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High Torque Flux Switching Permanent Magnet Machine in Segmented Outer Rotor using Appropriate Split Ratio for Electric Scooter Propulsion

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ABSTRACT

Recently, permanent magnet synchronous machine (PMSM) having the diameter of 11inches was successfully developed and installed in electric scooter vehicle (ESV) for propulsion. It consists of segmented stators of 24 armature slots and 100 pieces of permanent magnet of 2 kg weight mounted on rotating rotor. Upon the huge amount of materials and permanent magnet used, PMSM produced 110Nm only. Looking at the size, this torque is low and could not sustain acceleration for long distance travels. To overcome the challenge of low torque, this paper presents a new machine type, flux switching motor (FSM) with 1 kg weight of permanent magnet flux source employing segmented outer rotor. Six ranges of split ratio of 0.80-0.85 for outer rotor 24slot-14pole FSPM motor configurations were designed and compared. The 2D-FEA by JMAG software version 14 is used to examine its performance in term of flux linkage, cogging torque, back-emf and average torque which the structure with split ratio of 0.85 took lead by securing highest torque profile of 209Nm. It also achieved low cogging torque to operate in safe region. In conclusion, appropriate split ratio significantly enhances high torque capability of permanent magnet flux switching motor for electric scooter propulsion.

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1. INTRODUCTION

Electric scooter vehicles (ESVs) have been developed as personal and efficient means of road transportation propelled by electric motor. These motors are powered by electricity stored in rechargeable battery. ESVs have the advantage of convenient parking, environmental friendly operation and no noise. While, there are many types of electric motors, permanent magnet synchronous motor (PMSM) has been installed in ESV with an average toque of 110 Nm [1]. Permanent magnet motors (PMMs) have been popular for traction vehicle drive because; it ensures loss-free excitation and eliminates the complications of external electric circuit connections. Moreover, permanent magnet motors have high torque and high efficiency [2]-[4]. Typically, permanent magnet synchronous motor utilizes so much mass of 2 kg permanent magnet (PM) making its construction fragile and market price very expensive. Unfortunately, the performance of PMSM is low because rotating weighty PMs are mounted rotor as shown in Figure 1. ESV is a two and three brand of electric vehicle have attracted high demands worldwide [5]. For now, performance of PMSM needs to be improved in terms of torque to sustain acceleration for long distance travels. To overcome the challenges associated with PMSM, this paper presents a permanent magnet flux switching motor (FSM) employing segmented outer rotor in which all active parts of armature winding and permanent magnet flux source are located on the stationary stator leaving the rotating rotor passive to contain with rotation for optimum performance [6]. This machine uses less materials for its construction, making its construction cost low. FSM has three kinds arising from excitation sources such as flux switching permanent magnet machine (FSPMM) whose source of excitation is PM, field excitation flux switching machine with field excitation coil (FEFSM) and hybrid excitation flux switching machine (HEFSM) which employs both PM and FE as main source and secondary source respectively [7]-[9]. Due to its loss-free source of excitation, the choice of FSPM motor is adopted for ESV application. Furthermore, the rotary component of electric motor, the rotor is classified into toothed or salient and segmented rotor respectively. This proposed motor is designed using segmented outer rotor while PMSM employed cylindrical/round rotor type. Segmented rotor has been used in the past in inner structure machine and its performance was excellent [10]-[12]. However, it appears that transiting this to the outer structure posed challenges of securing the rotor segments without adding an excessive amount of inactive material [13]. The objective of this design is to properly secure these rotating segments while ensuring optimum performance in terms of high torque that matches size of 11 inches. Figure 2 illustrates the growth demand of ESVs from 2014 - 2024 [5].

There are numerous advantages for employing segmented rotor in PMFSM such as short flux path and shorter end windings thus significantly increasing the saliency ratio compared to using toothed rotors and in a similar effect to the application of flux barriers [14]. Furthermore, each armature stator tooth experiences bipolar flux and effectively increases the magnetic loading capability in the magnetic structure because the flux undergoes the flux change compared to a design for unipolar flux [15]. More still, the use of segmented rotor with PMs requires single tooth armature windings which secures the ruggedness of its motor for every application.

