Magnetic Design Considerations for an Axial Flux PM Machine with Field Control Capability.

D. GONZÁLEZ, J. A. TAPIA, , R. WALLACE, M. A. VALENZUELA, Electrical Engineering Dept. University of Concepcion, Chile.

In PM machines, magnets are generally located on the rotor, without Joule effect losses, no brushes and sliding contact to provide energy to the field. All these features mean that the PM machine offers better efficiency, reliability and power density. Modern PMs based on NdFeB allows us to mount directly on the rotor surface given high air gap flux density, reduced volume and lower manufacturer requirements . In addition, low price and excellent magnet attributes increase the ability to integrate this type of machine into new applications. However, for variable speed applications, PM machines present difficulties due to the constant excitation of the magnets. The induced voltage increases linearly with frequency reducing the speed range operation over rated speed. As a result, the air gap flux has to be controlled for the overrated speed operation. Several control techniques to command the air gap flux have been discussed in the literature. On the other hand, the axial flux machine brings us the high torque and power density that is particularly required for traction and power generation applications, compared to radial configurations.

In this paper, an axial flux surface-mounted PM machine configuration allowing us to control the air gap flux is proposed. To perform this control, the machine designers consider modifying the rotor pole. In order to reduce the *d-axis* reluctance, a portion of the magnet was substituted by an iron part. In this manner, a demagnetizing *d-axis* flux component can easily be generated by the armature reaction, so that the total air gap flux is reduced.

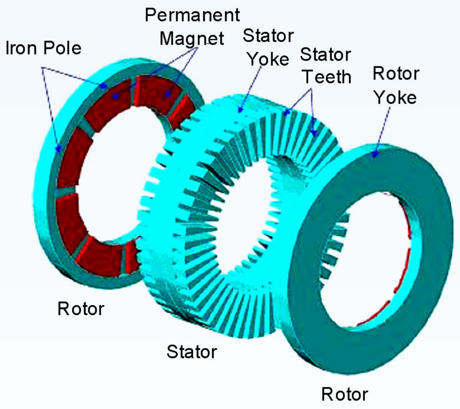

Figure 1: Axial flux PM machine with field weakening capability.

A 3D Finite Element Analysis (3D-FEA) for the proposed machine was carried out with MAGSOFT's FLUX3D commercial software. This analysis demonstrates the feasibility of controlling the air gap flux. In addition, several magnetic design considerations were assessed to maximize its operation.

I - Description and operation of the axial flux PM machine

The machine topology comprises a central stator and two rotors as depicted in Figure 1. The stator contains two sets of 3-phase AC windings (not shown), one in front of each rotor. Rotors are North-North, so that each side of the machine has an independent magnetic circuit and the control can be performed separately. The rotor poles are shaped by two parts, a permanent magnet and an iron part. In this manner, *d-axis* path can be taken as a combination of the iron and magnet reluctance.

The vector control technique allows us to obtain the best machine performance across the whole range of operations. In particular, over the rated speed, the voltage must be constrained to 1.0 pu. To perform such as control, the armature reaction is used to demagnetize the machine by controlling the stator current vector. Due to the low reluctance achieved with the iron, the section *d-axis* current component is greatly reduced.

II - Finite Element Analysis

1- Geometry and Mesh Generation.

The machine simulation by FLUX3D starts from a three-dimensional geometry construction. In the GEOMETRY model a graphic representation of the magnetic structure to analyse has to be constructed. Due to the symmetry of the magnetic circuit, is possible simulate only one or two poles of the machine, depending of the results sought.

Once the geometry is complete the three-dimensional elements used by the Finite Element Method have to be generated. These are obtained using the initial mesh generation in each face and volume of the structure. The geometry and mesh generation for two machine poles are depicted in figure 2.

