses of copper conductors, eddy current losses in the permanent magnets), and hence efficiency.

In other words, for those materials resulting in higher torque density, such iso-torque condition translates into better machine compactness. And moreover, also the total power losses are proportional with the axial length.

This numerical study takes advantage of the in-house developed methodology for the enhanced calculation of the iron losses in electrical machines. At the heart of our approach is the electromagnetic finite element modelling of the machine-material combination under study. Advanced pre-processing and post-processing modelling routines result in an improved description of the material behaviour of the electrical steel. This magnetic machine model includes elements to improve magnetic loss calculations, via taking into account e.g. higher order harmonics, rotational loss and effect of punched edges. More details about the iron loss modelling formulations and approach can be found in [4].

4 Results of material comparison

The numerical results of the material comparison at the nominal operational point are given in Tables 2 and 3, for PMSM and WRSM topologies respectively. As a reference, a standard industry grade (IEC 60404-8-4) is used. A high permeability industry grade is also included in this comparison, to indicate the potential of high polarization on the torque density. Indeed, as can be derived from Fig. 3 the polarization in the stator teeth is typically 0.1T higher for M330P-35A than for M330-35A.

PMSM	Industry Standard	Industry High perm	iCARe® Save		iCARe® Torque	
	M330-35A	M330P-35A	Save 20	Save 30	Torque 27	Torque 30
Torque density (torque /m axial length)	Ref.	**2.2%**	**-0.4%**	**0.40%**	**0.69%**	**1.6%**
Compactness (m^3)	Ref.	**-2.1%**	**0.4%**	**-0.39%**	**-0.68%**	**-1.6%**
Active material loss (nominal)	Ref.	**15%**	**-21%**	**-15%**	**-20%**	**-14%**
Active material efficiency (nominal)	Ref.	**-0.52%**	**0.77%**	**0.54%**	**0.73%**	**0.52%**

Table 2: Electrical steel comparison for PMSM at nominal speed.
All values are relative compared to the values for M330-35A.

WRSM	Industry Standard	Industry High perm	iCARe® Save		iCARe® Torque	
	M330-35A	M330P-35A	Save 20	Save 30	Torque 27	Torque 30
Torque density (torque /m axial length)	Ref.	**4.4%**	**-1.7%**	**0.17%**	**0.16%**	**2.1%**
Compactness (m^3)	Ref.	**-4.2%**	**1.8%**	**-0.17%**	**-0.16%**	**-2.1%**
Active material loss (nominal)	Ref.	**8.3%**	**-17%**	**-12%**	**-16%**	**-13%**
Active material efficiency (nominal)	Ref.	**-0.33%**	**0.67%**	**0.47%**	**0.64%**	**0.51%**

Table 3: Electrical steel comparison for WRSM at nominal speed.
All values are relative compared to the values for M330-35A.

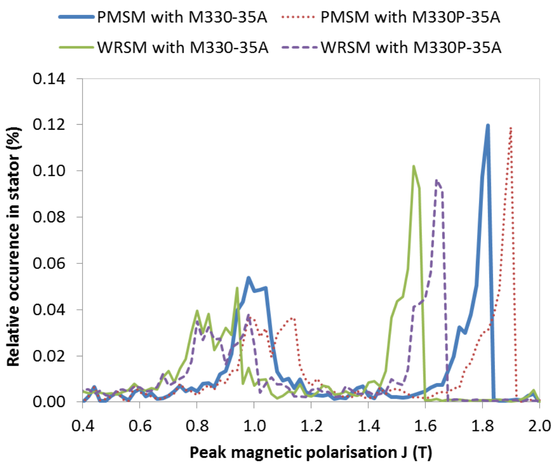

Figure 3: Histograms of J_{peak} (= relative occurrence of peak magnetic polarisation evaluated over one electrical period) in the stator for both topologies and both reference materials (M330-35A and M330P-35A). The highest peak corresponds with the polarisation in the stator teeth. For M330-35A this peak is at 1.81T for PMSM and 1.57T for WRSM.

This results in a 2.2% higher torque density for M330P-35A compared to M330-35A in the PMSM case (and 4.4% in case of the WRSM). In this iso-torque comparison a high torque density translates into a higher compactness of the machine (less axial length). However, with the M330P-35A the iron losses increase dramatically compared to the reference case of M330-35A (see Figures 4 and 5), resulting in a lower active material efficiency (taking into account the losses of active materials: electrical steel, copper, magnets).

In search for a better compromise between high polarisation and low iron losses, four iCARe® grades are benchmarked: two Save grades and two Torque grades. The grades Save 20 and Save 30 have a thickness 0.20mm and 0.30mm respectively, whereas Torque 27 and Torque 30 are 0.27mm and 0.30mm thick.

