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Advancement of Modular Rotor Permanent Magnet Flux Switching Motor Using Local Optimization Approach

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ABSTRACT

Electric motor performance bound on torque which is the amount of turning power. This element overcomes inertia and sustains acceleration during long distance travel operation for vehicles. High torque motors have the benefit of fast performance response. Permanent magnet flux switching machine (PMFSM) has become a prominent research topic for various applications due to high torque and power capabilities. This paper presents the improved design structure of three phase 12S-10P modular rotor permanent magnet flux switching motor for optimum torque. The initial design structure generated of 34.44Nm which is considered low in maintaining fast response driving operation. Local optimization approach is used to treat design parameters to achieve the optimum output torque. As a result, the modular rotor PMFSM with 0.35kg PM can get optimum torque of 60.49Nm and output power of 23.34kW. This result demonstrates and validates permanent FSM magnet with modular rotor as a viable candidate for optimum torque capable of maintaining long driving acceleration.

Key words : Flux Switching, Local optimization, Modular rotor, Optimum torque

1. INTRODUCTION

Flux switching motor (FSM) has simple design structures with two fully pitched windings located on stator, which are classified as field windings and armature winding. It is similar to that used in inductor alternator with no winding on the rotor and the lamination profile similar to switched reluctance motor, which is a doubly salient machine with independent phase winding on the stator and solid laminated rotor [1-2]Over the past decade, several topologies of Flux switching machines (FSM) have been developed for different applications, such as automotive, domestic appliances, aerospace etc. FSM can be divided into three groups: Permanent magnet (PM) FSM, Field Excitation (FE)FSM and Hybrid Excitation (HE).The main source of flux of FSM are permanent magnet and field winding in PMFSM and FEFSM while the flux provided in HEFSM is by both field winding and permanent magnet[3-8].

Based on literature, Rauch and Johnson introduced the first PMFSM as a single-phase alternator in 1955[9-10] and subsequently received significant attention, especially in the application of electric force systems. In the meantime, the first introduced by Hoang *et al.*, in 1997[11].However, onventional design shown in Figure 1 is receiving the drawbacks of high volume PM. From then on, variety of PMSFM designs have been introduced. For reducing the number of PM consumption, the stator poles are substituted alternately by a simple stator tooth and consequently the new E-core is established [12-15] as shown in Figure 2. But there are some drawbacks that reduce the torque and efficiency of the E-core motor, such as flux cancellation and flux leakage [16].

Therefore, to deal with all above mentioned limitations, novel configuration of PMFSM based on modular rotor is proposed that will ensure less use of materials is proposed for lightweight electric vehicle.

