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Design and Analysis of Various Stator Shape Configurations in Dual Rotor Permanent Magnet Flux Switching Motor

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Abstract: The dual-rotor permanent magnet flux-switching machine (PMFSM) consists of a single stator shared by an inner rotor and an outer rotor. The direction and magnitude of the magnetic field can be altered by varying the current flowing through the switched flux rotor's windings. Because conventional PMFSM machines frequently have flux weakening capabilities and constant power operating regions that are undesirable for wide-range speed applications, variable flux permanent magnet machines are reported as an existing solution. This paper provides the design and performance analysis of a dual rotor PMFSM using a variety of shape configurations. In this paper, there are three designs utilizing wedge-shaped PMFSM, radial-shaped PMFSM, and rectangular-shaped PMFSM is proposed. JMAG-finite Designer's 18.0 element analysis is used in this paper where for all drawing procedure design, it uses the JMAG Editor while for analyze procedure for material, condition and properties setting use the JMAG Designer. The motor's cogging torque, flux linkage, flux distribution, and back-EMF are examined, followed by a load study that examines the motor's torque-speed characteristics and output power with various stator shape configurations. The analysis shows that rectangular shape PMFSM outperforms PMFSM with wedge shape configuration and radial shape configuration in terms of high average torques and power. Future possible attempt also includes optimizing the design parameter and efficiency analysis for all three design of dual rotor permanent magnet flux switching motor.

Keywords: Dual Rotor Permanent Magnet Flux Switching Motor, Wedge Shape, Radial Shape, Rectangular Shape.

1. Introduction

A dual-rotor permanent magnet flux-switching machine (PMFSM) is a type of electric motor that uses permanent magnets to generate a magnetic field and generate torque. It consists of two rotors rotating around a common axis, hence the term "dual rotor." The motor has high efficiency, reliability, and low noise compared to other types of motors, making it suitable for various applications. The dual-

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rotor PMFSM consists of a single stator shared by an inner rotor and an outer rotor. A magnetic coupling exists between the inner and outer rotors, which makes this machine less fault-tolerant and reduces its performance. The previous knowledge of the behavior of machines under different fault conditions is the basis of an evaluation of the effects of faults on the machine [1].

PMFSM can be considered as popular for high power density as it can eliminate excitation copper losses. PMFSM is widely used nowadays and has been used for years as an effective solution to electric motors. The presently existing permanent magnet machines for electric motor applications have the problem of flux leakage weakening capability and constant power operating regions which are not desirable for wide range speed application in yokeless stator topology while other machines have a critical factor of high-cost permanent magnet material [2]. In case of that changing the usual shape to wedge shape PMFSM will increase the effectiveness of PMFSMs. Thus, the configuration of PMFSM is introduced to study performance effect by switching the different configuration, which is wedge shape PMFSM, radial shape PMFSM, and rectangular shape PMFSM. Additionally, the design of the permanent structure will enhance field winding to provide room for future improvement. [3]-[4].

The primary objective of this paper is to compare various stator shape configurations of dual rotor PMFSM to analyze between three shapes which configuration has better performance. To achieve the main objective, there are some specific objectives that must be fulfilled, which are to design and analyze the dual rotor wedge shape permanent magnet flux switching motor, dual rotor radial shape permanent magnet flux switching motors and dual rotor yokeless shape permanent magnet flux switching motors. Then, to compare the performance of the various shape configurations of dual rotor PMFSM.

An electric motor with two rotors one a switched flux rotor and the other a permanent magnet rotor is known as a dual rotor permanent magnet flux switching motor (DRPMFSM). The switched flux rotor can change its magnetic field by changing the direction of the current flowing through its windings, in contrast to the permanent magnet rotor, which produces a magnetic field that is constantly present. The motor rotates when current is applied to the windings of the switched flux rotor because the magnetic field it produces interacts with the field of the permanent magnet rotor [5]. The direction and magnitude of the magnetic field can be altered by varying the current flowing through the switched flux rotor's windings, which enables precise control of the motor's torque and speed [6].

