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Performances of direct drive and magnetically geared PMSMs with different cooling technologies

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The reduction of CO_2/NO_x emissions in air transportation requires massive electrification of aircraft propulsion. The paper presents electromagnetic and thermal design of surface mounted and magnetically geared PM machines. The aim is to analyze the performances of such machines in the frame of electrified aircraft propulsion. Several cooling technologies will be used to assess the effectiveness of each propulsion solution regarding torque and power densities.

Index Terms—**Air and liquid cooling, Magnetic gear, Optimization, PMSM**

I. Introduction

The reduction of CO_2/NO_x emissions in air transportation requires massive electrification of aircraft propulsion. Permanent magnet machines exhibit the highest power density and efficiency [1], particularly for high-speed operation. For medium and low speed applications, it is weight/size effective to combine such a high-speed machine together with a mechanical gearbox to achieve a compact drive. However, this association has some disadvantages mainly due to reliability issues which are very important in aircraft. Magnetic gears can achieve high specific torque density so their combination to PM synchronous machines results in high torque density drive while this contactless torque transmission avoids the problems of jamming [2], [3]. More recently, it has been shown that magnetically geared PMSM can also achieve the required increase in torque density and power density in aerospace applications [4].

This paper investigates the potential benefit of using magnetic gear machines at medium speeds compatible with those found in aircraft propulsion. A general electromagnetic and thermal study is conducted for different cooling technologies to compare the performances of direct drive and magnetically geared PM machines.

II. Magnetically Geared PM Machine

A 2D cross section view of the considered magnetically geared PM machine is shown in Figure 1. This concept, named Pseudo-Direct Drive (PDD) PM machine, has been introduced in [2]. It combines a PMSM and a magnetic gear in the same device. The magnetic gear principle of operation is based on modulating the magnetic field created by p_h PM pole-pairs (high-speed rotor) by N_s ferromagnetic pole pieces (low-speed rotor). The obtained field interacts with stationary p_l PM pole-pairs of the external armature to transmit torque to the low-speed load. The combination $p_l=N_s-p_h$ results in the highest torque transmission capability of the gear. The 3-phase winding in the external armature creates a rotating magnetic field which interacts with the p_h PM pole-pairs to generate the torque on the high-speed rotor.

We define the gear ratio is defined as the ratio of the "high-speed rotor" speed Ω_h and the "low speed rotor" speed Ω:

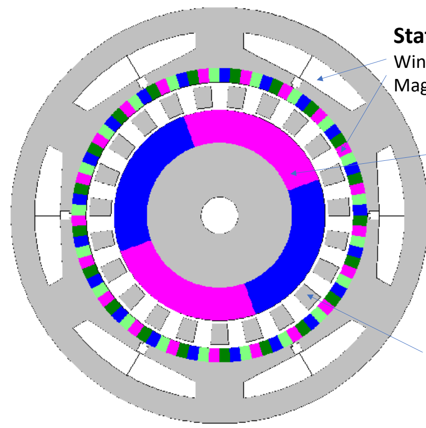

Fig. 1. 2D cross section view of magnetically geared PMSM (PDD)

$$G_r = \frac{\Omega}{\Omega_h} = \frac{p_h}{N_s} \quad (1)$$

Notice that the steady mean torque on the high-speed rotor is null as the machine's torque cancels the gear's high-speed torque.

III. Design of the Magnetic Gear PM Machine

The design of the PDD is complex owing the large number of geometric and physical parameters to be considered. The design process requires the analysis of a magnetically coupled PM machine and magnetic gear. Here, we choose to study the two sub-systems separately.

A. *Magnetic gear design*

2D finite element computations are conducted under linear conditions to achieve different parametric studies to determine the optimal torque transmission capabilities of the magnetic gear. For specified low speed torque and a given gear ratio, these parametric studies allow to define the optimal geometrical parameters. Note that G_r and p_h are chosen such as the high-speed Ω_h leads to frequency value compatible with the iron losses of the selected lamination of the ferromagnetic circuits.

B. *PM machine design*

The electromagnetic sizing of any electrical machine uses the concepts of magnetic and electric loading [5]-[6]. The starting point for the sizing is the expression of the electromagnetic power transmitted throughout the air-gap. For the machine side which rotates at the speed Ω_h in rad/s, the transmitted power is:

$$P_{em} = 2\Omega_h k_w \cos(\psi) \,.\, (BH) . \pi R_a^2 L \qquad (2)$$

Where k_w is the winding factor (1st harmonic), ψ the phase shift between tangential field and normal flux density, R_a the armature bore radius, L the axial length, B the stator bore rms normal flux density (magnetic loading) and H the stator bore rms tangential magnetic field (electric loading).

