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Performance Analysis On Segmented Interior Permanent Magnet Synchronous Motor (IPMSM)

Mohamad Afiq Izzuddin Abd Latib, Roziah Aziz*, **Mahyuzie Jenal,**
Erwan Sulaiman and **M. Zarafi Ahmad**

Faculty of Electrical and Electronic Engineering, Universiti Tun Hussein Onn Malaysia, 86400, Parit Raja, Batu Pahat Johor, Malaysia.

*Corresponding author: roziah@uthm.edu.my, Tel: 607-4537000 ext: 1289

Abstract: Permanent magnet synchronous motor (PMSM) is an ac motor that uses a magnet inserted into the rotor or mounted on the surface of the motor rotor. In this study, the conventional and segmented interior permanent magnet synchronous motor (IPMSM) will be constructed and analyzed for the best motor types. In the segmented IPMSM, the magnet of each pole is segmented, and between each segment, there exists a rotor iron bridge. Moreover, for the segmented IPMSM, there are three different designs of the width of the iron bridge, which is 2mm, 1mm and 0.5mm. All the design will be analyzed by using JMAG Designer software. Furthermore, no-load analysis is performed to evaluate cogging torque, flux linkage, flux distribution and back-EMF of the motor model. After that, load analysis will be conduct, which measures the torque-speed characteristics, output power, flux weakening and constant power speed range (CPSR) of each type of motor. In this project, a wide CPSR is achievable in segmented IPMSM due to its inherent flux-weakening capability. So, the maximum speed of the motor is higher in segmented than a conventional motor.

Keywords: Constant Power Speed Range (CPSR), Interior Permanent Magnet Synchronous Motor (IPMSM), flux weakening.

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1. INTRODUCTION

An electric motor is an electrical machine that will convert electrical energy into mechanical energy. Most electric motors operate through the interaction between the motor's magnetic field and electric current in a wire winding to generate force in the form of rotation of a shaft. Furthermore, permanent magnet (PM) devices are used for various industrial applications, including traction and spindle drive [1]. Wide constant power speed range and optimization of the cogging torque are essential for spindle motor drives. A PM motor is an ac machine that uses magnets embedded in or connected to the motor's rotor surface. Instead of having the stator field produce one by combining it with the rotor, the magnets create a steady motor flux, as is the case with an inductor.

Moreover, a typical surface permanent magnet (SPM) motor has a structure where a permanent magnet is placed on the surface of the rotor. This motor uses magnets to produce magnetic torque. On the other side, by embedding a permanent magnet onto the rotor itself, the permanent interior magnet (IPM) motor uses reluctance by magnetic resistance, in addition to magnetic torque. The IPM has a structure of permanent magnets inserted into the rotor, have attractions for systems requiring high-power density and high efficiency [2]. Therefore, IPM motors are increasingly popular in various industrial and domestic applications due to PM manufacturing and technology [3].

Most of the permanent interior magnet (IPM) motor available today have a minimal constant power speed range (CPSR) [4]. While the current IPM motor is economical and easy to build, the machine's performance is rapidly declining at top speed. Therefore, this type of IPM motor is unsuitable for applications requiring continuous power for a wide range of rates. So, in this project, the segmented IPM motor will be used to achieve an extensive flux weakening range. The segmented IPM motor is called that because of its segmented magnet poles structure. Each pole's magnet is segmented in this motor, and there is a rotor iron bridge between each segment. Because of its segmented magnet poles structure, we will call this type of IPM motor as 'segmented IPM (SIPM) motor' in this work. The segmented IPM motor has an easy-to-construct design because the lamination structure is very similar to the commercially available IPM motor. In addition, the segmented IPM system has an intrinsic flux-weakening capability due to its segmented poles and iron bridges. Table 1 shows more about the advantages and disadvantages of segmented IPM motors.

