Design and Analysis of Axial Flux Permanent Magnet Synchronous Machine

Won-Young Jo*, In-Jae Lee*, Yun-Hyun Cho†, Dae-Hyun Koo and Yon-Do Chun****

Abstract - In this article, a special kind of axial flux permanent magnet machine has proved to be suitable for high torque and low speed applications. An innovative design of the machine has been proposed in order to make the machine suitable for traction applications by means of field-weakening. The aim of this paper is to analyze, in general terms, the basic equations that describe the operating conditions of such machines. Optimal sizes for design can be obtained by calculating the power density and the air-gap flux density, etc.

Keywords: Axial flux permanent magnet synchronous machine (AFPMSM), Design strategy, Field weakening, Optimal size, Power density

1. Introduction

Recently, many factors point to the necessity of introducing a new propulsion concept for transportation vehicles. The exhausts emitted by the internal combustion engine of passenger vehicles, trucks and busses alike such as CO, SO_2, and NO_x have proved to be severe air pollutants effecting the quality of life in many aspects. Hybrid cars represent a solution to the problem of pollution. A very important issue in any hybrid vehicle is the limited space available inside the vehicle. With this in mind, axial flux permanent magnet (AFPM) machines represent an optimal solution. In fact, the higher torque density of these machines, compared to the conventional radial flux machines, results in considerable space reduction. The innovative AFPM machine design, presented in this paper, is obtained by adding stator teeth to the conventional air-gap wound stator [1-2].

In this paper, the machine enables us to reach high speeds in field-weakening operation. The main equations used for the design of the machine will be presented in the following part. As well, the general sizing equations can be applied to axial flux permanent magnet synchronous machine (AFPMSM) topologies and optimum machine design with high power/torque density, air-gap magnetic flux density and high performance can be achieved [1-5].

2. Design Strategy

The driving characteristics of a typical drive application requires that for the steady state of the time, the machine has to operate with the output power of 15[kW], the output torque of 100[Nm], and the speed of up to 1800[rpm], respectively. The peak torque is 200[Nm] at 1350[rpm]. The maximum output speed is 2600[rpm], which is set by the maximum speed of the industrial diesel engine.

In keeping with general motor design practice, a winding coil current density of 4[A/mm^2] (root-mean-square value) has been chosen as the continuous safe current loading. The average practical safe operating value will depend on the duty cycle of the machine [3-4].

3. General Description

3.1 Stator and Rotor Configuration

The AFPMSM was designed with a single rotor, a double-sided airgap, and stators. The isotropic rotor is placed between teeth of the double-sided stators as shown in Fig. 1. The stator back yokes are attached to the lateral case covers of the motor. The lateral case covers are made with rolled steel material. The stator teeth are individually fixed to the stator disk. The fan-shaped magnets of the rotor are mounted in holes of the rotor disk without the back yokes. Fig. 2 shows the structure of the AFPMSM [6-8].

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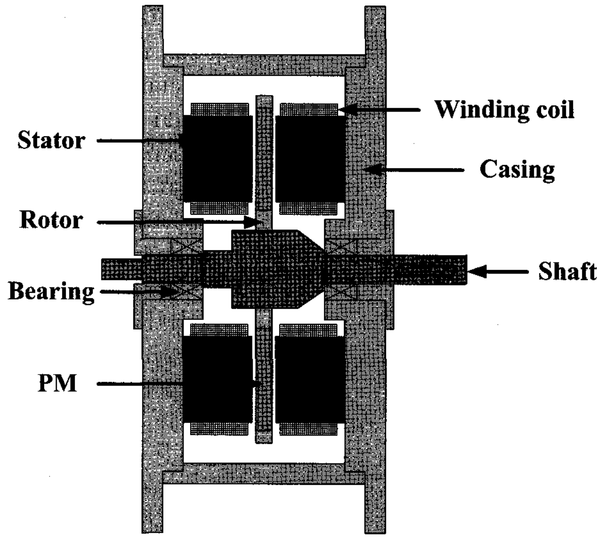

Fig. 1. Cross section view of the AFPMSM

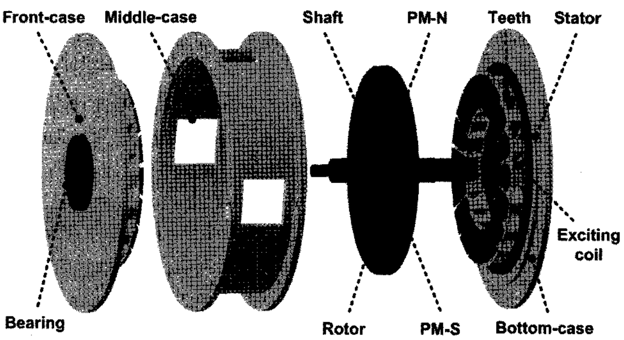

Fig. 2. The structure of the AFPMSM

3.2 Coil Windings

The stator windings must fulfill the following requirements [3-5]:

- Must use the concentric winding method to allow easier manufacture.
- Must obtain a sinusoidal distribution of the magnetic-motive force in order to avoid torque pulsations.
- The winding factors (the distribution factor and the pitch factor) must have high values so that the output power does not decrease.