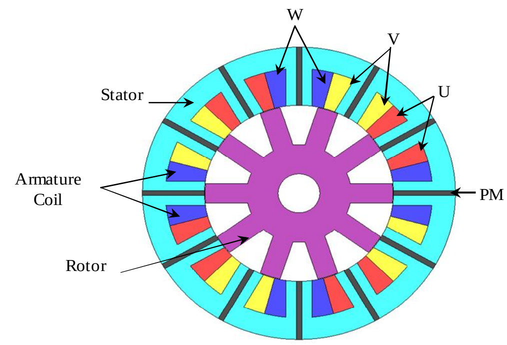

Figure 1: 12S-10P Conventional PMFSM Topologies

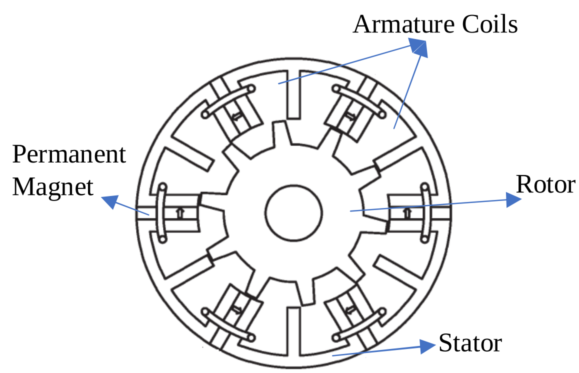

Figure 2:E-Core Permanent Magnet FSM Topologies

The objective of this paper is to improve the initial design structure with higher magnetic loading in order to optimize its performance with optimum torque, while designing the proposed motor with less materials and at low cost. Figure 3(a) shows the initial design of three phase 12S/10P modular rotor PPMFSM in which the stationary stator comprises of both the winding conductor and the flux source. The conductor is alternately wound on stator tooth on 12number of poles while the permanent magnet flux source of 0.35kg mass is mounted alternately on the tip of the remaining 12stator teeth [17].

2.OPTIMIZATION OF 12S/10P MODULAR ROTOR PMFSM

The performance analysis of initial structures of modular rotor PMFMS with 12slot-10 pole is analyzed comprehensively in the previous section. Initial design of 12S/10P modular rotor PMFSM achieved an average torque value of 34.44 Nm, which was affected by design, material and assembly, the size of motor needed to generate higher average torque under the same electric loading restrictions. Therefore, the initial design of modular rotor PMFSM have to be optimized to achieve the optimum average torque.

Many optimization methods have been proposed for motor design to improve performance. They are grouped under deterministic and heuristic methods. Heuristic approach includes Global Algorithms (GA) and Particle Swarm Optimization (PSO), and they are used because of their faster searching ability[18-20].However, they pose challenges because it is difficult for incremental variation of motor radius and armature slot. The initial and optimized design dimensions of the proposed motor, 12S/10P modular rotor PMFSM is shown in Figure 3.

The design specifications for the motor under this study are as defined in Table 1. The parameters of the initial design have been selected according to outer stator radius which is approximately 85% of the total motor radius. Moreover, the current density is limited to 30 A_{rms}/mm^2 for the armature coils. Diameter of the motor, and shaft diameter of the objective motor are 150mm, 70mm, and 60mm, respectively. The 2D finite element analysis has employed. Neomax-35AH material is used for permanent magnet having the residual flux density and coercive force at 20^{O}C are 1.2T and 932kA/m, but for the stator and rotor parts the electrical steel 35H210 is used. Additionally, the external rotor shaft is material of aluminum employed to secure the segmented rotor .

2.1 Performance of optimized Modular rotor PMFSM

First of all, rotor was optimized for modular PMFSM machine until rotor reached saturation point than stator was optimized. Seven cycles of local optimization were conducted for rotor only and two cycles of stator were conducted as shown in Figure 3(b) with optimum average torque achieved with cycle 6 of rotor and cycle 1 for stator. In cycle 7, the average torque is seen begin reducing in value. Therefore, details performance of the optimized 12S/10P modular rotor PMFSM is described.

2.2Torque performance at armature current density

The torque capability of the optimized design 12S/10P modular rotor PMFSM is analyzed with the PM and armature current density J_a varied from 0 A_{rms}/mm^2-30 A_{rms}/mm^2, respectively. From the plot shown in Figure 4, it is seen that with increase in the current value, output torque increases but the changing torque will be decreasing gradually.