Table 1. The advantages and disadvantages of segmented IPM motors

Advantages	Disadvantages
• Easy to construct • Cost-effective • More comprehensive constant power speed range (CPSR) • Improve flux weakening	• Needed higher current to achieve the desired torque • Increases the copper losses for a given value of torque • Lower cogging torque

2. METHODOLOGY

2.1 Workflow

The workflow of the methodology for this project is shown in Figure 1. Based on the flowchart, the first step is to design the conventional and segmented IPMSM in the JMAG-Geometry Editor correctly based on the parameters used. After that, update the model into the JMAG Designer. Then, set the material and condition into the rotor, magnet, armature coil, and stator. The connection for the coil is connected based on the distributed winding. In each slot, the distributed winding is likewise the distribution of conductors. Under multiple slots, the conductors are positioned. The distributed winding eliminates the reaction of the armature and assists in improved cooling.

Moreover, set the maximum current and frequency into the three-phase current source to start the load analysis test. Next, set the rotor magnet, segment geometry design, selection of core and magnet materials for the segmented IPMSM. Finally, collect the data from both types of the motor and compare the speed, flux linkage, and back emf.

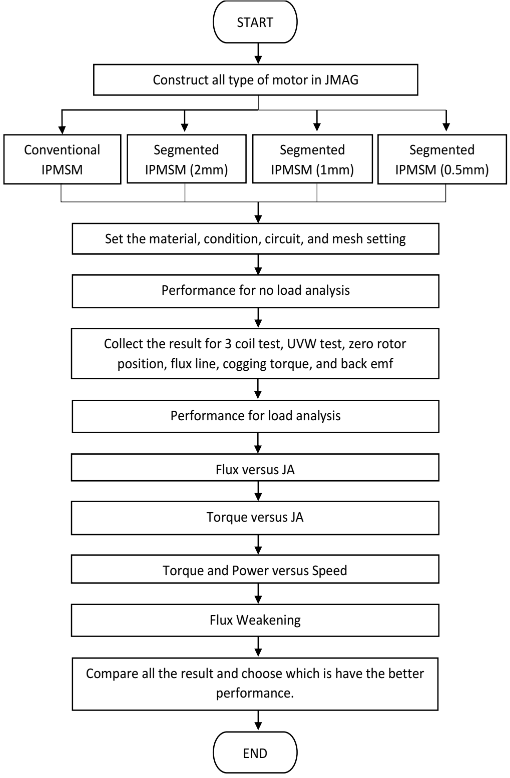

Figure 1. Flowchart to study the performance for each type of motor

2.2 Parameters and Specification

In this project, the IPMSM motor has been chosen because of its characteristic. Many industries have been using this motor, especially in an electric motor. The segmented IPMSM motor will be introduced to get better performance than the conventional IPMSM motor. Table 2 shows the parameters and specifications of the conventional and segmented IPMSM used as a motor design for this project. In the segmented IPMSM, it just has a little bit different in the permanent magnet design.

Table 2. Design parameters of conventional and segmented IPMSM [1]

Parameter	Conventional IPMSM	Segmented IPMSM
Stator bore diameter	82mm	82mm
Stator outer diameter	130mm	130mm
Rotor diameter	81mm	81mm
Shaft diameter	24mm	24mm
Air gap length	0.5mm	0.5mm
No. of slot	24	24
Slot height	11.45mm	11.45mm
Slot width	5mm	5mm
Slot opening	2.5mm	2.5mm
Magnet width	34mm	13mm
Magnet length	8mm	4mm
Width of the iron bridge	-	2mm
No. of poles	4	4
No. of series turns per phase	46	46

2.3 Material and Condition Setting

Before setting the materials and conditions into the motor design, the transient analysis should be added first into the project simulation. After that, set the material and condition that has been used in this motor as shown in Table 3 below. Furthermore, By dragging the item from the right-hand-side toolbox to its functional materials and conditions, the material and condition of the motor may be set.

