Evolution in Electrical and Electronic Engineering Vol. 4 No. 1 (2023) 441-449
© Universiti Tun Hussein Onn Malaysia Publisher's Office

EEEE

Homepage: http://publisher.uthm.edu.my/periodicals/index.php/eeee
e-ISSN : 2756-8458

Optimal Design of a High-Speed Single-Phase Flux Reversal Motor of Air Blower

Nurul Ameera A.Rahman[1], **Mahyuzie Jenal**[1]*,

[1]Faculty of Electrical and Electronic Engineering,
Universiti Tun Hussein Onn Malaysia, Batu Pahat, 86400, MALAYSIA

*Corresponding Author Designation

DOI: https://doi.org/10.30880/eeee.2023.04.01.052
Received 16 January 2023; Accepted 15 February 2023; Available online 30 April 2023

Abstract: This thesis described the optimal design of a single-phase high-speed flux reversal motor (FRM) for air blower application. Based on the literature, FRM is an electrical machine with a simple and reliable rotor structure which is significant for high-speed applications. The FRM efficiency can be boosted by using the full inner stator's surface. Many previous research has shown the development of the FRM with various designs and numbers of rotor and stator slots, which have influenced the size and performance of the motor. For a high-speed application, a three-phase FRM with several salient pole designs was constructed, resulting in a low torque value with a high cogging torque. Therefore, a high-speed single-phase FRM with a modular rotor design was proposed in order to determine the best design for the motor in an air blower application. In this thesis, the performance of both motors was analyzed using FEM to reduce the cogging torque value as well as the flux path, which can reduce losses while increasing efficiency. The operating principle of the motor has been investigated and validated by the flux linkage, torque, power, and speed characteristics. The motors are also set to rotate in only one direction, making them suitable for unidirectional rotation applications such as air blowers. The optimal design of a high-speed single-phase FRM with modular rotor design is a better suited approach as a result of this study.

Keywords: Single-phase, Flux Reversal Motor, Air blower, Modular rotor

1. Introduction

Single-phase machines have a low beginning torque since they only have one phase. As a result, they are utilized extensively in low-power applications such as vacuum cleaners [1], blenders [2], and other home appliances that do not call for a high starting capability [3]. The frequency converters used in single-phase motors are less complicated and less expensive than those used in three-phase motors. This is the primary benefit. There are several distinct varieties of single-phase motors with magnets, including synchronous motors with magnets on the rotor surface and motors with magnets on the stator surface.

In recent years, studies have been done on Flux Reversal Motor (FRM) and becoming well known for their benefits of having a simple and reliable rotor that is suitable for low-cost high-speed applications. Installing permanent magnets on the surface of the stator solves the problem of initial rotor

**Corresponding author: mahyuzie@uthm.edu.my*

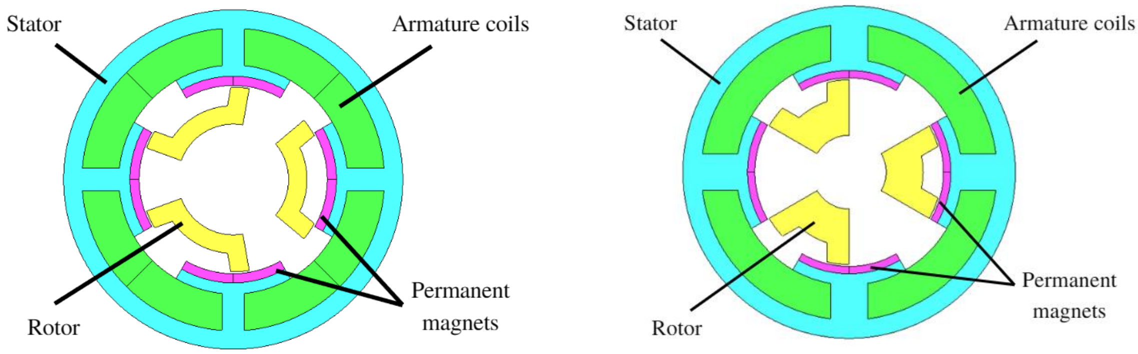
positioning. Therefore, the motor can be started even in the single-phase design [4]. The permanent-magnet flux linking the stator phase concentrated coils reverses polarity as the rotor travels. The main advantage is that the FRM is more robust and easier to manufacture and, because of its simple structure, it is cost-effective and suitable for mass production [5].

