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# Analysis of Slotted and Slot Less Permanent Magnet DC Motor for Drone Applications

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**Abstract**: When it comes to choosing BLDC motors, the advantages and disadvantages of slotted brushless DC motors (BLDC) and slotless BLDC might be confusing. The goal of this study was to use JMAG-Designer Software to define the characteristics of slotted and slotless BLDCs. The results of this study revealed that slotted BLDC produces more torque than slotless BLDC. The power output of slotted and slotless BLDCs was nearly identical, but the slotless BLDC's speed was ten-time faster than the slotted BLDC's. Because slotted BLDCs produced greater ripple torque than slotless BLDCs, slotted BLDCs vibrated more than slotless BLDCs.

**Keywords**: Brushless Direct Current, Finite Element Method (FEMM) Software, Magnetic Flux Density, Permanent Magnet.

## 1. Introduction

Slotless permanent magnet (PM) motors appear to be an appealing solution for high-speed applications, as they are almost insensitive to magneto-motive force harmonics and pulse width modulation (PWM) current ripple, and have lower stator iron and rotor losses (significant with square wave current control [1]. When variable-speed operations are required, permanent magnet (PM) motor drives are desirable. They may be constructed in a variety of ways and perform well across a wide range of tasks [2].

Slotted stators were used in the original brushless DC (BLDC) motors, and the bulk of BLDC motors are still produced this way. However, this design creates cogging torque, making smooth motion difficult, especially at low speeds. Slotless motors were created as a result of a novel design that eliminated the slots in the stator (which are the primary cause of cogging torque).

1.1 Different Slotted and Slotless BLDC Motor Design.

In a conventional slotted dc motor, the presence of teeth or stator slots between the coil of the motor is different in structure compared to the slotless dc motor which has no slot. slotless dc motors are motors without slotted or teeth for the copper winding inside the stator which makes the winding encapsulated in epoxy resin and gives the structure of the winding shape and rigidity. In the other words,

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this 'self-supporting winding' has the primary benefit of eliminating the cogging torque because of the lack of teeth in the lamination of the stator.

The stator teeth are more prone to saturation near the rated operation. The higher local flux density in the teeth generates higher harmonics in air-gap flux distribution leading to unwanted BEMF harmonics and higher core loss. In conventional slotted machines, the permeance is not constant along the air gap which causes additional harmonics in the air-gap flux [3].

The existing permanent magnet DC motor, the Slotted Brushless DC Motor, has a significant flaw in that it produces cogging torque. The stator of a slotted BLDC is built up of slotted steel laminations stacked together, with copper windings put into the slots. Cogging torque is created by irregular air-gap permeance, which causes the magnets to seek a position of minimum resistance all of the time [4]. Cogging torque has the principal consequence of making the motor spinning jerky (rather than smooth), especially at low motor speeds.

## 2. Methodology

Before deciding on the best PMDC motor for drone applications, compare the differences between the two motor designs using previous discoveries and analysis of their properties. The flux-linkage waveform, cogging torque value, and average torque of both designed slotted and slotless BLDC motors must all be taken into account when calculating the results.

### 2.1 Methods

The design and analysis of this project are separated into two stages, the first of which involves utilising JMAG-Geometry Editor to draw the machine's parts, such as the rotor, stator, armature coils, and permanent magnet (PM). JMAG-Designer is used to apply machine materials and condition settings. Using the flowchart shown in Figure 1, the overall design and analysis procedures to proceed with the machine operating principle are simplified. The processes are then repeated for the alternative motor design.