Table 3: The materials and conditions for the motors

PARTS	MATERIALS	CONDITIONS
Rotor	Nippon Steel 35H210	Motion: rotation Torque: nodal force
Stator	Nippon Steel 35H210	-
Armature Coil	Conductor Copper	FEM Coil
Permanent Magnet	Neomax-35AH (irreversible) (Radial Anisotropic Pattern)	Motion: rotation Torque: nodal force

2.4 Study Analysis

Next, set the magnetic study and properties. Firstly, click on the study. Then, choose magnetic transient and click properties. Next, click the step control to set the steps, end time, and division, while click the complete model conversion to set the stack length. The steps, end time, division, and stack length are set to 37, 0.02s, 36, and 151 mm. The end time has been set based on the calculation in equation 1, 2, and 3 below. Where fm is the frequency of the motor, n is the speed of the motor (r/min), fe is electrical frequency, Nr is the number of poles and Te is the end time.

$$fm = \frac{n}{120} \qquad (1)$$

$$fe = fmNr \qquad (2)$$

$$Te = \frac{1}{fe} \qquad (3)$$

3. RESULT AND ANALYSIS

3.1 Cogging Torque

Cogging torque is the torque needed between the stator's magnets on the rotor and iron teeth to overcome the opposing torque generated by the attractive magnetic force. This torque is position-dependent and relies on the number of magnetic poles for its periodicity per revolution and the number of teeth on the stator. Therefore, cogging torque for such a motor to work is an undesirable element.

Figure 2 shows the cogging torque graph of conventional and segmented IPMSM. The graph is plotted when there is no current supply to the armature coil, and the highest peak cogging torque for conventional and segmented (2mm) is 1.097Nm and 0.687Nm. Based on the result., the segmented IPMSM design has lower cogging torque than conventional IPMSM. However, when the width of the iron bridge is decreased, the cogging torque of the segmented motor will increase. When the width of the iron bridge is set to 0.5mm, the cogging torque is increased to 1.228958Nm in 12.03% than a conventional motor. However, the cogging torque ripple for the segmented permanent magnet less than the conventional motor.

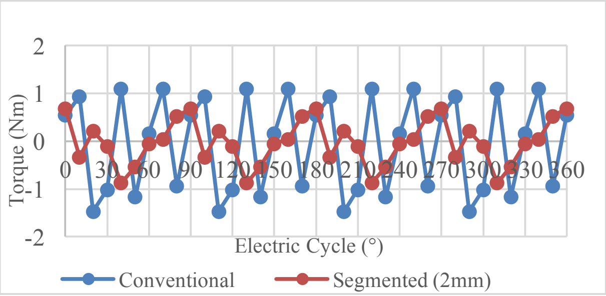

Figure 2: The graph of cogging torque for conventional IPMSM

3.2 Torque versus Armature Coil Current Density, J_A

The load analysis is analyzed by supplying the armature coil current density, J_A. Torque and flux relationships are evaluated at different J_A locations to determine the torque variation pattern when injecting the different current values into the FEM coil of the motor. The strength of the armature current varies from 0 to 30 J_A during the load test.

The current maximum density value is calculated based on Equation 4 where I_A is inject current value of armature coil, (Apeak), J_A is armature coil current density (Arms/mm2), α_A is armature coil filling factor (set to 0.5), δ_A is armature coil slot area and N_A is the number of turns.

$$I_A = \frac{\sqrt{2} J_A \alpha_A \delta_A}{N_A} \qquad (4)$$

The analysis of the torque versus J_A was performed to determine if the graph is increasing or decreasing. The torque value used is the maximum average value from $5J_A$ to $30J_A$. Figure 3 shows the maximum torque graph versus the J_A value for all designs of conventional and segmented IPMSM. The result obtained for this analysis is an increase in the graph. However, the torque for segmented IPMSM is lower than the conventional IPMSM. Besides that, when the width of the iron bridge is increased, the torque will decrease. The torque decreases because the flux of the motor decreases when the width of the iron bridge rises.

