Optimal Design of an Axial Flux Permanent Magnet Motor with Flux Control Capability For Electric Vehicles

Farshad Kiani *, Mohammad Ardebili

* Department of Electrical Engineering, K.N.Toosi University, Tehran, Iran

Phone Number: +98-9393532921

*Corresponding Author's E-mail: f.kiani1991@yahoo.com

Abstract

This paper presents a new axial flux surface mounted permanent magnet motor topology with field control capability which is a good candidate for electric vehicles. The advantage of this motor is the possibility of field weakening at high speeds, which is the most important demand for such applications. The motor structure and sizing equations are discussed. Optimal configuration is then obtained using design optimization. In order to demonstrate the mechanism of the field control and characteristics of this motor, a 1 kW axial flux motor is analysed in detail, using 3D Finite Element Analysis. The air gap flux density, flux linkage and control range components have been evaluated. The FEA results have well validated the analytical design process.

Keywords: OPTIMIZATION, AXIAL FLUX MACHINES, ELECTRIC VEHICLE, PERMANENT MAGNET MACHINES, FLUX WEAKENING.

1. Introduction

In the last decades PM machines have gained attention in extensive applications due to their high efficiency, high torque and power density. In electric vehicle applications, efficiency and torque density are two key factors, as a result, the PM machines are a good candidate in this application [1]. NdFeB magnets can be mounted directly on the rotor surface that provide high air gap flux density. This leads to elimination of field copper loss, reduced volume and lower manufacturing labor and cost [2]. However, for variable speed applications, PM machines suffer from the fixed excitation of the magnets, thus they have a limited high speed area. However, between PM machines the radial flux PM (RFPM) widely is used in different applications, the axial flux permanent magnet (AFPM) machines have been trendy in a specific applications where the RFPM machines would not be suitable, such as electric vehicles [3,4]. In low speed applications, there is an unavoidable need for a large number of poles and accordingly a much increased diameter, both of which may be done more easily in axial flux machines than in conventional radial flux ones. The topologies for double sided AFPM machines are the axial flux one-stator–two-rotor (TORUS) and two-stator–one-rotor (AFIR) [5], while either of the two arrangements (external stator or external rotor) is practical. The external-rotor (TORUS) arrangement is considered advantageous when space is limited, mechanical robustness is required, and torque-to-volume ratio is crucial [6]. Consequently, TORUS structure would be fit for electric vehicles. However, the key disadvantage of the AFPMs is related to the high speed region which the air gap flux should be weakened. An optimal drive for electric vehicle should offer extended high speed capability. It can be achieved by proper machine geometry design and complex field weakening control strategies [7]-[9].
The common techniques for field weakening are: control techniques and modification of machine topology. Control techniques are based on shifting the stator current in such a way, that is weakens the excitation field. This requires an unfavorable oversized machine and the current convertor. The capability of converter limits the flux weakening range of the PM machines. Besides, flux control using these methods increases the total losses of machine and risk of permanent magnet demagnetization. With a high current injection in d-axis, the operation of permanent magnets will be limited in the irreversible demagnetization region and the permanent magnets will be demagnetized forever and after the d-axis current is removed they never are capable to return to their original operating point. Using these techniques, achievable speed range is limited by the permissible demagnetizing current indicated by the demagnetization characteristics of the permanent magnets [8].

In order to eliminate the effects of d-axis current injection, the search for methods to realize field control capability in PM machines has been of great interest. Currently, there are several substitutions so as to overcome disadvantages of d-axis current injection in these machines. Machines with new topologies are considered more favorable than above mentioned techniques. Innovative structures have been presented in the studies with flux control capability [11-22].

