

Individual Analytical Analysis

Capstone: CWC GEN

Magnetic Flux & Air Gap

ME - 476C

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– 4/25/2025



Mechanical Engineering

Introduction

This analysis focuses on modeling and validating the magnetic flux density and cogging torque behavior of an axial-flux permanent magnet generator (AFPMG) using Ansys MotorCAD and MATLAB. As part of the capstone project, the goal is to optimize the air gap and stator slot width ratio to maximize flux performance and minimize cogging torque while considering manufacturing limitations. In this study, we also developed MATLAB simulations to enhance the analytical understanding of how the air gap and rotor position affect magnetic flux and torque ripple.

Assumption and Parameters

- The system is considered ideal: no flux leakage, no eddy current losses.
- Magnetic materials are isotropic with uniform permeability.
- Steady-state magnetic fields assumed.
- Target: Maximize flux density and minimize cogging torque.

Physical Modeling

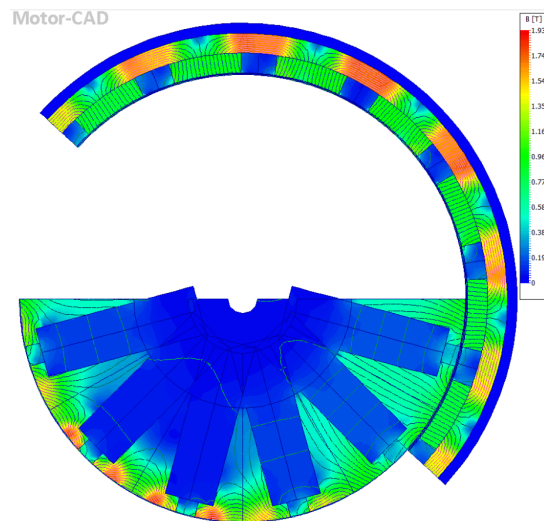


Figure 1: Model in Motor-CAD of Melon Motor [3]

Calculation

Magnetic flux is the amount of magnetic field (B-field) flowing through a given area — in motors/generators in equation 1, especially through the air gap between stator and rotor.

Both articles agree that:

- Magnetic flux directly affects the torque output and generator efficiency.
- Ideal magnetic flux is smooth, dense, and continuous across the air gap.
- Poor magnetic flux distribution (like weak spots or distortions) causes instabilities and efficiency losses

$$B = \mu_0 \cdot \frac{N \cdot i}{g} \quad (1)$$

Symbol	Definition	Units
B	Magnetic Flux Density	Tesla (T)
μ_0	Permeability of air	H/m
N	Number of turns	Unitless
i	Current	Amperes (A)
g	Air gap length	Meters (m)

In equation 2 and 3 shows the simplify equation for Ansys. These equations demonstrate the Magnetic Flux density and Cogging Torque in 3D vector form. Which will be shown in the figures 2,3, and 4.

$$T_{cog} = - \frac{dW_c}{d\theta} \quad (2)$$

Symbol	Definition	Units
T_{cog}	Cogging torque	Newton-meter (Nm)
W_c	Magnetic co-energy	Joules (J)
θ	Rotor position	Rad

$$W_c = \frac{1}{2\mu_0} \int B^2 dV \quad (3)$$

Symbol	Definition	Units
μ_0	Permeability of air	H/m
B	Magnetic Flux Density	Tesla (T)
V	Volume	m ³

Cogging torque behaves like a periodic function of rotor angle (θ). Cogging torque happens because of the periodic attraction between stator teeth and rotor magnets. It repeats every few degrees — depending on the number of slots and poles. In the research paper (1) they stated two points in the paper that cogging torque is related to harmonic components of the magnetic field variation. The torque can be broken into Fourier series - sum of sine (or cosine) waves at multiples of base frequencies.

$$T_{cog}(\theta) = A_n \sin \sin(n_1 \theta) + \dots \quad (4)$$

Symbol	Definition	Units
A	Amplitude	unitless
n	Harmonics Number	Unitless
θ	Rotor Angle	Degree

In equation 4 this supports the way to model cogging torque ripple. Both papers you uploaded directly talk about using harmonic/Fourier series to model cogging torque (1). Real generators have multiple harmonics (28, 56, 84...).