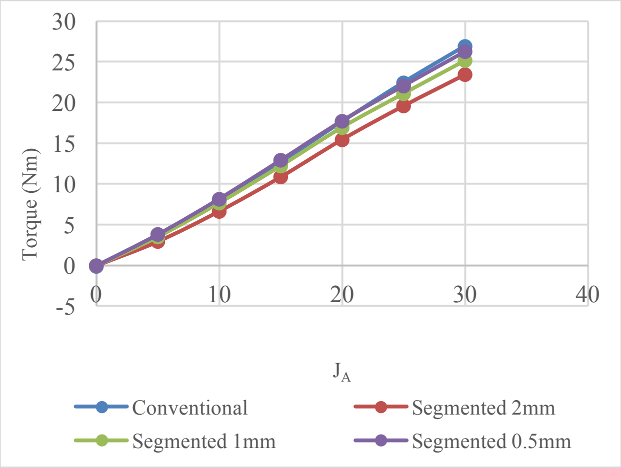

Figure 3: The graph of torque versus JA for conventional and segmented IPMSM

3.3 Torque and Power versus Speed

The maximum torque, power, and speed values were calculated by doing the power and torque analysis. Modifying the torque and speed data in the previous simulation makes it possible to measure output power. All the necessary data are collected. Equation 4 is used to replace all data. Meanwhile, equation 5 calculates the motor's output power based on the torque and the speed curve. Where the Nm is motor speed (rpm), and τ is torque. This simulation is analyzed at different angles of the output armature current ranging from 0° to 80° to determine the actual maximum torque. A comparison is made between the structure of the motor in terms of torque, power, and engine speed.

$$Po = (\text{〖}2\pi N\text{〗}\ m\ \tau)/60 \qquad (5)$$

Figure 4 and Figure 5 show the torque and power versus speed for all motor design. Based on the figure, the base speed, maximum torque, and power for conventional

IPMSM are 927.41rpm, 26.91Nm, and 2874.35W, respectively. Next, the base speed, maximum torque, and power for segmented IPMSM (2mm) are 960.72rpm, 23.45Nm, and 2492.762W, respectively. Furthermore, the base speed, maximum torque, and power for segmented IPMSM (1mm) are 962.76rpm, 25.16Nm, and 2675.15W, respectively. Lastly, the base speed, maximum torque, and power for segmented IPMSM (0.5mm) are 962.75rpm, 26.26Nm, and 2789.91W, respectively. The maximum speed of the motor depends on the rotor design and width of the iron bridge

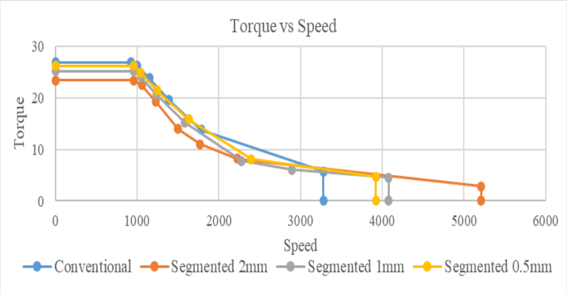

Figure 4. Torque versus Speed for all types of motor

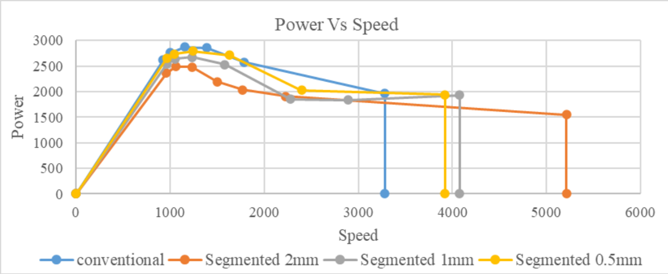

Figure 5. Power versus Speed for all types of motor

Figure 6 shows the bar chart comparison of maximum torque with maximum power for all four motor types. Based on the bar chart, the result of the torque and output power of conventional IPMSM design can be compared with the iron bridge's different size width for segmented IPMSM. The torque and output power produced by conventional IPMSM are 26.91 Nm and 2874.35W, respectively. Therefore, the conventional IPMSM has the highest maximum torque and output power based on the bar chart compared to segmented IPMSM. Furthermore, for segmented IPMSM, when the width of the iron bridge is increased, the maximum torque and power will be decreased.