High efficiency by utilizing permanent magnets and flux switching, high efficiency is made possible, which results in less energy being lost as heat. High power density because the flux switching rotor and permanent magnets' small size and light weight enable the motor to produce a lot of power in a relatively small space. High-performance operation is made possible by the precise control of the magnetic field and torque, making it ideal for demanding applications like electric vehicles and industrial machinery. Operation at high speeds because the motor's ability to operate at high speeds without sacrificing efficiency and power density is made possible by the permanent magnets and flux switching rotor. Better thermal performance because of the motor's high efficiency, less heat is generated during operation, resulting in better thermal performance. Low acoustic noise because of its high efficiency and high speed, the motor produces little noise [7].

2. Methodology

This chapter provides explanations on the design of various shape PMFSM separately in two ways such as JMAG Geometry and JMAG Designer. JMAG-Designer 18.1 is used as a 2D-FEA solver. For JMAG Geometry editors used to design each part of the motor separately as FEM, rotor, stator, and armature coil. JMAG-designer is used to insert condition settings and materials for each part of the motor and simulate the motor that has been designed.

2.1 Parameter and Specification

Table 1 displays the design specification for the project methodology. The first step is to open the JMAG-Designer to create a 2D geometry editor by using the Geometry Editor. After that, open the geometry editor by right-clicking on the project manager and then click 'Create Geometry. Then, the part of the dual rotor PMFSM was designed using the specification shown in Table 1.

Table 1: Parameters and Specification of 9S-15P Design PMFSM

Parameters	9-slot/ 15-pole
Outer radius	45 mm
Stator outer radius	39 mm
Stator inner radius	22 mm
PM width	6 deg
Air gap	0.5 mm
Rotor tooth width	12 deg
Rotor tooth height	3 mm
Stator tooth width	10 deg
Stack length	25 mm
Shaft radius	10 mm

2.2 Methods

The JMAG Designer's 18.0 design processes include mesh and magnetic study properties, condition setting, circuit setting, material setting, and run analysis. Figure 1 illustrates the design of a dual rotor permanent magnet flux switching motor and the performance analysis of PMFSM.

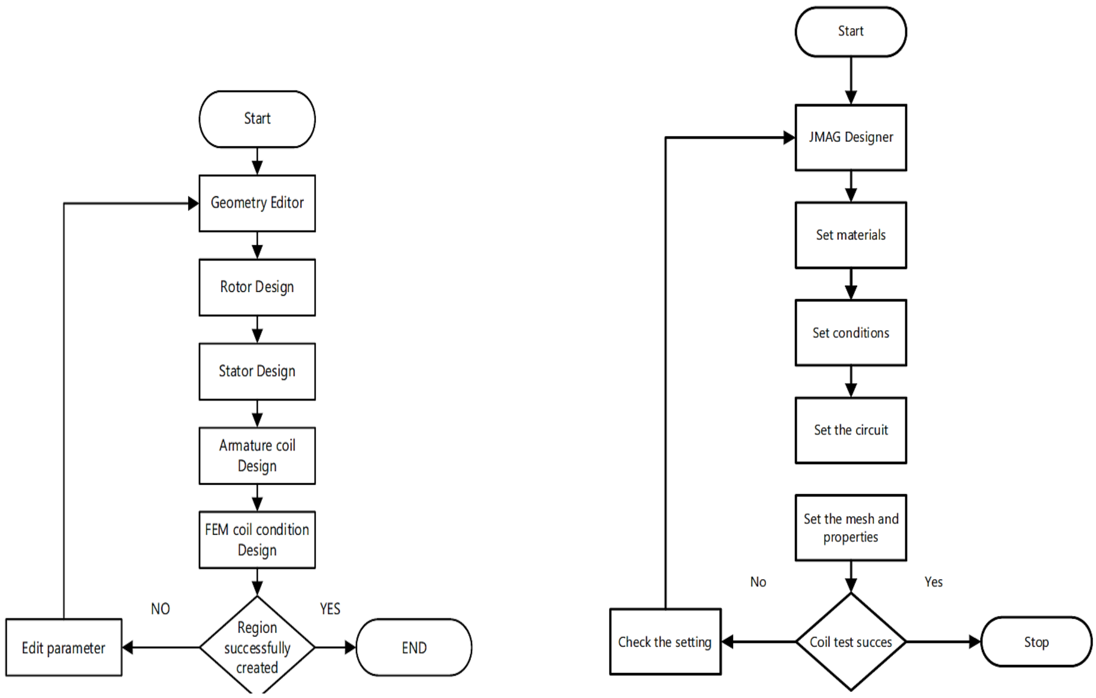


Figure 1: The design of dual rotor permanent magnet flux switching motor and performance analysis of PMFSM

2.3 Material and Condition

Table 2 shows the material and condition settings for dual rotor PMFSM parts. To set up the materials, click on the toolbox at the right-hand side of the JMAG Designer and find each material for every part of the motor by referring to Table 2.