These days, many researchers are striving to design a FRM with a modular rotor structure because the salient rotor structure has problems with its flux and losses [6]. Additionally, the modular rotor design not only offered a high average output torque compared to other rotor designs but also called for a relatively small amount of copper. The suggested modular rotor motors have a very stable rotor form since all windings and field excitation coils are located on the stator. Furthermore, the modular rotor structure was also intended to help in the reduction of the salient rotor problem by minimizing the flux route along the rotor. Another simple technique introduced for reducing the cogging torque in PM machines is rotor skewing with rotor teeth pairing method i.e., adjusting the width of pair of rotor teeth [7] [8].

By utilizing a fundamentally simple toothed rotor constructed of a steel lamination, the cost of rotor manufacturing is minimized in contrast to a rotor with magnets on its surface and with a retaining ring, and the motor's durability is increased [8]. A comprehensive analysis and simulation for high-speed FRM conducted by [9] also show that under proper control, the FRM can operate as a high-speed motor with a wide speed range and good torque performance with two operation modes available for motoring operation.

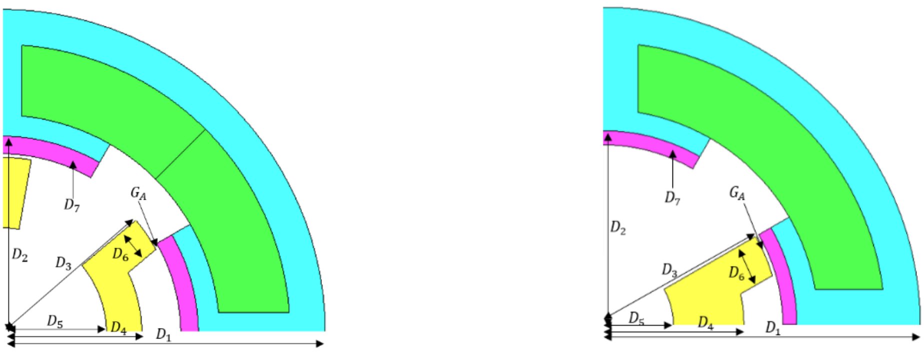
2. Parameters and Specification Design of Single-phase FRM

Initially, single-phase FRM with a modular rotor structure as shown in Figure 1 was designed to analyze the motor performances. The design requirements and specifications are based on the existing design of the motor but in this work, there are two designs proposed to find an optimal design of a high-speed single-phase FRM for an air blower. The parameters and specifications of the proposed designs were illustrated as shown in Figure 2, Table 1, and Table 2.



(a) design 1 (b) design 2

Figure 1: The proposed designs of single-phase FRM with modular rotor structure



(a) design 1 (b) design 2

Figure 2: The proposed designs of single-phase FRM with modular rotor structure

Table 1: The parameter of the proposed designs

Indicator	Parameter	Value		Unit
		Design 1	Design 2	
-	No. of phase	1	1	-
-	Stator poles	4	4	-
-	Rotor poles	6	6	-
D_1	Outer radius of stator	46	45	mm
D_2	Inner radius of stator	27.5	27.5	mm
D_3	Outer radius of rotor	25	25	mm
D_4	Inner radius of rotor	20	20	mm
D_5	Shaft radius	10	15	mm
G_A	Airgap length	0.5	0.5	mm
D_6	Rotor pole width	5	10	mm
D_7	Thickness of pms	2.5	2.5	mm
-	Motor stack length	70	70	mm
-	No of turn per coil	643	677	-