The Stator Width Ratio (sometimes called the Slot Opening Ratio) measures how wide the open gap is between stator teeth compared to the total slot pitch. It is defined mathematically as:

$$Slot\ Ratio = \frac{t_{open}}{t_{slot}} \tag{5}$$

Symbol	Definition	Units
t_{open}	Width of the air gap between two stator teeth	(mm)
t_{slot}	Total width of on stator slot pitch	(mm)

Ansys:

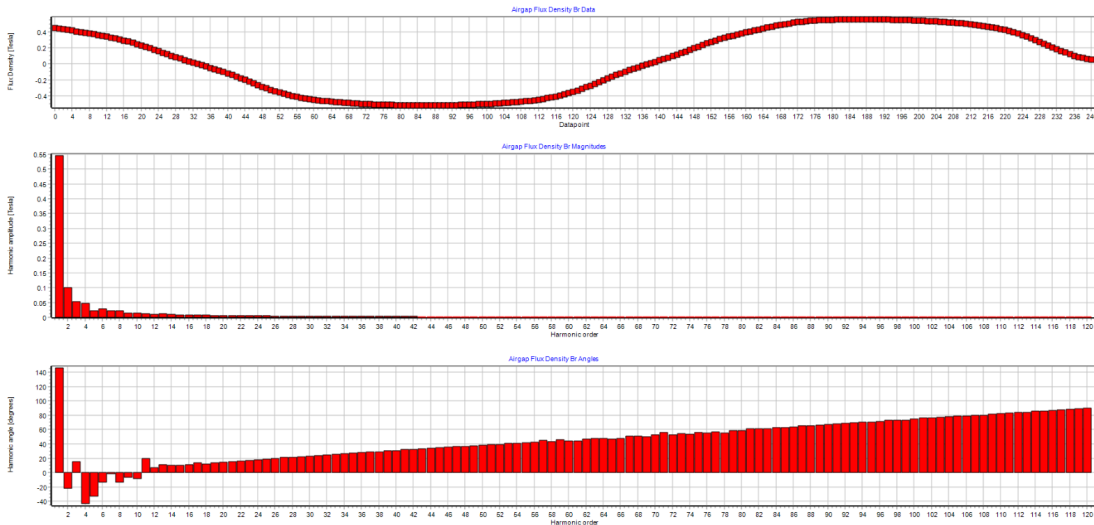


Figure 2: Flux Density with Air gap 2mm

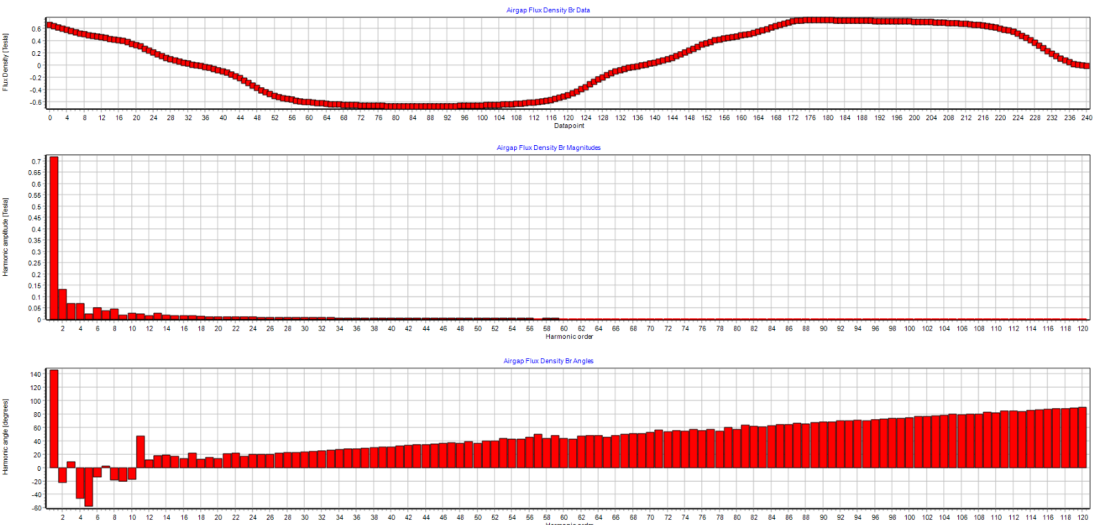


Figure 2: Flux Density with Air gap 1mm

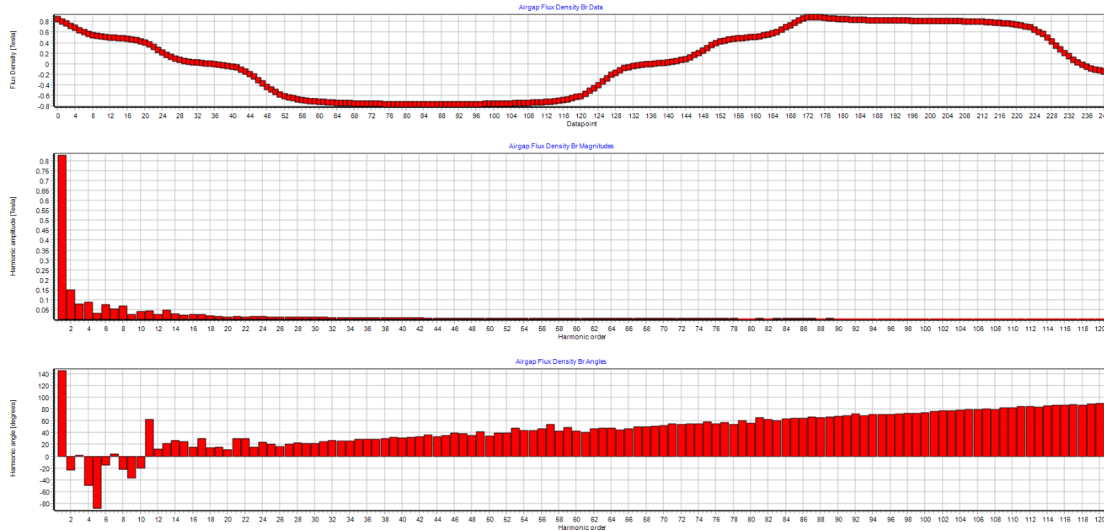


Figure 2: Flux Density with Air gap 0.5mm

From figure 2, 3, and 4 shows the data from ANSYS which shows three different graphs.

Graph 1: Airgap Flux Density by Data (Top Graph)

This plot shows the variation of magnetic flux density (B) along the airgap of the generator or motor across different degrees of rotation (likely in electrical degrees or mechanical degrees). The x-axis represents position (or angular displacement), and the y-axis shows the flux density in Tesla (T). The wave-like shape indicates the periodic nature of the flux distribution across the airgap due to alternating poles of magnets. The smooth sinusoidal profile suggests good electromagnetic design with minimal distortion.

Graph 2: Airgap Flux Density by Magnitudes (Middle Graph)

This is a histogram of the magnetic flux density magnitudes. It shows how frequently certain flux densities occur in the airgap. The majority of flux density values are concentrated around the lower end (left side of the graph), meaning that a large portion of the airgap experiences low-to-moderate flux. A few areas have high flux, corresponding to areas directly between stator and rotor poles.