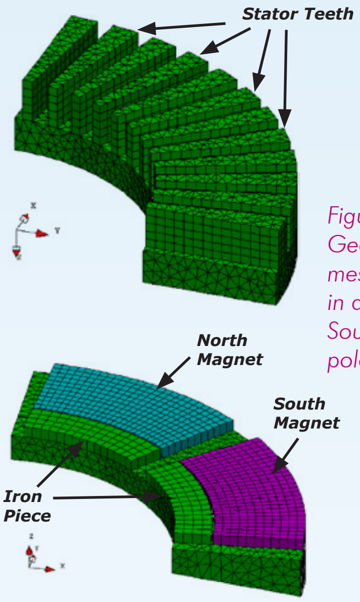

Figure 2: Geometry and mesh generation in a North and South machine poles.

2- Demagnetizing *d-axis* Flux Component Analysis.

The FLUX3D software gives magnitude and path of the all flux component in the machine pole. The first analysis was a no-load configuration, that is, only a flux component imposed by the magnet. It flows by the section of teeth in front of the magnet, while the upper portion and the iron part (in the rotor pole) have a low flux density.

In order to prove the field weakening capability of the proposed topology, a negative flux was injected in *d-axis*. The stator vector current was directed in front of the magnet, resulting in a significant reduction in the air gap flux. As is depicted in figure 3, the upper portion of the stator teeth has a high saturation by armature reaction flux in the *d-axis*.

(continued on page 7)

Magnetic Design Considerations for an Axial Flux PM Machine... (continued)

D. GONZÁLEZ, J. A. TAPIA, , R. WALLACE, M. A. VALENZUELA, Electrical Engineering Dept. University of Concepcion, Chile.

Similar effects are observed in the iron part of the rotor pole. It allows an easy flow of the negative flux injected. The resultant air gap flux value is depended of the negative flux component magnitude. According to the current value was increased in the *d-axis*, the total air gap flux was reduced. This effect is showed in figure 4.

3- Iron to Magnet Ratio Analysis

D-axis reluctance is mainly defined by the amount of iron and magnet present over the rotor pole, depicted in figure 5. In fact, flux control is based on the ability to inject negative *d-axis* current. The total air gap flux variation for different Iron-to-Magnet ratio (IMR) values is shown in figure 6. It can be seen that air gap flux is easily controlled by the armature reaction. IMR is a key factor over the range where this control is achieved.

4- Stator Teeth Saturation Analysis

Due to its axial geometry, stator teeth have a trapezoidal shape which affects the flux distribution over the rotor yoke. For the rectangular geometry of this magnetic circuit portion, stator teeth and rotor yoke saturation is depicted in figure 7. It is clear; the flux density distribution over the stator teeth is uneven, resulting in a poor utilization of the rotor yoke iron. However, if the yoke geometry is made trapezoidal, as shown in figure 8, flux density is smoother than the previous case. As a result, total flux on the machine is increased for the same amount of iron.

III - Conclusion

An axial flux surface-mounted PM machine with control flux capability was investigated. It was demonstrated that the modification to the rotor pole eases air gap flux control with an adequate control of the *d-axis* current. Adequate IMR value allows us to increase the air gap flux control range. However, a large iron section degraded the machine power density. Trapezoidal rotor yoke geometry improves the iron utilization introduced by stator teeth. The topology proposed extends the operating range over rated speed. To provide a practical demonstration of the theoretical results obtained, a 3 kVA prototype was built in our laboratory.

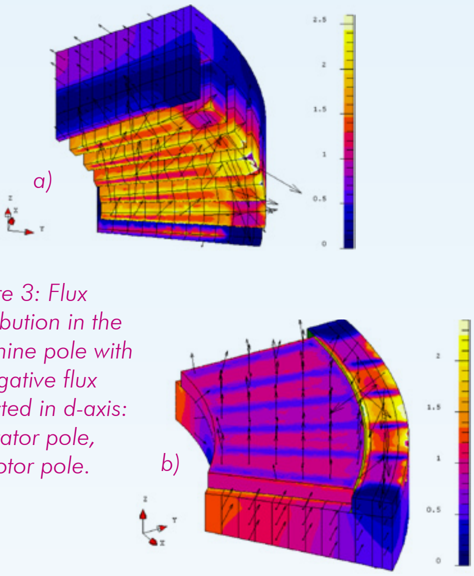

Figure 3: Flux distribution in the machine pole with a negative flux injected in d-axis: a) Stator pole, b) Rotor pole.