In 1993, Shakal and colleagues introduced a Double Salient Permanent Magnet (DSPM) machine. In this structure ferrite type PMs are placed in the inner surface of the stator core and a DC field winding is located in the stator core [11]. In 1995, Lipo presented a Double Salient Permanent Magnet machine. In this structure, flux control is achieved by modifying the PM flux reluctance path [12-14]. In 1995, L. Xu and colleagues introduced a RFPM machine with a novel structure with control capability of machine flux [8]. By using $I_d$ current which is change the flux path of machine and without decreasing of PM flux magnitude, the machine flux control is attainable [15]. In 2001, Tapia presented a Consequent Pole Permanent Magnet (CPPM) machine. It's a RFPM machine structure which air gap flux is controlled by a simple method. Nevertheless, the total volume of machine is increased and machine power density due to using a DC field winding is reduced [1, 16]. Aforementioned structures are RFPM machine. There are different AFPM structure with flux weakening capability.

In 1998, Profumo and Tenconi presented an AFPM machine with true field control capability [17], which is AFIR type. Hsu in 2000 [18] and Liang in 2002 [19] suggested another fascinating AFPM machine with capability of field control. In this structure air gap flux control is achievable by using a DC field winding and adjusting the magnitude and polarity of it. In 2002, Aydin and colleagues proposed an AFPM machine with a new structure using a DC coil. In this structure the risk of PMs demagnetization is eliminated and it's capable to reduce air gap flux in a reasonable range, but this structure is complex and needs to divide rotor in two sections [20-22].

This paper presents a machine topology, in which field weakening is achieved with a simple stator fixed DC coil. To control the field in the range from zero up to maximum value, which offers wide speed variations, this coil has to be fed by a simple DC chopper. The proposed structure has a slightly simpler solution with respect to other structures. Hence, the goal of this paper is to develop a simple method for the optimal design of a machine which guaranties field weakening in a wide range and desired torque.

The reminder of this paper is organized as follows: in section two the general principles of air gap field control is discussed. The machine structure is discussed in section three. Section four describes the sizing equations. Optimal structure is analyzed using FEA in section five. Finally, the paper is concluded in section six.

2. Description of air gap field control

Figure 1 (a) shows two sides of the stator coil over a pole pair in a PM machine. In normal operation, the air gap fluxes with opposite polarities are acting on two sides of the coil. When there is a relative movement between the coil and air gap flux a back EMF is induced. Figure 1 (b) shows field weakening operation of the PM machine with direct axis current injection. With injection of current into d-axis of
machine, a field across d-axis is created that can weaken the resultant air gap flux. The magnitudes of the air gap fluxes at both coil sides are equally weakened thus inducing a smaller back EMF. A small back EMF is achievable even when the magnitude of air gap fluxes is high. The polarities of the air gap flux has great importance in this method.

Figure1: Conventional field weakening method (a) Normal situation, (b) Conventional field weakening

In new method of air gap field control, using DC field winding located on the stator, the iron poles of the rotor are magnetized. In this structure, the adjustable DC coil flux is combined with the constant PM flux. The resultant air gap flux over a pole can be weakened or strengthened according to the magnitude and direction of the DC field winding current. In this method, polarities of the air gap flux play an important role for weakening or strengthening of the back EMF. Since flux control of the machine is achieved by the iron poles, the demagnetization risk of PMs is eliminated. Furthermore, due to using a DC field coil, necessity of using brushes or slip rings is removed in this structure. Principles of air gap field control in this technique are shown in figure2.

Figure2: New technique of field weakening (a) Positive, (b) Negative

3. The proposed machine structure

The general principles of air gap flux control over one pole pair in an AFPM machine are presented in figure3. Rotor pole made of PM material and ferromagnetic material. The PM must have adequate thickness in order to drive the desired flux through both sets of air gaps facing iron pole and PM pole. Iron poles are magnetized using DC field winding current. According to magnitude and direction of DC field winding current, air gap flux can be strengthened or weakened.

Figure3 (a) shows when the DC control coil has no current. This configuration is suitable for electric vehicles running at medium speed with a medium torque requirements.

figure3 (b) shows when the DC control coil has negative current. This situation corresponds to the case shown in figure2 (a). In this situation, average air gap flux density is increased and highest back EMF would be produced. This situation is most suitable for low speed and high torque operation in electric vehicles.

