Investigation of mechanical field weakening of axial flux permanent magnet motor

M Syaifuddin Mohd1,3, A Rashid A Aziz1,3 and M Syafiq Mohd2
1Mechanical Engineering Department, Universiti Teknologi PETRONAS, Bandar Seri Iskandar, Malaysia
2Electrical and Electronics Engineering Department, Universiti Teknologi PETRONAS, Bandar Seri Iskandar, Malaysia
3Centre for Automotive Research and Electric Mobility (CAREM), Universiti Teknologi PETRONAS, Bandar Seri Iskandar, Malaysia

E-mail: syaifuddin@petronas.com.my

Abstract. An investigation of axial flux permanent magnet motor (AFPM) characteristics was conducted with a proposed mechanical field weakening control mechanisms (by means of stator-rotor force manipulation) on the motor through modeling and experimentation. By varying the air gap between at least two bistable positions, the peak torque and top speed of the motor can be extended. The motor high efficiency region can also be extended to cover greater part of the motor operating points. An analytical model of the motor had been developed to study the correlation between the total attraction force (between the rotor and the stator) and the operating parameters of the motor. The test results shows that the motor output complies with the prediction of the research hypothesis and it is likely that a spring locking mechanism can be built to dynamically adjust the air gap of the motor to increase the operating range and could be applied in electric drivetrain applications to improve overall efficiency of electric and hybrid electric vehicles.

1. Introduction
Axial flux permanent magnet motor (AFPM) inherently has one of the highest specific power due to torque generation from the inner radius to outer radius of the magnets on the rotor face as compared with radial flux permanent magnet motor (RFPM), where torque is only generated at the outer radius of the motor where the magnets are located. However, the permanent flux linkage between the rotor and stator causes a fixed relationship between winding current and motor torque. This “torque constant”, kT, also causes a fixed top speed for a PM motor. The higher the kT, or torque per amp, the lower the top speed of the motor [1].

Various methods of getting around this property have been developed in radial flux PM motors. Some of these methods allow for increasing the top speed of the motor by 2 or 3 times what would otherwise be achievable. Unfortunately, this is achieved at a severe cost in terms of loss and motor efficiency. This is because kT reduction is done purely by using winding current that has been offset the maximum phase current amplitude which would deliver maximum torque output from the motor shaft [2].

The axial flux motor on the other hand is different from other types of PM motors in that the same effect of varying kT can be achieved without introducing additional losses because it can be
accomplished by the virtue of altering the geometry of the motor. One of the reasons the torque constant, $k_T$ is called a constant is because it is an inherent property due to the geometry of the motor. Although there are many different contributors to $k_T$, the one, which is of the main interest is the air gap, or the distance between the magnet rotor and the stator. The size of the air gap determines the electromagnetic coupling between the rotor and the stator and therefore the value of $k_T$. By simply moving either the rotor or the stator axially relative to the other, $k_T$ can be adjusted.

![Figure 1. Axial Flux Permanent Magnet Motor Topology.](image)

J. Jermakian et al. introduced a pioneering work on testing and modeling of variable air gap axial flux permanent magnet motor and discussed on the operating characteristics of the motor at different air gaps and the effects on operating speeds and torque outputs [3-6]. Later, J. Kern et al. Oh, Kern [7] from Argonne National Lab continue with modeling and simulation work using the same type of motor topology and study the motor operation in all four quadrants. It is determined that the main advantage of adjusting the flux is that the motor torque-speed characteristics can better match the changing load especially in applications which requires variable operating load and speed such as an electric vehicle. The challenge in implementing an electric machine with these qualities is to develop a control strategy that takes advantage of the available efficiency improvements without using excessive energy to mechanically adjust the air gap and reduce the potential energy savings [7].

There are several existing patents [8-10], patent applications [11, 12] and publications [2, 13, 14] on different ways to achieve mechanical field weakening. All of the methods described employ the use of servo motors or some other mechanical devices, which need to be powered externally to the motor and will add to the system mass and costs. At present, the proposed method of manipulating the rotor-stator attractive force to vary the air gap distance appears to be novel in comparison to the prior work on mechanical field weakening of a PM motor.

2. Research methodology

An analytical model of an axial flux PM motor had been developed and simulated in a Matlab Simulink environment. The peak torque values from simulations had been validated with peak torque output of an actual motor [3] with the same design parameters and configurations. A model of a Belleville spring mechanism is also included in the simulation to reduce the electromagnetic axial force between the rotor and the stator.

In addition, a quasi-static 2-dimensional finite element analysis (FEA) model was created by modeling the motor as multiple layers from inside radius, $R_i$ to the outside radius, $R_o$. A periodic type boundary condition as shown in Figure 3 is utilized since the magnetic field repeat periodically at every pole pitch at no-load operation and every double pole pitch under-load conditions [15]. The main results from the finite element analysis are the flux distribution and the back emf waveform. The back emf waveform shape is then utilized to refine the dynamic model of the motor in the Matlab Simulink environment. Figure 2 shows the validation of the analytical model as compared with an actual motor torque output data.
Figure 2. FEA electromagnetic simulation of a single pole pair with periodic boundary condition applied.

