

AXIAL FLUX INTERIOR PERMANENT MAGNET SYNCHRONOUS MOTOR WITH SINUSOIDALLY SHAPED MAGNETS

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Abstract

A new permanent magnet design for axial flux interior permanent magnet (AFIPM) motor is described in this paper. Poleshoes are traditionally used to produce sinusoidal flux linkage and sinusoidal EMF especially in the case of radial flux synchronous machines. Poleshoes are not a practical solution in the case of axial flux PM machine. The use of poleshoes in the production of sinusoidal back EMF may be avoided by using new magnet shaping which produces sinusoidal EMF itself. The complex machine geometry of AFIPM machine with the proposed magnet shaping result that analytical and 2D Finite Element Method (FEM) calculations do not perform well enough. As a result, AFIPM synchronous motor with the proposed magnet shaping is studied after analytical and 2D FEM calculations by using 3D FEM model.

Introduction

Axial flux permanent magnet (AFPM) synchronous machines have been studied with increasing interest during 1990's, mainly because the AFPM synchronous machine structure and performance fit very well into the requirements of the electrical vehicles' wheel motors (low-speed, high-torque) [1]-[2]. Other AFPM motor applications, like different kind of ship propulsion drives, are studied also [3]-[4]. The main topologies of the AFPM machines are presented in Fig. 1.

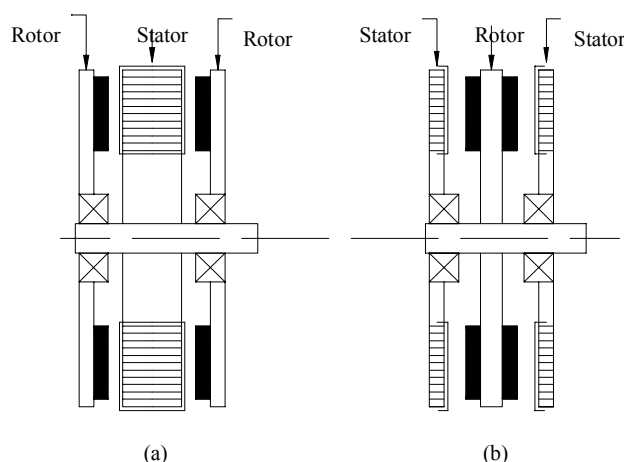


Fig. 1. Main topologies of axial flux PM synchronous machines. a) AFPM machine, b) AFIPM machine [2].

Recently, a new application for axial flux interior permanent magnet (AFIPM) synchronous motor is found from paper industry. There the aim is to integrate some of the cylinders of paper machine directly into the AFIPM motors. By using this integrated system, the use of gearbox in driving system

of the cylinders can be avoided and thus some savings in required space and costs as well as improved reliability of driving system is achieved. In principle AFIPM motor with parallel connected stators can operate at reduced load even if one of the stators is damaged. The operating environment of electrical machines in paper industry applications is very challenging especially for the point of permanent magnets because of high environment temperature. Thus, the successful cooling of the machine is necessary.

To minimize the cogging torque and noise, the four-cornered magnets of the AFIPM machine rotors are traditionally skewed. Magnets are installed either directly onto the surface of the solid rotor disc or mounted into holes in the rotor disc [1], [4]. As a result, trapezoidal EMF waveform is achieved. A sinusoidal or almost sinusoidal EMF waveform may be achieved by using angulated magnets or poleshoes on magnets. This paper presents a new magnet shaping which produces sinusoidal flux linkage behaviour and thus a sinusoidal back EMF, too. The proposed magnet shaping is studied by using FEM analysis. The prototype machine is under construction.

Sinusoidal magnet

The new magnet design produces sinusoidal EMF waveform by using flat magnets without poleshoes. This is possible when the outline of the magnet is described by equation

$$y(x) = A \cdot \sin(x) + B \cdot \sin(3x), \quad (1)$$

where A and B are constants [5].

For magnet including only fundamental component of sine wave, Fig. 2a, the outline of the magnet is defined by equation

$$y(x) = h \cdot \sin\left(\frac{\pi \cdot x}{w}\right), \quad (2)$$

where h is the height of magnet and w is the length of magnet base.

