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Design of a 200 kW PM SynRel Motor without rare-earth magnets for electric vehicle

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Abstract

This paper presents a design of a 200 kW permanent magnet (PM)-assisted synchronous reluctance machine (PMASynRM) using ferrite magnets. This machine was developed for an electrical vehicle application requiring high torque and high power density. The challenge was to design a high power and high speed electric machine using ferrite magnets. In this article, a suitable design is proposed with respect to the demagnetization of the ferrite magnets, mechanical strength, thermal behaviour and torque ripple. Electromagnetic characteristics including torque, output power, losses and efficiency are calculated using 2-D Finite Element Analysis (FEA).The mechanical stress and thermal analysis have been also performed using finite elements analysis.

Key words: Permanent Magnet (PM)-assisted synchronous reluctance machine, ferrite magnet, demagnetization, mechanical strength, torque ripple

Introduction

In recent years, several research projects have been carried out on the electrification of vehicles which is becoming a hot topic these days especially with the emergence of many new electric vehicles in the market. Theses works are focused a global approach for hybridation and electrification of the vehicle as a system[9]. These are also focused on main components such as batteries [10] and electrical machines. For hybrid electrics vehicles (HEVs) and electric vehicles (EVs), permanent magnet synchronous machines (PMSMs) with rare-earth permanent magnets (PMs) are widely used [1]. Many topologies of PMSMs for traction applications are actively studied [2]. PMSM using rare-earth PMs has some advantages, combining high power and torque density, a relevant power factor, a wide constant power speed range and a high efficiency. However, price and availability of rare-earth materials, like Dysprosium or Neodymium, will probably become a problem in a few years [8]. Therefore, electrical machines with less or no rare-earth material will be relevant for EVs and HEVs applications. For this purpose, one solution is to use a Switched Reluctance Motor (SRM) without PMs. This technology has some advantages such as a simple structure, rotor robustness and the potential to operate at high temperature and to have a torque-speed range which can be competitive with PMSMs employed in EVs and HEVs [3]. Nevertheless, high level of vibrations and acoustic noises constitute usually a problem [2]. Synchronous reluctance machine (SynRM) can also be a candidate for a free rare-earth material machine, but its torque and power density, power factor and efficiency are lower in comparison to PMSMs [3]. By adding the proper amount of Ferrite PMs in SynRM, the torque density and power density can be greatly improved [4]. This kind of topology, called PM-assisted SynRM (PMASynRM), presents a reduced total costs due to the use of ferrite magnets instead of rare-earth materials such as Neodymium and Dysprosium. To achieve the required performances, the rotor structure of the PMASynRM must be designed with an adequate process. Furthermore, the irreversible demagnetization of the ferrite magnets in cold weather, the mechanical strength of rotor at the maximum speed,the thermal behaviour and torque ripple should be considered in the design methodology. In this paper, the design of a low cost PM-assisted synchronous reluctance machine using ferrite magnets is proposed using Finite Element Method (FEM). The demagnetization, mechanical strength, thermal behaviour and torque ripple have been all taken into account in the design process. Electromagnetic characteristics such as torque, output power and efficiency are given.

1 Requirements and machine design process

The objective of this study is to design a new PMASynRM with the following requirements :

- DC Voltage = 800V
- Maximum torque : 424 N.m @ 590A.peak
- Maximum power : 200 kW @ 5000rpm
- Maximum power at high speed : 70 kW
- Maximum functional speed: 17500rpm

Some geometric constraints are also taken into account :

- Stator outer diameter : 220 mm
- Stack length : 200 mm
- Airgap = 0.6 mm.

The topology of the PMASynRM motor considered in this paper is shown in Figure 1. The particularity of this design is an asymmetrical rotor with three flux barriers and 7 magnets per pole. The PMASynRM is filled with ferrite magnet (blue and red in the figure below).

A ferrite magnet with a new composition (NMF G15) was chosen for its superior characteristics, namely, the coercive force of this ferrite magnet is assumed to be 345 kA/m at -40 ° C. NMF G15 demagnetization curve is given in Figure 2. The resulting motor for this application has a maximum current density of 24 Arms/mm2, imposing a water cooling system and potting for end windings.

