Performances Evaluation of a Magnetic Gear with High Transmission Ratio Used for High Speed Applications

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Abstract— The paper presents a study of a magnetic gear (MG) used for high speed applications (26000 r/min); its performances are numerically evaluated. Against common mechanical gears, for which the high trasmission ratio at high power is obtained only by linking several gears, the MG offers a better power density since just one unit can be used (even for high powers), and with acceptable levels of ripples in the torque wave. The paper investigates also the use of different magnet materials, other than the very expesive rear-earth ones, to evaluate the MG's performances. It is clear that the main loss source on a MG is the iron loss component, which is affecting directly its efficiency. Thus, the use a different core meterials will be considered for a final evaluation of the MG's operation to decide on the obtained performances: power density and efficiency.

1. INTRODUCTION

The advantages of the magnetic gear (MG) are clear: there is no need for lubrication, no local heat (and losses) due to teeth contact and no risk for teeth breaking [1–3]. Moreover, a MG offers a higher range of use since for high transmission ratio there is no need to link 2, 3 or more gears together; thus, globally, the efficiency and power density are improved. Besides, with a specific configuration of the MG is possible to obtain smooth mechanical characteristics — i.e., torque and speed.

The attention of the designer, when dealing with a MG, is focused on the used materials, especially the permanent magnets and the active steel. Here, several rear-earth and non-rear-earth materials will be evaluated for the excitation of the MG, as well as different steel materials and sheets thickness. The parralle magnetization variant will be considered, since the radial one is not appropriated for the studied topoloy. To be more specific, the goal of the paper is to evaluate the performances of a high transmission-ration magnetic gear when using Nd-Fe-B, Alnico and Ferite for the magnets, M400, M330 and Vacoflux48 materials for the iron core, with different widths of the sheets (0.5 mm 0.35 mm, 0.2 mm) and parallel magnetization for the magnets. The performances will be evaluated in terms of power density and losses. Regarding this last parameter, it is clear that the main loss component is in the active iron, but for high speed applications the mechanical loss component cannot be neglected [4, 5]. All these elements will be investigated, as well as the torque wave characteristic, which should be as smooth as possible. Thus, we will have an overall picture of the efficiency and performances of the proposed high transmission ratio MG, used for high speed applications.

2. THE MAIN DATA OF THE APPLICATION AND THE TOPOLOGY OF THE MG

The popsed *high speed and high transmission ratio magnetic gear* (HS-HTR-MG) has a common topology: the inner high-speed rotor is with reduced number of pair o poles (1), equipped with inset permanent magnets — to avoid the increase of the inner air-gap, we do not considered a surface mounted solution, with retaining ring; instead, careful attention should be paid to the mechanical resistance of the steel, due to high centrifucal forces. Next, the middle part of the MG is composed by 17 fixed-teeth made of magnetic steel, alternating with empty space (air). Finally, the outer and low speed rotor, is containing 16 pair of poles and is equiped with surface mounted magnets. The cross section of the studied HS-HTR-MG is given in Figure 1.

The main data of the application under study are: 25 kW for the output power, input speed is 26'000 r/min and the output speed is 1625 r/min, meaning that the transmission ratio is 1/16.

The magnetic characteristics of the used steel material, considered for the performances comparison are given in Figure 2.

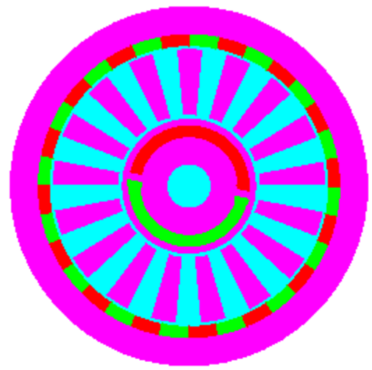


Figure 1: The cross section of the studied HS-HTR-MG.