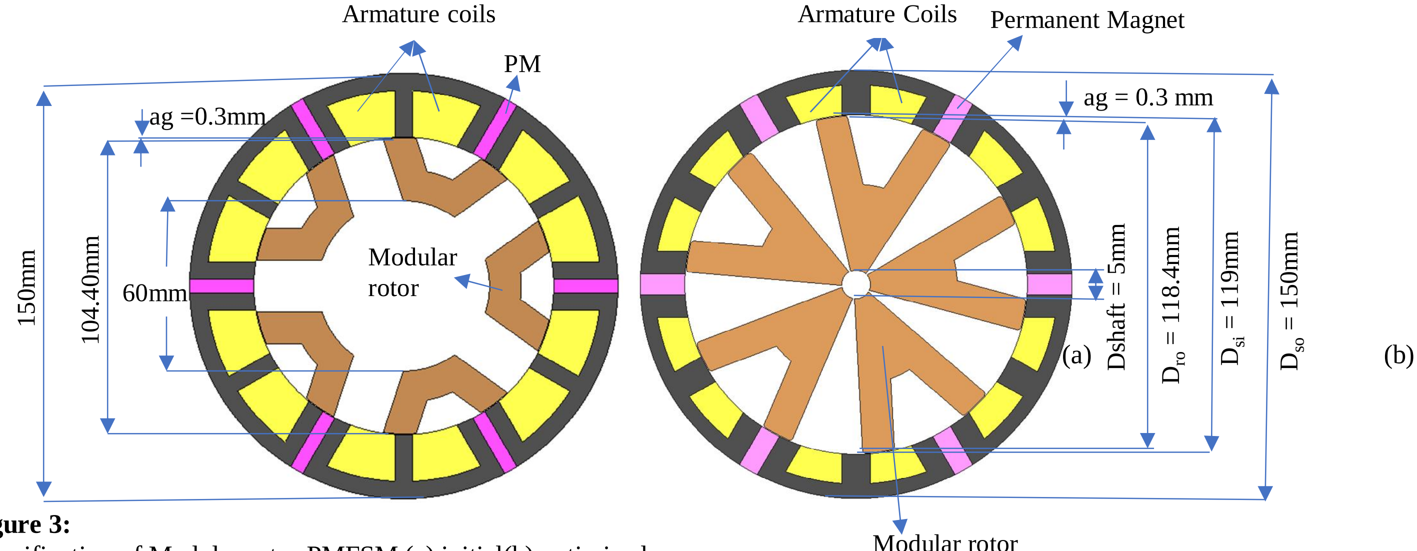

Figure 3:
Specification of Modular rotor PMFSM (a) initial(b) optimized

Table 1: Initial and final design parameters of 12S-10P Modular rotor PMFSM

Parameter	Initial	Final
PM volume (kg)	0.35	0.35
Shaft radius (mm)	30	5
Rotor radius (mm)	52.20	59.20
Rotor pole height (mm)	12.34	24.74
Rotor pole width (mm)	11.10	11.13
PM height (mm)	22.5	15.5
Stator outer core thickness (mm)	6	5
Stator pole width (mm)	16.52	5
Armature coil depth (mm)	6	8
PM width (mm)	4.9	7.1
Segment pole angle	36°	23°
Air gap length (mm)	0.3	0.3

The output torque increase is not linearly proportional with increase in current value due to saturation effect. It is obvious that when the motor is injected with J_a 0 A_{rms}/mm^2 - 5 A_{rms}/mm^2, the output torque is increased from 0 -14.943 Nm. However, when J_a is increased from 5A_{rms}/mm^2 - 10 A_{rms}/mm^2 an additional torque value 13.135 Nm is generated. Further current values of 10 A_{rms}/mm^2 -15 A_{rms}/mm^2 generated additional torque value of 10.9431 Nm while 15 A_{rms}/mm^2 - 20 A_{rms}/mm^2, 20 A_{rms}/mm^2 - 25 A_{rms}/mm^2 and 25 A_{rms}/mm^2 - 30 A_{rms}/mm^2 generated decreasing torque values of 9.049 Nm, 7.165 Nm and 5.254 Nm with high current. The reason for increase in average torque in the optimized design is rotor radius and stator pole width are increased which provides enough permeance for flux to flow through. The design of three-phase 12S/10P modular rotor PMFSM has therefore achieved an optimum average torque of 60.49 Nm