Table 2: Material and Condition for PMFSM

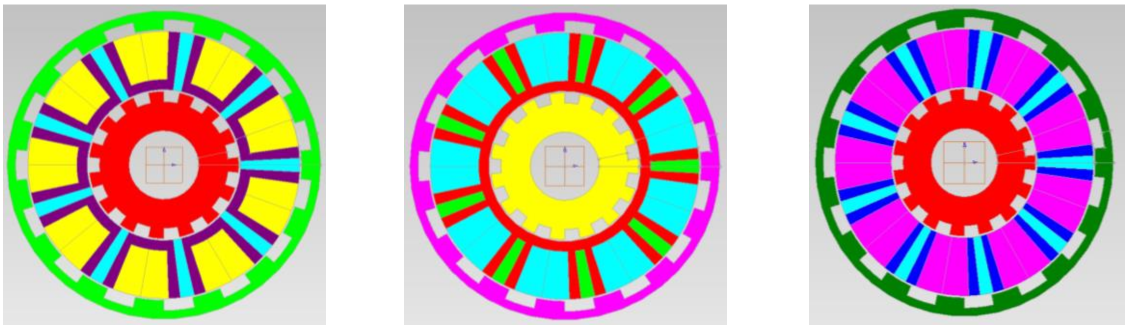
Parts	Materials	Conditions
Inner rotor	Nippon Steel 35H210	Motion: rotation Torque: nodal force
Outer rotor	Nippon Steel 35H210	Motion: rotation Torque: nodal force
Stator	Nippon Steel 35H210	-
Armature coil	Conductor Copper	FEM Coil
Permanent magnet	Neomax-P8H (irreversible) (Magnetization pattern: circular direction)	-

3. Results and Discussion

This section analyses the performance of a PMFSM with three different stator configuration topologies with 9 Slot-15 Poles. Using appropriate materials, environmental factors, and mesh, the design of a dual rotor PMFSM is established. The no-load analysis at zero rotor position is used to determine the performance of the planned motor. The performance of the dual rotor PMFSM design was compared to that of the three stator designs. Tests with and without loads determine the motor's performance.

3.1 Design Configuration

Figure 2 shows the complete design for wedge-shaped dual rotor PMFSM, radial shape dual rotor PMFSM, and rectangular shape dual rotor PMFSM. Each design is tested by no load analysis and load analysis to determine the performance of the motor [8].



(a) **(b)** **(c)**

Figure 2: Design of 9S-15P dual rotor PMFSM (a) Wedge Shape DRPMFSM (b) Radial Shape DRPMFSM (c) Rectangular Shape DRPMFSM

3.2 No load Test Analysis

In the no-load analysis part, which meant no supply by the armature current density, JA. The IA is equal to 0 $\mathrm{Arms/mm^2}$. The outcomes that must be considered in this analysis are the cogging torque, the back-EMF, and the magnetic flux linkage at the desired angle. When a cosine wave's largest factor is at zero degrees, or in some other circumstances, when it is at 180 degrees, this is known as the zero-rotor position. According to Figure 3, the U flux contains the entire design when it is at the zero-rotor position. According to the diagram, the flux linkage for the wedge shape DRPMFSM is 0.000387 ϕ, followed by the radial shape DRPMFSM, which is around 0.000457 ϕ, and finally, the rectangle shape DRPMSFM, which has the lowest value when compared to the other two designs, is about 0.00032547.