Table 2: The specification of the proposed design

Parts	Materials	Condition
Rotor	Nippon Steel 35H210	Motion: rotation Torque: nodal force
Stator	Nippon Steel 35H210	-
Armature Coil	Conductor Copper	FEM Coil
Permanent Magnet	Neomax35AH (irreversible) (radial pattern (circular direction))	-

The performance analysis of the machine in terms of the back-emf, cogging torque, flux lines, and flux distribution is observed in no load analysis. For the load analysis, the motors were observed for their torque performance at various armature current densities. The armature current density is varied from 0 to 30 Arms/mm2. The calculation of the armature current was shown in Equation 1 below. Then the data calculated will be used by inserting the values into the circuit in JMAG Designer to do the torque performance at various current density conditions.

$$I_a = \frac{J_a \alpha S_a}{N_a} \qquad (Eq. 1)$$

From Eq. 1, α is the filling factor, while Ia is the armature current, and Na is the number of turns. The proposed design's value of rms armature current and peak armature current is displayed in Table 3 below. By entering the values into the circuit, the calculated current density will be utilized to analyze the load state.

Table 3: Armature current density

Armature current density, (Ja)	Design 1		Design 2	
	Ia rms	Ia peak	Ia rms	Ia peak
5	0.9825	1.3895	1.5904	2.2492
10	1.9651	2.7790	3.1809	4.4985

15	2.9476	4.1685	4.7713	6.7477
20	3.9301	5.5581	6.3618	8.9969
25	4.9127	6.9476	7.9522	11.2462
30	5.8952	8.3371	9.5427	13.4954

3. Results and Discussion

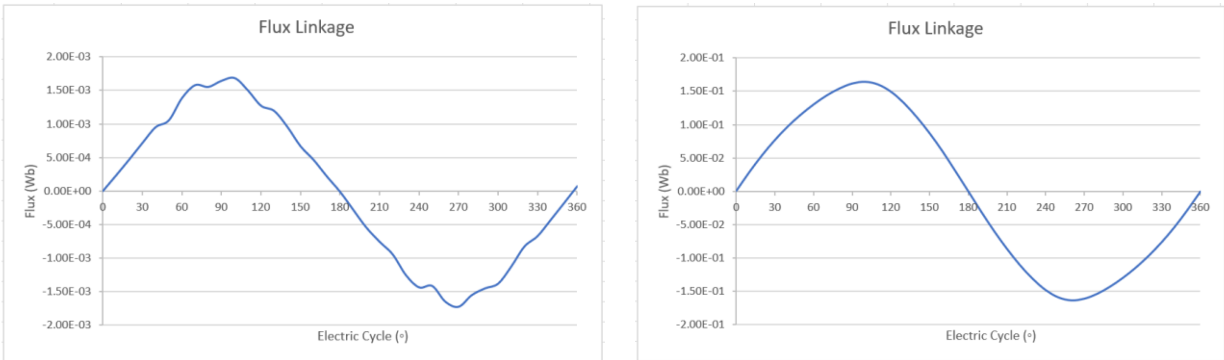
The operating principle of single-phase FRM was investigated with no load analysis and the performances of those two proposed designs were obtained by adding load analysis. No load analysis such as coil-flux linkage, cogging torque, back-emf, flux lines, and distribution while the load analysis in terms of the torque for every armature current density condition.

3.1 Operating Principle Investigation of single-phase FRM

The armature current density, Ja values were set as without load (0 Arms/mm2) while PM flux linkage remains constant throughout the study. Consequently, the maximum flux generates the flux lines and flux lines distribution in the machine. Moreover, back electromotive force (EMF) and cogging torque need to be observed at the desired angle.