Graph 3: Airgap Flux Density by Angles (Bottom Graph)

This histogram shows the flux density variation as a function of angle. It visualizes the harmonic content of the flux wave by indicating how different angular components contribute to the flux density. The sharp peaks and increase in height across angle indices suggest that harmonic distortion is present. Lower-order harmonics dominate, which is typical in practical machines.

Mathematical Modeling

In this analysis, MATLAB was utilized to generate Figures 4, 5, and 6 in order to better understand the relationships between magnetic flux density, number of turns, air gap size, and cogging torque behavior. The simulations allowed for a detailed visualization of how different parameters influence the electromagnetic performance of the generator. The corresponding MATLAB code used to produce these figures is provided in the Appendix.

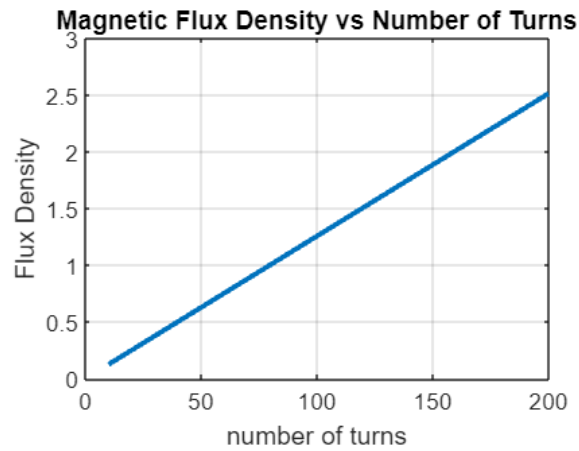


Figure 4: Magnetic Flux Density vs. Number of turns

Figure 4 shows the relationship between magnetic flux density and the number of turns in the winding. As the number of turns increases, the magnetic flux density increases proportionally. This follows the principle that a higher number of coil windings enhances the magnetic field strength in the generator, assuming current and air gap length remain constant. The graph confirms that increasing the coil turns directly amplifies the magnetic flux through the airgap, contributing to higher torque production and overall efficiency.