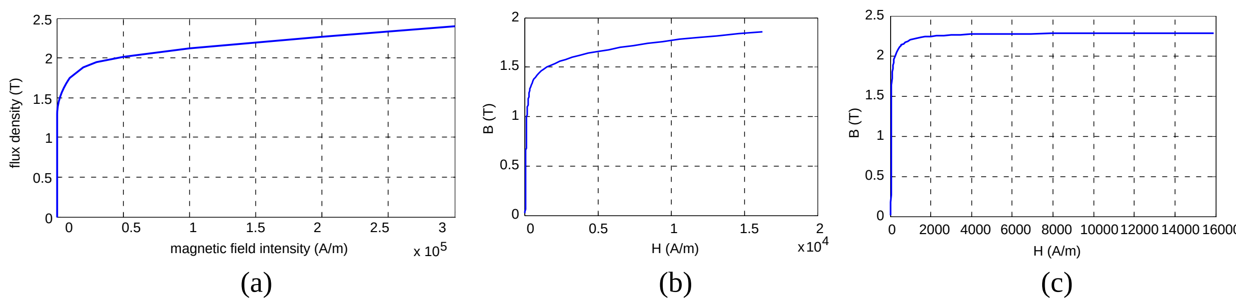


Figure 2: Magnetic characteristics of the used steel: (a) M400-50A; (b) M335-35A; (c) Vacoflux48.

3. THE NUMERICAL ANALYSIS AND THE PERFORMANCES OF THE STUDIED MG

For the simulation results, the *Flux2D* software has been used, since it permits to use two different speeds for two different rotating parts. The geometry, the materials associations and the transitory regime conditions have been considered for the studied MG. The results for when using M400-50A steel (0.5 mm sheet) and Nd-Fe-B magnet material and parallel magnetization are presented in Figure 3–6. In Figure 3, the iron saturation within the active parts of the MG is presented. It is depicted that some parts of the static and rotating parts are saturated. This iron saturation produces iron losses. While the input torque and power (and speed, at 26000 r/min) are applied at the inner-rotor, Figure 4, the MG produces the output power and torque, Figure 5. Very smooth mechanical characteristics (torque wave) is obtained for constant speed operation. The main losses component of the MG, represented by the iron losses in the static and rotating parts, is shown in Figure 6.

Similar simulation results have been obtained from the following cases: while the magnets were of Alnico material, or Ferrite, while the used iron is of M330 steel (0.35 mm sheets) or Vacoflux48 (0.2 mm sheet). The characteristics of the used materials are presented in Table 1 and the performances' comparison is given in Table 2. The simulated iron losses results, for the MG with Vacoflux48 steel, and the same Nd-Fe-B for the magnets, are presented in Figure 7 — a very

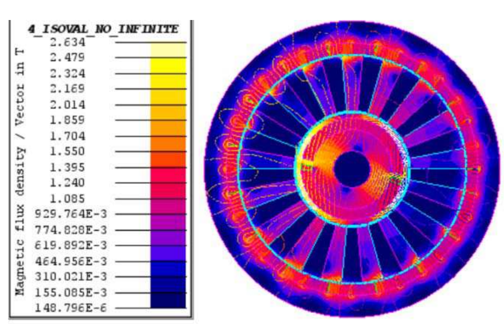


Figure 3: The field and flux density distribution in the active parts of the MG.

