XII-th International Workshop on Optimization and Inverse Problems in Electromagnetism
September 19 – 21, 2012, Ghent, Belgium

Optimization of the rotor geometry of a permanent magnet synchronous machine

Isabelle Hofman[1,2], Peter Sergeant[1,2] and Alex Van den Bossche[2]

[1]Dept. Electrotechnology, University College Ghent, Valentin Vaerwyckweg 1, B-9000 Ghent, Belgium
[2]Dept. of Electrical Energy, Systems and Automation, Ghent University,
Sint-Pietersnieuwstraat 41, B-9000 Ghent, Belgium

Abstract. Converting an induction machine (IM) to a permanent magnet synchronous motor (PMSM) can be a solution to increase the efficiency. Therefore we started from an original 1.5 kW 6-pole IM and converted it into a 6-pole PMSM. The stator of the 6-pole IM was kept unchanged and the rotor was converted into a permanent NdFeB magnet rotor. Furthermore we want to optimize the rotor geometry to obtain high efficiency and low magnet volume to reduce the magnet cost. In addition the cogging torque should be low, and the mechanical power should be at least equal to the nominal power of the induction machine at nominal current. The optimized parameters are the magnet thickness (t_m), the number of magnet segments per pole (N_p) and the magnet pole angle (α_m). For simulating the 6-pole PMSM's a transient 2D finite element model (FEM) was used, taking into account iron and copper losses. A geometry ($N_p = 5$, $\alpha_m = 150°$, $t_m = 3$ mm) was found so that the PMSM has 9% more efficiency and nevertheless rather low cogging torque (0.51 Nm) and magnet volume (1100 mm³).

Keywords: Efficiency, Finite Element Analysis, Permanent magnet synchronous machine

MODEL

To convert an IM into a PMSM, a numerical model is made of the resulting 1.5 kW 6-pole PMSM. Figure 1 shows the geometry of the converted 6-pole PMSM ($N_p = 4$, $\alpha_m = 142°$, $t_m = 5$ mm). Table 1 gives the properties of the 6-pole IM and PMSM's.

The 6-pole PMSM's numerical model is a transient 2D finite element model (FEM), taking into account the rotor movement. The model is based on [1], were also the efficiency influence of the electrical steel in the stator was investigated by using different material grades. As we used a single valued constitutive law, hysteresis is disregarded in FEM but the hysteresis losses are taken into account in the loss model. The iron losses in the stator depend on the time dependent induction waveform B(t) and its time derivative dB/dt in each point of the stator. In different mesh points in the iron, induction waveforms B(t) were recorded while the machine was rotating (moving mesh technique). The hysteresis, classical and excess loss (iron losses) is computed for each waveform and for several load conditions. A time domain loss model was used to compute the iron losses [2]. The copper losses are computed according to the enforced stator current and the measured resistance at the steady state temperature of 50°C.

OPTIMIZATION AND RESULTS

As mentioned in the abstract, the goals are high efficiency, low magnet volume, low cogging torque and a mechanical power larger or equal to the power of the induction machine at rated current. The efficiency that we maximize is the average efficiency in a speed range $0.5\Omega_{nom}$-Ω_{nom} and in a current range $0.6I_{nom}$-$1.25I_{nom}$. The parameters to optimize are the magnet thickness t_m, the number of segments per pole N_p and the magnet pole angle α_m: see Fig. 1. The outer rotor diameter is chosen fixed, in order to fit into the original stator and have a fixed air gap. A domain scan is done for 4 magnet thicknesses, 6 magnet pole angles and 3 magnet segments per pole configurations.

An optimum in efficiency and magnet volume is visualized by using a Pareto diagram: Fig. 2a. Each marker in the figure denotes one machine. A number of machines does not have the minimal required power at the nominal current: they are shown in Fig. 2a below the dashed line. These machines are eliminated from the selection procedure. In this figure, a machine configuration can be chosen that is a good compromise between efficiency and magnet volume.

In order to evaluate the cogging torque, for each machine, the cogging torque waveform is calculated as a function of time in the rotating machine (with 0 A current in the stator windings). For the cost value, the cogging torque is chosen to be the maximum of this waveform. We want to reduce the cogging torque by changing the 3 parameters to optimize, without losing the good combination of high efficiency and low magnet volume of Fig. 2a. For the chosen combination, Fig. 2b shows that a machine with low cogging torque can be built, without losing the high efficiency: see solid line in Fig. 2a and 2b. However, if no attention is paid to cogging torque, there is a risk to select a machine with high efficiency but also very high cogging torque. In Fig. 2 the marker with the black color face is a PMSM with $N_p = 5$, $\alpha_m = 150°$, $t_m = 3$ mm. This machine has a rather low magnet volume (1100 mm³) and cogging torque (0.51Nm) but still a high average efficiency (82.7%).