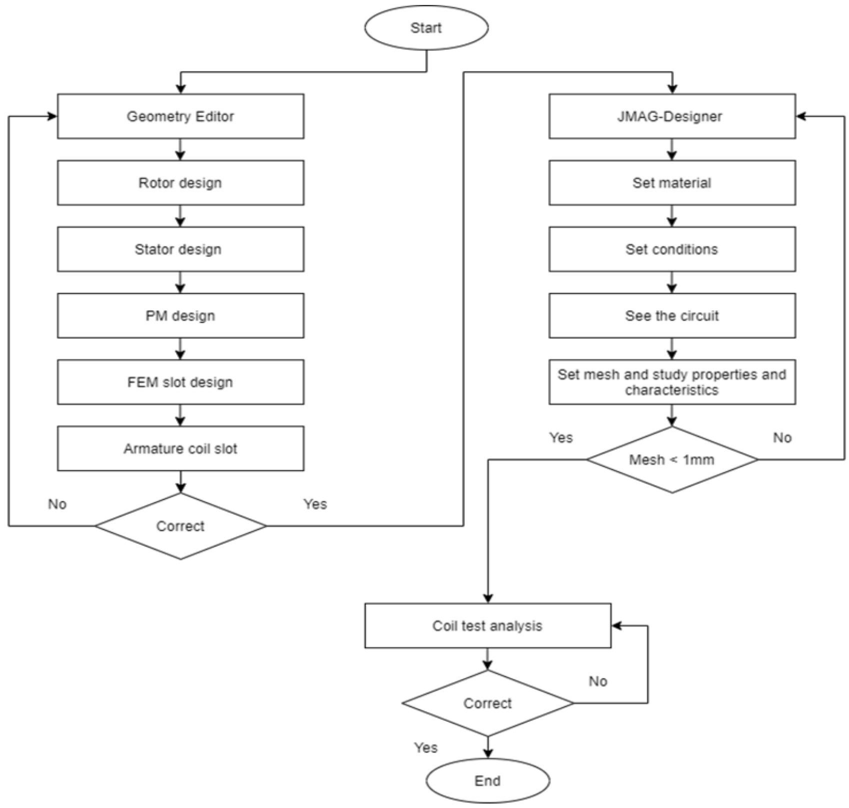



**Figure 1: Operating principles using JMAG-Geometry Editor and JMAG-Designer.**

After completing the design, if there have some errors and the region is not created successfully then the whole procedure of the design is repeated. After the design is completed successfully without error the next step is to transfer the design to JMAG Designer. Table 1 shows the design parameters and specifications for both slotted and slotless BLDC motors. In order to complete the drawing of both designs, this parameter has been used to make the comparison fair and square. The advantages of the slotless design were not having slots or teeth between the coil and making it more prone to have a high value of torque because of the larger coil area.

**Table 1: Design parameters for slotted and slotless BLDC motor**

| Parameter | Design Specifications | | Unit |
|---|---|---|---|
| | Slotted | Slotless | |
| Number of slots | 4 | 0 | - |
| Number of poles | 4 | 4 | - |
| Air gap length | 0.5 | 0.5 | mm |
| Rated Speed | 3600 | 3600 | rpm |
| Rotor Outer/Inner Radius | 20/15 | 20/15 | mm |
| Coil Outer/Inner Radius | 44/24 | 44/24 | mm |
| Stator Outer/Inner Radius | 50/44 | 50/44 | mm |
| Shaft Radius | 15 | 15 | mm |
| Permanent Magnet Length | 3.5 | 3.5 | mm |
| Armature Coil Width | 20 | 20 | mm |
| PM Outer/Inner | 23.5/20 | 23.5/20 | mm |
| Permanent Magnet Area | 478.3075 | 478.3075 | $mm^2$ |
| Coil Area | 484.0213 | 534.07072 | $mm^2$ |
| No. of Turns | 154 | 170 | - |

### 2.2 Optimization Methods

Figure 2 depicts the workflow optimization of Slotless BLDC motors in order to discover which are best for drone applications. Analyze the most efficient design and attributes for drone applications. Improve the design of the Slotless BLDC motor to make it more suitable for drone use. The radius of each portion of the motor, as well as the area of the coil and permanent magnet, were all parts of this project that needed to be optimised. This is due to the fact that each of these components has an impact on the end output. To make the comparison fair and square, the parameters of the unoptimized design were used as the major reference for this optimization, which was done without affecting the volume of the permanent magnet or the air gap length. The parameters of each part must be considered when comparing the performance of the unoptimized slotless and optimised slotless designs. Because of the differences in measurement in each section for both designs, Table 3.5 shows the optimization parameters that must be used to obtain the most effective results for both motor design and performance comparisons.