Figure3 (c) shows when the DC control coil has positive current, the average air gap flux density is reduced and lowest back EMF would be produced. This situation is most suitable for high speed and
low torque operation in electric vehicles. It should be noted that under no situation the PM is not demagnetized due to this field control system.

The AFPM motors with dual rotor and single stator (TORUS) have high torque and low volume. Therefore, this structure is suitable for electric vehicle application [3, 25]. Proposed machine is composed of dual rotors and single stator. The rotor has a steel core and surface mounted poles which are PM type and iron type, a shaft and a magnetic tube placed between DC field winding and shaft. Rotor PM poles are North-South (NS) type. Some space between PM and iron poles is considered for reducing the flux leakage.

![Figure 3: Principal of field control in AFPM machines by (a) zero, (b) negative and (c) positive DC coil current](image)

The correct shape of poles is a key factor in reducing the magnitude of harmonics in PM machines since the shape of PMs and iron pole should be selected according to total machine harmonics. Air gap lengths above PM pole and iron pole are different, length of air gap above iron pole is smaller than the length of air gap above PM pole. Because having high reluctance path above PM pole and lower reluctance path above the iron pole. The structure of proposed AFPM machine is shown in figure4.

![Figure 4: The structure of proposed AFPM machine](image)
The stator contains two sets of three phase AC windings. Stator and rotor yoke are constructed using iron laminations. Between the inner radius of stator core and stator end winding, the DC field winding is located. To obtain optimal design, the machine volume as a key feature in electric vehicles was reduced.

4. Sizing equations of proposed machine

Main dimensions of each electrical machine are determined via electrical machine output power equation. A general purpose sizing equation for AFPM machines takes the following form [26]:

\[
P_{\text{out}} = \frac{m \pi}{m_1} K_e K_p K_i A B_g \eta \frac{f}{p} (1 - \lambda^2) \frac{1 + \frac{\lambda}{2}}{2} D_o^3
\]  

(1)

\(P_{\text{out}}\) is rated output power of the machine, \(m\) number of phases of the machine, \(m_1\) number of phases of each stator, \(K_e\) EMF factor, \(K_p\) power waveform factor and \(K_i\) current waveform factor. \(B_g\) is magnetic loading, \(A\) electrical loading, \(\eta\) machine efficiency, \(f\) rated frequency, \(p\) number of pole, \(\lambda\) diameter ratio of the machine:

\[
\lambda = \frac{D_i}{D_o}
\]  

(2)

where \(D_o\) and \(D_i\) are the machine outer and inner diameters, respectively.

Using Equations (1) and (2), the outer diameter of machine can be calculated as:

\[
D_o = \sqrt[3]{\frac{P_{\text{out}}}{\frac{\pi m}{2 m_1} K_e K_p K_i A B_g \eta \frac{f}{p} (1 - \lambda^2) \frac{1 + \frac{\lambda}{2}}{2}}}
\]  

(3)

And the outer diameter of the machine with consideration of end winding length in radial direction is given by [20, 23]:

\[
D_t = D_o + 2W_{\text{cu}}
\]  

(4)

where \(W_{\text{cu}}\) is the radial length of end winding and can be determined as [26]:

\[
W_{\text{cu}} = \frac{D_l - \sqrt{D_l^2 - 2AD_m}}{\alpha_s K_{\text{cu}} J_s} \frac{\alpha_s K_{\text{cu}} J_s}{2}
\]  

(5)

where \(D_m\) is the average diameter of the machine, \(J_s\) the slot current density, \(\alpha_s\) proportion of stator slot width to stator slot pitch, and \(K_{\text{cu}}\) the copper fill factor.