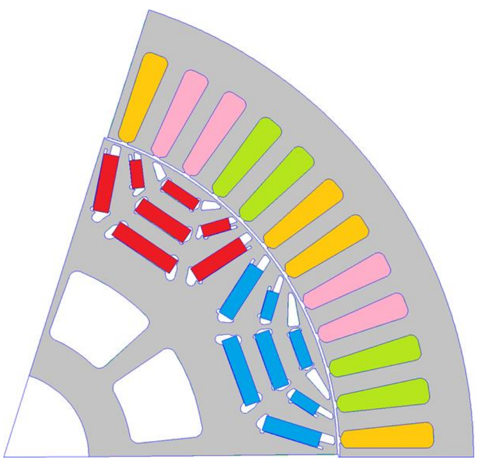

Figure 1: Motor geometry

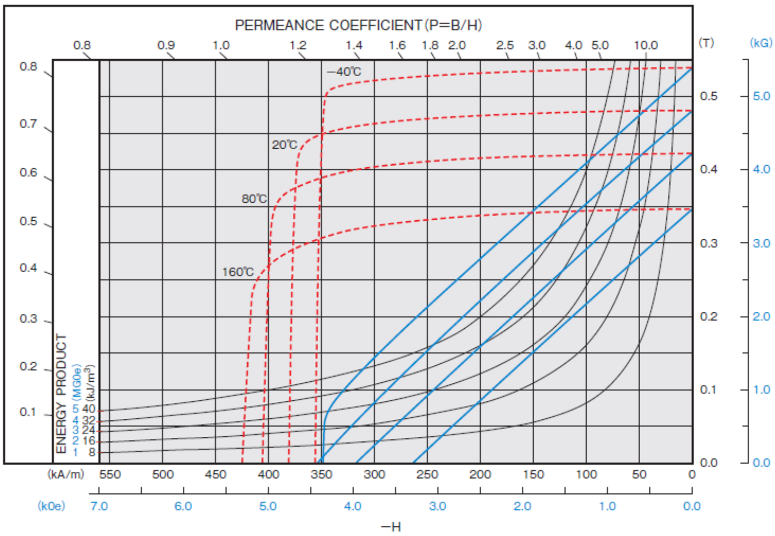

Figure 2: Demagnetization curve of ferrite magnet (-40 °C).

1.1 Design process methodology

The design procedure is performed using finite element analysis .The rotor ribs and barriers are designed in order to respect maximal mechanical strength in the high-speed region and to counter the effect of armature reaction field on the PM to avoid demagnetization. The final design is obtained by optimizing the barriers positions in order to improve the average torque and reduce torque ripple.

1.2 Electro magnetic performances

The output torque and power versus speed are shown in Figure 3. With the proposed design, the maximum output power is around 221 kW at 5100 rpm with the peak torque equal to 424 N·m respecting the requirements. At maximum speed (17 500 rpm), the peak power is equal to 93kW.

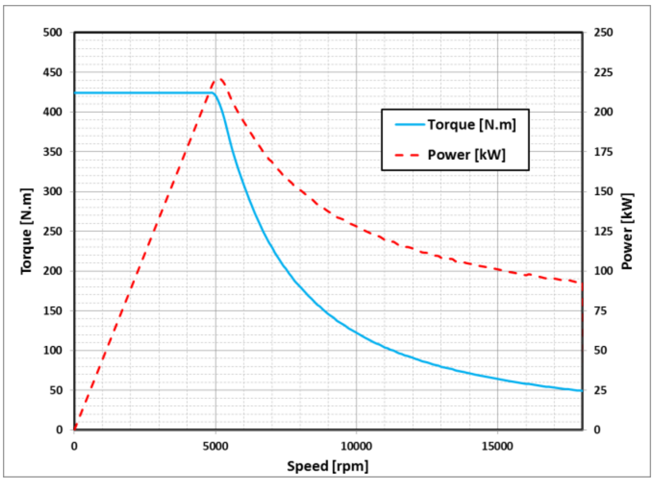

Figure 3: Torque and output power vs. speed characteristics.