By considering the same magnet width w and height h for proposed magnet shaping and conventional sector-like magnet, it is possible to compare the flux produced by sinusoidal magnet and sector-like magnet. The surface area of a sinusoidally shaped magnet is about 30 % smaller compared to a sector-like magnet resulting reduced total flux produced by the magnet. It is possible to improve this situation by using a permanent magnet material with a higher remanence flux density, by increasing w , by decreasing the physical length of airgap or – in a three-phase machine – by adding a third harmonic in the magnet shaping according to Eq. (1).

In practice, the width of the magnet at outer machine radius may not be increased because some space between north and south poles must be left. The use of higher remanence magnet materials is limited to low temperature machines. If the air-gap physical length is decreased, it must be done with care in order to avoid mechanical contact between rotor and stator during operation. Thus, the most effective method to increase the air-gap flux is the use of the third harmonic in the magnet outline. This is possible due to the fact that in the case of Y-connected 3-phase machine, the third harmonic does not cause any harmful effects to the performance of the machine. In this case, the outline of magnet is defined by equation

$$y(x) = A \cdot \sin\left(\frac{\pi \cdot x}{w}\right) + B \cdot \sin\left(\frac{\pi \cdot 3x}{w}\right). \quad (3)$$

In Eq. (3), coefficients A and B should be select so that $\max \{y(x)\} = h$.

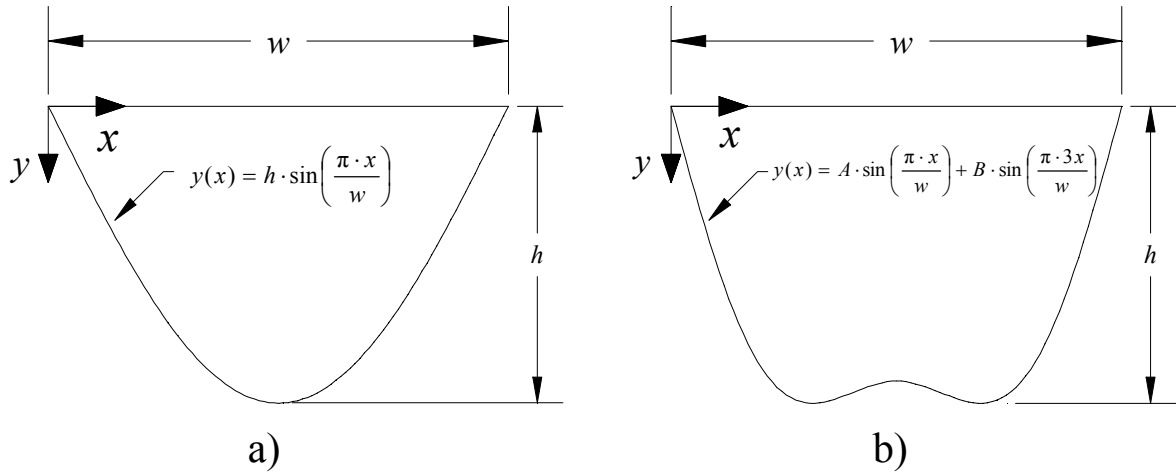


Fig. 2. a) Magnet with sinusoidal outline. b) Magnet with sinusoidal outline including third harmonic.

Motor design

The analytical motor design is made at average machine radius. The main parameters of the motor are presented in Table 1. The results are confirmed by using a 2D FEM obtained at average machine radius. However, in case of sinusoidal magnet outline quasi 3D FEM computation described by Gair [6] and Cvetkovski [7] is preferred. Finally, 3D FEM model is constructed. In order to validate results, the prototype machine will be constructed.

Table 1. Motor data.