The consequent air gap flux can be split into two terms by the flux superposition rule: the constant flux of the PMs and the variable flux of the DC field winding. Therefore, resultant air gap flux over one pole with assumption of any saturation and armature effects can be defined as [20, 23]:

\[
\phi_p = \phi_{\text{PM}} + \phi_{\text{DC}}
\]  

(6)
where $\varphi_p$ is the net air gap flux above one pole, $\varphi_{p/PM}$ the air gap flux produced via the PMs, and $\varphi_{p/DC}$ is the air gap flux produced through the DC field winding. Also, the components of equation (6) can be rewrite as [20, 23]:

$$\varphi_{p/PM} = \varphi_{PM/PM} + \varphi_{iron/PM} \quad (7)$$

$$\varphi_{p/DC} = \varphi_{PM/DC} + \varphi_{iron/DC} \quad (8)$$

where $\varphi_{PM/PM}$, $\varphi_{iron/PM}$, $\varphi_{PM/DC}$ and $\varphi_{iron/DC}$ are the air gap flux produced via the PM above the PM pole, PM above the iron pole, DC winding above the PM pole, and DC winding above the iron pole, correspondingly.

The flux above the PMs produced by the PM and the iron pole flux created via DC field winding can be written as functions of peak air gap flux density ($B_g$), air gap area ($S$), and the average to peak air gap flux density ratio ($\alpha$).

Using (6), (7) and (8) equations, the air gap flux density can be written as [20, 13]:

$$B_g = \frac{\alpha_{p/PM}}{\alpha_p} B_{g/PM} + \frac{\alpha_{p/DC}}{\alpha_p} B_{g/DC} \quad (9)$$

$$B_{g/PM} = \frac{1}{2} \left( \alpha_i \frac{\alpha_{PM/PM}}{\alpha_{p/PM}} B_{g-PM/PM} + \alpha_i \frac{\alpha_{iron/PM}}{\alpha_{p/PM}} B_{g-iron/PM} \right) \quad (10)$$

$$B_{g/DC} = \frac{1}{2} \left( \alpha_i \frac{\alpha_{PM/DC}}{\alpha_{p/DC}} B_{g-PM/DC} + \alpha_i \frac{\alpha_{iron/DC}}{\alpha_{p/DC}} B_{g-iron/DC} \right) \quad (11)$$

where $\alpha_{i}$ is the pole arc and $\alpha_p$ is the average to peak air gap flux density ratio above a pole. $B_{g-PM/PM}$ and $B_{g-PM/DC}$ are the airgap flux densities above the magnet pole produced via the PM itself and DC field winding. Also, $B_{g-iron/PM}$ and $B_{g-iron/DC}$ are the airgap flux densities above the iron pole produced by the magnet and DC field winding.

The air gap flux density in front of the iron pole created by the PM can be calculated as [20, 23]:

$$B_{g-iron/PM} = -(1 - K_{dFCAFPM}) B_{g-PM/PM} \quad (12)$$

where $K_{dFCAFPM}$ is the leakage flux factor between two different poles in rotor [20, 23].

The air gap flux density above the iron pole caused through the DC field winding is calculated as [20, 23]:

$$B_{g-iron/DC} = K_{DC} \mu_0 \frac{N_{DC} I_{DC}}{2g} \quad (13)$$

where $I_{DC}$ is the DC field winding current, $N_{DC}$ the DC field winding turns, $g$ air gap length, $K_{DC}$ is +1 for field strengthening, 0 for zero DC field winding current and -1 for field weakening mode.

Air gap flux density above PM pole produced via the DC field winding is calculated as [20, 23]:

International Journal of Mechatronics, Electrical and Computer Technology (IJMEC)
Universal Scientific Organization, www.aeusco.org
ISSN: 2411-6173, EISSN: 2305-0543

4588
Two types of power are defined for the proposed AFPM: $P_{g-PM}$, the portion of the air gap power which is proportional to the PM magnetization and $P_{g-iron}$, changes according to the magnitude and direction of the DC field winding ampere turns. In order to determine the proportion of the iron pole power to PM pole power, different design constraints have to be taken into account. Generally, this relationship can be stated as [24]:

\[
K_{pw} = \frac{P_{g-iron}}{P_{g-PM}}
\]  

(15)

$K_{pw}$ is the Air gap Power ratio. It can be shown that [24]:

\[
K_{pw} = \frac{B_{g-iron/DC}}{B_{g-PM/PM}}
\]

(16)

According to equation (13) for $B_{g-iron/DC}$:

\[
K_{pw}B_{g-PM/PM} = K_{DC}\mu_0 \frac{N_{DC}I_{DC}}{2g}
\]

