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# DESIGN OF A PERMANENT MAGNET MACHINE ABLE TO WORK AT HIGH TEMPERATURES.

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**Abstract** – The paper presents a methodology for assessing the effects of using different materials for magnetic wedges and applying magnet segmentation on the power losses and performance of permanent magnet machines operating at high temperatures. Time stepping finite element simulation in 2D and 3D is employed to obtain field and current distributions, power losses and derive torque ripples under various configurations.

## I. INTRODUCTION

Aircrafts designed to have lower environmental footprints will use more electric power that will replace hydraulic power and hot air sources. The aircraft industry will need compact and reliable generators and actuators able to work in a very hot environment, especially near the propulsion turbines. With the classical polymer-based winding technology the internal temperatures cannot exceed about 280°C for steady state operations. In order to work continuously at higher internal temperatures it is necessary to use inorganic Electrical Insulation Systems (EIS) and to adapt the machine design to this inorganic technology [1,2]. The inorganic insulation layers have poor mechanical characteristics and the coils must be rigid objects placed on the stator teeth. The structure of the motor winding must be a fractional-slot concentrated winding. Two structures are available for rotor: for the first one, the magnets are placed on the external surface or the rotor; for the second one, the magnets are buried in soft magnetic parts of the rotor. To ensure an adequate magnetic behaviour at high temperature (HT°), special permanent magnets were chosen characterized by relatively large electrical conductivity in comparison to standard magnets. For this reasons a special attention must be paid to the eddy currents in permanent magnet. To analyse this phenomenon the time-stepping 2D and 3D finite element method (FEM) was used. The maximum continuous operating temperature of permanent magnets depends on the temperature coefficients  $TC(HcJ)$  of the coercivity,  $TC(Br)$ , of the remanent polarization, and the load line  $B/\mu_0H$  of the magnet. The high temperature necessitates the use of permanent magnets with a high Curie point. In our case the chosen material is Vacomax  $Sm_2Co_{17}$  [3], characterised by high electrical conductivity compared with ferrites. The numbers of poles and slots were carefully chosen to reduce the high frequency slotting effects on PM losses and torque ripples. A popular method to limit the ripple torque and eddy current losses in PMs involves the use of magnetic wedges. The numbers of poles and slots were carefully chosen to reduce the high frequency slotting effects on PM losses and torque ripples [4-7]. A popular method to limit the ripple torque and eddy current losses in PMs involves the use of

magnetic wedges. Three different designs have been considered in this paper: without magnetic wedges (NM), with magnetic wedges build from the same material as the stator core (M), and semi-magnetic wedges made of a composite material (SM).

## II. SIMULATION METHOD

For the purpose of the 3D simulation a quarter of the machine has been considered to benefit from the magnetic symmetry. The windings are modelled by connections to external resistances. The time stepping analysis was performed assuming constant speed of rotation of the rotor. The 3D mesh contains 4.264778 million elements in total. In the magnets, as the conductive areas, the elements size was chosen to be less than one-third of the penetration depth. Moreover, the distribution of the density of the mesh is greater than to correctly reproduce the effect of rotation of the rotor relative to the stator. To reduce the computation times the simulations were performed on a virtual machine with eight cores

First the simulation was performed for the surface magnets machine. The current density distribution on and close to the surface of the permanent magnets is shown in Fig. 1.

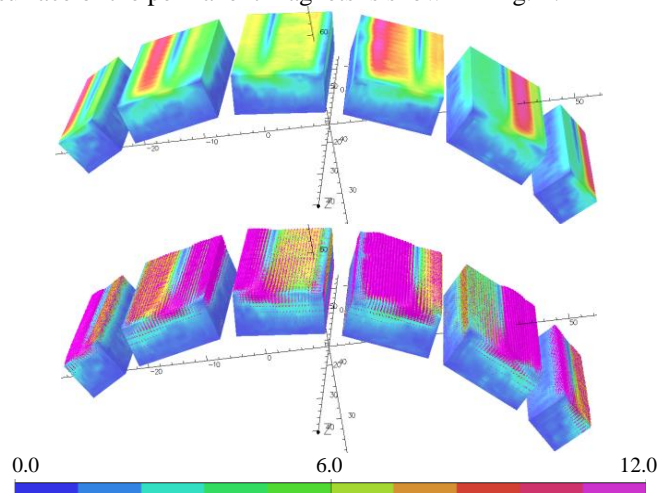


Fig. 1: Current density distribution on the surface of PM.