Rated output power	55 kW	Physical length of airgap	2.0 mm
Rated input frequency	120 Hz	Axial length of rotor structure	70 mm
Number of poles	24	Stator outer radius	369 mm
Number of slots per stator	72	Stators' winding connection	Parallel
Permanent magnet material	Nd-B-Fe	Thickness of PM	5.0 mm

The motor is fed by using a commercial DTC-inverter (Direct Torque Control). The position sensorless DTC-control sets requirements to the inductance ratio of the motor. In principle, it is possible to align the rotor with the stator A-phase axis by using sufficient dc-magnetisation before start. However, if the motor may not rotate before start, the rotor angle may be determined based on the differences between the direct- and quadrature axis inductances. The required inductance ratio L_q/L_d should be 0,8 or less in this case. For the point of DTC-control, it do not matter whether the quadrature axis inductance is higher than the direct axis inductance or vice versa because this can be adjusted in the software. In this design, the required inductance ratio is achieved by using additional iron plates below the magnets. The cross section of rotor pole is presented in Fig. 3.

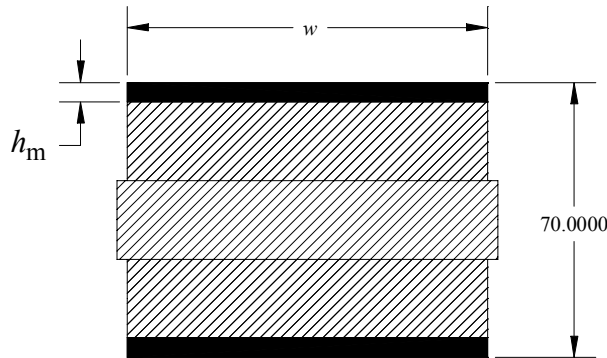


Fig. 3. Cross section of rotor pole obtained at external radius of machine.

FEM-computations

The proposed magnet shaping was studied by using Flux2D™ and Flux3D™ FEM software packages. The problem size and the computation time are minimised if a 3D model including only one pole is introduced. In XY-plane, the symmetry condition that imposes a normal magnetic field is used so that only one stator pole and one half of rotor pole structure is needed to be modelled. The 3D model of AFIPM machine is presented in Fig. 4. However, in back EMF computations it is more straightforward to use a pole pair instead of one pole. By fixing the magnet position into an appropriate parameter it is possible to rotate the rotor with discrete steps and solve a set of magnetostatic problems in order to detect the back EMF waveform and the waveform of cogging torque as a function of the rotor position.

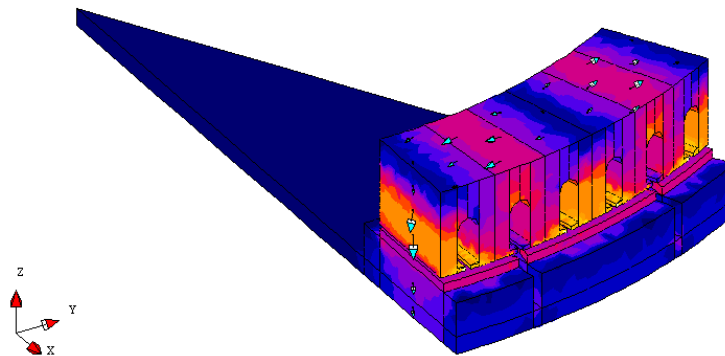


Fig. 4. A 3D FEM model of AFIPM machine. Flux density distribution in no-load condition.

FEM-computations were applied for magnet shaping presented in Fig. 2 a. Stator geometry was kept as a constant during calculations. Back EMF computation results as well as the flux density distribution in the air-gap are shown in Fig. 5. The back EMF was computed according to equation

$$e = -\xi N \cdot \frac{\Delta\phi}{\Delta t}, \quad (4)$$

where ξN is the number of coil turns per phase and ϕ is the coil flux obtained from 3D FEM. The time step Δt is proportional to the change of rotor angular position between computation points at known rotor angular speed.

