Evolution in Electrical and Electronic Engineering Vol. 3 No. 1 (2022) 528-536
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EEEE

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

Advancement of a Modular Rotor Permanent Magnet Flux Switching Machine for High Torque Performance

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DOI: https://doi.org/10.30880/eeee.2022.03.01.061
Received 19 January 2022; Accepted 30 May 2022; Available online 30 June 2022

Abstract: There has been recent interest in permanent magnet flux switching machines (PMFSM) that make the rotor simple, robust, and brushless with all flux sources located in the stator. However, some drawbacks of the conventional rotor and stator of PMFSM may reduce the torque and efficiency of the motor due to the flux cancellation, flux leakage and longer flux path in the motor. PMFSM based on the modular rotor is designed and investigated to ensure less use of material while high torque performance using JMAG Designer Version 14.0 software. A local optimization method is used to enhance the performance of modular rotor PMFSM. The performance of the motor has improved as the increase of torque value from an initial 56.98 to 60.28Nm, 77.49% to 82.33% of efficiency while a drop of output power from 5.17kW to 4.42kW and the objective has been achieved.

Keywords: Conventional PMFSM, Optimized PMFSM

1. Introduction

The issue of global warming in the 21st century is a significant public concern today. As stated in [1]-[3], one of the key factors that lead to natural weather is caused by the release of man-made greenhouse gases (GHGs). At present, the most possible solution to overcome this problem to reduce pollution of emissions and achieve high efficiency is the use of electrical vehicles (EV) powered by a battery-charged electric motor [4]. EV is categorized as driver preferences [5].

Flux Switching Machine (FSM) was introduced in 1955 as a single-phase alternator by Rauch and Johnson [6] and three phases by E. Hoang et al [7]. The major type of electric motor under serious consideration for Electric Vehicles is the Flux Switching Machine (FSM). FSM can be divided into three internal different sources namely permanent magnet flux switching motor (PMFSM), field excitation flux switching motor (FEFSM) and hybrid excitation flux switching motor (HEFSM).

The use of Permanent Magnet Flux Switching (PMFS) motor is highly applicable for the application of electric vehicle (EV) [8]. The salient rotor has some drawbacks that may affect the performance of

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**Corresponding author: erwan@uthm.edu.my* the motor such as lower average torque and efficiency. However, 10 pole/12 slots modular rotor PMFSM is designed to handle the limitation. The objectives of this project are to enhance the performance of modular rotor PMFSM, optimize the initial modular rotor structure for optimal torque performance and compare the performance of an initial and optimized motor design. Thus, this project is concerned with the scopes to design the 12S/10P modular rotor PMFSM using JMAG designer with the motor diameter, stack-length and airgap fixed. The local optimization method is used to investigate the performance of the electric motor with each parameter freely adjusted and analyze performance comparison between initial and optimized motor design.

2. Methodology

The methodology of this investigation is executed in detail to complete and simplify the data collection process in a more organized systematic way. A 12 slot 10 rotor pole (12S/10P) number has been designed. In this study, JMAG Designer Version 14.0 software is used to sketch up each part of the modular rotor in 2D finite element analysis (FEA) and to analyze the performance of the modular rotor PMFSM in detail while enhancing modular rotor performance by using local optimization method.

2.1 Design and Performance Analysis of Modular Rotor PMFSM

The first objective of this project can be achieved by designing the 12S/10P modular rotor PMFSM. The initial design the of the proposed design is including the arrangement of the rotor, armature coil permanent magnet and stator. Concept of the E-core stator shape implemented where permanent magnet (PM) inserted in the middle of the stator tooth. In addition, modular rotor shape is used to reduce longer flux path while the increase of torque performance. Figure 1 shows the flowchart of motor design and performance analysis.