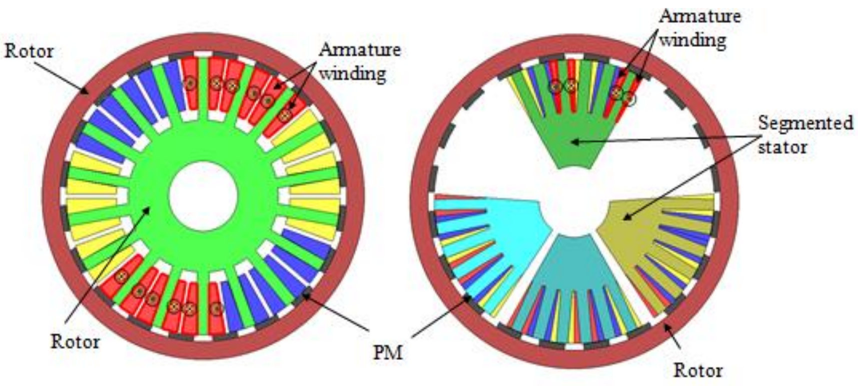

Figure 1. Examples of three-phase PMSM (a) Toothed stator (b) Segmented stator

Figure 2. Brands demand of electric scooters [5]

2. DESIGN REQUIREMENTS, RESTRICTION AND SPECIFICATIONS

Design specification and requirements of the 24SSlot-14pole FSPM motor understudy for ESV are the same with conventional PMSM [1]. Every electrical restriction related with inverter are as listed in Table 1. The limit of armature current density is set at 30Arms/mm2 for the armature coils. The target torque of the proposed motor is set to be much more than 110Nm with the output power more than 6kW. The rotor structure is segmented and secured using external shaft made of aluminium. The Commercial 2D-FEA Software package, JMAG released by Japanese Research Institute (JRI) is used for the design. Figure 3 shows cross-sections of three-phase design of FSPM motor employing segmented rotor having 12 armature coils with four set of windings and 12 PMs flux source alternately placed on the stator tooth in radial magnetizing direction.

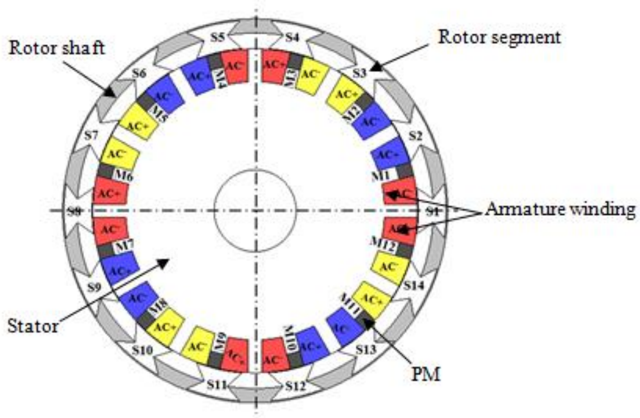

Figure 3. Cross sections of 24 slot-14pole FSPM motor (Outer rotor)

Table 1. Machine Specifications and Restrictions

Parameter descriptions	Outer rotor PMSM	Segmented outer rotor FSPM motor
Diameter of motor (mm)	297.4	297.4
No. of phase	3	3
Type of rotor	Cylindrical/round	Segmented
No. of rotor pole	100	14
Type of pole	Toothed	Segmented
No. of stator pole	18	12
Type of stator	Segmented	Toothed
Air- gap length (mm)	0.5	0.5
Stack length	100	100
DC. voltage inverter (V)	415	415
Inverter current (A_{rms})	360	360
Armature slot area (mm^2)	NA	432
Location of active parts	Stator/rotor	Stator
No. of conductor	18	18
Average torque (Nm)	110	>>>110
Power output (kW)	6	>>>6
Speed of motor (km/hr.)	1900	1900

2.1. Design of the Segmented Rotor

The choice of an unconventional rotor segment for the proposed FSPM motor is necessary to reduce manufacturing cost, lowering iron loss while achieving high flux linkage and high torque capability. It is on record that rotor segment exhibits good receptacle of the flux at the air gap periphery with pole depth being in relation to the width and span for useful working flux density to subsist in the segment core [16]-[17]. For speed operation, external rotor shaft is useful for rotor retainment. Figure 4 illustrates segmented shapes considered for outer rotor configuration. Segment shape in Figure 4 (a) shows the geometry employed in field wound flux switching machine (FWFSM) [13]. However, this design has drawbacks ranging from lack of employment of external rotor shaft. Therefore, this machine understudy, adopts a new design with modifications for rotor retainment as shown in Figure 4(b). Geometric design follows the relationship between rotor segment span angle and rotor tooth width and is similar to segment of a circle to length of arc given in Equation (1):

$$\theta = \frac{180 \, x \, \text{rotor tooth width radius(mm)}}{\pi \, x \, \text{inner rotor radius(mm)}} \tag{1}$$