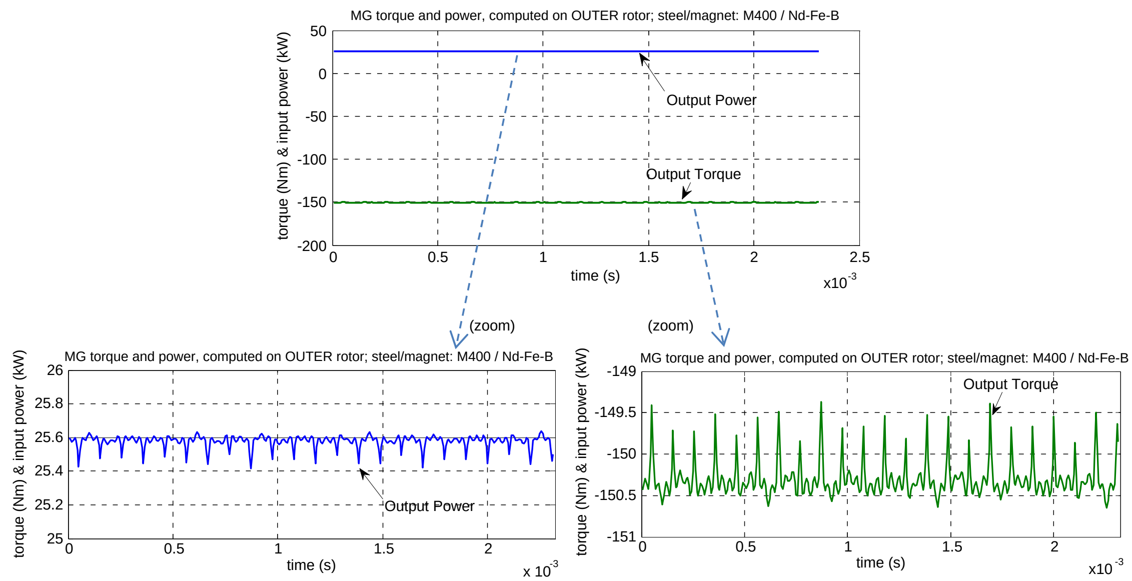


Figure 4: Simulated results for the MG with M400 steel and Nd-Fe-B magnet: input torque and power.

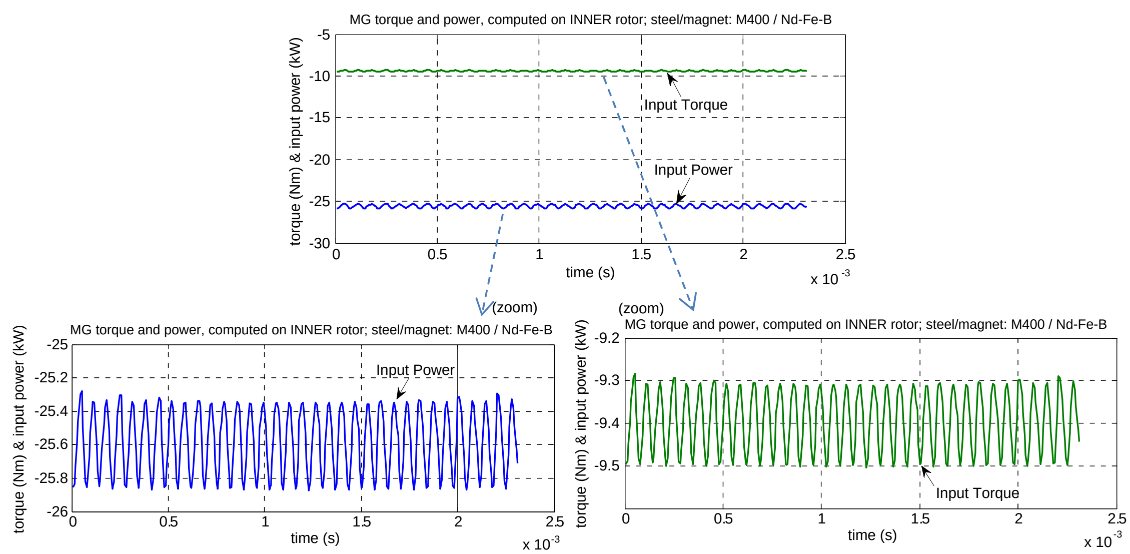


Figure 5: Simulated results for the MG with M400 steel and Nd-Fe-B magnet: output torque and power.

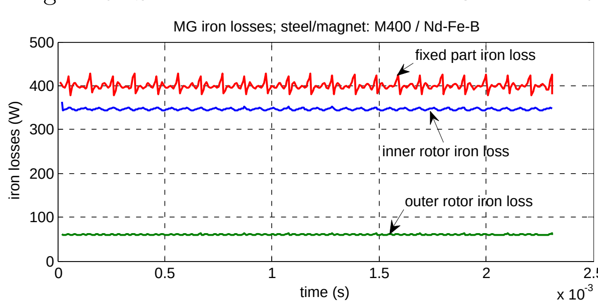


Figure 6: Simulated results for the MG with M400 steel and Nd-Fe-B magnet: iron losses in the active parts.

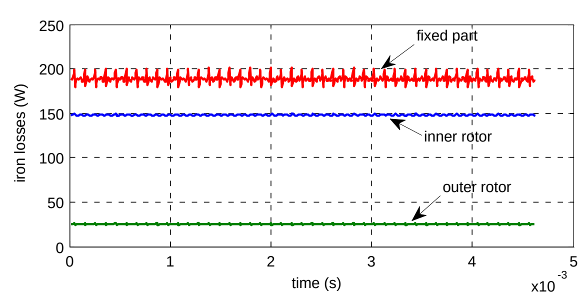


Figure 7: Simulated results for the MG with Vacoflux48 steel and Nd-Fe-B magnets: iron losses in the MG's active parts.

reduced iron loss level can be noticed.