The thinnest Save grade (Save 20) results in the highest achievable efficiency due to its significantly lower iron losses, see Figures 4 and 5). However, the torque density is worse than for the reference case (see Tables 2 and 3). On the other hand for the other three iCARe® grades the torque density is better than the reference case. Best in class is the Torque 30 where the torque density improvement reaches almost the level of the high permeability industry grade M330P-35A. Moreover the Torque 30 combines this outstanding torque density with an efficiency which is in the same range as the Save 30 grade. On the other hand, the Torque 27 combines a slight increase of torque density with a loss reduction in the same range as Save 20.

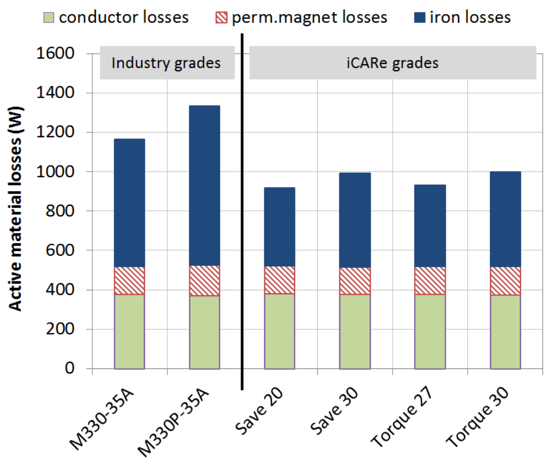

Figure 4: for the PMSM case, active material losses (conductor losses, permanent magnet losses and iron losses) as a function of material choice. Conductor and magnet losses only vary slightly (min. value is only 2% lower than max for conductor losses, and min. value is 9% lower than max for magnet losses).

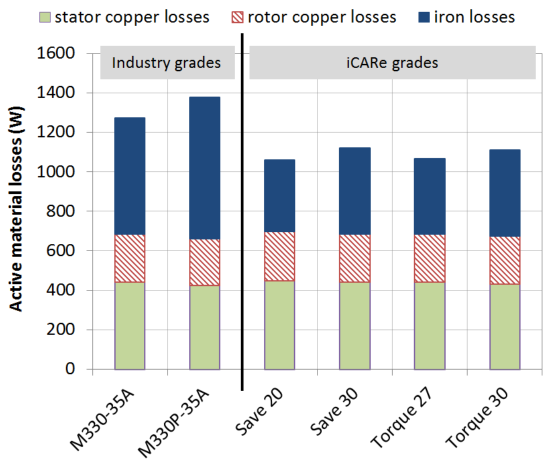

Figure 5: for the WRSM case, active material losses (conductor losses, permanent magnet losses and iron losses) as a function of material choice. Conductor only vary slightly (min. value is only 5% lower than max).

5 Conclusion

The following conclusions can be drawn from this numerical study, when comparing the investigated iCARe® electrical grades with the reference grade M330-35A:

- iCARe® Torque grades result in a good compromise between high torque production and low losses of all active materials. The higher torque density that can be achieved especially with the Torque 30 grade enables a lighter and smaller machine design (hence saving on copper and magnet cost), or for a given weight and bill of materials resulting in a more powerful machine, leading to better vehicle performance: better break-away torque and better acceleration. Moreover Torque grades enable design modifications on teeth/yoke width and Cu slot area, which can lead to an optimal geometry giving another trade-off between electrical steel, copper and permanent magnets in the 2D lamination geometry.

- with the iCARe® Save grades, due to the lowest iron losses, the highest efficiency is obtained (hence smaller batteries are possible for the same drive range, or vice versa depending on the vehicle design strategy). Hence, if best performance in terms of efficiency is the most important selection criterion, regardless the extra material and processing cost, then Save 20 comes first, although Torque 27 is close in efficiency level as the Save 20 and moreover the Torque 27 has the additional advantages of a somewhat higher torque density. When aiming for somewhat thicker laminations, such as 0.30mm, the Save 30 grade also combines a significantly higher efficiency with a somewhat higher torque density.

- M330P-35A, the high permeability variant of the reference grade, gives the highest improvement in torque production (resulting in a smaller machine, saving on copper and magnets), but has the drawback of a significantly lower efficiency.

In general, the iCARe® Save and iCARe® Torque grades finalised in 0.27mm or 0.3mm thickness appear to be effective compromise materials for the considered applications and considered frequency ranges, leading to the best value/cost ratio, both during construction and exploitation. The final material choice obviously depends on what is considered most important by the machine and vehicle producer, what comes first: highest efficiency or highest torque performance.

In conclusion, the current study shows that, not only ArcelorMittal provides the electrical steels to optimise the power density, efficiency, torque, of challenging applications, but ArcelorMittal also provides the technical support allowing to maximise the benefit of the chosen electrical steel grade.

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