3.1.1 Flux Linkage Analysis

Flux linkage analysis were conducted by with the coil test process in order to identify the pattern of flux linkage produced by each armature coil and to check the characteristics of the flux linkages. The polarity and winding direction of the armature coil is in clockwise direction while the PMs direction is set in opposite from each other or alternately. The coil flux linkage is tested with the motor rotating at constant speed which is 800 rpm were illustrated in Figure 3.

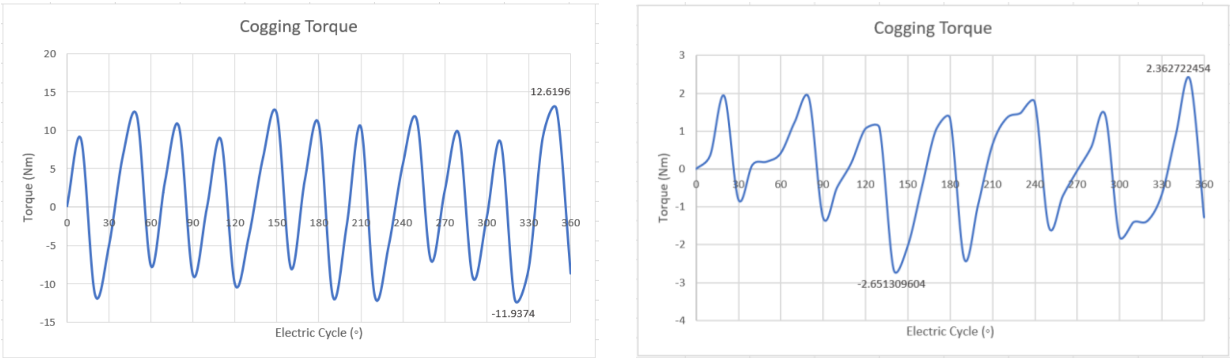


(a) (b)

Figure 3: Flux linkage analysis of the proposed designs

3.1.2 Cogging Torque

Cogging torque is the value of torque required to overcome the opposing torque produced by the attractive magnetic force between the stator's magnets towards the rotor tooth and PMs to create internal power. This torque is depending on the number of magnetic poles and the number of stator teeth for its periodicity per revolution. Moreover, cogging torque is an unwanted value for a motor to operate. The lower cogging torque is better because it will increase the performance and efficiency of the motor. Based on Figure 4, the graph plotted when there is no current supply to the armature coil and the highest peak cogging torque for the proposed design 1 is 12.619 Nm while design 2 is 2.362 Nm.

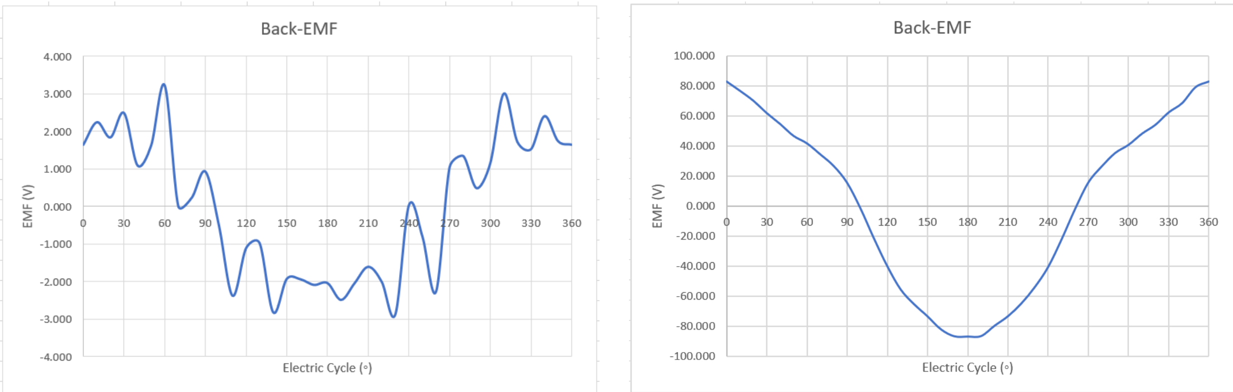


(a) (b)

