Study the Influence of Air-gap Variation on Axial Forces in Axial Flux Permanent Magnet Motor Using 3D-FEM

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Abstract – *This paper describes the effect of air-gap variation on performance of a 28 pole axial flux permanent magnet motor (AFPM) with concentrated stator winding. The AFPM is modeled using three-dimensional finite-element method. This model includes all geometrical and physical characteristics of the machine components. Use of this accurate modeling makes it possible to obtain the demanded signals for a very high precision analysis. The rotor of machine however is likely to be displaced from its original location and cause to air-gap variation. It is found that the air-gap variation has a detrimental effect on air-gap flux density and amount of axial forces. Reduction of air-gap increases the air-gap flux density and consequently increases the amount of axial force between rotor and stator. This extra force can cause bearing damages and lifetime reduction.*

Keywords*: Axial flux permanent magnet (AFPM) motor, air-gap variation, three-dimensional finite-element method (3D-FEM).*

I. Introduction

Axial Flux Permanent Magnet Machines (AFPM) first appeared in the technical literature in the mid 70s. Soon their fields of application spread widely. Axial flux permanent magnet (AFPM) machines have been used increasingly in various applications due to their high efficiency, compact construction and their higher torque at low speed [F. Caricchi et al, 1996], [A. Parviainen et al, 2005]. AFPM topologies make it possible to design high pole machines. Thus, it can be directly coupled to the turbines with low-speed, such as wind and hydro turbines [Y. Chen et al, 2004], [S. M. Hosseini et al, 2008]. Their robust structure and compactness present high-speed axial-flux machines qualified for distributed generating application [A. S. Holmes et al, 2005]. It is also a suitable candidate for electric vehicle (EV) and traction [Y.-P. Yang and D. S. Chuang, 2007].

Most of motors have inbuilt deformity due to manufacturing defects such as unbalance structure, bearing deficiency and misalignment [Ungtae Kim and Dennis K. Lieu, 2005]. The rotor of machine however is likely to be displaced from its original location. The displacement can occur during normal machine operation or during abnormal and fault conditions within the machine [Jawad Faiz and Siavash Pakdelian, 2006]. This displacement changes the air-gap length and subsequently affects all the machine characteristics. This fault affects the normal operation of the machine and leads to motor vibration and decrease the motor lifetime.

Analysis of air-gap deformity in radial flux motors has been the subject of many literatures [S. Nandi et al, 2005], [Bashir Mahdi Ebrahimi et al, 2008], [Jawad Faiz and Siavash Pakdelian, 2008], [Jawad Faiz et al, 2008]. But, nothing has been reported on the analysis of air-gap deformity in AFPMs.

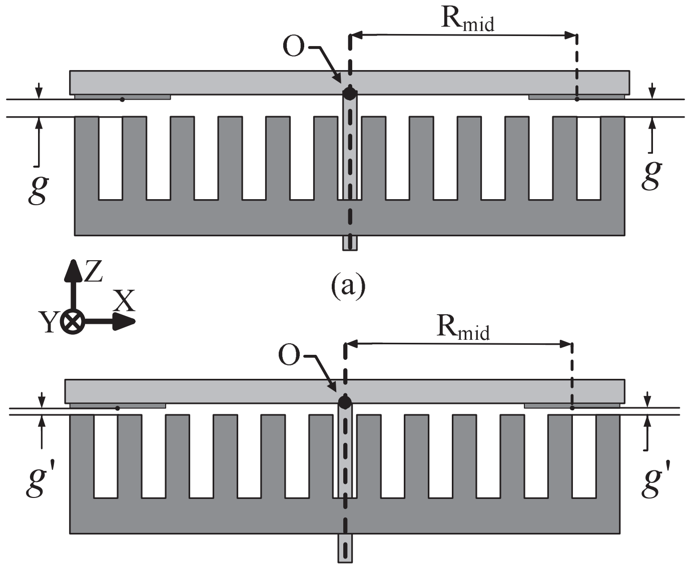


Fig. 1. Schematic representation of rotor displacement in axial flux permanent magnet motor. (a) healthy motor (b) motor with air-gap deformity.