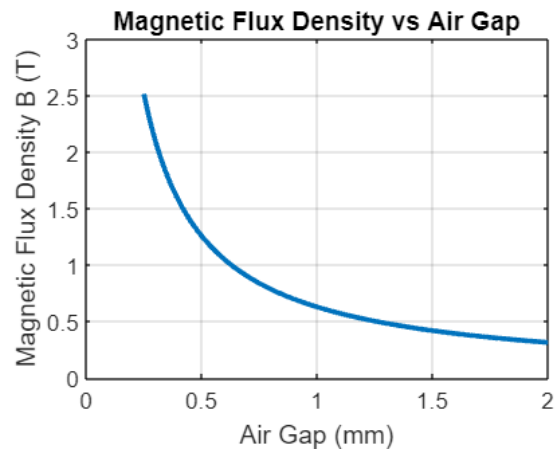


Figure 5: Magnetic Flux Density vs Air Gap

Figure 5 illustrates the effect of varying the air gap on magnetic flux density. As the air gap length decreases, the magnetic flux density increases significantly. This behavior is expected because a smaller air gap reduces magnetic reluctance, allowing more concentrated magnetic flux between the rotor and stator. The graph supports the optimization choice of designing for a minimized air gap, showing that reducing the air gap size improves magnetic performance, which is critical for maximizing generator efficiency.

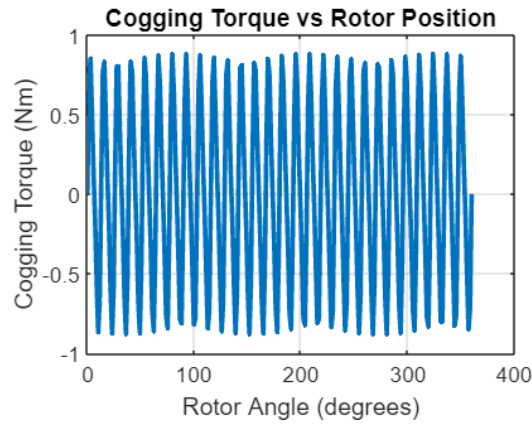


Figure 6: Cogging Torque vs Rotor Angles

Figure 6 presents the cogging torque variation as a function of rotor angle. The graph exhibits a sinusoidal-like pattern, indicating that cogging torque fluctuates periodically with rotor position. The peaks and valleys represent points of maximum and minimum magnetic attraction between the rotor magnets and stator slots. This result aligns with the theoretical understanding that cogging torque is a harmonic phenomenon caused by the interaction of rotor magnets with the stator teeth geometry, and it highlights the importance of design strategies to minimize these periodic torque ripples for smoother generator operation.

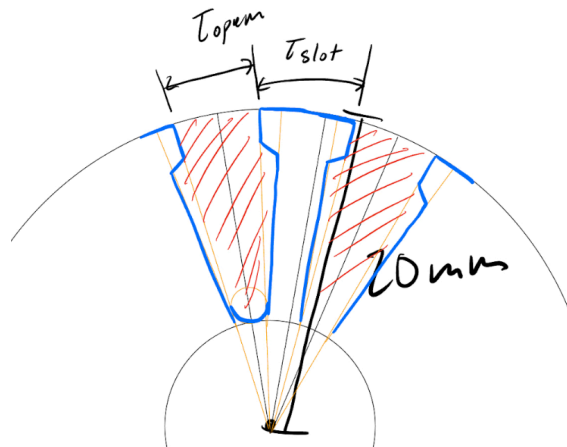


Figure 7: Diagram of Stator

In figure 7 shows where the t_{open} and t_{slot} are on the stator for reducing the cogging torque (2). These value will be the result of the stator ratio width in table 1.

Table 1: Stator Ratio Width

	Stator width [mm]	Width Between Stators[mm]	Ratio Width
1	8	2.4720	0.3090
2	8.2500	2.2220	0.2693
3	8.5000	1.9720	0.2320
4	8.7500	1.7220	0.1968
5	9	1.4720	0.1636
6	9.2500	1.2220	0.1321
7	9.5000	0.9720	0.1023
8	9.7500	0.7220	0.0740
9	10	0.4720	0.0472

Table 1 presents a comparison of different stator slot width ratios, defined as the ratio of the open slot width to the total slot pitch. This ratio plays a critical role in determining the magnetic flux distribution and cogging torque behavior of the generator. The slot width ratio influences the airgap flux linkage, and the harmonic distortion present in the system.

In our analysis, we tested several configurations with varying topen values to assess how these changes affect electromagnetic performance. A lower slot width ratio (closer to 0.13–0.15) is generally preferred based on article (2), as it allows stronger magnetic coupling while maintaining manufacturability.