(17)

And solving for $N_{DC}I_{DC}$

\[
N_{DC}I_{DC} = \frac{2g}{K_{DC}\mu_0} K_{pw}B_{g-PM/PM}
\]

(18)

Equation (18) denotes the amount of field Ampere-Turns necessary for a given value of power ratio and flux density in the PM section. For excitations based on ferrite, the major component of the air gap flux arises from the DC field winding excitation, in this case $K_{pw} > 1$. For a rare earth type of PM (such as NdFeB), this factor is close to unity. In order to maximize the use of the iron, similar maximum flux density values in both sides of the air gap must be selected. Therefore, the iron pole power and PM pole power are similar. In other words, $K_{pw} = 1$ [24].

The AFPM machine's equations can be adjusted and used in the proposed AFPM structure. The length of machine in axial direction is [20, 23]:

\[
L_{ax} = L_s + 2L_r + 2g
\]

(19)

where $L_s$ is the length of the stator in axial direction, $L_r$ the length of the rotor in axial direction, and $g$ the air gap length of the machine.

The length of the stator core in axial direction is:

\[
L_s = L_{cs} + 2d_s
\]

(20)

where $L_{cs}$ is the length of the stator core in axial direction, and $d_s$ the length of the stator slot in axial direction. The length of the stator core in axial direction $L_{cs}$ can be calculated as:

\[
L_{cs} = \frac{B_g\alpha_p\pi D_o(1 + \lambda)}{2B_{cs}p}
\]

(21)
where $B_{cs}$ is the stator core flux density. $B_{cs}$ in TORUS structure can be assumed as [25]:

$$5 \cdot 47 \cdot f^{-0.32} \quad f > 40 \text{ Hz}$$

$$1 \cdot 7 \cdot t o \ 1 \cdot 8 \quad f \leq 40 \text{ Hz}$$

(22)

The semi-closed rectangular slot with related dimensions is shown in figure 5.

Figure 5: Slot dimensions at the inner diameter of the stator axial cross-section.

The number of conductors per slot can be calculated as:

$$n_{cs} = \frac{2N_{ph}}{pq}$$

(23)

where $N_{ph}$ is the number of series turns per phase per stator, and $q$ number of slots per phase per pole.

Accordingly, the total slot current $I_s$ is expressed as:

$$I_s = n_{cs} I$$

(24)

where $I$ is the rms value of the rated phase current. The area of the slot $A_s$ can be constrained as

$$A_s \geq \frac{I_s}{I_{s \text{ max}} K_{cu}}$$

(25)

$K_{cu}$ is the copper fill factor. The conductor area calculated for the rated current value and for the minimum possible slot area becomes:

$$A_c = \frac{I}{I_{s \text{ max}}} = \frac{A_s K_{cu}}{n_{cs}} = \frac{W_{sb} d_b K_{cu}}{n_{cs}}$$

(26)

The slot pitch at the inner diameter of the stator is

$$\tau_{st} = \frac{D_i \pi}{pq m} = W_{sb} + W_{tbi}$$

(27)

Considering the fact that the total air gap flux per pole will flow through the teeth (the pole area is reduced proportional to the ratio of the tooth bottom width and the slot pitch), the minimum tooth bottom width can be expressed as

$$W_{tbi} = \tau_{st} \frac{B_g}{B_{t \text{ max}}}$$

(28)
where $B_t^{\text{max}}$ is maximum flux density in teeth. With calculation of the tooth bottom width using equation (28), and calculation of the slot bottom width using equation (27), the slot depth $d_b$ can be calculated using equation (26).

The slot-top dimensions $w_s$, $d_{t1}$ and $d_{t2}$ should be properly selected by considering the fact that slot leakage increases with decreasing slot-top width and the cogging torque increases by increasing it. Therefore, the best compromise can be determined by using FE analysis after preliminary analytical calculations. Besides, $d_{t1}$ and $d_{t2}$, which contribute to the total slot depth, should be kept as small as possible in order not to increase the length of the stator core in axial direction.