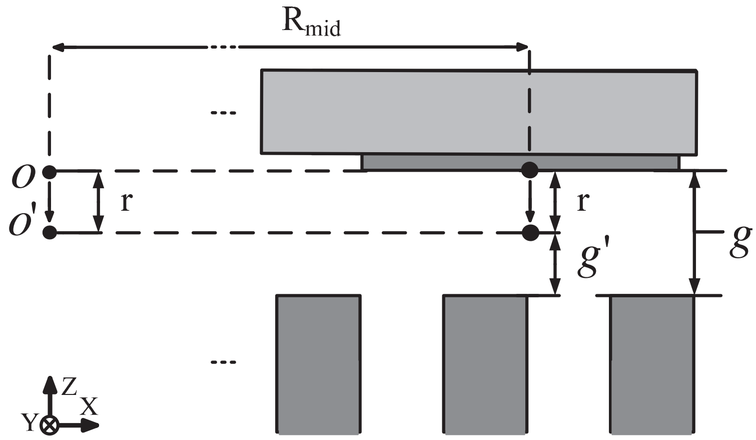


Fig. 2. Schematic representation of static air-gap displacement in axial flux permanent magnet motor

However, like the conventional radial flux machines, Because of manufacturing imperfections, the rotor air-gap variation is inevitable. Consequently, it is of great interest to investigate the axial force, which tends to bearing defects.

In this paper, a surface mounted axial flux permanent magnet (AFPM) motor with air-gap variation has been modeled using 3-dimentional finite element method. Magnetic flux density of air-gap and axial forces between rotor and stator in healthy motor and in fault condition has been calculated. It is observed that air-gap variation has significant effects on air-gap flux pattern and axial force of the motor.

II. Air-gap Variation in AFPM

An issue coming up from the fabrication and normal operation of the motor is the displacement of the rotor with respect to the stator. This fault appears due to inherent mechanical tolerances and defects in the bearing system that supports the rotor [C. Peter Cho and Barry K. Fussell, 1993].

TABLE I

SPECIFICATION OF THE MOTOR

Quantity	Value
Rated power(kW)	2.2
No load voltage(V)	210
Rated phase current(A)	3.5
Frequency(Hz)	300
Speed(rpm)	1285
Phase connection	Δ
Pole pairs	14
Air gap length(mm)	1.2
Rotor diameter(mm)	206
Remanence of magnets(T)	1.24
Thickness of magnets(mm)	3
Outer diameter of stator(mm)	200
Inner diameter of stator(mm)	116
Slot width(mm)	13.6
Slot height(mm)	40
Number of slots	24
Width of stator back iron(mm)	10.5
Width of rotor back iron(mm)	10
Wire diameter(mm)	1.5
Number of turns per coil	130
Phase resistance at 300Hz(Ω)	2.5
Stator inductance(mH)	10

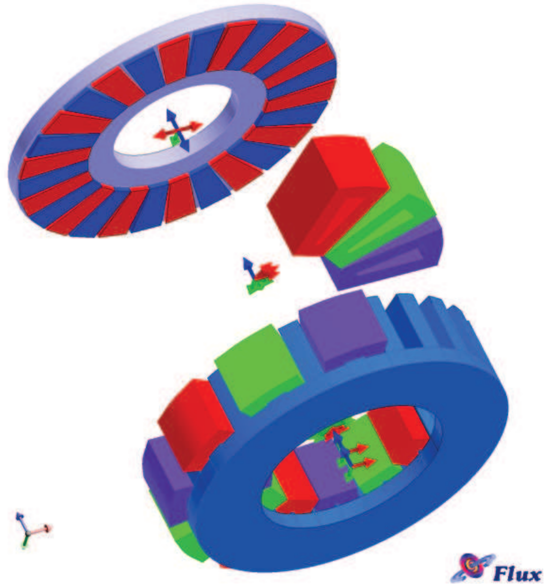


Fig. 3. Three-dimentional FEM model of AFPM

Fig. 2 shows the rotor axial displacement. In such a case, air-gap length uniformly decreases along the rotor. If the rotor shaft assembly is adequately rigid, then the level of air-gap displacement remains constant. The air-gap displacement factor is defined as follows:

$$ADF = \frac{r}{g'} \times 100 \qquad \{1\}$$

Where g' is the air-gap length in fault condition, and r is given by:

$$r = g - g' \qquad \{2\}$$

Where g is the air-gap length in healthy condition. Air-gap displacement degrees more than 50% will not be considered in this paper.