Table 3 shows the comparison of three different design configurations of the motor between the conventional motor. Based on the table, the performance of the segmented motor will be decreased when the width of the iron bridge increases. The maximum torque of segmented IPMSM when the width of the iron bride is set to 2mm is dropped by 12.89%, compared to conventional IPMSM. Its maximum power also drops by 13.28%. However, when the width of the iron bridge is set to 0.5mm, the difference of maximum torque and power is smaller than the other segmented IPMSM, which are 2.44% and 2.94%, respectively.

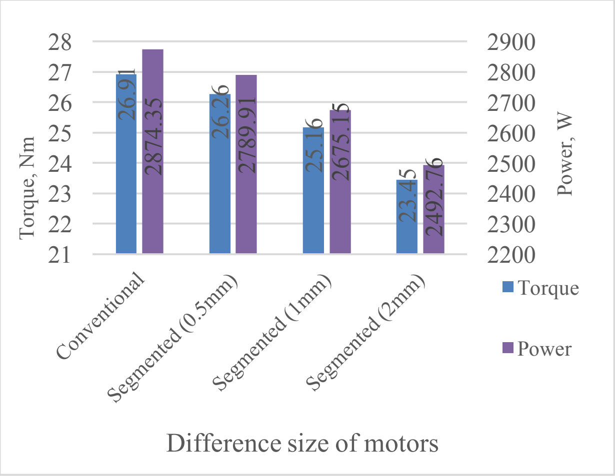

Figure 6: The bar chart comparison of maximum torque with maximum power for all motor

Table 3. Comparison of three design configurations of the motor with the conventional IPMSM

Type of motors	Segmented (0.5mm)	Segmented (1mm)	Segmented (2mm)
Torque, Nm	−2.44%	−6.50%	−12.89%
Power, W	−2.94%	−6.93%	−13.28%

3.4 Flux Weakening

The motor reached its full speed at the maximum torque point called the rated speed (also called base speed when talking about flux weakening). Above this point, the motor torque decreases rapidly towards its minimum value, depending on the load torque profile. Therefore, the torque of the motor must be reduced to increase the speed above the rated value. Reducing the magnetizing current, which induces the magnetizing flux, is a standard method for regulating synchronous motors. This mechanism is referred to as field-weakening. Flux weakening allows a machine to run above base speed in the constant-power high-speed region when there are a set inverter voltage and current. All the stator current can create torque (constant torque region) below the base level. Above base speed, to oppose the permanent magnet flux, part of the stator current must be used, while the remaining portion is used to generate torque.

Based on the result in Figure 4 and Figure 5, base speed, maximum speed, and constant power speed range (CPSR) are transferred into Table 4. The table shows that the low speed for segmented IPMSM (2mm) is higher than the conventional IPMSM. Segmented IPMSM (2mm) starts from 0rpm to 960.72rpm. However, for conventional motor, it begins from 0rpm to 927.41rpm. At this region, the motor is operated under the maximum torque per ampere control (MTPA). The MTPA control is under the current and voltage limits at rated speed for motor operation.

Table 4. The constant power speed range for each motor

Types of motor	Base speed, $\square_{\text{base}}$ (rpm)	Maximum constant power speed, $\square_{\text{max}}$ (rpm)	Constant power speed range (CPSR)
Conventional	927.41	3281.27	3.5381
Segmented (2mm)	960.72	5211.64	5.4247
Segmented (1mm)	962.76	4078.75	4.2365
Segmented (0.5mm)	962.75	3920.73	4.0724