The length of the rotor core in axial direction is

$$L_r = L_{cr} + L_{pm}$$

where $L_{cr}$ is the length of the rotor core in axial direction, and $L_{pm}$ the length of PM in axial direction.

The length of rotor core in axial direction $L_{cr}$ can be calculated as [10, 23]:

$$L_{cr} = \frac{K_f B_{g-PM/PM} \pi D_o (1 + \lambda)}{4 K_d B_{cr} p}$$

where $B_{cr}$ is the rotor core flux density, $K_d$ the leakage flux factor, and $K_f$ the peak air gap flux density correction factor.

The PM length of the machine can be calculated as:

$$L_{pm} = \frac{\mu_r B_{g-PM/PM}}{B_r - B_{g-PM/PM}} \frac{K_f (g K_{c-AC})}{K_d}$$

where $\mu_r$ is relative permeability of the magnet, $B_r$ the permanent magnet material residual flux density and $K_{c-AC}$ the AC winding carter coefficient. Carter coefficient values can be calculated using FEA.

The DC field winding dimension can be calculated using the necessary field Ampere-Turns and DC field winding current density [20, 23].

$$L_{ss-DC} = \frac{N_{DC} I_{DC}}{H_{ss-DC} J_{ss-DC} K_{cu-DC}}$$

where $L_{ss-DC}$ is the axial length of DC field winding, $H_{ss-DC}$ the radial height of the DC field winding, $K_{cu-DC}$ the DC field winding slot fill factor, and $J_{ss-DC}$ DC field winding current density.

A 1 kW, 375 rpm proposed AFPM machine by aforementioned equations was designed for using in electric vehicles according to (1)–(32), parameters often affect each other and vary instantaneously; thus, the AFPM machine optimization is a nonlinear problem. In this research, Genetic Algorithm (GA) was used for achieving optimal design. GA is a strong tool that can solve various complex and nonlinear optimization problems [27, 28].

To use GA, it is necessary to identify a number of parameters as the genes establishing the chromosomes and to introduce objective functions into the algorithm via fitness function. In this research, ten parameters were selected as genes and they are: magnetic loading, electrical loading, outer diameter, inner to outer diameter ratio, pole-pitch to pole-arc ratio, number of turns per phase, stator current density, DC field winding current density, DC field winding height and DC field winding ampere-Turns. The design parameters that are characteristics and dimensions of the machine and their limitations were considered as:

- $0.4 \leq B_g \leq 1.2 \ T$
- $10000 \leq A \leq 30000 \ \frac{A}{m}$
• \( D_o \leq 250 \text{ mm} \)
• \( 0.4 \leq \lambda \leq 0.7 \)
• \( 0.6 \leq \alpha_p \leq 0.9 \)
• \( 50 \leq N_{ph} \leq 300 \)
• \( 3 \leq J_s \leq 10 \frac{A}{mm^2} \)
• \( 5 \leq J_{s-DC} \leq 15 \frac{A}{mm^2} \)
• \( 10 \leq H_{ss-DC} \leq 40 \text{ mm} \)
• \( 500 \leq N_{DC} \leq 3000 \text{ A.T} \)

Table 1: Design requirements and optimization restrictions

<table>
<thead>
<tr>
<th>Stator and rotor core and PM material limitation</th>
<th>Generator features and restrictions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residual flux density</td>
<td>1.1 T</td>
</tr>
<tr>
<td>Relative permeability</td>
<td>1.05 ( \frac{H}{m} )</td>
</tr>
<tr>
<td>Maximum flux density in stator core</td>
<td>1.5 T</td>
</tr>
<tr>
<td>Maximum flux density in rotor core</td>
<td>1.5 T</td>
</tr>
<tr>
<td>Residual flux density</td>
<td>1.1 T</td>
</tr>
<tr>
<td>Relative permeability</td>
<td>1.05 ( \frac{H}{m} )</td>
</tr>
<tr>
<td>Maximum flux density in stator core</td>
<td>1.5 T</td>
</tr>
<tr>
<td>Maximum flux density in rotor core</td>
<td>1.5 T</td>
</tr>
</tbody>
</table>