1.3 Evaluation of the Irreversible Demagnetization Rate

A particular challenge in designing a PM machine with ferrite magnets is the management of the low remanent flux and relative low coercivity which makes them susceptible to demagnetization. In a typical application, the demagnetization is more severe at the magnet corners and near the air-gap. In the design process, demagnetization phenomenon is investigated for a magnet temperature of -40 °C considered as the worst operating condition for the ferrite material. The demagnetization rate (DR) is shown in Figure 4, showing a limited demagnetization rate of about 1,9% at the rated current (590 A.peak). and 4.9% at 677 A peak (maximum short-circuit test current). Therefore, the proposed design presents a high tolerance to magnet demagnetization.

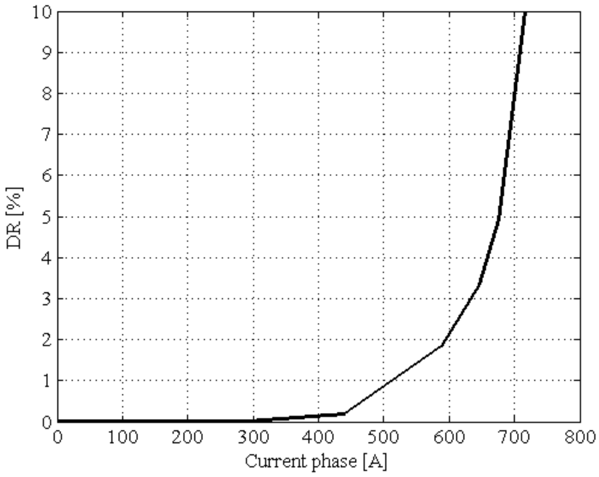

Figure 4: Demagnetization rate of PMASynRM at – 40 °C

1.4 Torque ripple reduction

The torque ripple reduction is achieved by optimizing the barriers position. Figure 5shows the torque ripple map. At maximum torque , the torque ripple is less than 5 %. High values of torque ripple occur at flux weakening operation points and can reach15%

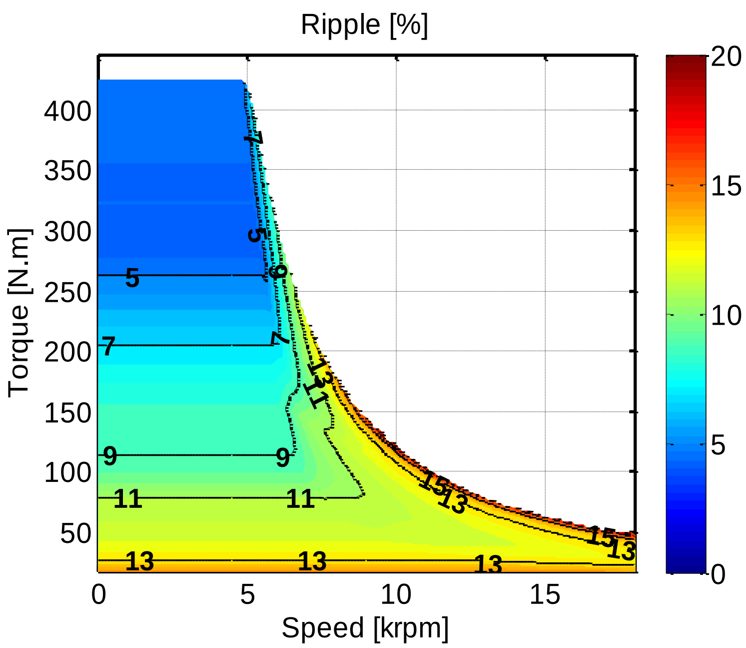

Figure 5:Torque ripple map

1.5 Efficiency map

The efficiency map has been determined using a FEM software taking into account iron losses which are estimated using Bertotti's model [11]. The efficiency map of the proposed PMASynRM is given in Figure 7. The maximum efficiency is about 96%. The Iron losses map is also given in Figure 6 b), with a maximum of 5 kW. As for copper losses, they can reach 10 kW as shown in Figure 6 b).