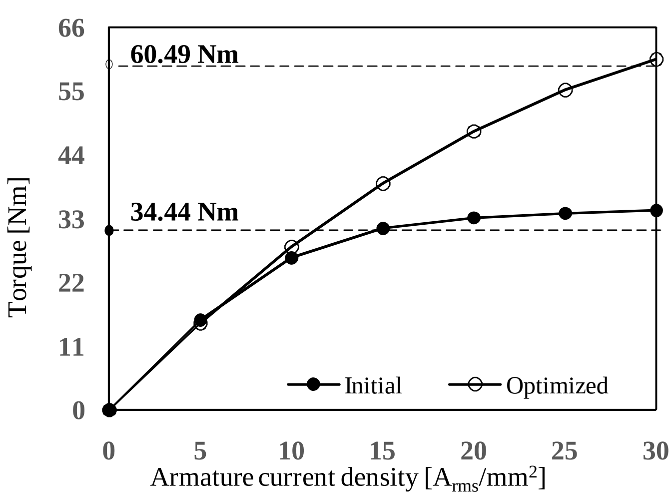

Figure 4: Torque performance at various armature current density Ja

2.3 Torque and power versus speed characteristics

Figure 5 illustrates the plot of the output torque against the speed characteristics in which, at the base speed of 3737.69 rev/min, maximum torque of 60.49 Nm is achieved with the maximum armature current density J_a (30A_{rms}/mm^2). It is seen that when the motor is operated beyond the base speed, the torque begins to reduce due to low volumetric efficiency arising from the saturation. Meanwhile, at the lowest torque of 6.71 Nm, the highest speed of 13090.59 rev/min is achieved. Similarly, the plot of average torque and power of the optimized design is presented in Figure 6. From the plot, it is seen that the motor generated an output power of 23.34 kW at the maximum torque. However, the power is seen to remain constant throughout the entire torque region because the supplied voltage and frequency had remained in their boundaries. Meanwhile, there is an obvious power ripple at the maximum power due to residual periodic variation in the supply voltage. Nonetheless, there is an enormous gain in terms of torque in the optimized design than the initial design which achieved an output power of approximately 7.67 kW.

Losses in the proposed motor include iron and copper losses that were calculated by 2D-FEA, as illustrated. Under the load driving scenarios, the losses and efficiency of the optimized design, designated as points 1 to 8, were chosen under high, moderate, and low torques at different speed ranges to determine the losses. It is clear from point1 that it achieved the highest torque at the lowest speed with the highest copper loss of about 3.3 kW because it was injected with maximum armature current density J_a. Other points recorded low copper loss due to low current values. At point 1 condition, the efficiency is 82.62 %. Meanwhile, at point 2, with low Ja of 3.3 A_{rms}/mm^2 under high speed operation, the highest iron loss is recorded, resulting in an efficiency of 69.86%. Points 3 to 8 (moderate torque and medium speed), which were injected with various J_a values, produced efficiency performance ranging from 86.69 % to 82.14 %.The corresponding output power, iron loss, copper loss and motor efficiency at each operating point is illustrated in Figure 7. Additionally, the copper loss in the armature coil and the iron loss in both the stator and the rotor are illustrated in Figure 8. It can be noticed from the plot that when the speed increased, the iron loss in the stator and the rotor also increased. The efficiency achieved at operating point 1 is 82.63 % due to high copper and iron losses as illustrated in Figure 9. Meanwhile, average efficiency of the optimized motor is recorded to be 81.49%. Meanwhile, the summarize losses investigation and motor efficiencies of the initial and improvised model are summarized in Table 2 correspondingly.