The construction of winding as shown in Fig. 2 satisfied most of the above requirements. The MMF produced by the winding coils can be expressed by the Fourier series:

$$MMF(x) = \sum_{n=1,3,\cdots}^{\infty} b_n \sin(x) \tag{1}$$

For a maximum value of *MMF(x)* is 1, the Fourier coefficients are shown in Table 1.

Table 1. Fourier coefficients of the MMF

N	b_n	n	b_n
1	1.065	13	-0.082
3	0	15	0
5	-0.057	17	0.017
7	0.041	19	-0.015
9	0	21	0
11	-0.097	23	0.046

The winding factors for the fundamental are defined by the expressions:

$$k_d = \frac{\sin(q\alpha_r / z)}{q\sin(\alpha_r / z)} \text{ and } k_p = \sin(\frac{\beta\pi}{2}) \tag{2}$$

where, k_d is the distribution factor, k_p is the pitch factor, q is number of slots per phase and per pole, a_r is electrical degrees corresponding to one slot, $\beta = y/\tau$, y is the coil span in number of slots, and τ is the polar pitch in number of slots. Finally the winding factor k_w is given by:

$$k_w = k_d k_p \tag{3}$$

4. Electromagnetic Design

4.1 Torque Calculation

The occurred force produced by the stator current and permanent magnet in rotor disk is calculated as the following equation using Fleming's rule:

$$dF_x = I(dr \times B_g) = A_{(r)}(dS \times B_g) \tag{4}$$

where, if it expresses I as the equivalent current of the stator, it is equal to the following equation:

$$Idr = A_{(r)}dS\,,\ \sqrt{2}A_{(r)} = A_{m(r)} \tag{5}$$

where, dr and dS are the differential radius and the differential surface in the rotor disk, respectively [1]. And B_g is the vector of the axis-component of airgap flux density at a value of any differential radius r. And the peak value of armature line current density (specific electric loading) in the stator $A_{m(r)}$ is evaluated as:

$$A_{m(r)} = \frac{\sqrt{2}m_1 N_1 I}{\pi r} \tag{6}$$

where, m_1 is the number of phases, and N_1 is the number of winding coils per phase. Based on (4), the electromagnetic torque in the AFPMSMs is expressed as:

$$dT_d = rdF_x = 2\alpha_i m_1 N_1 k_w I B_g r dr \tag{7}$$

where, a_i is the magnetic-field factor of the sinusoidal wave in air-gap(=2/ π) and it assumes that the flux density in airgap B_g is regular in the axis-direction.

Therefore, the resulting equation from (7) is given by:

$$T_d = 0.25\alpha_i m_1 N_1 k_w I B_g (D_o^2 - D_i^2) \tag{8}$$

where, D_o is the outer diameter, D_i is the inner diameter.

4.2 Back *EMF* (Electro-motive Force)

The AFPMSM proposed in this paper has p pieces of magnetic poles. The flux per pole is given by:

$$\Phi_{pole} = \alpha_i \pi \frac{(D_o^2 - D_i^2)}{4} \frac{B_{mg}}{2p} \tag{9}$$

where, p is the number of magnetic poles, B_{mg} is the maximum flux density in the airgap, a_i is the factor of the sinusoidal wave in a magnetic-field (=2/ π).

The RMS value of the induced *EMF* in each phase E_f is equal to:

$$E_f = \sqrt{2}\pi n_s N_1 k_w B_{mg} \frac{(D_o^2 - D_i^2)}{8} \tag{10}$$

where, n_s is the revolution per second.

4.3 Magnetic Equivalent Circuit Model

The maximum flux density in each part of the magnetic circuit is obtained by using the principle of continuity of the flux flowing. The magnetic flux loop of the AFPMSM is indicated in Fig. 3. The corresponding lumped magnetic equivalent circuit is plotted in Fig. 4(a), where R_s, R_g, R_m and R_{ml} are the relative reluctances of stator iron, airgap, permanent magnet, and leakage path, respectively. Φ_r, Φ_m, Φ_e and Φ_l are the magnet flux, the efficient flux, and the leakage flux, respectively [4-5].