As can be seen, the skin depth is small; hence the total losses in the magnet are not high, despite the large value of the surface current. However, the permanent magnet losses cause significant concern as – due to the design of the machine – the removal of heat from the rotor is inhibited. Excessive losses in the rotor may therefore result in local

temperatures exceeding the Curie point and hence causing an irreversible demagnetization of parts of the magnet. Some limitation of the losses in the magnets may be accomplished by magnet segmentation [8]. Magnet segmentation results in significant reduction of PM losses. Design enables a significant reduction in losses in the magnets is the design of the magnets embedded into the rotor known as interior PM. Therefore, with similar stator winding, the voltage induced in the phase is smaller than in the case of surface mounted magnets. Figure 2 shows the stator voltage, the cogging torque at no-load and the comparison with the case of surface-mounted magnets.

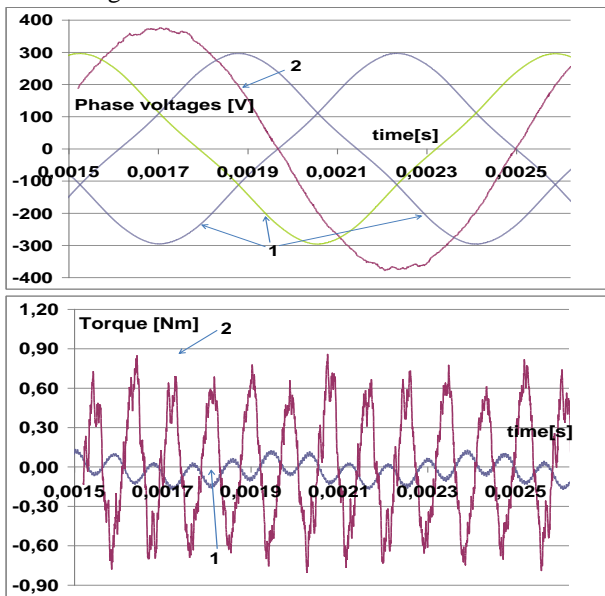


Fig. 2: Comparison of stator voltages for the embedded (1) surface magnet (2) (upper figure). Comparison of cogging torque for embedded (1) and surface magnets (-2). (lower figure).

The benefits of the embedded structure are a smoother voltage and a much smaller cogging torque even than for the construction of non-magnetic wedges. For the loaded generator, the embedded magnets structure has also a much lower torque ripple. The permanent magnet is protected from pulsating fields by the iron of the rotor. Consequently, eddy currents are induced mainly on the surface of the magnet and in the region of the upper corners.

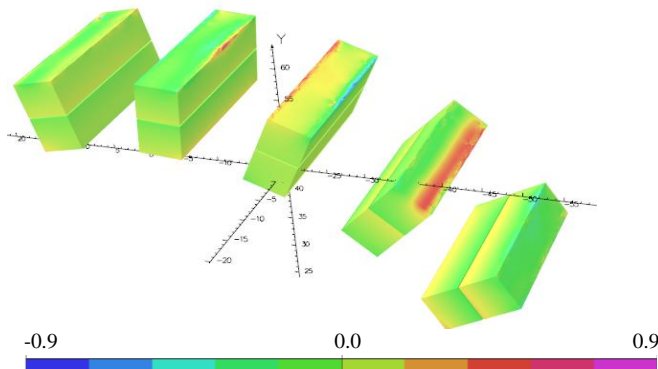


Fig. 3: Magnitude of current density ( $A/mm^2$ ) calculated using 3D model.

Lower losses in the magnets and a smaller cogging torque are possible by adding magnetic wedges between the stator teeth. The best effect is obtained using wedges made of

stainless martensitic steel, which characteristics are similar to the magnetic material of the core. For composite wedges of low permeability the cogging torque is higher. Figure 3 shows the distribution of the axial component of the current density for the motor with wedges made from the stainless martensitic steel. Through the use of magnetic wedges made of martensitic steel it was possible to reduce the losses in the structure with the surface magnet to a value of 22.9 W, and for the structure with embedded magnets to 0.72 W (1.07 W for the structure without the wedges).

### III. CONCLUSIONS

The paper proposes a methodology for computational assessment of the influence of the type of the material used for magnetic wedges and conductivity and segmentation of the permanent magnets on the power losses in the magnets. Additional analysis is provided and comparison of two designs, the surface mounted magnets and the case of the magnets built into the rotor is presented. The comparison consider the torque ripple, which is important from the point of view of mechanical vibration, and power losses in the magnets, which may create a potential hazard due to local overheating of the magnets. A number of simulations, which enabled the dimensioning of the machine were carried out.

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