Table 1 Properties of the 6-pole machine

Properties 1.5 kW, 6-pole machine			
General		*Rotor IM*	
Nominal speed IM	910 rpm	Outer diameter	109.4 mm
Nom. phase current (400 V, Y)	3.90 A	Shaft diameter	30 mm
Nom. power factor IM	0.73	Number of slots	33
Stator		Radial height of slots	15.3 mm
Outer diameter	158.4 mm	Air gap IM	0.25 mm
Inner diameter	109.9 mm	*Rotor PMSM*	
Copper resistance	5.11 Ω	Iron yoke diameter	Variable
Sheet thickness	0.5 mm	Number of segments per pole N_p	Variable: 3, 4 or 5
Stack width	80.7 mm	Magnet pole angle α_m	Variable: 84 - 165°
Number of slots	36	Magnet (radial) thickness t_m	Variable: 2 - 7 mm
Turns per slot	60	Magnet permeability	μ_0
Number of poles	6	Magnet remanence	1.05 T
Magnetic steel type	M800-50A	Air gap thickness PMSM	2.5 mm

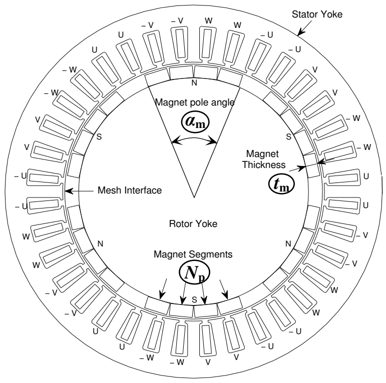

Figure 1 Geometry of the experimentally tested (N_p = 4, α_m = 142°, t_m = 5 mm) 1.5 kW, 6-pole PMSM. The variables in a circle are optimized.

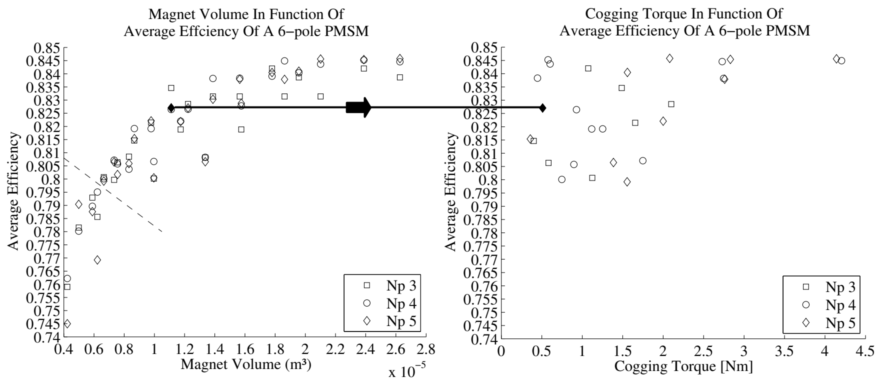

Figure 2 (a) Magnet volume in function of average efficiency and (b) cogging torque in function of average efficiency.

EXPERIMENTAL VALIDATION

For experimental validation, a machine was built with N_p = 4, α_m = 142°, t_m = 5 mm. The average efficiency of the 1.5 kW 6-pole IM (73.5%) increased after conversion into a PMSM with 14%, both tested on the same setup. The computed average efficiency of the 6-pole PMSM is 87.0%. The correspondence is good, compared with the measured result of the PMSM.

CONCLUSIONS

Conversion of an IM into a PMSM results in an efficiency increasing. The average efficiency increased by 14%. Optimization of the rotor shows that one can chose a machine with low magnet volume, high average efficiency, low cogging torque, and sufficient mechanical power.

REFERENCES

[1] I. Hofman, P. Sergeant, A. Van den Bossche, "Influence of soft magnetic material in a permanent magnet synchronous machine with a commercial induction machine stator," IEEE Trans. Magn., Vol. 48, pp. 1645-1648, Apr. 2012.

[2] E. Barbisio, F. Fiorillo, C. Ragusa, "Predicting loss in magnetic steel under arbitrary induction waveform and with minor hysteresis loops,"EEE Trans. Magn., Vol. 40, pp. 1810–1819, Jul. 2004.