Reluctances of the permanent magnet and airgap can be expressed as:

$$R_m = \frac{l_m}{\mu_0 \mu_r A_m} \tag{11}$$

$$R_g = \frac{g_e}{\mu_0 A_g} \tag{12}$$

where, l_m is the magnet length, A_m is the cross-section area per pole, A_g is the airgap area per pole, μ_r is the relative permeability of the permanent magnet, and g_e is the effective airgap length. $g_e=k_c g$, where k_c is the Carter coefficient given by the following equation:

$$k_c = \left[1 - \frac{1}{\frac{\tau_s}{w_s}(5\frac{g_c}{w_s} + 1)} \right]^{-1} \tag{13}$$

where, g_c is the effective airgap length for the Carter coefficient, $g_c=g+l_m/\mu_r$.

If the reluctance of the stator back irons can be neglected because the values are very small, the magnetic equivalent circuit can be further simplified as shown in Fig. 4(b). In this figure it is presented as the permeance instead of the reluctance in order to allow for simpler calculation [1]. The magnet leakage permeance is given as:

$$P_{ml} = \frac{\mu_0 (D_o - D_i)}{2\pi} \ln(1 + \pi \frac{g}{\tau_f}) \tag{14}$$

where, τ_f is the magnet spacer width. Therefore, the magnet flux and the efficient flux can be defined as:

$$\Phi_m = \Phi_r \frac{P_g + 4P_{ml}}{2P_m + P_g + 4P_{ml}} \tag{15}$$

$$\Phi_e = \Phi_r \frac{P_g}{2P_m + P_g + 4P_{ml}} \tag{16}$$

The flux densities in the airgap and stator back yoke are described as:

$$B_g = \frac{\Phi_e}{A_g} = \frac{B_r P_g}{2P_m + P_g + 4P_{ml}} \frac{A_m}{A_g} \tag{17}$$

$$B_{sb} = \frac{\Phi_e}{2A_{by}} = \frac{B_r P_g}{2P_m + P_g + 4P_{ml}} \frac{A_m}{2A_{by}} \tag{18}$$

where, A_{by} is the area of the stator back yoke, and B_r is the permanent flux density of the permanent magnet [6], [10].

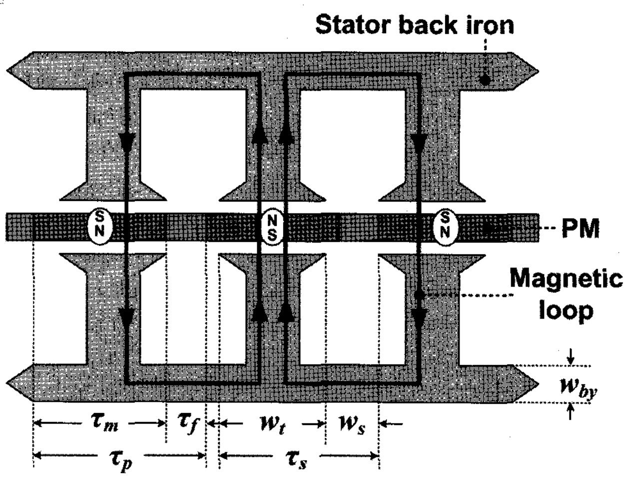

Fig. 3. The magnetic flux loop of the AFPMSM

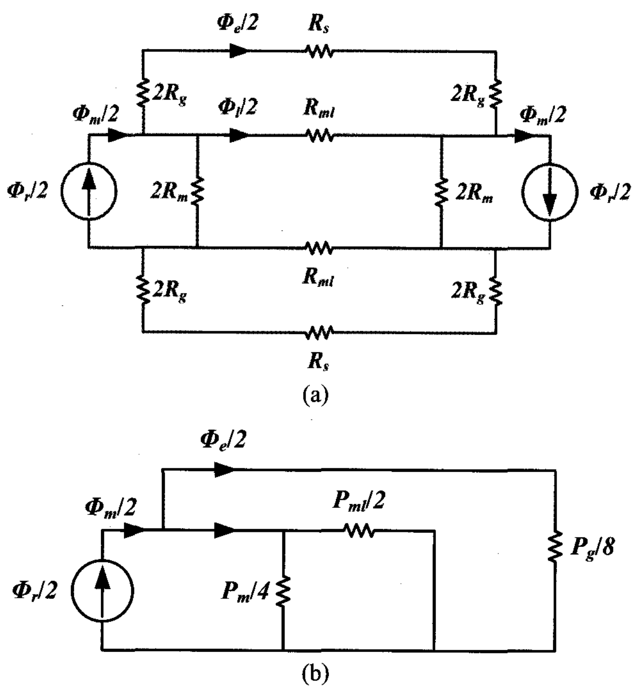

Fig. 4. (a) The lumped magnetic equivalent circuit, and (b) the simplified one.