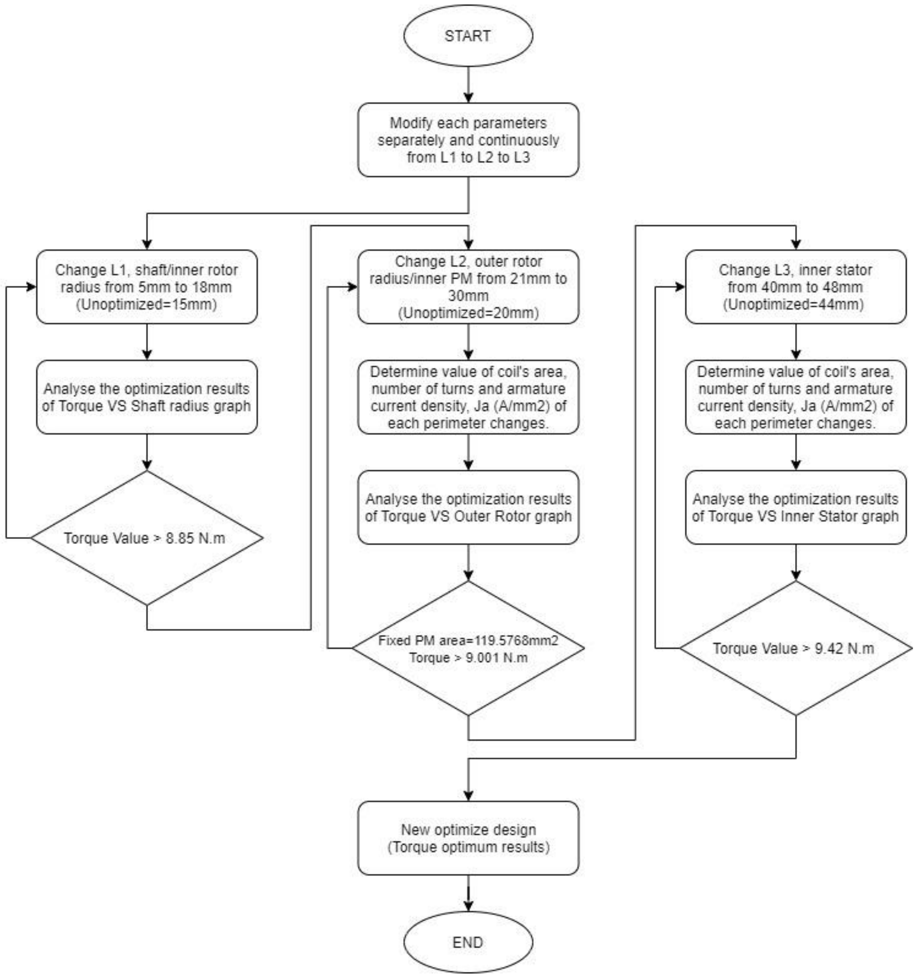



**Figure 2 : Workflow of optimization**

According to Table 2, the number of poles for the initial slotless design and the improved slotless design is the same. It's to ensure a level playing field in the comparison. The radius of the rotor, stator, shaft, and coil area have all been tuned to produce the same measurement of permanent magnet area and air gap length. When compared to the initial slotless and improved slotless designs, the outcomes of parameter optimization make a tremendous impact.

**Table 2: Parameters of initial slotted, slotless and optimize slotless.**

| Parameter | Design Specifications | | | Unit |
|---|---|---|---|---|
| | Slotted | Slotless | Optimize Slotless | |
| Number of slots | 4 | 0 | 0 | - |
| Number of poles | 4 | 4 | 4 | - |
| Air gap length | 0.5 | 0.5 | 0.5 | mm |
| Rated Speed | 3600 | 3600 | 3600 | rpm |
| Rotor Outer/Inner Radius | 20/15 | 20/15 | 26/14 | mm |
| Coil Outer/Inner Radius | 44/24 | 44/24 | 45/29.279333 | mm |
| Stator Outer/Inner Radius | 50/44 | 50/44 | 50/45 | mm |
| Shaft Radius | 15 | 15 | 14 | mm |
| Permanent Magnet Length | 3.5 | 3.5 | 3.5 | mm |
| Armature Coil Width | 20 | 20 | 15.720667 | mm |