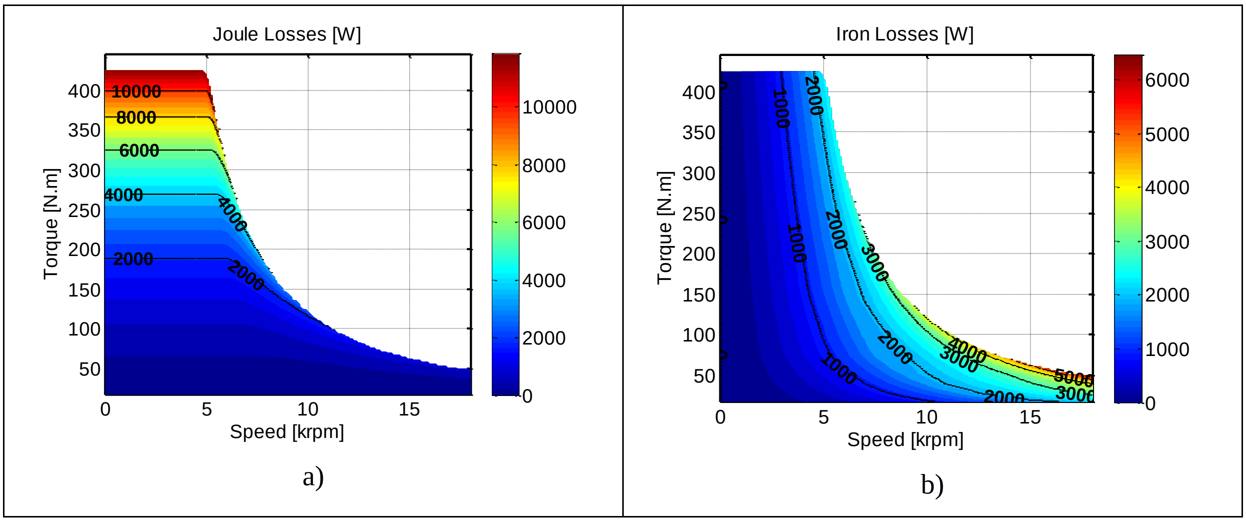

Figure 6:a) Joule losses and b) Iron losses maps

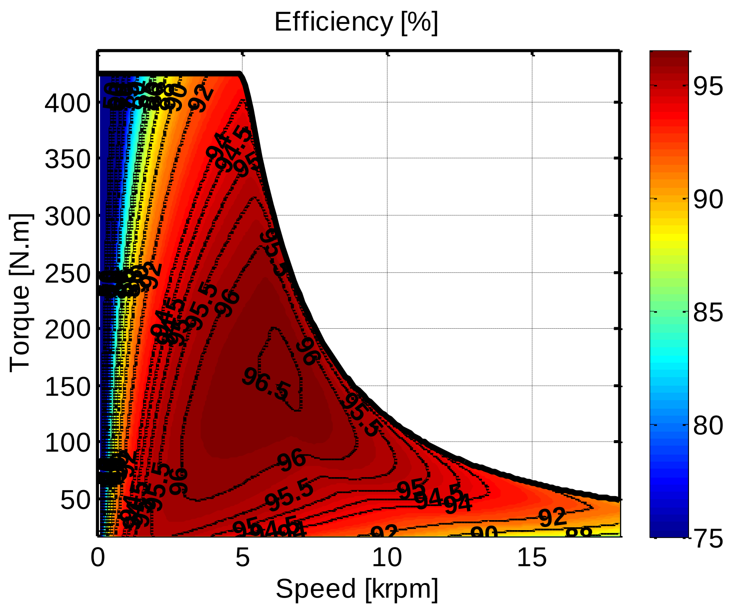

Figure 7: Efficiency map

1.6 Mechanical stress

The mechanical strength of the rotor has been examined using FEM. We have studied the stress generated by centrifugal forces at 17500 rpm. To validate our design, the Von-Mises criteria is used with a maximum mechanical stress of 450 MPa. Figure 8 shows the distribution of the von Mises stress at maximum speed. The ferrite magnets were hidden in this picture. Maximum stress occurs in the bridges connecting the PMs in the lowest barrier . At 17500 rpm, the maximum mechanical stress is about 433 Mpa which approves the design.