The torque is therefore proportional to the product (BH) and the volume at the stator bore. For a surface mounted PMSM, the air-gap rms normal flux density is calculated analytically in 2D [3]. For radially magnetized magnets and $p > 1$, the value of B is calculated on the stator bore radius R_a by:

$$\mathrm{B} = \frac{4B_{rem}}{\pi} . \sin\left(\frac{\beta\pi}{2}\right) . \frac{p}{1-p^2} . R_a^{-p-1} . \left(\frac{\frac{2R_a^{2p}}{R_{cr}^{p-1}} - R_m^{p+1} . \left((1-p) + \frac{R_m^{-2p}}{R_a^{-2p}} . (1+p) \right)}{\left(1 - \left(\frac{R_a}{R_{cr}}\right)^{2p} \right)} + (1-p) . R_m^{p+1} \right) \qquad (3)$$

Where R_m and R_{cr} are respectively the stator bore radius, the magnet outer radius and the rotor yoke outer radius, B_{rem} the remanent flux density, p the number of pole pairs and β, the angular opening of the magnets. For sizing the PM machine in the PDD, R_a and B values are issued from the gear sizing.

The electric loading H is:

$$H = \frac{NI}{2\pi R_a} \qquad (4)$$

Where N is the total number of conductors and I the rms current flowing in the conductor. Relations (2)-(4) allow the determination of R_a and L as well as the other stator and rotor dimensions by specifying a current density and a maximal saturation level in iron.

IV. Results and Conclusion

Simulation studies are conducted propulsion motor rated 150 kW, 1000 rpm. Air cooling with a convection coefficient of $h = 150\ W/m^2K$ is considered. Both PDD and PMSM have been sized for this specification. A minimal efficiency of 0.95 is required from the design while the external diameter is less than 0.6 m. The designed PDD is shown in Figure 2 where we plot the flux density distribution. The harmonics of the radial flux density distribution on the stator bore are shown in figure 3 where the preponderant harmonics corresponds to $\mathrm{p}_h = 6$ and $\mathrm{p}_l = 11$, so a gear ratio $\mathrm{G}_r = 2{,}833$. The external diameter of the designed PDD is 0,6 m and its axial length is 0,23 m. This result in a total active mass of about 190 kg.

The designed PMSM has the same diameter but an axial length of 0,31 m, resulting in a total mass of 250 kg which is 33% higher than the PDD one.

In the full paper, more results will be presented regarding the performances for liquid cooled machines.

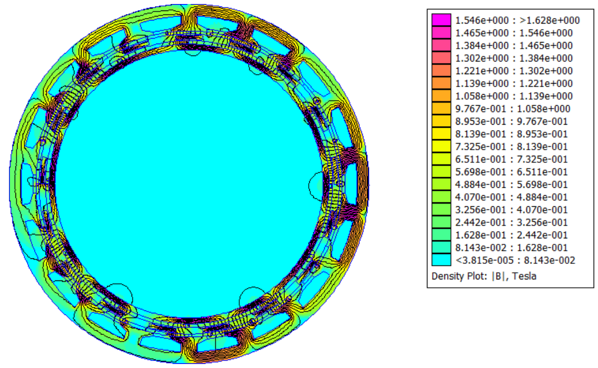

Fig. 2. Flux density distribution in the PDD ($\mathrm{p}_h = 6$, $\mathrm{N}_s = 17$, $\mathrm{G}_r = 2{,}833$)

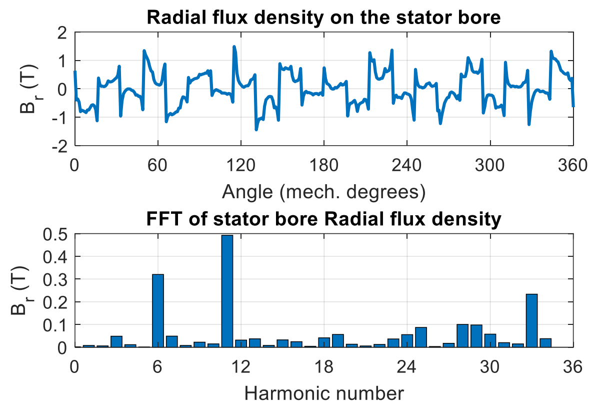

Fig. 3. Radial flux density on the stator bore and its harmonics.

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