On the other hand, the CPSR for the segmented IPMSM (2mm) is higher (53.32%) than conventional IPMSM, from 3.5381 to 5.4247. The CPSR can be calculated using Equation 6, which is □base is speed base, and □max is the maximum constant power speed. In this region, the motor is controlled by the flux-weakening method. Thus, these comparisons could be concluded that the performance of segmented IPMSM as a wide constant power speed range (CPSR) machine is far better than the conventional IPMSM. Moreover, when the iron bridge's width for segmented IPMSM increases, the CPSR of the motor will decrease.

$$\mathrm{CPSR}=\omega\_\mathrm{max}/\omega\_\mathrm{base} \tag{6}$$

Next, the maximum U-phase flux linkage will be calculating with the armature coil current density, J_A is varying from -30, -25, -20, -15, -10, -5, 0, 5, 10, 15, 20, 25, and 30 A/mm2. After that, calculate the input current of the armature coil, I_{rms} (A). This value will be used for each design of the motor to be analyzed. The graph of torque and power versus speed has been calculated with the negative value of armature coil current density, J_A from -30J_A until -5J_A. This simulation is analyzed at different angles of the output armature current ranging from 0° to 80° to determine the actual maximum torque. A comparison is made between the structure of the motor in terms of torque, power, and engine speed. The result of base speed, maximum speed, and constant power speed range (CPSR) are transferred into Table 5.

Table 5. The constant power speed range for each motor for negative JA

Types of motor	Base speed, $\square_{\text{base}}$ (rpm)	Maximum constant power speed, $\square_{\text{max}}$ (rpm)	Constant power speed range (CPSR)
Conventional	846.32	1423.13	1.68
Segmented (2mm)	855.56	1717.29	2.01
Segmented (1mm)	846.53	1488.41	1.76
Segmented (0.5mm)	842.51	1390.63	1.65

The result in Table 5 shows that the low speed for segmented IPMSM (2mm) is higher than the conventional IPMSM. Segmented IPMSM (2mm) starts from 0rpm to 855.56rpm. However, conventional motor starts from 0rpm to 846.32rpm. At this region, the motor is operated under the maximum torque per ampere control (MTPA) same as the previous simulation for positive JA. The MTPA control is under the current and voltage limits at rated speed for motor operation.

On the other hand, the CPSR for the segmented IPMSM (2mm) is higher (19.64%) than conventional IPMSM, from 1.68 to 2.01. The CPSR can be calculated using Equation 6. The CPSR of the segmented (2mm) for negative J_A is lower than the positive J_A, however, the CPSR for both results are still higher than the conventional IPMSM. Same as the previous simulation for positive JA, the motor is controlled by the flux-weakening method at this region. Finally, these comparisons could be concluded that the performance of segmented IPMSM as a wide constant power speed range (CPSR) machine is far better than the conventional IPMSM. Moreover, when the iron bridge's width for segmented IPMSM increases, the CPSR of the motor will decrease.

4. CONCLUSION

In conclusion, all the objectives in this project have been achieved. First, the conventional and segmented IPMSM is successfully constructed in JMAG software. Furthermore, after completing the construction of all motor in 2-dimensional design, the performance analysis such as the no-load test and load test has been complete to achieve the second objective. Next, in this project, the comparison between the conventional IPMSM and segmented IPMSM also done successfully. In both machines, the same stator was used for direct comparison.

Based on the result, it was evident from the comparative study that the Segmented IPMSM could provide a much wider constant power speed ratio (CPSR). So, a wide CPSR is achievable in such a motor due to its inherent flux-weakening capability. Such wide CPSR has affected her to not be achievable with conventional IPMSM. However, the cogging torque produced by the segmented IPMSM is lower than the conventional IPMSM, but the torque ripple is lower than conventional IPMSM. In addition, when the width of the iron bridge of the segmented IPMSM is decreased, the cogging torque of the motor will increase.

As an added advantage of segmented IPMSM, its construction is simple and similar to commercially available IPM machines. Therefore, the segmented IPMSM design is a good competitor for other applications such as traction where a large CPSR is fundamentally desired, such as for electric and hybrid electric vehicles.

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