Figure 4: Cogging torque of the proposed designs

3.1.3 Back-EMF

The back electromotive force or also known as the induced voltage is the voltage occurring in electric machines when there is corresponding motion between the stator windings and the rotor magnetic field. The induced voltage waveform with less distortion has good performance in the motor. The back-emf of the proposed rotor at a maximum J_A of 30 Arms/mm2 is illustrated in Figure 5. From the graph, the back-emf of design 1 has generated maximum value with 13.5V while design 2 has generated a less distorted wave with maximum value of back-emf achieved is 82.95V.

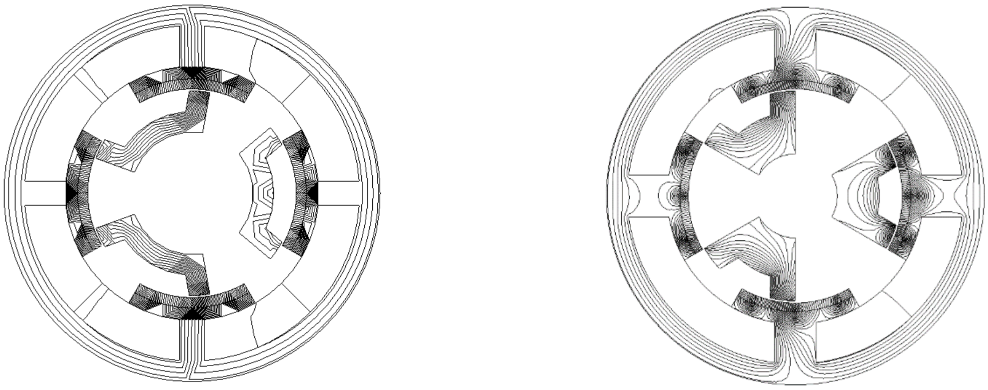


(a) (b)

Figure 5: Back-EMF of the proposed designs

3.1.4 Flux Line

The flux path is generated due to the magneto motive force (mmf) of the permanent magnet and armature coil. Analysis of the flux line is conducted to determine the flux characteristics of the proposed design as illustrated in Figure 6 All flux lines flow from the stator to the rotor and return to the stator to make a complete flux cycle. The flux will fail if it has to go a long distance because it reduces the overall quality of the flux linkage. The flux line of the high-speed single-phase FRM design is observed under no load condition where the armature current density, Ja set to 0 Arms/mm2 at the zero-degree position. From the results, the concentration of the short flux line, which is a full cycle of flux, occurs more between two adjacent stator teeth to one rotor tooth. Hence, the number of rotor poles influenced the flux line characteristics, where Tr is calculated based on the number of rotor teeth against the number of stator teeth.

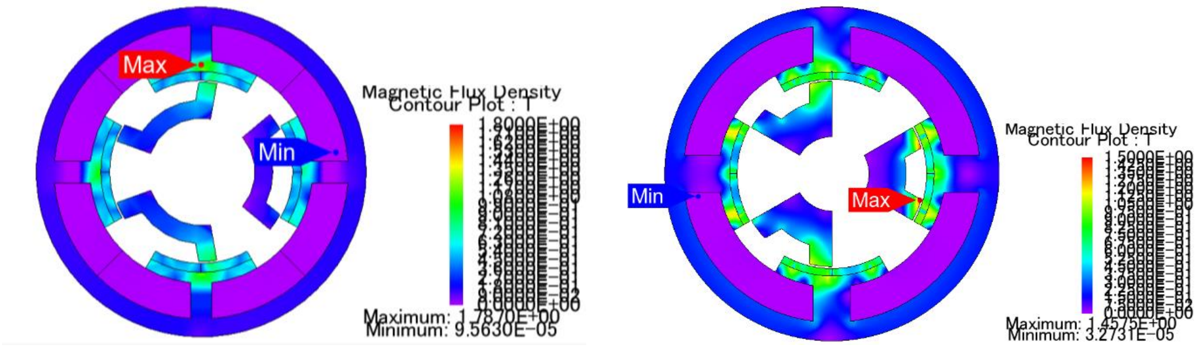


(a) (b)