| | | | | |
|---|---|---|---|---|
| PM Outer/Inner | 23.5/20 | 23.5/20 | 26/28.779333 | mm |
| Permanent Magnet Area | 478.3075 | 478.3075 | 478.3075 | $mm^2$ |
| Coil Area | 484.0213 | 534.07072 | 458.5628 | $mm^2$ |
| No. of Turns | 154 | 170 | 146 | - |

## 3. Results and Discussion

Figure 3 depicted a comparison of permanent magnet flux data during a no-load measurement. Because the rpm value for each design is 3600 rpm, the graph's end time was the same. Only the number of turns differed, which was 154 for the slotted design, 170 for the first slotless, and 146 for the optimized slotless. Each design has a varied area, which influences the number of turns. From the first slotless design to the optimized slotless design, the permanent magnet flux improved.

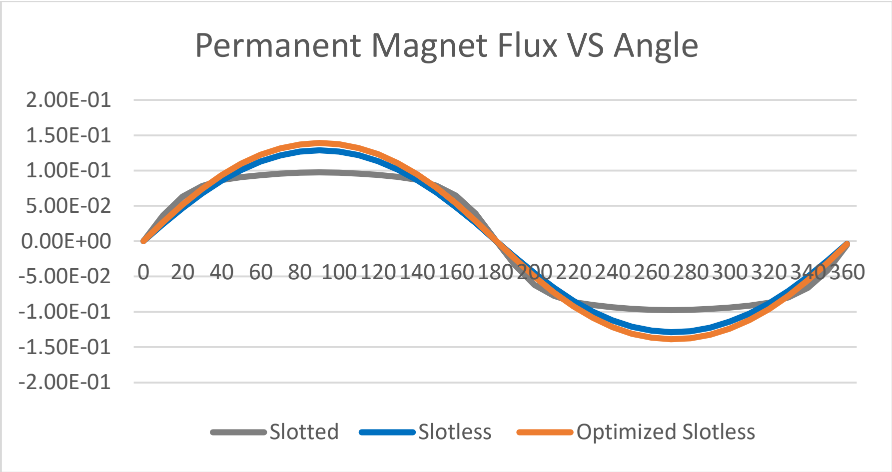



**Figure 3: Permanent Magnet Flux Vs Angle**

The result reflects the initial slotless and optimised slotless flux linkage, no load analysis cogging torque, and load analysis average torque. The initial cogging torque for the slotless design was 0.108081 N.m, which is higher than 0.026232 N.m for the slotted design. The slotted design's average torque is higher than the slotless design's, at 14.21486 N.m and 8.855784 N.m, respectively. The optimization of L1, L2, and L3 perimeters at the initial slotless design was accomplished in order to minimize the value of cogging torque and maximize the performance of torque for the slotless design motor. The graph of cogging torque for the initial and optimized slotless designs is shown in Figure 4.