Figure 3. Peak torque values – Simulation & Test Data.

Figure 4 shows the torque output of one of the motors as a function of phase angle offsets. As the phase angle is advanced or retarded, the maximum amount of torque generated is reduced while the rotor-stator attraction force is either respectively decreased or increased. The loss in torque production due to the phase current offset is directly converted into these additional rotor-stator forces. Based on these results, it is possible to determine the total rotor-stator attraction force as a function of the three main parameters; size of air gap, phase current offset and amplitude of phase current.
Figure 4. Torque as a function of phase current offset and amplitude.

An analytical model of the rotor-stator attraction force was developed based on the test data. However, the derivation of the equations for the analytical model of the electromagnetic force is too extensive to be covered in this paper, thus only the reduced final equations (for the given motor dimensions and design parameters) are shown below:

- Electromagnetic attraction force of rotor and stator \[16\], \(F_{r-s}\):

\[
F_{r-s} = \int B_G(x)^2/(2\mu_0) \, dA
\]  
(1)

where:

- \(B_G\) – air gap flux density, \(\mu_0\) - permeability of air
- \(A\) – rotor magnet area, \(x\) – air gap distance

- Attraction force due to induced magnetic field, \(F(I,\theta,x)\):

\[
F(I,\theta,x) = (-4kT(x) \cdot I \cdot \theta^2) / (Reff \cdot \pi^2)
\]  
(2)

where:

- \(kT\) – torque constant, \(I\) – phase current magnitude
- \(\theta\) – phase current offset, \(Reff\) – effective radius of rotor

- Total attraction force, \(F_{total}\): 

\[
F_{total} = F_{r-s} + [-\text{sign}(\theta)] \cdot F(I,\theta,x)
\]  
(3)

The resultant equation for total attraction force is a function of 3 variables; magnitude of phase current, phase current offset and air gap distance. A typical four dimension sliced plot is shown in figure 5.
3. Results and discussion

The resultant four-dimensional matrix will be used in the dynamic model of the system. Based on the calculated total attraction force as a function of the three variables, it is possible to design a bistable air gap control mechanism by manipulation of the internal forces and insertion of a Belleville spring mechanism to reduce the total attraction force.

The mechanism of the proposed system can be explained using the force profiles in figure 6 above as following:

1. As the phase current is advanced to -30º, the total attraction force is reduced to less than 840 N becoming lower than the repulsion force from the Belleville spring mechanism.
2. Hence, the rotor is pushed away from the stator as $F_{spring} > F_{total}$ until the maximum air gap distance is achieved. The motor is now capable of delivering torque at higher speed at a larger air gap.
3. To return the rotor back to the minimum air gap distance, the phase current is changed back to 0º (or even several additional degrees to increase the attraction force). Now the total attraction force is becoming larger than the repulsion force from the spring mechanism.
4. Therefore, the rotor is pulled back to the minimum air gap distance as $F_{spring} < F_{total}$.

In the actual operation of the motor, a locking mechanism might be required to lock the rotor at the minimum or maximum air gaps. The effects of cogging torque and torque ripples on the proposed mechanism will also be investigated later using a dynamic model of the system.

The dynamic simulation of motor-controller-load is performed in Matlab Simulink environment. The model takes into account the actual shape of the back EMF and the shape of the current waveform — sinusoidal or trapezoidal — injected into the windings [17] and includes a model of the motor drive subsystem to simulate the control of the phase current timing. The main outputs of the simulations are the torque output of the motor, rotational speed of the motor and the variation in the rotor-stator attraction force as the functions of air gap length and phase current offsets.

---

**Figure 5.** 4D plot of total attraction force (in N).
4. Scaled down experimentation
A custom made test bench (as shown in figure 7) for a scaled down 700 Watt motor was fabricated with two load cells to measure i. the axial attraction force between rotor and the stator and ii. torque output from the motor. Two operating parameters of the motor can be physically adjusted: i. air gap size by 1 mm increment by inserting spacers on the rotor assembly and ii. phase current offset by 10 electrical degrees increment of the hall sensor position. Figure 8 shows the construction of the rotor and stator coils.

**Figure 6.** Rotor-stator axial forces at $I = 100$ amps.

**Figure 7.** Custom test bench set-up to measure torque and axial force.

**Figure 8.** (a) Stator coils and (b) Rotor assembly.
Preliminary results in figure 9 suggest that the shape of the torque output profiles comply with the model prediction. However, the peak torque of the 700 Watt motor is ‘flat’ between 30 degrees and -30 degrees phase angle offset compared with the sinusoidal shape of the torque output of a typical motor as shown in figure 7. This can be explained by the six-step motor drive scheme used for the 700 Watt motor compared with the sinusoidal drive scheme used for the motor in the larger motor.