Figure 6: Flux line of the proposed designs

3.1.5 Flux Distribution

Flux distribution should be taken as crucial consideration because flux distribution affected the machine's performance. From the model plot, the space between the permanent magnet and armature coil slots has a large amount of flux density and it also contributes to the flux saturation. A higher amount of flux saturation can make it less production of flux generation. Moreover, it also reduces the performance of machines, especially in terms of power and torque. Based on the observation of the flux distribution, design 1 have the maximum flux density is 1.7870 Nm which represents by green color and the minimum value is 0.00009 Nm which represents by purple color as shown in Figure 7 (a) while for design 2 the maximum flux density is 1.4575 Nm which represents by orange color and the minimum value is 0.00003 Nm which represents by purple color as shown in Figure 7 (b) below.



(a) (b)

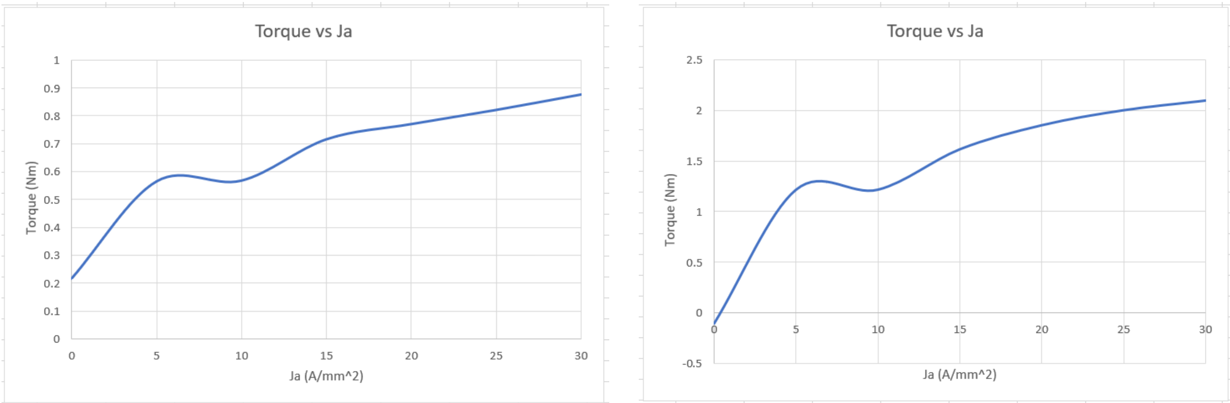
Figure 7: Flux distribution of the proposed designs

3.2 Load Analysis

It is possible to assess the performance of the motor under load conditions. The load test condition can be executed by changing the armature current density from 0 Arms/mm2 to 30 Arms/mm2. Based on the torque performance, power, speed, iron and copper losses, and efficiency, the load state of the motor is examined.

3.2.1 Torque vs Armature current density characteristic

Figure 8 shows the results of the torque performance of high-speed single-phase FRM from minimum current density, 0 Arms/mm2 to maximum current density, 30 Arms/mm2. The results obtained show that the value of torque increased as the value of Ja increased. The maximum output torque obtained for design 1 is 0.876 Nm and design 2 is 2.216 Nm at Ja 30 Arms/mm2.