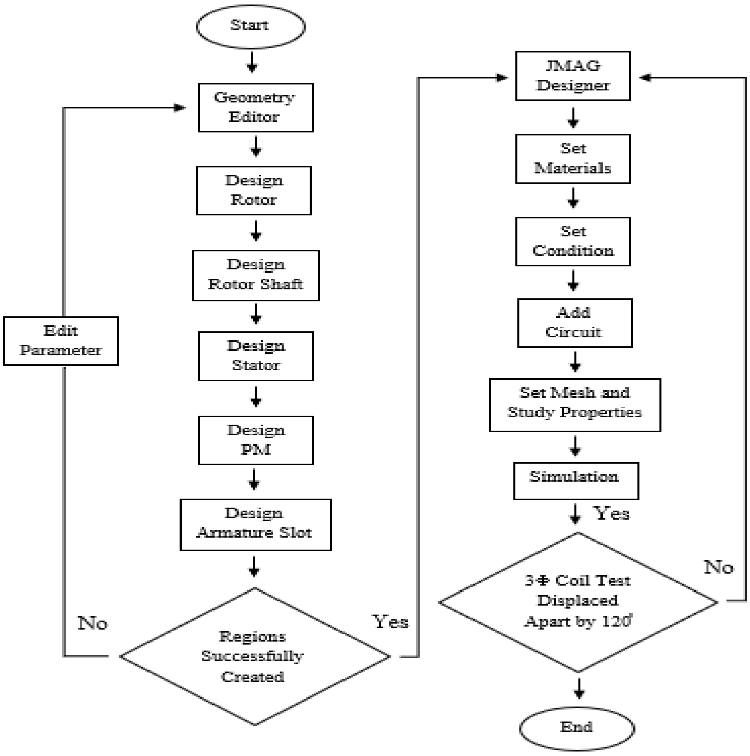

Figure 1: Workflow of motor design and performance analysis

2.2 Optimization of 12S/10P modular rotor PMFSM

The initial design was optimized to obtain the optimum torque and power of the design. The rotor and stator parameters have been labelled as D1 to D10. In this method, the parameter needs to be adjusted using the proposed calculation until achieves the targeted performance. The general flow of the local optimization method is mentioned in Figure 2.

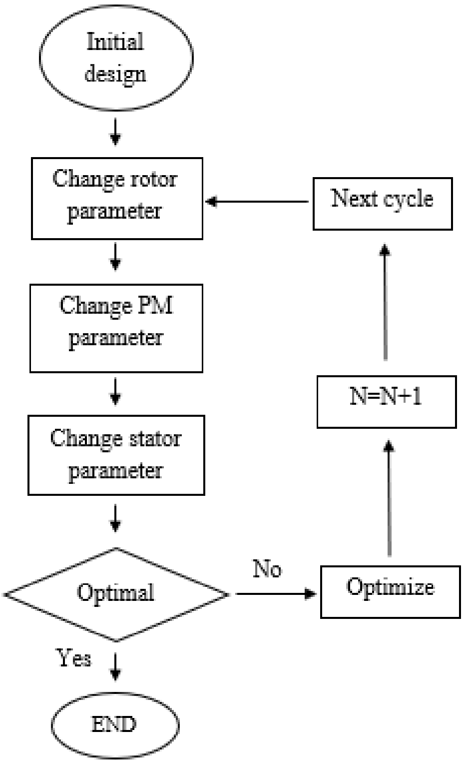

Figure 2: General flow of optimization method

The sensitive parameter of the rotor and stator are labeled as shown in Figure 3. The rotor parts include rotor inner radius (R1), rotor shaft length (R2), rotor pole width (R3), rotor outer radius (R4), rotor segment angle (Θ) and permanent magnet labeled as PM length (R9) and PM width (R10). The airgap and PM weight are fixed by 0.3mm and 0.35kg. Next, the stator parameter is defined as stator pole width (R6), stator middle tooth (R7) and stator outer yoke (R8). The outer stator radius keeps constant at 75mm. All the parameters changed to get the saturated value for optimum torque.