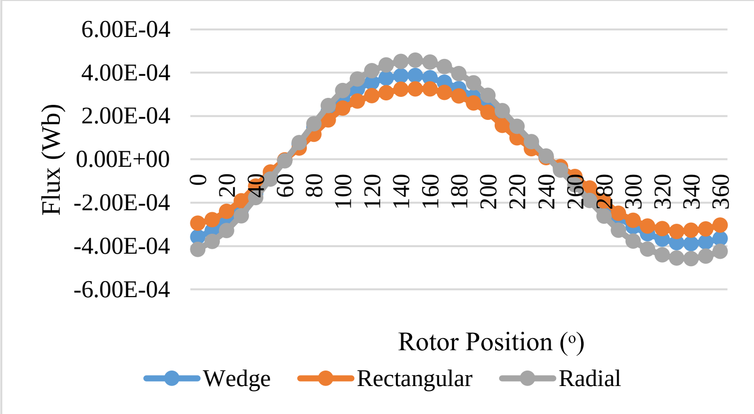
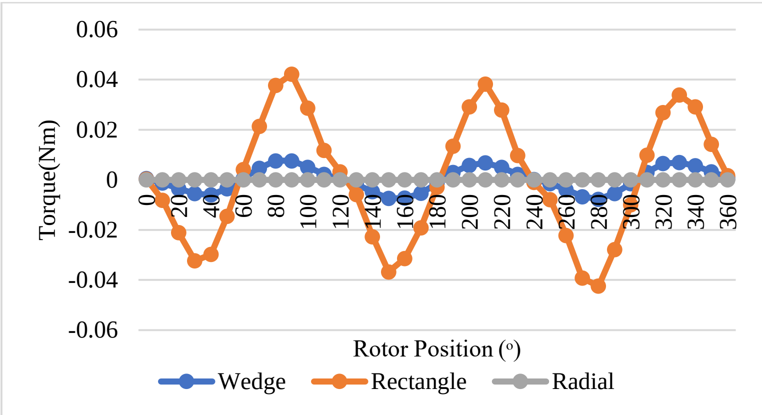


Figure 3: Zero Rotor Position (U-flux)

Figure 4 shows the comparison of the cogging torque graph for 9S-15P wedge shape DRPMFSM, radial and rectangular shape DRPMFSM. It is observed that the wedge shape DRPMFSM indicates 0.0076 Nm peaks for the inner rotor while 0.0602 Nm for the outer rotor. Next, the radial shape DRPMFSM indicates 1.13E-07 Nm peaks for the inner rotor and 0.0505 Nm for the outer rotor. Lastly, the rectangular shape DRPMFSM indicates 0.0421 Nm peaks for the inner rotor and 0.1428 Nm for the outer rotor.



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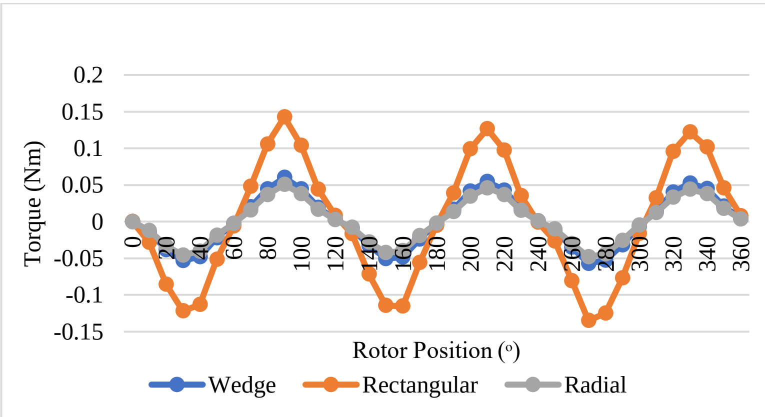


b)

Figure 4: Cogging Torque a) Inner rotor b) Outer rotor

Figure 5 shows back-EMF for wedge shape DRPMFSM has maximum value 0.4024 V at the angle 35° and a minimum value -0.387 V at angle 210°.Next, the radial shape DRPMFSM has maximum value

0.458 V at the angle 35º and minimum value -0.441 V at angle 210º.Lastly, the rectangular shape DRPMFSM has maximum value 0.4001 V at the angle 35º and minimum value-0.3665 V at angle 210º.

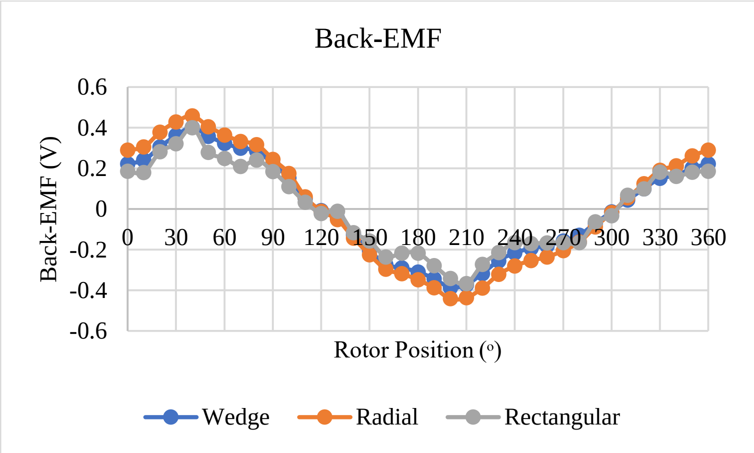


Figure 5: Back-EMF a) Wedge Shape DRPMFSM b) Radial Shape DRPMFSM c) Rectangular Shape DRPMFSM