Figure 4. Rotor segments under consideration

2.2. Split Ratio Analysis

Split ratio, which is the ratio of dimension of two main components of electric machine namely; stator and rotor respectively [18]. Specifically, in outer rotor machines, the ratio of stator external radius to rotor external radius is necessary to be improved since it fundamentally impacts torque output profile [19]. At initial stage, six different ranges of split ratios of 0.80-0.85 were designed and compared which implies the stator possessed 80%-85% of each machine size according to outer rotor design principle [20]. The highest value of torque is accomplished when the ratio is set at 0.85 as shown in Figure 5. Therefore, appropriate dimension of outer stator and corresponding rotor is required. The highest torque for the initial design is achieved with split ratio of 85% (0.85), thus it is selected as the appropriate stator to rotor design dimension.

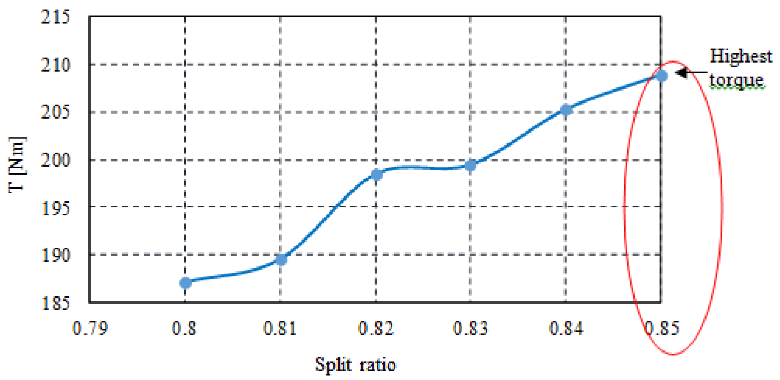

Figure 5. Torque versus split ratio comparison

3. NO-LOAD ANALYSIS

Under no-load analysis test, armature current density Ja value will be set Ja =0 Arms/mm2 while PM flux linkage is remaining constant throughout the paper. As a result, the maximum generated flux lines and flux distribution in the motor, cogging torque, and induced emf are comprehension examined.

3.1. Coil Arrangement Test

The purpose of coil arrangement is to set the correct position of each armature coil and validating the operation FSPM motor. First of all, all windings are set in clockwise direction while no current was injected except the excitation flux from the PM. By comparing the flux linkage of each armature coil which must be 120 degrees apart making three-phase balance system as U, V and W phases. These have been combined as shown in Figure 6.

3.2. Cogging Torque

Cogging torque is the unwanted torque that causes noise and makes machine to vibrate during motor operation if it exceeds the acceptable range. The FSPM motor for pure electric scooter propulsion should build a torque on the rotor which is expressed in Equation (2). Meanwhile, the acceptable range of cogging torque for machine safe operation must not exceed 10% of the average torque [21]. Figure 7 presents the cogging torque peak-to-peak of the motor understudy generated by the PM at the rotation of 25 electrical degrees having six electrical cycles. However, this torque value is expected to reduce during design improvement and optimization.

$$T = T_{avg} + T_{cogg} \tag{2}$$

where, T_{avg} and T_{cogg} are the average generated torque and related cogging torque respectively. It is necessary to specify that energy alteration inside the electric motor created by the movement of rotor results cogging torque.