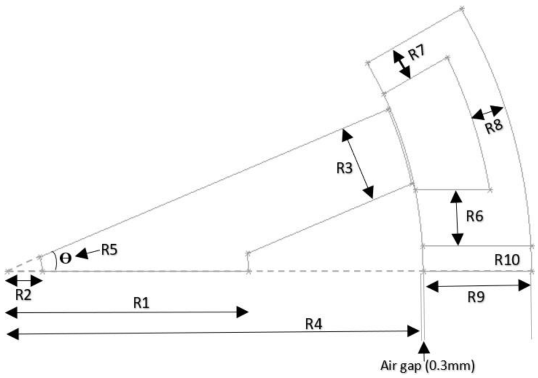

Figure 3: Design parameter for R1 until R10

2.3 Performance Comparison between Initial and Optimized Modular Rotor

This part will discuss the comparison of an initial and optimized modular rotor with E-core topology stored in the stator to reduce longer flux path as well as iron losses. This 10pole/12slot motor is analyzed in different scenarios to know which of the machine can operate in high torque performance. Figure 4 shows the flowchart of the comparison for an initial and optimized model.

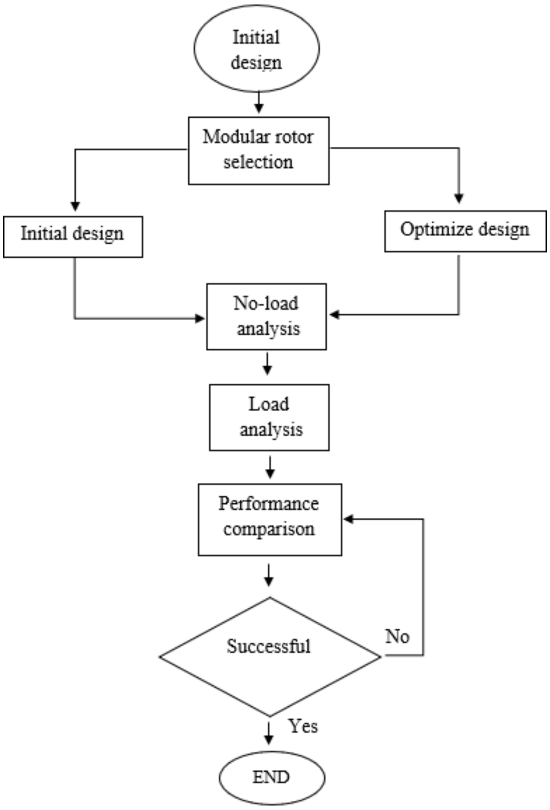

Figure 4: Workflow of design comparison

3. Results and Discussion

The performance of modular rotor PMFSM was analyzed using 2D-FEA package with JMAG Studio version 14.0. The flux pattern and the performance of the model were obtained using two methods which are load and no-load analysis. In the meantime, the local optimization method is applied by changing all the sensitive parameters to achieve the target of high average torque of the modular rotor PMFSM. After achieving the targeted torque on the final cycle of optimization, comparisons between the initial and optimized design are performed to analyze the changes of the motor performance.

3.1 Design and Performance analysis of modular rotor PMFSM

The structure of the modular rotor is made by JMAG software to sketch each part of the design by following the right process until getting the successful machine. The proposed design is separated into four sections (a) modular rotor, (b) 6 numbers of E-core stator, (c) 12 numbers of armature core windings and (d) 6 numbers of permanent magnet shape. Thus, all the parts will be merged with their respective location to construct an initial modular rotor PMFSM design as shown in Figure 5.

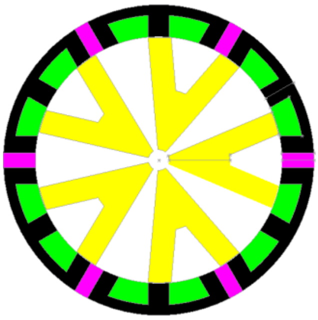

Figure 5: Initial design of modular rotor PMFSM

In the proposed modular rotor PMFSM, this machine has been investigated in terms of average torque against armature current density, J_a. The armature current density varied at 5 – 10 A_{rms}/mm^2 and the results are illustrated in Figure 6. Figure 7 shows the curve of torque and power vs speed of modular rotor PMFSM where the maximum torque is 56.98 Nm and achieves the lowest speed at 866.4 rev/min. However, when the torque reduces from 56.98 Nm - 14.46 Nm, the output power also will reduce from 5.22kW – 2.57kW but the speed will rise to a maximum value at 1697.2 rev/min.