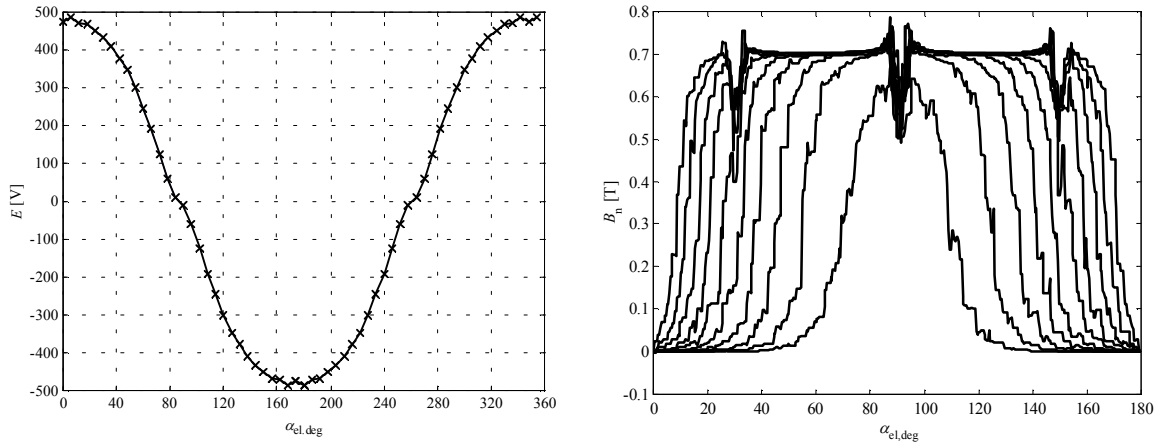


Fig. 5. Back EMF for magnet with sinusoidal outline according to 3D FEM computation and the normal component of flux density distribution in airgap with different radius of motor.

Cogging torque

The cogging torque computations for sinusoidal magnets were performed by using quasi 3D computation. In quasi 3D computation the machine is split into several slices which are obtained at different rotor radius. The main advantage in use of 2D FEM is a remarkably shorter computation time compared to 3D FEM. In the case of quasi 3D, the cogging torque T_{cog} is calculated according to equation

$$T_{cog}(\alpha_{mech}) = \sum_{i=1}^5 T_{cog,i}(\alpha_{mech}), \quad (5)$$

where α_{mech} is the mechanical angle of rotor.

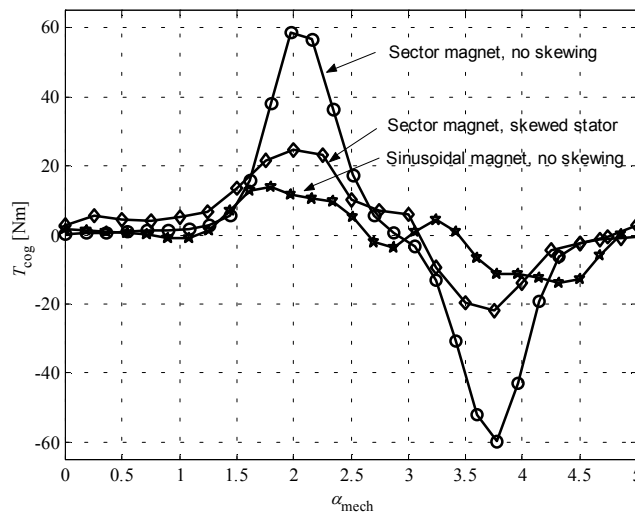


Fig. 6. Cogging torque. In the case of sector magnet with skewed stator slot, the stator slot skewing is one slot pitch. Cogging torque produced by sinusoidal magnet is computed by using quasi 3D method by using five slices.

The magnet with sinusoidal outline reduces the cogging torque compared to sector-like magnet without magnet skewing because the whole magnet edge does not meet the stator slot opening simultaneously. For the magnet presented in Fig. 2b), the appearance of cogging torque is probable if coefficients A and B are selected so that the stator slot opening is parallel with an almost straight magnet side edge. The coefficients A and B must be evaluated with care if this kind of magnet shaping is used.

Conclusions

According to 3D FEM computations, the proposed magnet design produces an almost sinusoidal back EMF waveform itself. The shape of the magnet helps to reduce cogging torque imposing that the stator slot skewing is not necessary, which simplifies the manufacturing of the stator. The biggest disadvantage of the proposed design is the loss of magnet volume compared to sector-like magnet resulting to loss of maximum torque produced by the motor. This disadvantage may, however, be mainly avoided by adding a suitable amount of the third harmonic in the magnet shape.

Acknowledgements

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