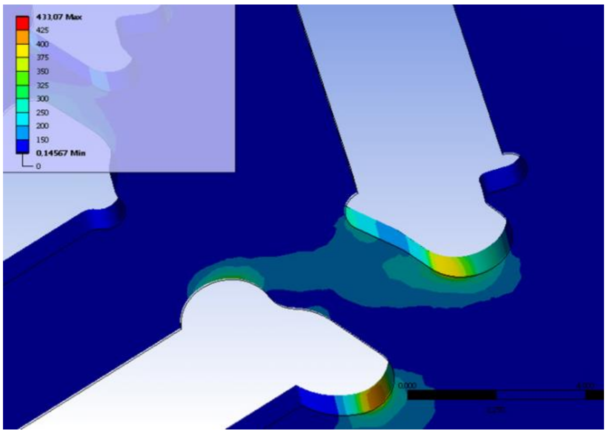

Figure 8: Von Mises stress at the maximum speed

1.7 Thermal analysis

The thermal analysis is performed using Motor CAD software (Figure 9). For this analysis, a stator water cooling system is used. The water flow is about 10 l/min and the inlet temperature of the water is considered at 65 °C. The simulation is carried out by considering an ambient temperature of 40°C. Moreover, to reduce the temperature, potting (λ=0.6W/m/°C) is used in the slot and the end windings. The analysis is done in both steady and transient cases.

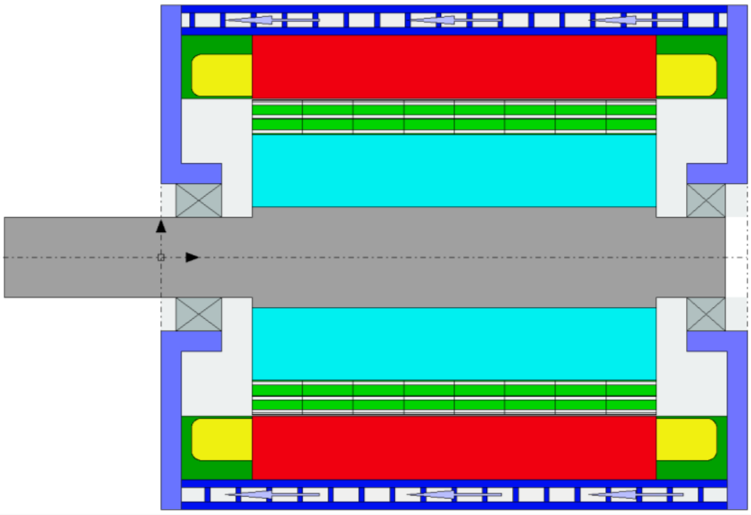

Figure 9: Axial section of the Motor and Housing

Figure 10 shows the duty cycle considered for our application. The electric motor operates for 60 minutes at a nominal power of 70 kW @5°500rpm before generating a peak power og 200 kW @5°500rpm for 30 s. Figure 11 shows the evolution of the temperature in the windings (hotspot), in the magnets as well as in rotor and stator back iron. The maximum temperature in the winding and the magnet at nominal operation is respectively about 124 ° C and 135 ° C. At 200 kw, the temperatures in the windings and in the magnets reach respectively 171.5°C and 139 °C after 30 s. At these temperatues, Class H isolation must be used. This class has 180°C as temperature limit.