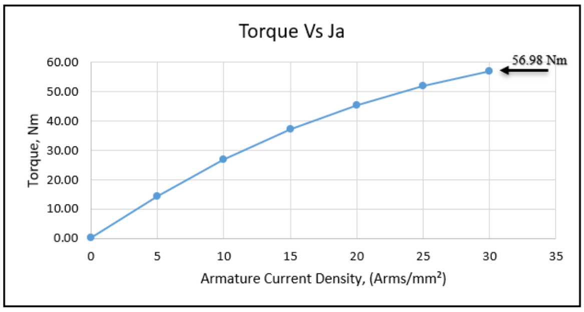

Figure 6: Torque versus J_a

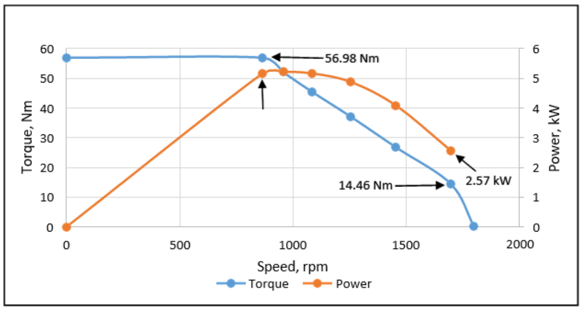

Figure 7: Torque and power vs speed

To enhance the losses and efficiency, 8 different points were selected at different levels of torque between high, middle, and low-level torque as shown in Figure 8. Figure 9 plots the differences between iron losses, copper losses and efficiency of the initial design. The total value of losses and efficiency of initial modular rotor PMFSM are recorded where iron losses in 1759.5W, copper losses at 5090.1W and average efficiency is 77.49%.

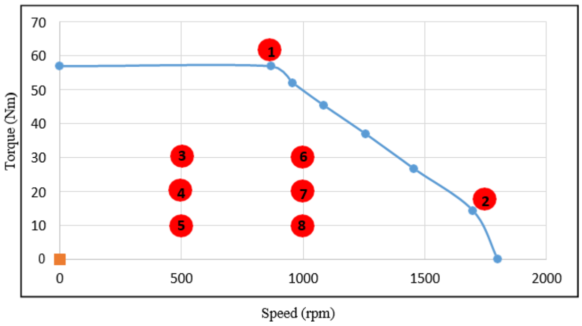

Figure 8: Torque vs speed at different points

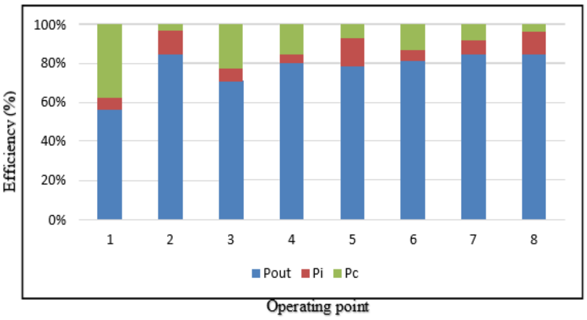

Figure 9: Efficiency and losses of motor

3.2 Optimization of modular rotor PMFSM

The initial 10 pole/12 slot modular rotor design can achieve better performance by using the local optimization method to get higher torque as much as possible. To work on optimized analysis, the parameter of R1, R2, R3, R4, R5, R6, R7, R8, R9 and R10 are adjusted until get the optimum value as stated in the methodology. First, the rotor parameter has been optimized by running cycle by cycle until getting the optimum value with saturated results and the same step is used for the optimization of the stator structure. As shown in Figure 10, the initial design has achieved the maximum torque of 56.98Nm and the torque has increased to 60.28Nm after running the optimization cycle to the motor which means 5.79% of the average torque has increased. Similarly, the armature current density varied at 30 $Arms/mm^2$ as the maximum torque of the Optimized design is 60.28Nm and the speed of the motor was reduced at 699.5 rev/min while the power reduced from 5.17kW to 4.42kW as shown in Figure 11.