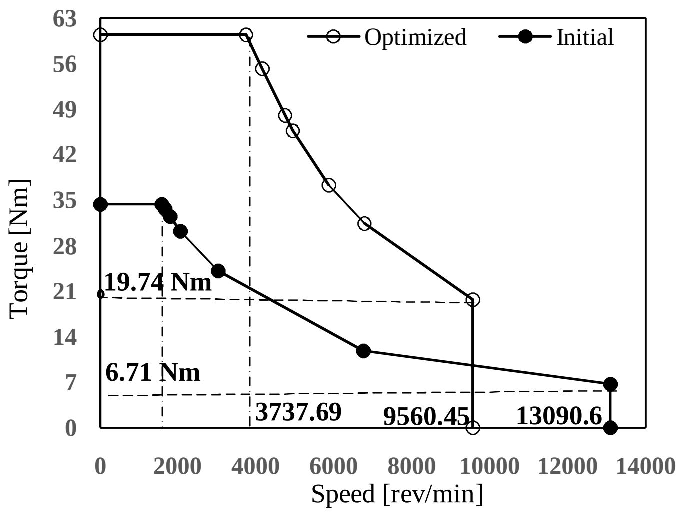

Figure 5: Torque versus speed characteristics of Modular rotor PMFSM

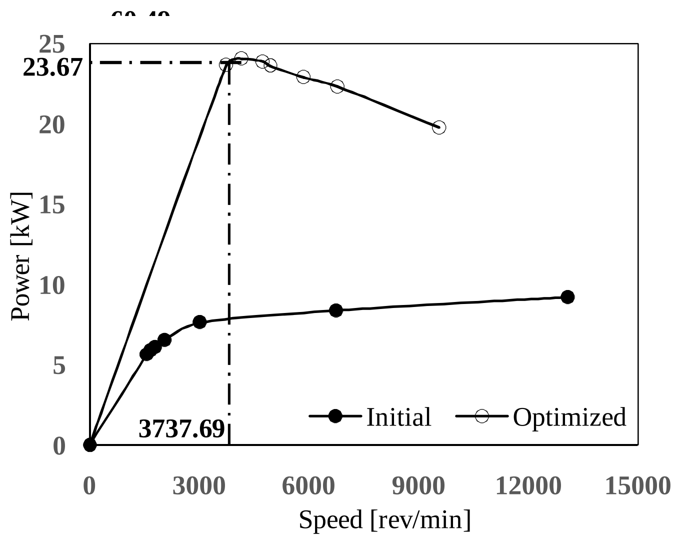

Figure 6: Power versus speed characteristics of Modular rotor PMFSM

5. CONCLUSION

This paper has presented the performance of an improve design of modular rotor PMFSM for high torque applications. Initial design achieved a low output torque which is considered not suitable to sustain acceleration. Whereas, the initial design generated toque of 34.44Nm. local optimization technique is employed to obtain the optimum torque. The improved design generated an optimum output torque of 60.49Nm with a increase of 26.05Nm. the 2D finite element analysis employed JMAG designer in simulation and performance analysis in terms of output torque, output power, torque, power and speed characteristics, copper, and iron losses. Obviously, improved designs have many gains such as high output torque and output power, reduce iron losses. In conclusion, the goal of this research is to get the maximum performances under some restrictions and specifications for high torque applications is successfully achieved.

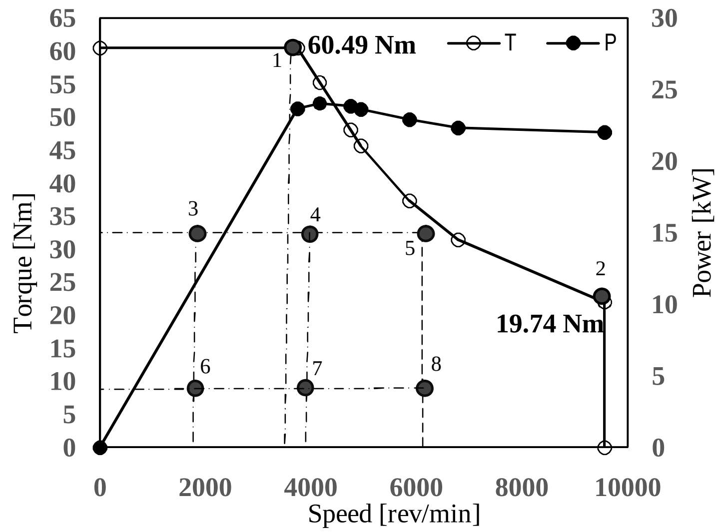

Figure 7: Torque and power versus speed of optimized design at specific operating points