III. Motor Specifications

Fig. 3 shows a three-phase, 210-V, 2200-W, 1850-rpm, Δ-connected AFPM machine that was modeled studying air-gap variation. It consists of a stator with 24 slots and 12 single layer trapezoidally shaped coils with fractional winding. The Coils with a same color belong to one phase. The rotor disc consists of 28 magnets of alternating polarity. The machine parameters are given in Table I [Fabrizio Marignetti et al, 2006], [Fabrizio Marignetti et al, 2008].

IV. Finite Element Simulation

Many literates have demonstrated that accurately analyzing the behavior of Axial Flux PM Machines is not an easy task because these types of machines are intrinsically 3-D machines [Fabrizio Marignetti et al, 2008]. Three dimensional finite-element method (FEM) allows a precise analysis of magnetic devices taking into account geometric details and magnetic nonlinearity. So, it is an appropriate method for analyzing air-gap variation in AFPMs. Use of this accurate modeling makes it possible to obtain the demanded signals for a very high precision analysis. Three-dimensional finite-element analysis (3D-FEA) software FLUX2D/3D by CEDRAT is used to simulate the motor [CEDRAT Group, 2009]. Fig.3 shows The FEM model that was used in this paper.

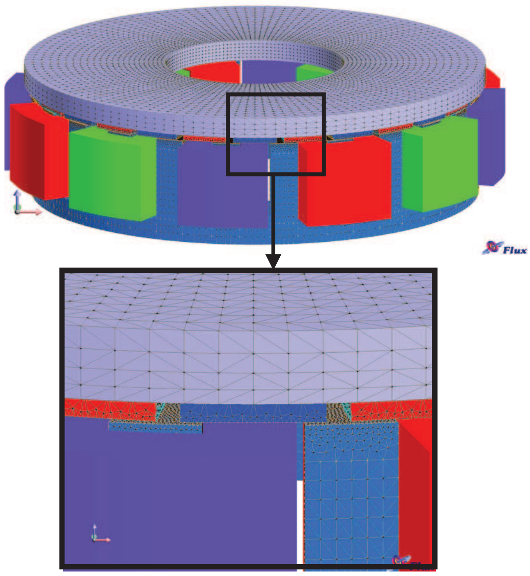


Fig. 4. Three-dimensional mesh model.