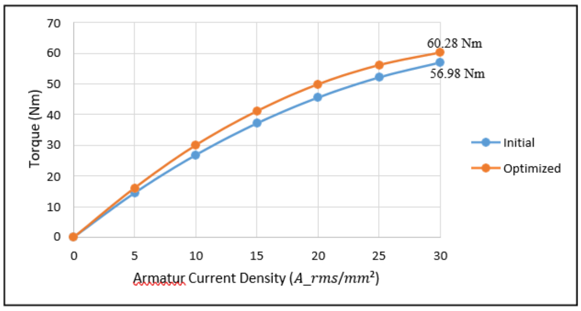

Figure 10: Torque versus Ja

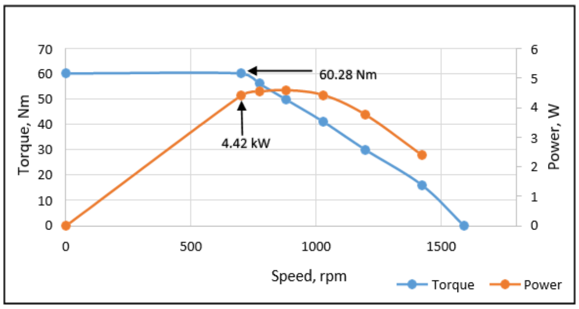

Figure 11: Torque and power vs speed

The losses and efficiency were investigated at 8 operating points based on high, frequent, and low-speed performance. Figure 12 shows that the starting speed at point 1 is 699.55rpm which is the lowest speed among other points and achieved the highest torque at 60.28Nm. However, the comparison graph of the iron losses and copper losses for rotor and stator are plotted in Figure 13. The results show that the highest losses for both iron and copper were recorded at point 1 with 81.62% of efficiency. Overall, the efficiency of optimized design is higher than the initial design of modular rotor PMFSM where efficiency before the optimization is 77.49 % and after optimization is 82.83%. The detailed value of the initial and optimized design is shown in Table 1.