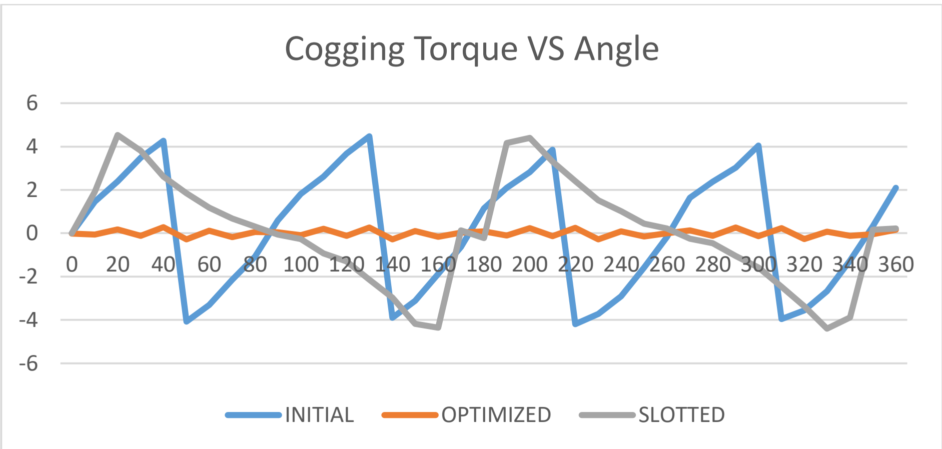



**Figure 4: Cogging torque VS Angle for the slotted, slotless and optimized slotless.**

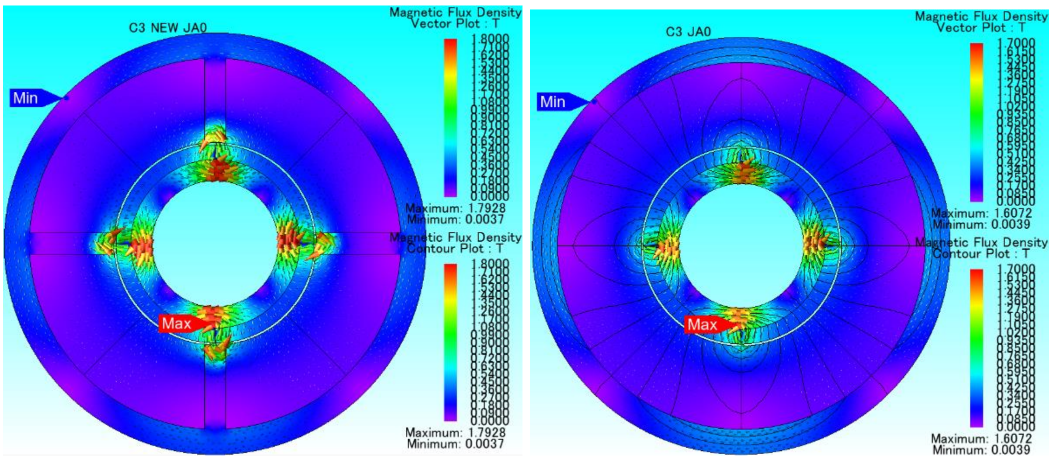
The comparison of cogging torque between slotted, initial slotless, and optimal slotless is shown in Figure 4. The research revealed that the slotted design's cogging torque was 0.026232 N.m, which was lower than the initial slotless design's cogging torque of 0.108081 N.m. The opoptimizedlotless cogging torque value was successfully reduced from 0.108081 N.m to 0.003135 N.m. Simultaneously, this improved slotless design outperformed the slotted design in terms of cogging torque factor, making it ideal for drone applications that demand low cogging torque. This is because in electrical devices, cogging torque causes noise and destructible pulsations, and in some situations, mechanical resonance occurs, causing major issues [3]. Lesser flux density values in slotless designs result in lower iron losses. The rotor losses are reduced by the greater effective airgap, which lowers flux density changes produced by magneto-motive force (M.M.F.) harmonics and pulse width modulation (PWM) current ripple. The comparison of cogging torque between slotted, initial slotless, and optimised slotless is shown in Table 3.

**Table 3: Cogging torque value of slotted, initial slotless and optimize slotless.**

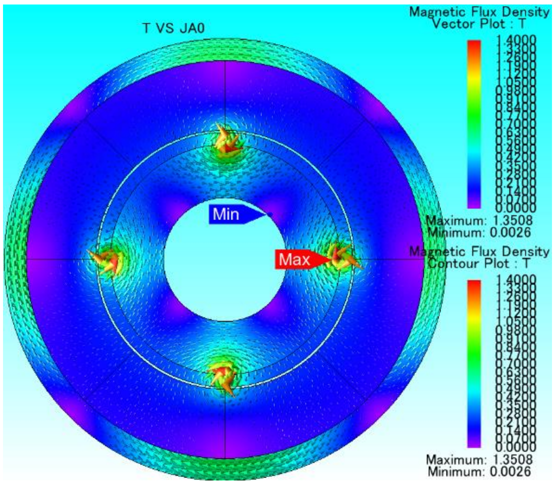
| Configuration | Slotted | Initial Slotless | Optimize Slotless |
|---|---|---|---|
| Cogging Torque (N.m) | 0.026232 | 0.108081 | 0.003135 |