3.3 Load Analysis

The motor is injected with a precise current density to imitate the load test. When a varied current value is injected into the motor FEM coil, the torque and flux relations at several JA regions are examined to identify the pattern of torque change. To ascertain the traits of torque, power, and speed, all 3 models are put to the test and run using JMAG simulation software. The total U-phase flux interaction at various JA that is shown in Figure 6 for the maximum U-flux for the wedge shape DRPMFSM is 0.0077 ϕ, followed by the radial shape DRPMFSM, which is around 0.0079 ϕ, and finally, the rectangle shape DRPMSFM, which has the lowest value when compared to the other two designs, is about 0.0072 ϕ.

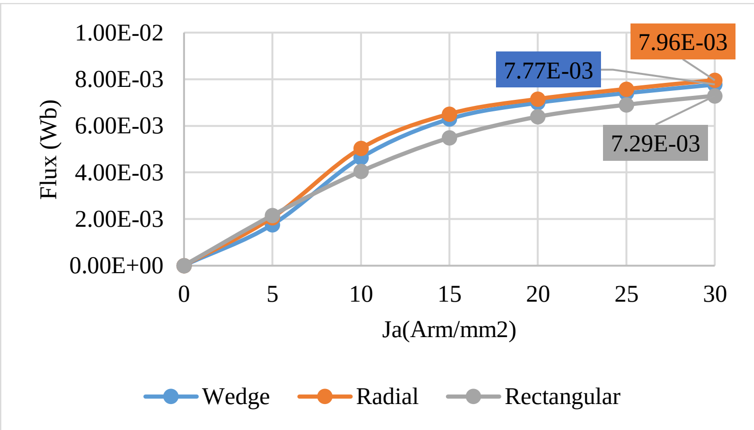
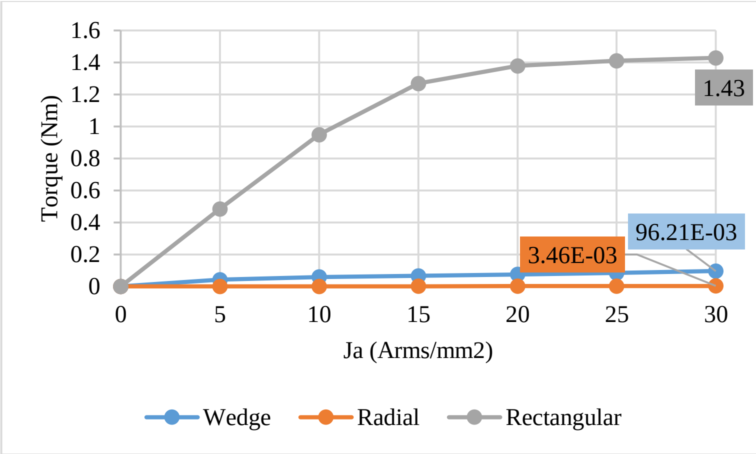


Figure 6: Maximum U phase flux at various JA

Figure 7 depicts the graph of torque at varying armature coil densities for all designs of the motor with various permanent magnet stator configurations. By referring the Figure 7, the highest torque for the inner rotor in wedge shape DRPMFSM is 0.0962 Nm, followed by the rectangular shape DRPMFSM, which is around 1.4277 Nm, and finally, the radial shape DRPMSFM, which has the lowest value when compared to the other two designs, is about 3.46e-3 Nm. While for highest torque for the inner rotor in wedge shape DRPMFSM is 2.1748 Nm, followed by the rectangular shape DRPMFSM, which is around 2.4433 Nm, and finally, the radial shape DRPMSFM, which has the lowest value when compared to the other two designs, is about 2.1415 Nm.