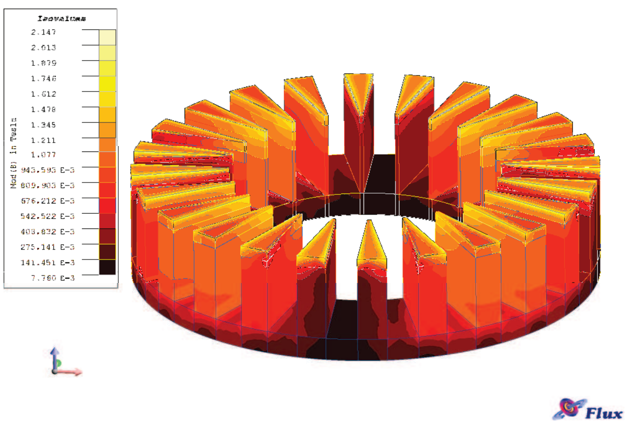


Fig. 5. Flux density distribution in the stator

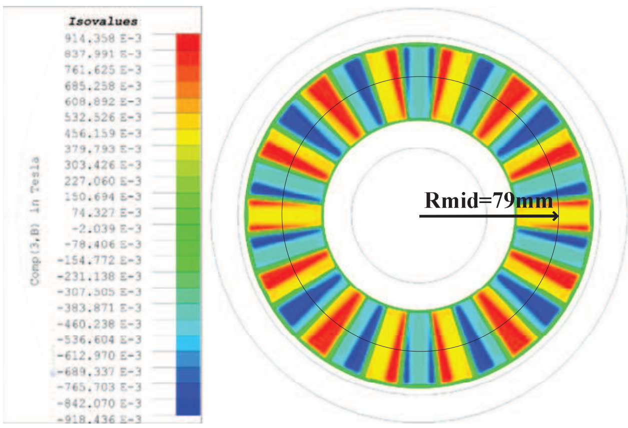
V. Primary Finite Element Results

The center of the stator is fixed at the origin of the global coordinate system, where magnetic force is evaluated. The center of the rotor is located at the origin of the local coordinate system, which rotate around the center of the global coordinate system, i.e., the center of the stator, by a constant step angle. Investigation of airgap variation models was made with the assumptions of a three-dimensional problem and nonlinear materials. A relatively large ADF of 50% of the nominal air gap was selected to magnify its effects. Fig. 4 shows mesh diagram of the proposed motor and as it shows, density of meshes increases near the air-gap in order to a precise simulation. Whole nodes number is 460,000 in this simulation. This amount of nodes is very high and will warrant the accuracy of simulation. Fig. 5 demonstrates the flux diagram of stator. It shows that maximum flux density in hotspots is 2.147 T.

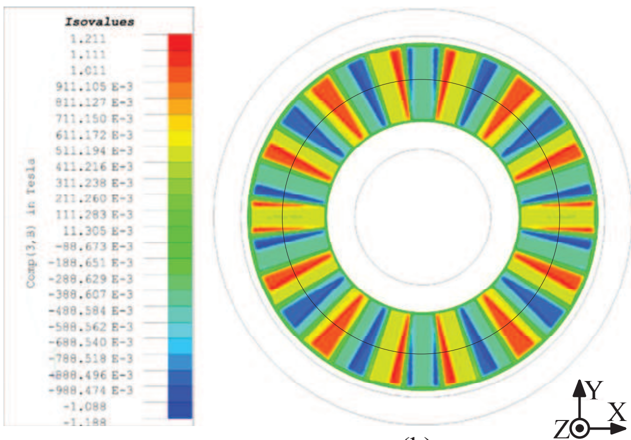
VI. Effect of Air-gap Variation in Air-gap Flux

One of the most important characteristics of the motor is Air-gap flux density. So, it was simulated under no-load condition to monitor the effect of air-gap variation in this characteristic.

Fig.6 shows the axial component of the no-load air-gap flux density duo to permanent magnets in healthy and fault conditions. Moreover, the z-component of the no-load air-gap flux density was computed over a circumference in the middle of air-gap. Fig.7 reports the waveforms. In addition, maximum flux density of air-gap was computed in different ADF.



(a)



(b)

Fig. 6. Axial component of the no-load air-gap flux density (a) healthy condition [ADF=0] (b) fault condition [ADF=0.5]