Torque density and efficiency are two important parameters in electric vehicles. Hence, these parameters were selected as fitness function in optimization. The following fitness function was considered for optimization:

\[
 fitness \ function = -\left[ (a \ast \eta) + (b \ast T_{density}) \right] \tag{33}
\]

where \( T_{density} \) is the machine torque density and calculated as:

\[
 T_{density} = \frac{P_{out}}{\frac{\pi}{4}D_o^2L_{ax}\omega_s} \tag{34}
\]

where \( \omega_s \) is the angular velocity of the machine. In order to realize the optimal fitness function, \( a \) and \( b \) should be selected appropriately [29].

Multi objective GA was used to maximize torque density and efficiency. Table 2 presents the detailed features of the optimized proposed structure.

Table 2: Main dimensions and specifications of optimal designed proposed AFPM machine

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of poles</td>
<td>16</td>
<td>Magnetic loading (T)</td>
<td>0.675</td>
</tr>
<tr>
<td>Number of stator slots</td>
<td>15</td>
<td>Electric loading (( A/m ))</td>
<td>23500</td>
</tr>
<tr>
<td>Outer diameter of stator (mm)</td>
<td>204</td>
<td>number of series turns per phase per stator</td>
<td>90</td>
</tr>
<tr>
<td>Inner diameter of stator (mm)</td>
<td>118</td>
<td>DC field winding Ampere-Turns (A.T)</td>
<td>2400</td>
</tr>
</tbody>
</table>
5. Finite Element Analysis of the Proposed AFPM Motor

The FEM within the proposed AFPM machine has been performed using commercial Maxwell 3D v.17.4.2 software. In order to achieve a reasonable range of flux control within the proposed machine, should be found optimal independent geometry parameters. These parameters are: air gap length above PM pole and air gap length above iron pole. The air gap flux above PM pole should be constant with any change in direction or magnitude of DC field winding. However, the air gap flux above iron pole should be a function of direction and magnitude of DC field winding. Thus, the air gap length above iron pole should be selected smaller than air gap length above PM pole. Therefore, DC field winding flux enter iron poles and magnetize them, while the PM pole flux remain constant. In order to find optimum lengths of two air gaps, using 3D FEA, different lengths were evaluated and optimum of them based on maximum air gap flux density above PM pole and maximum range of flux control were selected. Figure 6 shows the air gap flux density waveform in different cases.

As shown in figure 6, When the length of air gap above iron pole is 0.5 mm and length of air gap above PM pole is 3.5 mm the maximum air gap flux density above PM pole and maximum flux control range is attainable. Also, magnitude of air gap flux density above PM pole is constant. In this case, PM thickness is 8 mm and iron pole thickness is 11 mm.

Using a transient 3-D FEA the performance of the proposed method of air gap flux control was investigated with different excitation of DC field winding. Depending on the magnitude and direction of the DC field winding current, the air gap flux can be weakened or strengthened.

<table>
<thead>
<tr>
<th>Stator stack length (mm)</th>
<th>90</th>
<th>Torque density ($\frac{W}{cm^3}$)</th>
<th>0.0073</th>
</tr>
</thead>
<tbody>
<tr>
<td>PM thickness (mm)</td>
<td>5</td>
<td>Efficiency (%)</td>
<td>75.48</td>
</tr>
<tr>
<td>DC field winding height (mm)</td>
<td>15</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 6: Air gap flux density over a pole pair in different PM and iron air gap length (a) Iron air gap length/ PM air gap length=0.5/5.5, (b) Iron air gap length/ PM air gap length=0.5/4.5, (c) Iron air gap length/ PM air gap length=0.5/3.5, (d) Iron air gap length/ PM air gap length=0.5/2.5
Figure 7 (a) demonstrates the flux density distribution of AFPM machine with 3-D FEA when DC field has no current. As shown in figure 7 (a) magnitude of flux density in different parts of machine is suitable that is accordance with initial design of machine. Figure 7 (b) shows the distribution of air gap flux density AFPM machine over a pole pair in average air gap radius.