3.1 Flux Line Analysis and Flux Distribution Analysis

Figures 5 depict the flux line distribution and flux density analysis for the slotted design, initial slotless design, and optimize slotless of the flux line of the permanent magnet during no load testing (no current supply) at JA=0Arms/mm2 for both BLDC motor designs. The data shows that the original slotless design has a maximum magnetic density of 1.6072T and a minimum magnetic density of 0.0039T, whereas the optimum slotless design has a maximum magnetic density of 1.3508T and a minimum magnetic density of 0.0026T. Due to the volume of coil for the optimal slotless being less than the initial slotless, which affects the number of turns for each design, this flux line study revealed that the initial slotless had higher magnetic flux density than the initial slotless design. The initial slotless has 170 turns more than the optimum slotless, which has 146 turns. The value of magnetic flux density can be affected by the size of the rotor and the surface area of the permanent magnet.




(a) (b)




(c)

**Figure 5: Flux Line Distribution Analysis for (a) slotted, (b) initial slotless and (c) optimized slotless.**

3.2 Load Analysis of Slotted and Initials Slotless BLDC Motor.

The performance of the BLDC motor is investigated at a maximum Ja of 30Arms/mm2. The results of the analysis, as shown in Figure 5, reveal that the value of average torque between the initial slotless design and the optimum slotless design is nearly identical. This is due to the fact that the two slotless designs have distinct structures, and the slotless design's effective air-gap length is much longer. For slotted, initial slotless, and optimized slotless motors, Figure 6 displays the combination of permanent magnet and armature current flux vs angle.