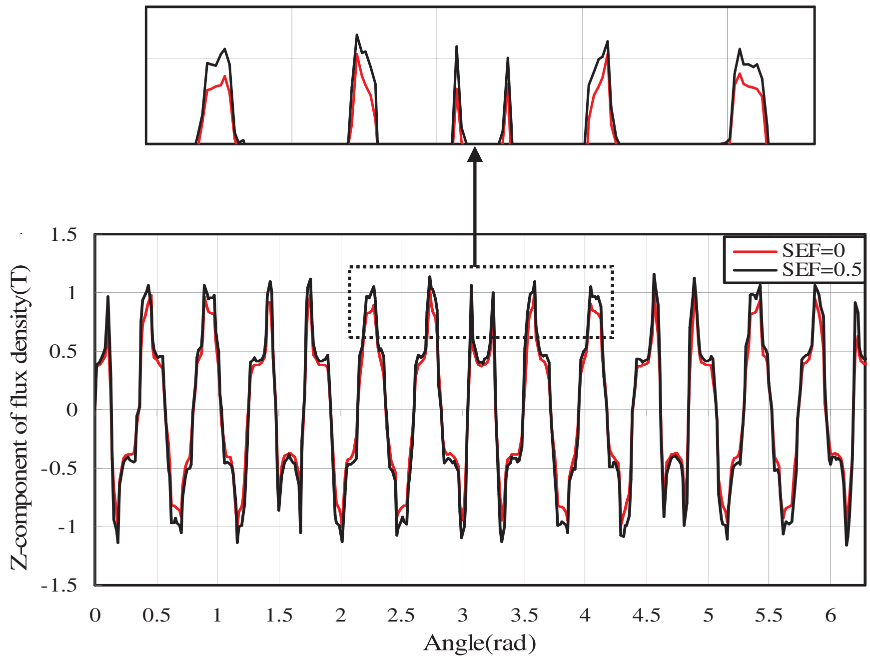


Fig. 7. z-component of the no-load air-gap flux density over a circumference in the middle of air-gap

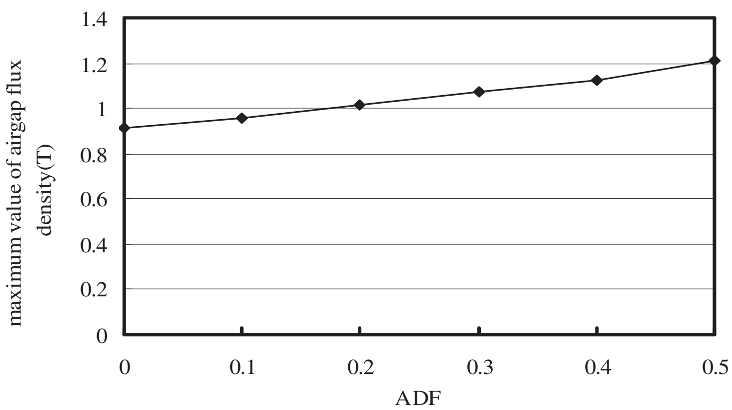


Fig. 8. Maximum value of air-gap flux density

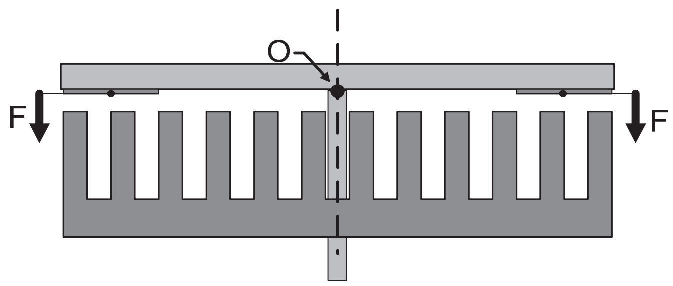


Fig. 9. Schematic representation of axial forces in axial flux permanent magnet motor

It is observed that centricity clearly affects the flux amplitude and its maximum value. The reason is that the flux path reluctance is mainly determined by the length of the air gap. When the rotor is acceded to the stator poles vertically, the length of gaps between rotor permanent magnets and their corresponding stator teeth are reduced. So, as seen in Fig.6, Fig. 7 and Fig. 8 air-gap variation affects flux density considerably and the flux densities and their maximum values rising in the air-gap.