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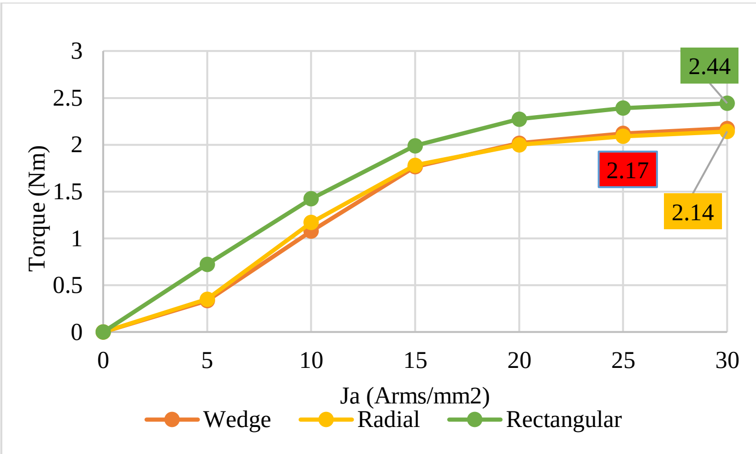
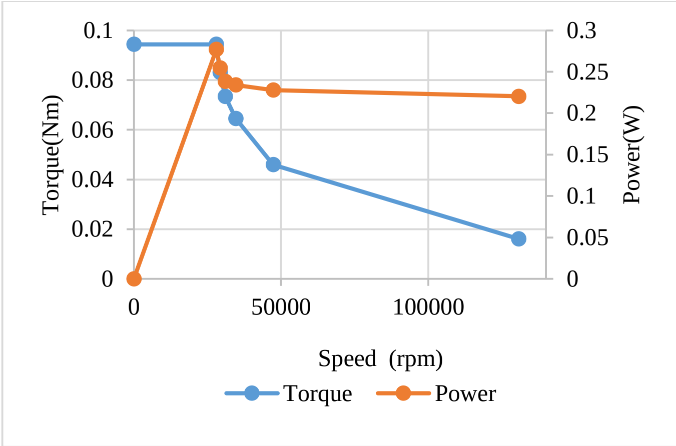


b)

Figure 7: Torque at Various armature coil a) Inner rotor torque b) Outer rotor torque

According to Figure 8, the inner rotor's maximum output power for the wedge-shaped DRPMFSM design is 0.2771W at a speed of roughly 28043.58 rpm. This design also generated a maximum speed of 130767.5 rpm and a maximum torque of 0.0943 Nm at a speed of 28043.58 rpm. Then, for a radial shape, DRPMFSM produced output power for 0.0106 W in conditions of speed at 27508.3 rpm and produced a maximum speed that is 119953 rpm while producing a maximum torque of 0.0037 Nm at a speed of 27508.3 rpm. Lastly, for a rectangular shape, DRPMFSM produced output power for 5.8865 W at a speed of 59570.2 rpm. This design also produced the maximum speed which is 112444 rpm while the maximum torque is 1.4185 Nm at speed 30596.6 rpm.



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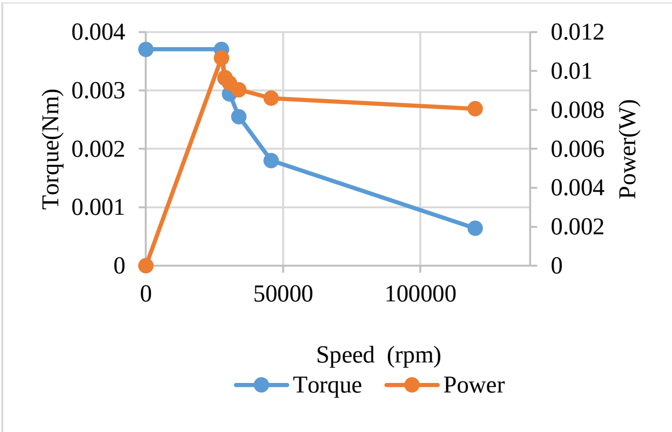