The maximum flux density in the airgap has a relation to others: the tooth, back yoke, etc. The maximum flux densities in the airgap and the back yoke take the form of

$$B_{g\max} = \frac{(D_o + D_i)\pi - 2w_s z}{(D_o + D_i)\pi} B_{d\max} \tag{19}$$

$$B_{y\max} = \frac{(D_o + D_i)\pi - 2w_s z}{4p\pi w_{by}} B_{d\max} \tag{20}$$

where, $B_{d\max}$ is the maximum flux density in the tooth of the stator, w_s is the width of the stator slots, z is the number of slots, and w_{by} is the width of the back yoke.

4.4 Magnetic-motive force

The inductance in the d-axis direction is calculated as the ratio between the magnetic flux produced by the 3-phase currents in the d-axis direction and the d-component of current flowing into the 1-phase winding coil:

$$L_d = \frac{\Psi_d}{I_d} = (m_1 N_1 k_w)\frac{1}{I_d}\frac{\pi}{m_1}(D_o^2 - D_i^2)\left(\frac{1}{2\pi}B_d\right) \tag{21}$$

If the permeability in the iron region is assumed to be infinite, the airgap flux density from the stator current in the d-axis direction can be evaluated as:

$$B_d = \mu_0 H = \mu_0 \frac{MMF_{res}}{\left(2l_g + \frac{l_m}{\mu_m}\right)} \tag{22}$$

where, *MMF* is calculated as $H = \frac{MMF}{l_{total}}$ using Ampere's law, $\oint Hdl = Ni = MMF$, MMF_{res} produced by 3-phase stator windings is:

$$MMF_{res} = 1.35 N_1 k_w I_{rms} \tag{23}$$

Therefore, the airgap flux density from the d-component of the current can be calculated as:

$$B_d = \frac{1.35}{\sqrt{2}}\mu_0 \frac{k_w N_1 I_d}{\left(2l_g + \frac{l_m}{\mu_m}\right)} \tag{24}$$

As a result, the inductance in the d-axis direction is

$$L_d = \frac{1.35}{2\sqrt{2}}(m_1 N_1 k_w)^2 \frac{\mu_0}{2l_g + \frac{l_m}{\mu_m}}(D_o^2 - D_i^2) \tag{25}$$

where, because the permeability of the permanent magnet μ_m is generally 1.04~1.06, it can be assumed as 1.

And the inductance in q-axis direction is also calculated as similar to that in the d-axis.

$$L_q = \frac{\Psi_q}{I_q} = (m_1 N_1 k_w)\frac{1}{I_q}\frac{\pi}{m_1}(D_o^2 - D_i^2)\left(\frac{1}{2\pi}B_q\right) \tag{26}$$

If Ampere's law is applied, the airgap flux density and the inductance in q-axis direction are evaluated as:

$$B_q = \mu_0 H = \frac{MMF_{res}}{2l_g} = \frac{1.35}{\sqrt{2}} \mu_0 \frac{k_w N_1 I_q}{2l_g} \quad (27)$$

$$L_q = \frac{1.35}{2\sqrt{2}} (m_1 N_1 k_w)^2 \frac{\mu_0}{2l_g} (D_o^2 - D_i^2) \quad (28)$$

4.5 Stator Back Yoke Thickness

Because the magnets produce standard flux density up to their surfaces, the total magnetic flux linkage in the airgap increases according to a higher radius and is calculated as:

$$\Phi_r = B_g \theta_m r dr \quad (29)$$

where, θ_m is the angle of pole pitch.