When DC field winding has no current, only PM poles produce flux in AFPM. The PM flux is depends upon PM geometry and the PM flux reluctance path. This constant flux created by axial PMs goes from one rotor to another rotor. Therefore, as shown in figure 7 (b) the magnitude of flux density in front of PM poles and iron poles is almost same.

\[\text{(a) } \text{Figure 7: Flux density in the proposed AFPM motor (a) Distribution of flux density with no DC field winding current, (b) Flux density over a pole pair in air gap}\]

Depending on the direction and magnitude of DC field winding, the air gap flux density can be reduced or increased. However, the flux strengthening due to limited DC field winding current density and iron saturation of the machine is restricted. When the DC current is injected into DC field winding in specific direction, the resultant flux of DC field winding goes from one rotor to another via stator and two air gaps. Adjusting of air gap flux is realized through control of this flux part. With combination of two flux component, PM flux which is almost constant and DC field flux determined by the magnitude and direction of DC field winding, create a variable flux in the machine air gaps.

Figure 8 shows air gap flux density over a pole pair. Depending on the direction and magnitude of the DC field winding current, the air gap flux above iron pole changes. With adjusting the DC field winding current, magnitude of PM flux changes hardly, thus with altering the direction and magnitude of DC field winding, the iron pole flux in the air gap is modified.

\[\text{(b) } \text{Figure 8: Air gap flux density over a pole pair with different DC field excitation currents}\]

In normal condition, the magnitude of DC field winding is zero, and flux above PM pole is almost constant. With injection of a positive current into the DC field winding, a flux component was created by DC field winding with opposite direction in comparison with normal condition. Therefore, the resultant flux of DC field winding above iron pole is deducted from the flux component of air gap which
created by PMs. Thus, the resultant flux of air gap is reduced. With injection of a negative current into DC field winding, the direction of DC field winding's flux is changed and this flux component is added to constant PM's flux above iron pole. Thus, the resultant air gap flux is increased.

Figure 9 shows the flux linkage waveform of three phase AC windings. As shown, the magnitude of flux linkage of three phase AC windings is altered with change in direction and magnitude of DC field winding, thus verifying the principle of the air gap flux control. When a positive DC current was injected into DC field winding, the magnitude of flux linkage of three phase AC winding is reduced. However, with injection of a negative DC current into DC field winding the magnitude of flux linkage of three phase AC winding is increased.

![Figure 9: Flux linkage of AC three phase winding with different DC coil excitation](image)

Figure 10 shows magnitude of stator flux linkage versus DC field winding current density. As shown in Figure 10, the stator flux linkage is reduced or increased regarding to normal condition that DC field current has no current. Thus, with a rational DC field winding current, a sensible range of field control is achievable.

![Figure 10: Air gap flux density above PM and iron pole versus DC coil current density](image)

As shown in figure 10, iron pole flux can be decreased or increased regarding to normal condition with no DC field winding current. With changing the DC field winding ampere turns from +6000 to -6000, the air gap flux range becomes approximately 65% with strengthening and 94% with weakening regarding to normal condition. Therefore, in this method with a sensible DC field winding current a rational range of field control capability is attainable.
Conclusion

A new structure in air gap flux control for AFPM machines with surface mounted PMs has been presented in this paper. First, the machine structure, principles and field weakening feature were illustrated. Optimal dimensions of the proposed machine were obtained by design optimization. To validate the flux weakening and strengthening capability of this structure the performance of this new structure has been analyzed using 3D FEA for different field excitation currents. The following conclusions are drawn:

- It was proven that with a sensible DC field winding current a suitable range of field control is achievable.
- In order to attain to an extensive field control range, the air gaps length above PM pole and iron pole in the proposed axial flux permanent magnet machine should not be identical. The air gap length above the iron pole should be smaller than the air gap length above the permanent magnet pole. The optimum ratio has been calculated using finite element analysis.
- It was also observed that the control of the axial flux permanent magnet machines could be achieved easily without any negative effects of current injection.

References