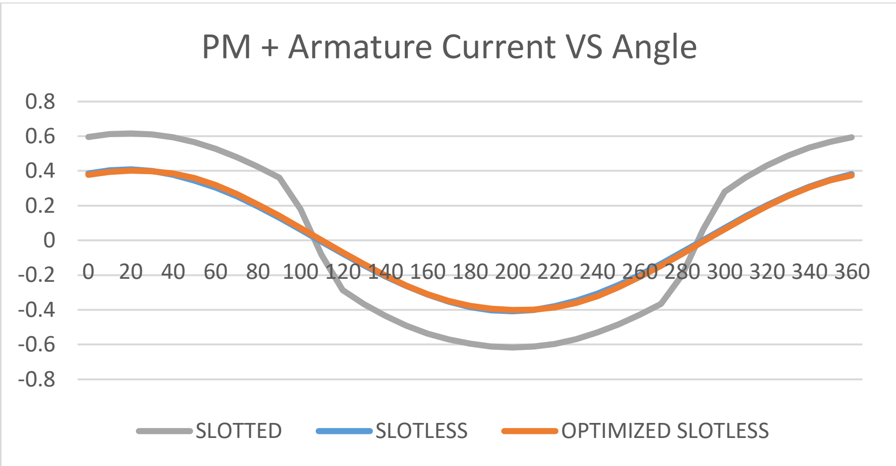



**Figure 6: Permanent Magnet and Armature Current flux Versus Angle**.

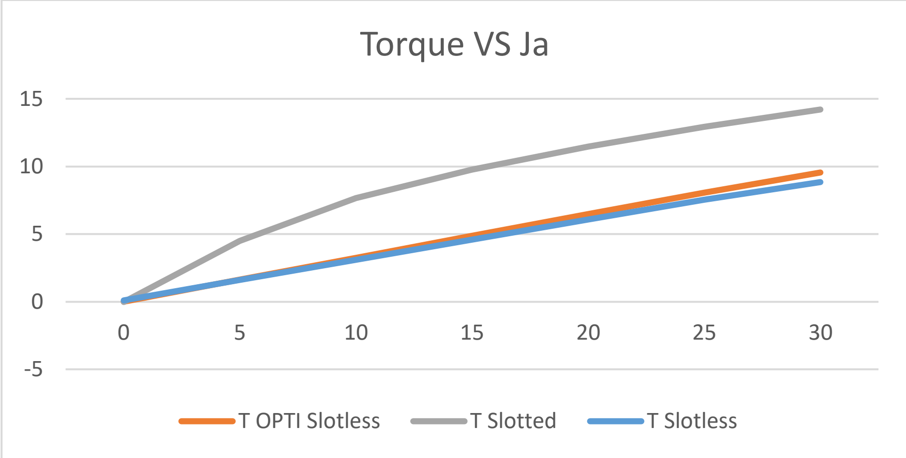



**Figure 7: Torque Versus JA (Arms/mm2).**

Figure 7 above indicates that the optimized slotless design performs 8% better than the initial slotless design, with initial slotless torque of 8.855784 N.m and an optimized slotless torque of 9.559572 N.m. The optimized slotless design had a torque average that was 37% lower than the slotted variant. This is because the slotless design's higher air gap has a greater impact on torque than the slotted design, which has the smallest air gap due to the existence of a slot or teeth. As a result, slotless design is a strong contender for precise applications that require torque that is ripple-free [4]. In comparison to slotted designs, this optimized slotless design was appropriate for drone or high-speed applications to preserve the motor's performance for long periods of time. The torque performance of slotted, initial slotless, and optimal slotless BLDC motors was compared in Table 4.

**Table 4: Comparison of torque performance at Ja 30 Arms/mm2.**

| Configuration | Slotted | Initial Slotless | Optimize Slotless |
|---|---|---|---|
| Average Torque (N.m) | 14.2148 | 8.855784 | 9.559572 |

3.2 Discussions

This project used simulation results to identify the differences in performance between slotted and slotless BLDC designs. The slotted design has a smaller cogging torque than the slotless design. Because the requirement for high speeds motors, such as drone applications, is to have a low value of cogging torque, the initial design may not be efficient for drone or high-speed use. Because there are no teeth or slots between the coils, slotless coils should have minimal cogging torque. However, little cogging torque was observed in this project for a specific slotless design. Zero cogging torque can smooth operation, reduce vibration, and enable compact design with the smooth high-speed operation and lower audible noise [4]. High-speed capability up to 100,000 RPM, excellent power-to-weight ratio, and excellent power-to-weight ratio can also enable compact design with the smooth high-speed operation and lower audible noise. This feature demonstrated that a slotless architecture was more efficient in drone applications than a slotted design.

Some slotless perimeter adjustments were made in order to attain the low cogging torque value. When compared to the slotted design, the slotless optimization produces a significant difference in low cogging torque. When compared to the optimized slotless design, the slotted cogging torque value was 11 percent greater, at 0.026232 N.m. In the slotless design, the optimization was successful in lowering the cogging torque value. When compared to the initial slotless design, the torque value for the optimization rose by 8%. The optimized slotless design's average torque value at Ja 30 Arms/mm2 was 9.559572 N.m, a gain of 8% over the first slotless design. However, the average torque value in a slotted design is approximately 37% higher than in a slotless configuration. This is due to the structural differences between the slotted and optimized slotless designs. As a result, slotless configurations are an excellent fit for precision applications that require ripple-free torque, such as high speeds or drone applications.

## 4. Conclusion

In conclusion, there is low cogging torque happen for some slotless specific designs and the comparison between slotted and slotless BLDC design was successful. Both designs were simulated in Finite Element Method Analysis and the result for slotted performance was better than slotless design in torque performance. However, in order to complete the requirement of high speeds applications such as drones, a low cogging torque value is needed to perform well in lower flux-density values yield lower iron losses. The higher effective air gap in slotless design reduces the flux density variations caused by the magneto-motive (M.M.F) harmonics and by the pulse width modulation (PWM) current ripple, and thus the rotor losses [2]. The slotless PM motor drives appeared a preferable solution for drone applications.

## Acknowledgement

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