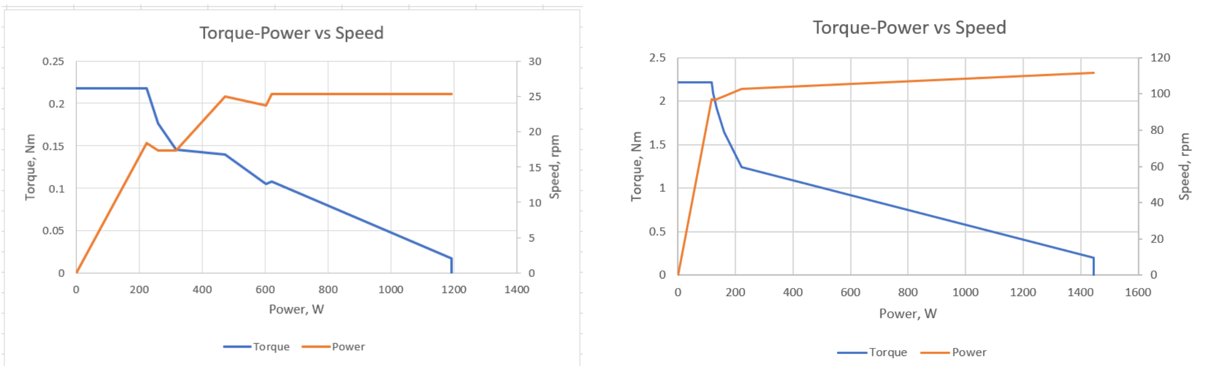


(a) (b)

Figure 8: Torque vs Armature current density characteristic

3.2.2 Torque and Power vs Speed Characteristic

The capability of the motor can be observed by the value of torque, power, and speed characteristics. The power of high-speed single-phase modular rotor FRM has been observed concerning armature current density 0 Arms/mm2 to 30 Arms/mm2. The power increase as the heat is generated Figure 9 shows the torque and power versus speed of the proposed design. It can be seen that the value of power at Ja 30 Arms/mm2 is the highest which is 0.0269 W at 116 rpm with a torque value of 2.216 Nm. Based on the results, the motor torque value is and it can be concluded that when the value of armature current density increases, the value of torque and power will increase respectively but the value of speed will decrease. Hence, as the power production increase it will reduce the winding loss.



(a) (b)

Figure 9: Torque and Power vs Speed characteristic

3.2.3 Power Losses and Efficiency

There are two types of losses in motors which are iron loss (Pi) and copper loss (Pc). The losses are defined by eight points from the value of under the torque versus speed graph. Figure 10 shows eight points of the high, moderate, and low values of torque at various speed ranges. Table 4 shows the detailed losses and efficiency of the motor of each eight points. Based on the results, point 6 pointed at the lowest iron losses at the lowest speed, 100.00 rpm while point 2 shows the highest value of iron losses which is 29.24 kW at the highest speed which is 1446.20 rpm. However, the average efficiency of this motor is 59.24%. Moreover, Figure 11 shows the overall iron and copper losses for the proposed motor design.

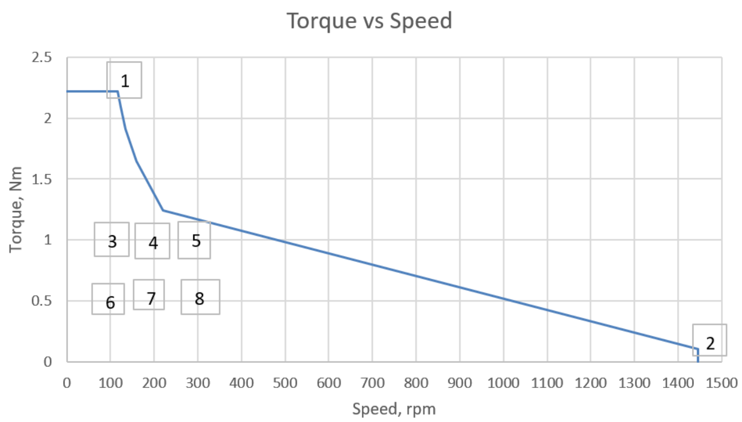


Figure 10: Points under the graph of torque vs speed

Table 4: Details of motor losses and efficiency

Point	1	2	3	4	5	6	7	8
Speed, rpm	116.00	1446.20	100.00	200.00	300.00	100.00	200.00	300.00
Iron losses, kw	10.96	29.20	2.31	2.19	2.57	0.89	0.90	1.46
Copper losses, kW	3296.38	91.57	123.21	123.21	123.21	30.80	30.80	30.80
Efficiency, %	7.21	71.05	44.34	61.46	70.46	61.20	75.93	82.30