![Figure 9. Motor torque and $F_{rs}$ versus phase angle offset.](image)

As predicted, the attraction force reduced by advancing the phase current and it reaches the minimum value at phase angle offset of 90 degrees. The electromagnetic force vector increases in the axial direction and reduces the rotor-stator attraction force as the phase current is advanced from 0 degree to 90 degree. As a result, the motor torque output is also reduced as the electromagnetic force vector decreases in the tangential direction to the rotor disc.

![Figure 10. Rotor-stator attraction force versus air gap size.](image)
Figure 10 shows the rotor-stator attraction force results versus the increment in air gap size from 1 mm to 8 mm. As the phase current of 20 Amps is advanced by 30 degree, the rotor-stator attraction force decreases in linear manner as it is a function of torque constant, KT which reduces linearly as a function of air gap size. A pre-compressed spring force profile shown in the same figure suggests that it is possible to dynamically vary the air gap using the method suggested in figure 5.

5. Conclusion
This research is investigating into the feasibility of manipulating the rotor-stator attractive force in order to mechanically introduced field weakening to axial flux PM motor. An analytical model of the axial flux PM motor had been developed and simulated in Matlab Simulink environment. Based on the simulated outputs of the rotor-stator attraction force profiles, it is feasible to design and control a bistable air gap switching mechanism. The model can be further improved and enhanced in order to study the system stability and to determine an appropriate control algorithm when the system is operating under dynamic transitional loads expected in actual applications. A custom made test bench (and motor controller) for a 700 W motor was built specifically to characterize the motor as a function of phase current, air gap size and phase current offset.

Based on current results, the motor output complies with the prediction of the research hypothesis and it is likely that a spring locking mechanism can be built to dynamically adjust the air gap of the motor to increase the operating range (higher torque at minimum air gap and higher top speed at maximum air gap). Additional sets of experiments can be conducted to further validate the model, to test transient response of the proposed system.

Acknowledgement
This work is partly funded by an STIRF (Short Term Internal Research) grant from Universiti Teknologi PETRONAS.

References
[1] Hanselman D C 2003 Brushless permanent magnet motor design (umaine.edu: The Writers' Collective)
[2] Lipo T, Aydin M, Field weakening of permanent magnet machines: Design approaches. EPE Power Electronics and Motion Control Conference (EPE-PEMC 04); 2004.
[3] Jermakian J, Mohd M-S, Motevalli V. Testing and modeling of variable airgap axial flux brushless DC motor. SAE Technical Paper, 2001 0148-7191.
[4] NGM. NGM Drive System’s Superior Performance Demonstrated in Solar Car Races. http://www.ngmcorp.com: New Generation Motors Corporation 1999.
[5] Patterson D, Recent advances in the design and construction of axial flux permanent magnet machines. Proceedings, IEEE Australia Summit; 1996; Darwin.
[6] Pinkham M. Chinese NdFeB Magnet Presence Grows Along with Demand. High Tech Materials Newsletter. 2002.
[7] Oh S C, Kern J, Bohn T, Rousseau A, Pasquier M. Axial flux variable gap motor: application in vehicle systems. SAE Technical Paper, 2002.
[8] Jermakian J B, Crain S G, Knudtson C D, Piacesi R F. Electric motor with active hysteresis-based control of winding currents and/or having an efficient stator winding arrangement and/or adjustable air gap. United States Patent Office: US Patents; 2000.
[9] Kim S-m. Motor having variable air gap. United States Patent Office: US Patent No. 5,770,908; 1998.
[10] Maslov B A, Soghomonian Z. Rotary permanent magnet electric motor with varying air gap between interfacing stator and rotor elements. United States Patents Office: U.S. Patent No. 6,727,630; 2004.
[11] Yagi H, Matsueda H, Saitou M. Wheel driving apparatus and electric vehicle including the same. United States Patents Office: US Patent Application No. US2009/0212728 A1; 2009.
[12] Ai X, Mularcik B, Knepper R. Electric motor with field weakening. United States Patents Office: US7960888 B2; 2011.

[13] Cirani M, Thelin P, Sadarangani C, Design procedure for an AFPM machine for field-weakening applications. Proceedings of the Nordic Workshop on Power and Industrial Electronics, NORpie; 2002 August 2002; Stockholm, Sweden.

[14] Chalmers B J, Akmeşe R, Musaba L, Design and field-weakening performance of permanent-magnet/reluctance motor with two-part rotor. IEE Proceedings-Electric Power Applications; 1998 2nd of March 1998.

[15] Hameyer K, Belmans R 1999 Numerical modelling and design of electrical machines and devices (Computational Mechanics: WIT Press)

[16] Gieras J F, Wang R-J, Kamper M J 2008 Axial flux permanent magnet brushless machines 1 (Springer Science & Business Media: Springer)

[17] Ong C-M 1998 Dynamic simulation of electric machinery: using MATLAB/SIMULINK 5 (Upper Saddle River, NJ: Prentice hall PTR)