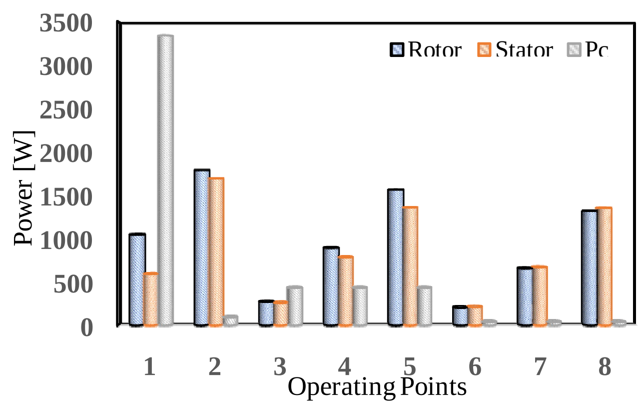

Figure 8: Iron loss and copper loss at various points

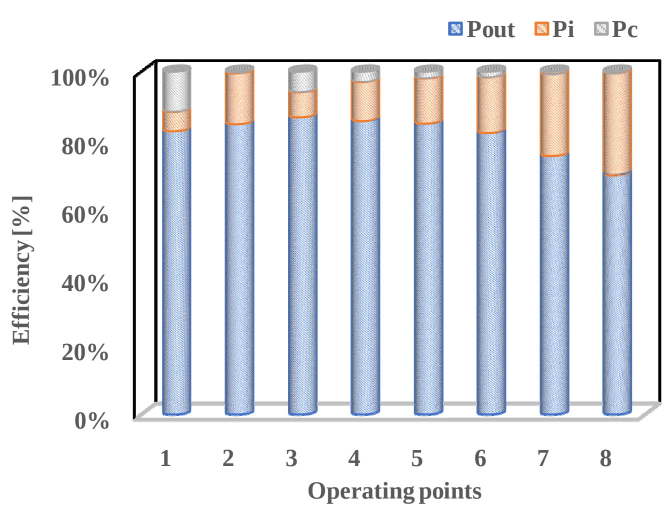

Figure 9: Efficiency and motor losses at operating points

Table 2: Detailed losses and efficiencies for initial and optimized design

Machine Modelling	Operating Points	Speed (rev/min)	Output Power (W)	Iron Loss (W)	Copper Loss (W)	Efficiency (%)
Initial	1	1572.952	5672.928	481.9189	6411.301	45.14
	2	13090.6	9204.157	2594.836	178.0917	76.84
	3	1000	1570.796	93.73941	164.1293	85.89
	4	3000	4712.389	546.1854	164.1293	86.90
	5	5000	7853.982	1297.39	164.1293	84.31
	6	1000	523.5988	68.15593	16.02825	86.14
	7	3000	1570.796	432.2566	16.02825	77.79
	8	5000	2617.994	1116.045	16.02825	69.81
Overall			33726.64	6630.527	7129.865	**76.61**
Optimized	1	3737.69	23676.77	1638.509	3339.71	82.62
	2	9560.456	19771.59	3482.005	92.76972	84.68
	3	2000	6283.185	531.8218	432.8264	86.69
	4	4000	12566.37	1677.397	432.8264	85.62
	5	6000	18849.56	2922.929	432.8264	84.88
	6	2000	2094.395	415.006	40.41049	82.13
	7	4000	4188.79	1324.843	40.41049	75.41
	8	6000	6283.185	2670.225	40.41049	69.86
Overall			93713.85	14662.73	4852.19	**81.49**

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