Figure 11: Motor losses and efficiency at operating points

4. Conclusion

In this study, an optimal design of a high-speed single-phase FRM was designed and analyzed using JMAG Designer 16.0 software. The design and testing of the high-speed single-phase FRM using JMAG-geometry and designer has been thoroughly outlined in chapters 3 and 4. The performance of the high-speed single-phase FRM was then studied and compared to theoretical data, including flux line and distribution, torque, speed, and power characteristics. The motors have a very simple configuration with a robust rotor and bipolar PMs on the stator, so it can be considered to be a low-cost machine for a high speed and a very low speed. The high cogging torque and flux leakage issues were resolved by reducing the rotor tooth size and pole. The proposed designs also demonstrated that the flux profile for the single-phase armature coils and the EMF profile were sinusoidal, proving the motor's operating principle. Both proposed design were compared in every analysis conducted and design 2 were further analyzed to its efficiency and recorded to achieve better performance. Finally, the design 2 proposed for optimal design of a high-speed single-phase FRM is better suited for use in an Air Blower.

Acknowledgment

The authors would also like to thank the Faculty of Electrical and Electronic Engineering, Universiti Tun Hussein Onn Malaysia for its support.

References

[1] Z. Q. Z. a. D. H. S. Bentouati, "Permanent magnet brushless DC motors for consumer products," in *Ninth International Conference on Electrical Machines and Drives,* Canterbury, Uk, 1999, pp 118-122 doi: 10.1049/cp:19991001..

[2] D. -H. L. a. J. -W. A. K. -I. Jeong, "Characteristic Analysis of a Novel Single-phase Hybrid SRM for Blender Application," in *IEEE Transportation Electrification Conference and Expo, Asia-Pacific (ITEC Asia-Pacific),* Bangkok, Thailand, 2018, pp. 1-5.

[3] V. P. V. K. D. G. Vladimir Dmitrievskii, "Optimum Design of High-Speed Single-Phase Flux Reversal Motor with Reduced Torque Ripple," *Applied Science*, vol. 10, p. 6024, January 2020.

[4] V. P. V. K. S. O. Vladimir Dmitrievskii, "Comparison of High-Speed Single-Phase Flux Reversal Motor and Hybrid Switched Reluctance Motor," in *20th International Symposium on Power Electronics (Ee),* Novi Sad, Serbia, 2019, October 23 - 26.

[5] S. H. W. T. H. K. a. J. L. S. M. I. Ki Bong Jang, "Starting and High-Speed Driving of Single-Phase Flux-Reversal Motor for Vacuum Cleaner," in *IEEE TRANSACTIONS ON MAGNETICS*, Jinju, Korea, 2005 October.

[6] A. D. R. R. R. K. S. Divya Kushwaha, "Study of 8/12 Flux Reversal Machine as an Alternator," Indian Institute of Technology (Banaras Hindu University), Varanasi, India, 2014.

[7] T. W. S. B. K. Kim, "Reduction of cogging torque in flux reversal machine by rotor teeth pairing," *IEEE Transaction on Magnetic,* vol. 10, pp. 3964-3966, 2005.

[8] V. D. V. K. Vladimir Prakht, "Optimal Design of a High-Speed Flux Reversal Motor with Bonded Rare-Earth Permanent Magnets," *Mathematics,* pp. 9, 256, 2021.

[9] S. A. N. I. B. Congxiao Wang, "High Speed Control Scheme of Flux Reversal Machine," in *IEEE,* Timisoara, Romania, 1999.