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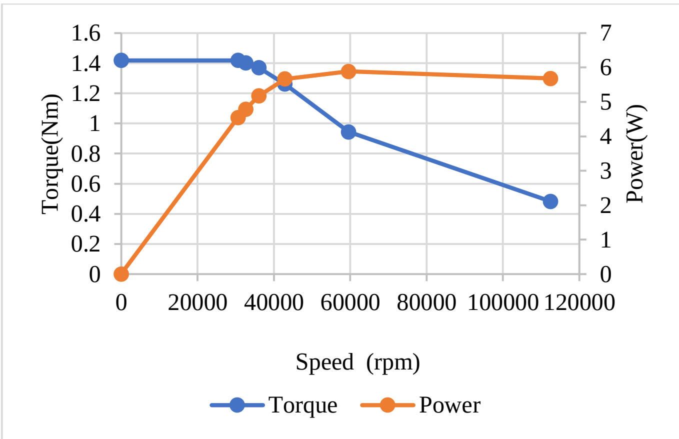
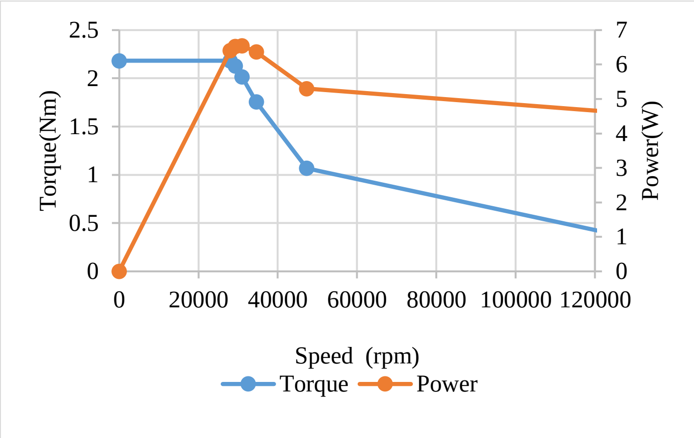


c)

Figure 8: Torque and Power vs Speed a) Wedge Shape DRPMFSM b) Radial Shape DRPMFSM c) Rectangular Shape DRPMFSM

Based on Figure 9, the outer rotor's maximum output power for the wedge-shaped DRPMFSM design is 6.5439 W at a speed of roughly 31001.52 rpm. This design also generated a maximum speed of 130767.5 rpm and a maximum torque of 2.1808 Nm at a speed of 28043.58 rpm. Then, for a radial shape, DRPMFSM produced output power for 6.3894 W in conditions of speed at 30424.6 rpm and produced a maximum speed that is 119953.2 rpm while producing a maximum torque of 2.1488 Nm at a speed of 27508.26 rpm. Lastly, for a rectangular shape, DRPMFSM produced an output power for

8.9077 W at a speed of 42878.6 rpm. This design also produced the maximum speed which is 112443.7 rpm while the maximum torque is 2.4439 Nm at speed 30596.58 rpm.



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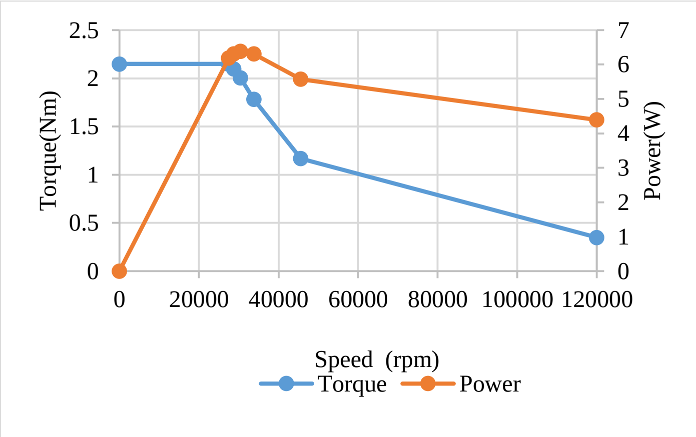

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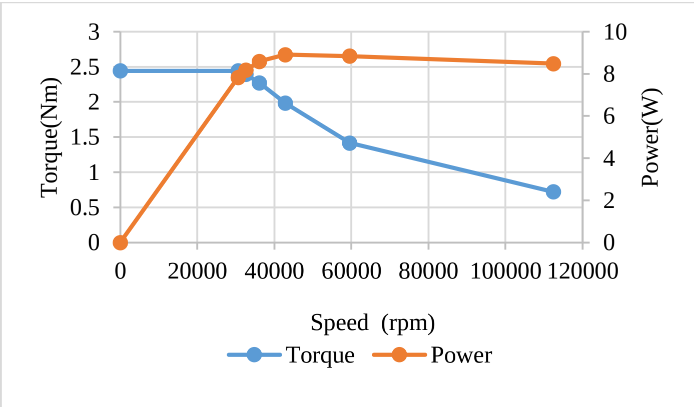

c)