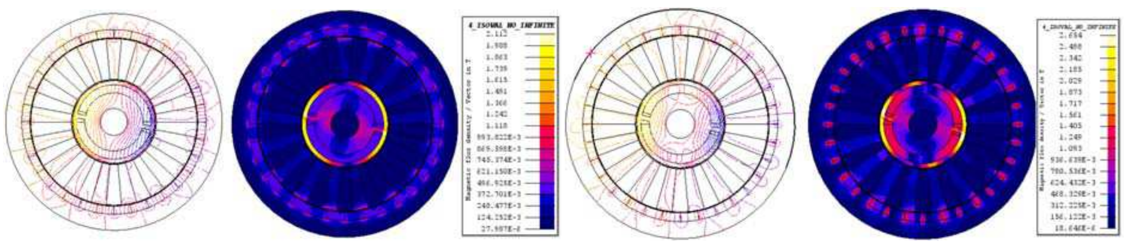
Regarding the Ferrite and Alnico magnets case, most of the magnets flux (energy) remains at the inner rotor level. This is because of the iron bridge, considerred for the inne-rotor, necessary to

Table 1: Materials properties for the studied MG.

Material / **Property**	**Permanent magnet**			**Feromagnetic Steel**		
	Nd-Fe-B	Alnico	Ferrite	M400 (0.5mm)	M335 (0.35mm)	Vacoflux48 (0.2mm)
Remanent flux-density	1.35 T	1.27 T	0.45 T			
Relative magnetic permeability	1.05	1	16	∼4000	∼4000	∼4000
Magnetic field intensity (coercitivity or at saturation)	−930 kA/m	−51.5 kA/m	−300 kA/m	50 kA/m	5 kA/m	1.9 kA/m
Saturation flux-density				2 T	1.6 T	2.25 T

Table 2: Performances comparison for different used materials.

Parameter / **MG' materials**	**Input torque (Nm)**	**Output torque (Nm)**	**Ripple of input torque (%)**	**Ripple of output torque (%)**	**Total iron losses (W)**
Nd-Fe-B + M400	9.34	150.3	2.14	0.79	806.9
Alnico + M400	0.82	13.14	1.82	0.68	51.9
Ferrite + M400	0.637	10.18	3.3	0.98	229
Nd-Fe-B + M335	9.34	150.3	2.35	0.86	870
Nd-Fe-B + Vacoflux48	9.34	150.3	1.68	0.84	396.6



(a) (b)

Figure 8: Field lines & flux density distribution in the MG with Vacoflux48 steel and (a) Ferrite or (b) Alnico magnet.

keep the magnets while high rotational speeds and centrifugal forces are reached. This iron bridge cannot be smaller, otherwise the rotor iron will break. A thinner iron birdge will be sufficient to force the magnets flux to pass from the inner to outer rotor, even in the case of Ferrite and Alnico magnets, but due to the high rotational speed for the inner rotor, this MG configuration is not suited for such materials, even if we have very good iron material (Vacoflux48).

The field and flux density distribution for Ferrite and Alnico materials is depicted in Figure 8. Here, one can see how the inner rotor flux remains at rotor level, because of the iron bridge. From the obtained results, it is clear that for such MG configuration (with iron bridge, needed for high rotational speed) the Ferrite and Alnico materials are not suited. Regarding the used steel, the M400 variant offers the most decreased torque ripples, — but the values are practically the same — while the Vacoflux48 is the best variant in terms of efficiency, due to very decreased iron losses. Nevertheless, the choise for one material or another should consider the cost of the steel too (the Vacoflux48 is very expensive).

4. CONCLUSIONS

This paper presents the performances comparison of a high speed magnetic gear suited for electric vehicle applications. For different steel and magnet materials (M400, M330 and Vacoflux48), with different sheet widths, for different magnet materials (Nd-Fe-B, Alnico and Ferrite) and parallel magnetization, the output characteristics were compared in terms of torque ripples and iron loss level (efficiency). It has been found that the M400/Nd-Fe-B offers the most reduced torque ripples, while the Vacoflux48 the best efficiency.

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