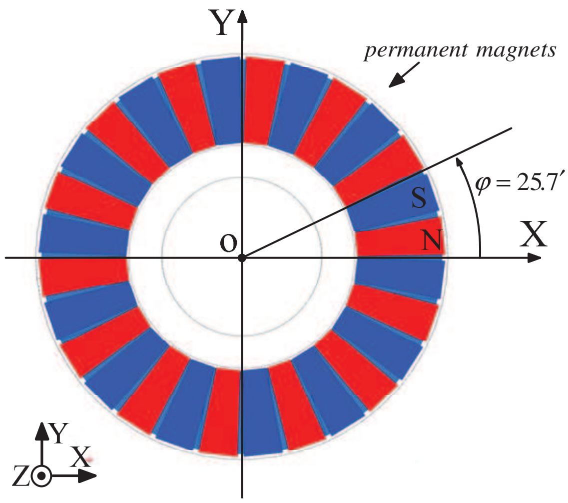


Fig. 10. Top view of permanent magnets

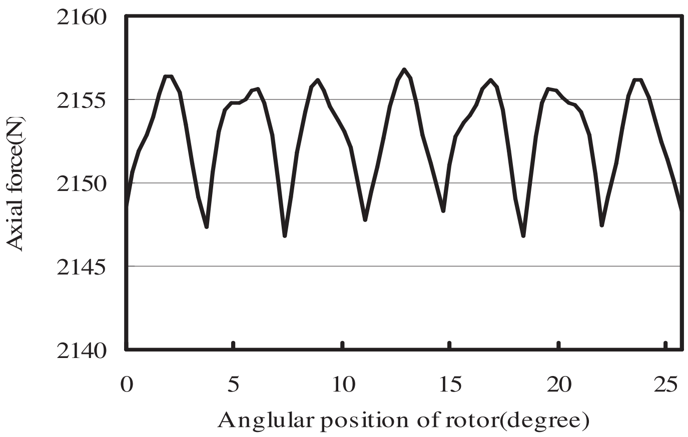


Fig. 11. Axial force between rotor and stator

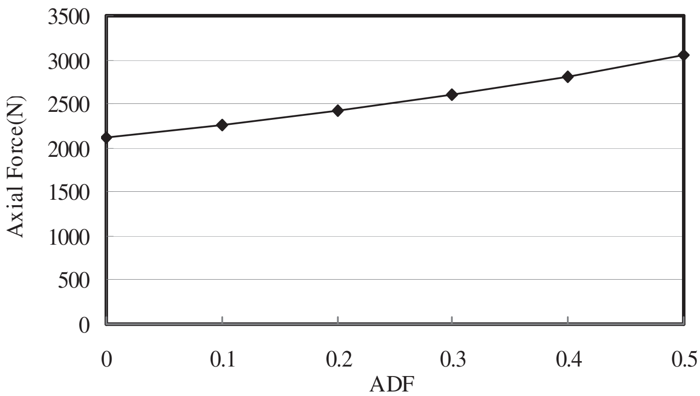


Fig. 12. Axial force between rotor and stator

VII. Effect of Air-gap variation in Axial Force Between Rotor and Stator

In axial flux permanent magnet machines, there is an axial force between rotor magnets and stator teeth. Fig. 9 represents the Schematic of this axial force. Fig 10 shows that the period of these force fluctuations is equal the angular distance between two identical permanent magnets. It means that after this amount of rotation, a *N* pole replaces by another coming one and the situation of permanent magnets toward the stator teeth becomes similar to the previous position. The force fluctuations will repeat a same manner in other periods. The period is obtained as follows:

$$\varphi = \frac{360}{\left(p/2 \right)} \qquad \{3\}$$

Where p is number of machine poles. Fig. 11 shows the total magnetic force fluctuates of the motor in one period. This trend will repeat in other periods. In order to have a simple view for amount of this force under different ADFs, its mean values was compared.

It observed that rotor displacement, resulting in extra magnetic force between rotor and stator. In fact, if the air-gap reduces, then the air-gap magnetic field increases. Consequently, attraction force due to the magnet will be greater, therefore the bearings should withstand a higher amount of axial forces. Fig. 12 shows mean value of axial force in different value of ADF. It shows that the value of axial forces rises by increasing the ADF. This is to be expected, since the attractive magnetic force on the rotor increases rapidly as the air gap decreases. Choice of the bearings for the motor was done accordance with the primary airgap length and its related force. So, this amount of stresses that act on the machine will decrease bearings lifetime and cause to bearing damages.

VIII. Conclusion

The effect of air-gap variation on air-gap flux density and axial forces of a 28 pole AFPM is investigated through 3-D finite-element analysis. The rotor of machine however is likely to be displaced from its original location and cause to air-gap variation. It is found that the air-gap variation has a detrimental effect on air-gap flux density and amount of axial forces. Reduction of air-gap increases the air-gap flux density and consequently increases the amount of axial force between rotor and stator. This extra force can cause bearing damages and lifetime reduction.

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