Figure 9: Torque and Power vs Speed a) Wedge Shape DRPMFSM b) Radial Shape DRPMFSM c) Rectangular Shape DRPMFSM

4. Conclusion

In this project, three different stator shape configurations wedge shape, radial shape, and rectangular shape for the 9S-15P dual rotor PMFSM have been studied. Three different dual-rotor PMFSM design processes have been thoroughly reviewed and explained. To verify each armature coil phase and to demonstrate how machines work, the coil arrangement test for the design was looked at. In addition, the performance of every dual rotor PMFSM design has been studied, including flux linkage, cogging torque, flux line distribution analysis, back-EMF, maximum torque, and power. All designs had their own performances, according to the analysis. There are significant differences in performance between wedge shape DRPMFSM, radial shape DRPMFSM and rectangular shape DRPMFSM, where rectangular shape DRPMFSM produce high torque and power compared to the other two designs but have the highest cogging torque and lowest flux. While for radial shape DRPMFSM has the highest flux and back-EMF but the lowest in Torque. Finally, wedge shape DRPMSFM have moderate result in all performance in all aspects.

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References

[1] K. Ayaz, F. Khan, N. Ahmed, S. Ishaq and A. Rasheed, "Novel: Wedge shape permanent magnet flux switching machine for electric and hybrid electric drives application," *2018 International Conference on Computing, Mathematics and Engineering Technologies (iCoMET)*, Sukkur, Pakistan, 2018, pp. 1-5, doi: 10.1109/ICOMET.2018.8346409.

[2] Hassan, M.K., Sulaiman, E., Romalan, G.M., Omar, M.F. and Jenal, M.,2015, October. Load analysis of dual Rotor Hybrid Excitation Flux Switching Machine (DR-HEFSM). In Energy Conversion (CENCON), 2015 IEEE Conference on (pp. 155-159). IEEE.

[3] Jusoh, L.I., Sulaiman, E., Kumar, R. and Bahrim, F.S., 2017. Design and Performance of 8Slot-12Pole Permanent Magnet Flux Switching Machines for Electric Bicycle Application. International Journal of Power Electronics and Drive Systems (IJPEDS), 8(1), pp.248-254

[4] Hassan, M.K., Sulaiman, E., Romalan, G.M., Omar, M.F. and Jenal, M.,2015, October. Load analysis of dual Rotor Hybrid Excitation Flux Switching Machine (DR-HEFSM). In Energy Conversion (CENCON), 2015 IEEE Conference on (pp. 155-159). IEEE

[5] W. Hua, M. Cheng, Z. Q. Zhu, and D. Howe, “Design of flux-switching permanent magnet machine considering the limitation of inverter flux weakening capability,” in Proc. 41st Annu. Meeting IEEE Ind. Appl. Soc.,Tampa, FL, USA, Oct. 2006, vol. 5, pp. 2403–2410.

[6] S. Sharifan, S. Ebrahimi, A. Oraee and H. Oraee, "Performance comparison between brushless PM and induction motors for hybrid electric vehicle applications," 2015 Intl Aegean Conference on Electrical Machines & Power Electronics (ACEMP), 2015 Intl Conference on Optimization of Electrical & Electronic Equipment (OPTIM) & 2015 Intl Symposium on Advanced Electromechanical Motion Systems (ELECTROMOTION),2015, pp. 719-724, doi: 10.1109/OPTIM.2015.749247

[7] M. Jenal, et al., “Development of a novel permanent magnet flux switching machine prototype for light weight electric vehicles”, 2015 IEEE Student Conference on Research and Development (SCOReD), Kuala Lumpur, pp. 739-744, 2015

[8] K. Ayaz, F. Khan, N. Ahmed, S. Ishaq and A. Rasheed, "Novel: Wedge shape permanent magnet flux switching machine for electric and hybrid electric drives application," *2018 International Conference on Computing, Mathematics and Engineering Technologies (iCoMET)*, Sukkur, Pakistan, 2018, pp. 1-5, doi: 10.1109/ICOMET.2018.8346409.