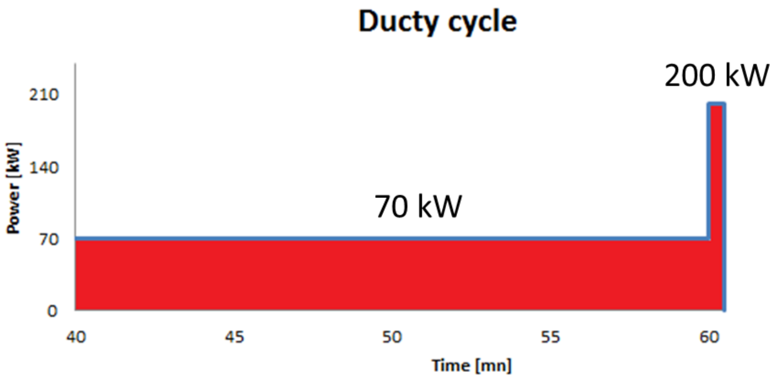

Figure 10: Duty cycle

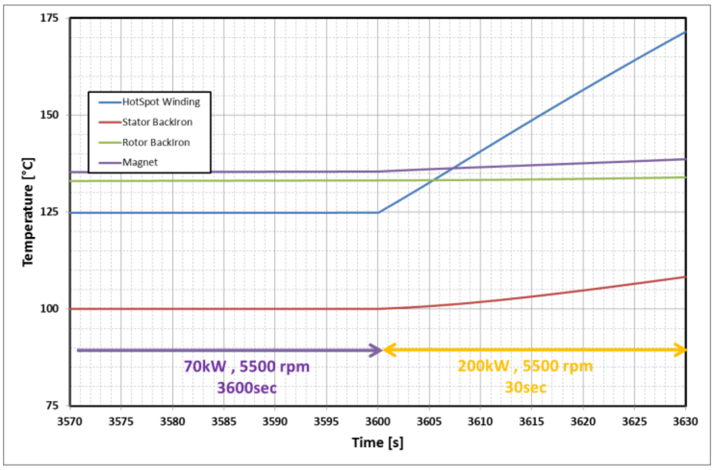

Figure 11: Temporal evolution of the temperature on duty cycle

2 Influence of the magnets type on the performances

In this section, the influence of the magnet type on the performances of the designed motor is investigated. Such, the ferrite magnets are replaced by Neodymium ones (NdFeB).In this case, the mass of magnet increase around 55%. Figure 12 shows the torque and output power versus the rotational speed.

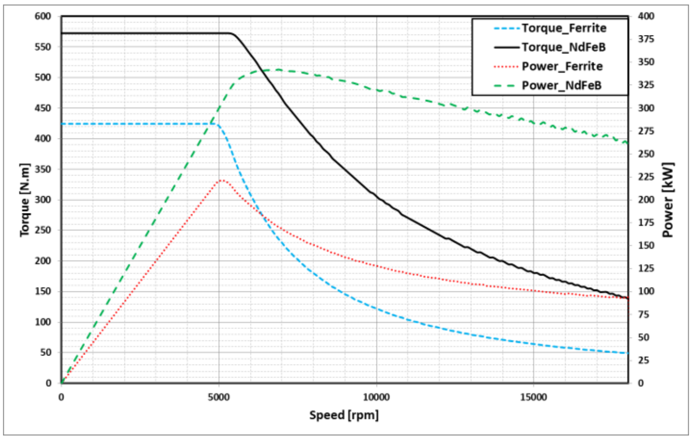

Figure 12: magnet type impact

Using NdFeB magnets (N38UH) instead of ferrites allows to increase the maximum torque by 35%. . However, the most important impact is in the constant power operating zone. In fact, the NdFeB magnets ensure a relatively constant power over a wide speed range unlike ferrites, where a drastic drop in power occurs when exceeding the base speed. For comparison, the power at maximum speed is dropped by 230% compared to that obtained with N38UH.

3 Conclusion

In this paper, a design of a ferrite permanent magnet (PM)-assisted synchronous reluctance machine (PMASynRM) with high power (221 KW) and high torque (424 N.m) is proposed. The motor design has an assymetric rotor with 3 flux barriers. Different phenomena's such as magnet demagnetization, mechanical strength, thermal behaviour and torque ripple were analysed. The ferrite magnets were also replaced by Neodymium ones and a performance comparison has been carried out with the initial ferrite motor design. Although a loss in electromagnetic performances is enevitable, this study has shown that with a proper design methodology, the ferrite PMASynRM can still represent an interesting solution for high power and high torque traction applications..

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