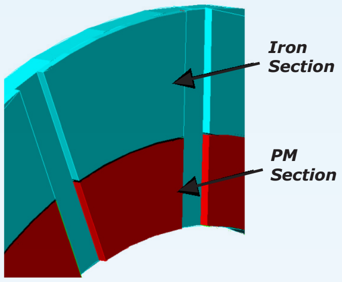

Figure 5: Rotor pole and Iron and Magnet section.

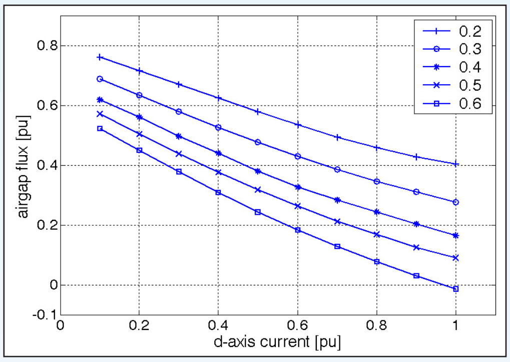

Figure 6. Air gap flux as a function of d-axis stator current for deferent IMR.

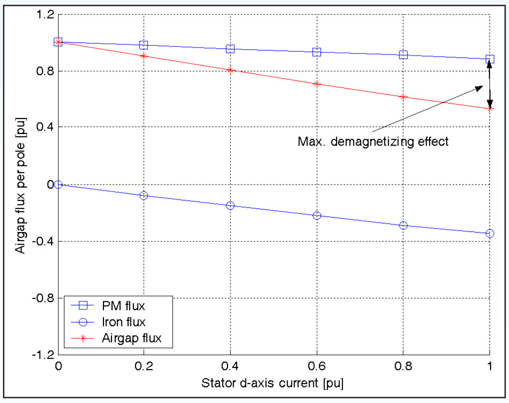

Figure 4: Flux component in the airgap machine.

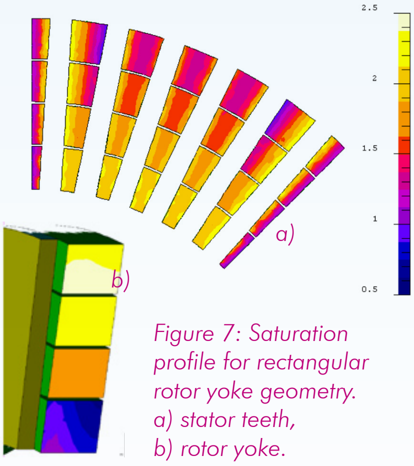

Figure 7: Saturation profile for rectangular rotor yoke geometry. a) stator teeth, b) rotor yoke.

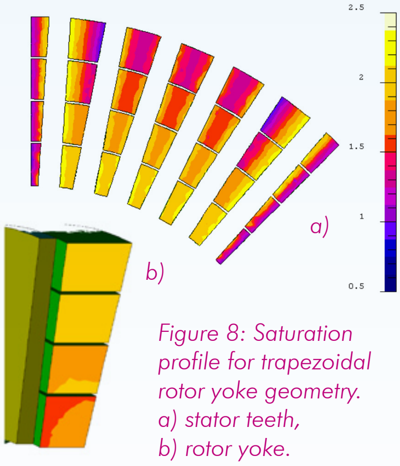

Figure 8: Saturation profile for trapezoidal rotor yoke geometry. a) stator teeth, b) rotor yoke.