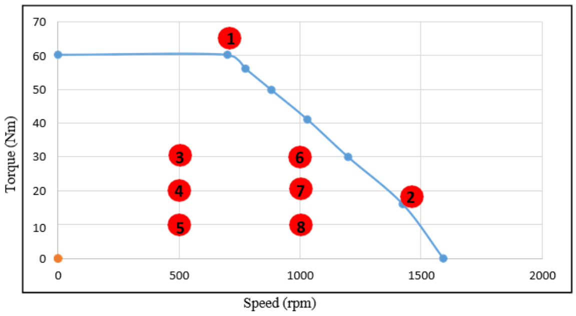

Figure 12: Torque vs speed at different points

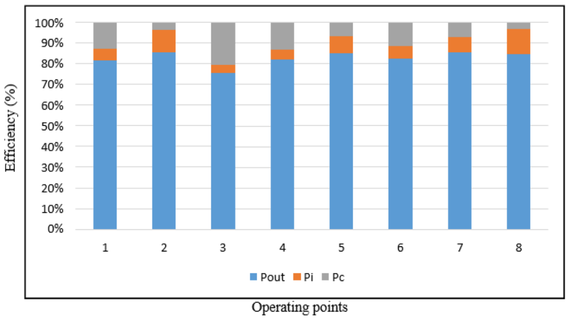

Figure 13: Efficiency and losses of the motor

Table 1: Motor Losses and Efficiency for Initial and Optimized Design

Type of Machine	Operates Point	Speed, rpm	Output Power, kW	Iron Loss, kW	Copper Loss, kW	Efficiency, %
Initial	1	866.40	5169.45	550.50	3469.03	56.26
	2	1697.20	2570.00	371.04	96.36	84.61
	3	500	1570.80	136.22	509.75	70.86
	4	500	1047.20	59.14	205.41	79.83
	5	500	523.60	97.01	47.22	78.40
	6	1000	3141.59	219.92	509.75	81.15
	7	1000	2094.40	177.05	205.41	84.56
	8	1000	1047.20	148.57	47.22	84.25
	Total		17164.23	1759.4	5090.14	
					Average	**77.49%**
Optimize	1	699.55	4416.20	300.00	694.45	81.62
	2	1422.4	2400.86	295.19	107.25	85.64
	3	500	1570.80	79.39	428.99	75.55
	4	500	1047.20	61.11	170.27	81.90
	5	500	523.60	49.55	41.23	85.22
	6	1000	3141.59	237.06	428.99	82.51
	7	1000	2094.40	183.06	170.27	85.57
	8	1000	1047.20	148.78	41.23	84.64
	Total		16241.83	1354.1	2082.67	
					Average	**82.83%**

3.3 Overall performance comparison between initial and optimized model

The performance analysis of the initial and optimized design of modular rotor PMFSM is investigated using 2D FEA. After the initial rotor and stator radius of the proposed motor are analyzed, the new structure of modular rotor parameters has been performed when working with the optimized process. As can see in Table 2, the rotor radius has been updated for the inner radius from 34.5mm-40.5mm but the rotor pole width and outer radius.

Table 2: Comparison parameters of initial and optimized modular rotor

Parameters	Details	Initial	Optimized
R1	Rotor Inner Radius (mm)	34.5	40.5
R2	Shaft Radius (mm)	5	5
R3	Rotor Pole Width (mm)	11.1	10.4
R4	Rotor Outer Radius	59.2	57.2
R5	Span Angle (°)	23	23
R6	Stator Pole Width (mm)	9	8.8
R7	Stator Middle Tooth (mm)	5	4.7
R8	Stator Outer Yoke (mm)	70	69.5
R9	PM Height (mm)	15.5	17.5
R10	PM Width (mm)	7.1	6.3
ag	Airgap	0.3	0.3

To enhance the performance of the initial and optimized 10pole/12slot modular rotor PMFSM, the current density is injected into the motor to investigate the changes in torque, power and more. From the results obtained, the output torque of the optimized motor has increased from an initial value of 50.98Nm to 60.28Nm and the output power has been reduced from 5.17kW to 4.42kW respectively when the current density is injected at 30 $Arms/mm^2$. Furthermore, the high efficiency of the machine model has been overcome by the optimized method where the proposed motor efficiency is 77.49% and 82.83% for the optimized motor decreased from 11.1mm-10.4mm and 59.2-57.2 respectively. While stator pole width, middle tooth and outer yoke reduced from 9mm-8.8mm, 5mm-4.7mm and 70mm-69.5mm respectively. Table 3 shows the performance comparison of the initial and optimized motor.

Table 3: Performance comparison of the initial and optimized model

Parameters	Unit	Initial	Optimized
Cogging Torque	wb	21	5
Average Torque	Nm	56.98	60.28
Output Power	kW	5.17	4.42
Speed	rpm	866.4	699.5
Efficiency	%	77.49	82.33
PM Weight	kg	0.35	0.35

4. Conclusion

In this paper, electric vehicle (EV) is a key factor in reducing the pollution of emissions. To choose the best candidate for FSM, a permanent magnet flux switching machine based on a modular rotor was designed. The analysis had taken to investigate the performance of 10 poles and 12 stator slots of modular rotor design by testing three-phase coil testing using JMAG Designer version 14 software. The proposed motor produced a sinusoidal sine wave at 120° shifted while following the principle of 3 phase waveform.

Under short circuit analysis, the highest average torque achieved 56.98 Nm in the initial design while 60.28Nm for optimized design when the highest armature current density was injected into the motor. The power of the motor in optimized condition was recorded at 4.22kW while efficiency at 82.83%.

Acknowledgement

The authors would like to thank the Faculty of Electrical and Electronic Engineering (FKEE) and University Tun Hussein Onn Malaysia (UTHM)for providing me guidance, knowledge and support throughout this research.

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