Only half of this magnetic flux linkage flows to the stator back yoke, so if maximum allowable flux density in the stator back yoke is B_{bymax}, the flux flowing into the back yoke is given by:

$$\Phi_{by} = B_{by\max} w_{by} k_{st} dr \quad (30)$$

where, k_{st} is the lamination stacking factor. As a result, by equating (23) and (24), the stator back yoke thickness is calculated as:

$$w_{by} = \frac{B_g \theta_m r}{2B_{by\max} k_{st}} \quad (31)$$

4.6 Airgap Flux Linkage and Airgap flux density

The airgap flux density, Φ_g, is generally defined as:

$$\Phi_g = \sqrt{(\Phi_m + L_d I_d)^2 + (L_q I_q)^2} \quad (32)$$

where, Φ_m is produced by permanent magnets, and $L_d I_d$ and $L_q I_q$ are produced by the inductance and the stator current in d and q-axis respectively[9]. The resulting equation for the airgap flux linkage is given by the following equation:

$$\Phi_g = k_w N_1 B_g \frac{(D_o^2 - D_i^2)}{2} \quad (33)$$

where, the airgap flux density B_g is defined as:

$$B_g = \sqrt{(B + B_d)^2 + (B_q)^2} \quad (34)$$

5. Optimum Size of the AFPMSM

In axial flux machines, the diameter ratio, D_i/D_o, and air-gap flux density are the two important design parameters having significant effect on the machine characteristics. Therefore, in order to find the optimum size of the machine performance, the diameter ratio and airgap flux density must be chosen carefully.

Table 2. Required Design Specification and Calculated Parameters of the AFPMSM.

Rated	Power, kW	15
	Voltage, V	380
	Current, A	4*5.87
	Speed, rpm	1800
	Torque, Nm	79.6
Stator	Slot number	18
	Material	S45C
Rotor	Pole number	16
	Material	S45C
Winding	Turns/coil, turns	90[turns]
	Conductor Diameter	1.2[mm]
Magnet	Br	1.28[T](20°)
	Material	Nd-Fe-B
	Coercivity	970[kA/m]
Airgap length		2[mm]
Winding connection type		4-Y

Table 2 displays the design specification of the AFPMSMs. Fig. 5 shows the power density variation as a function of air-gap flux density and the diameter ratio for the AFPMSMs. As can be seen from this figure, the maximum power density (or torque density) occurs at an airgap flux density of 1.0 T and a diameter ratio of 0.6 m. For that maximum power density point the machine efficiency is 94.0%. From this figure, the maximum power density is found to be 5.27 W/cm^3 [10].

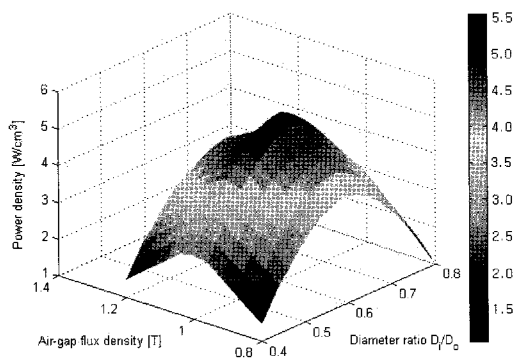

Fig. 5. Power density of AFPMSM vs. airgap flux density (B_g) vs. diameter ratio (D_i/D_o)

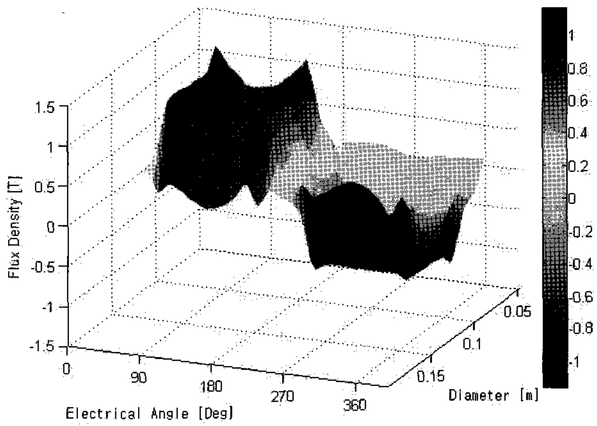

Fig. 6. The airgap magnetic flux density for AFPMSMs

Fig. 6 presents airgap flux density variation as a function of the diameter and various electrical angles for the AFPMSMs. From this figure, the average flux density, which is found to be about 1.0T, occurs from the inner diameter to the outer diameter.

5. Conclusion

The focus of this article has been to obtain the characteristic equations for the design and to find the optimum sizing for the output power. The electromagnetic design has been performed by applying the characteristic equations to the new type AFPMSM. In order to optimize the machine, the power density, the diameter ratio and the airgap flux density have been chosen carefully. The machines were compared in terms of the power density and the results were applied for design of this machine.

Acknowledgements

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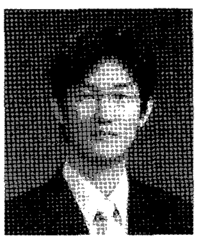

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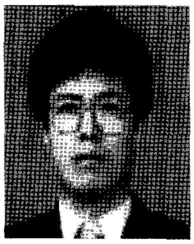

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