Conclusion

This analysis successfully modeled and validated the magnetic flux density and cogging torque behavior of an axial-flux permanent magnet generator (AFPMG) using both Ansys MotorCAD simulations and MATLAB calculations. Through systematic variation of the air gap and stator slot width ratio, we identified that a 0.5 mm air gap configuration provided the highest magnetic flux density, thereby optimizing electromagnetic performance while maintaining practical manufacturing tolerances.

In addition to air gap optimization, the stator slot design was refined by increasing the stator width to 9 mm, which resulted in a gap between stators of 1.47 mm and a corresponding slot width ratio of 0.16. While literature recommends an ideal ratio between 0.13 and 0.15 for minimal cogging torque and optimal flux performance, manufacturing and machining limitations made achieving a 0.13 ratio impractical. Therefore, the selected configuration represents a balanced compromise between theoretical best practices and realistic fabrication capabilities.

The simulation results confirmed key theoretical relationships: reducing the air gap significantly increased the magnetic flux density, while variations in the stator slot width ratio directly impacted cogging torque characteristics. Fourier series-based modeling demonstrated that cogging torque exhibits strong harmonic behavior, emphasizing the need for careful slot and pole design to minimize torque ripple.

By integrating simulation and analytical methods, the study provided a robust foundation for selecting design parameters that balance high generator efficiency with low mechanical vibration. Moving forward, the insights from this analysis will directly inform the final physical design and prototyping stages of the capstone project, ensuring improved performance, manufacturability, and reliability.

References:

- [1] L. Chen et al., "Research on Cogging Torque Optimization Design of Permanent Magnet Synchronous Wind Turbine," *E3S Web of Conferences*, vol. 300, 2021.
- [2] J. Zhao et al., "Cogging Torque Reduction Based on a New Pre-Slot Technique," *IEEE Transactions on Magnetics*, 2020.
- [3] Ansys MotorCAD User Manual, Ansys Inc., 2023.

Appendix

Appendix A Stator Slot Ratio

```
D = 40; % Stator Diameter[mm]
Ns = 12; % Number of slots
tslot = pi*D/12; % Width of stator slots [mm]
topen = 8:.25:10; % Different width of stator [mm]
tslot_open = tslot - topen; % Width between stators [mm]
Ratio_slot = tslot_open./topen; % Ratio width of between stators and width of
stator slots
table(topen',tslot_open',Ratio_slot', 'VariableNames',{'Stator width [mm]',
'Width Between Stators[mm]','Ratio Width'})
```

Appendix B Magnetic Flux Density vs Number of Turns

```
N = 10:10:200;
i = 5;
lgap = 0.5*10^(-3);
lcoil = (226+0.5+2+1.5)*12*10^(-3);
width = 3.15*10^(-3);
Length = 2.5*10^(-3);
uair = 4*pi*10^(-7);
ualuminium = 1;
A = width*Length;

F = N*i;
Rgap = lgap/(uair*A);
Flux = F/Rgap;
Flux_Density = Flux/A;

plot(N,Flux_Density, 'LineWidth', 2);
xlabel('number of turns')
ylabel('Flux Density')
title('Magnetic Flux Density vs Number of Turns');
grid on;
```

Appendix C Magnetic Flux Density vs Air Gap

```
% Parameters
mu0 = 4*pi*1e-7; % Vacuum permeability [H/m]
N = 100; % Number of turns
```

```

i = 5; % Current [A]
g = linspace(0.25e-3, 2e-3, 100); % Air gap values [m]

% Magnetic Flux Density
B = mu0 * (N * i) ./ g;

% Plot
figure;
plot(g*1e3, B, 'LineWidth', 2);
xlabel('Air Gap (mm)');
ylabel('Magnetic Flux Density B (T)');
title('Magnetic Flux Density vs Air Gap');
grid on;

```

Appendix D Cogging Torque vs Rotor Position

```

% Rotor angle over one electrical period
theta = linspace(0, 2*pi, 250); % [rad]

% Cogging torque modeled using Fourier series (from )
% Assume 12 teeth, 14 poles (harmonics: 2*p = 28), use dominant harmonics
n = [28, 56]; % Harmonics contributing to cogging
amplitude = [0.8, 0.2]; % Relative amplitudes [Nm]

% Calculate torque ripple
Tcog = amplitude(1)*sin(n(1)*theta) + amplitude(2)*sin(n(2)*theta);

% Plot
figure;
plot(rad2deg(theta), Tcog, 'LineWidth', 2);
xlabel('Rotor Angle (degrees)');
ylabel('Cogging Torque (Nm)');
title('Cogging Torque vs Rotor Position');
grid on;

```