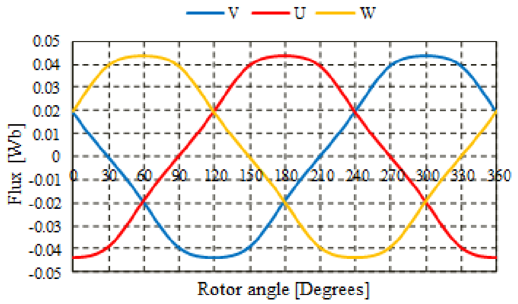

Figure 6. Three-phase 24slot-14pole magnetic flux linkage produced by the PM

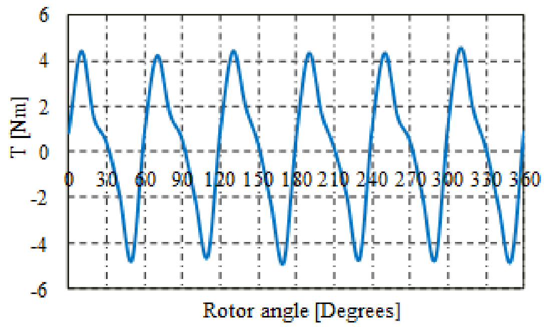

Figure 7. Cogging torque of 24slot-14pole FSPM Motor

3.3. Flux Lines and distribution

Another load-analysis for examination are flux lines and flux distribution for proposed 24slot-14pole FSPM motor. The impression behind flux lines is to monitor the flow of flux, while flux distribution reflects the influence of flux capacity and saturation in the motor. It is shown from Figure 8 that the flux lines make short tour from the inner stator tooth to outer rotor pole, link with it and back into the next stator tooth pole and making a bipolar flux linkage and completing full cycle. In the same vein, flux is seen to be distributed throughout the stator teeth and rotor which causes high flux linkage and flux density of 2.28T.

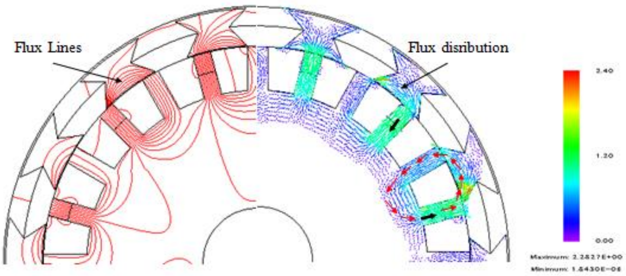

Figure 8. Flux lines and flux distribution of 24slots-14pole FSPM motor

3.4. Induced Back-Emf

The term induced back-emf, is the voltage that occurs in electric motors where there is relative motion between the armature of the motor and the magnetic field from the motor's field magnets, or windings**.** This voltage so produced opposes the current flowing through the coil, when the armature rotates. For 24slot-14pole FSPM motor understudy, PM generated induced voltages with the speed of 1900rev/min under open circuit condition is illustrated in Figure 9. It has the amplitude of roughly 210.V laded with harmonics which will be improved in design refinement and optimization.

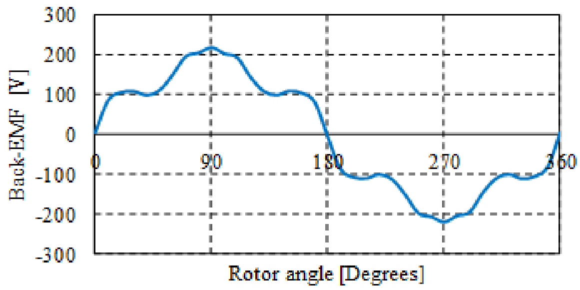

Figure 9. Induced back-EMF of 24slot-14pole FSPM motor

4. LOAD ANALYSIS

Under load analysis, the current density is injected into the armature coil and varied from J_a of 5A/mm^2 to maximum value of 30A/mm^2 to examine torque and speed characteristics. Furthermore, the computation of torque and power and finally, the efficiency of motor.

4.1. Torque at Various Armature Current Densities

The average output torque of the motor understudy is examined at various the armature current densities. The obtained results are illustrated in Figure 10, in which armature current density is varied from 0A$_{rms}$/mm^2 to 30A$_{rms}$/mm^2. From the plot, it is observed that the maximum torque is produced when armature current density is set at 30A$_{rms}$/mm^2 which is 209Nm. However, the graph shows that output torque increased linearly proportional to increase in armature current density. Moreover, it is expected that this value will still be enhanced to optimum value after design optimization.

4.2. Torque against Speed Charactaeristics

Having simulated average torque values at the various armature current densities of J_a 5 A/mm^2 to 30A/mm^2 at various angle rotation from 0 to 80 degrees respectively, average torque versus speed characteristics plot of the of 24 stator-14 pole FSPM motor is shown in Figure 11 in which at the base speed of 1,374 rev/min, the average torque of 209Nm is achieved. Similarly, at high speed operation, this begins to decrease beyond base speed.

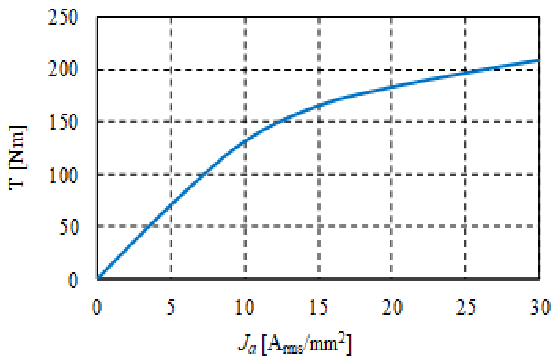

Figure 10. Average torque against armature current density J_a (A$_{rms}$/mm^2)

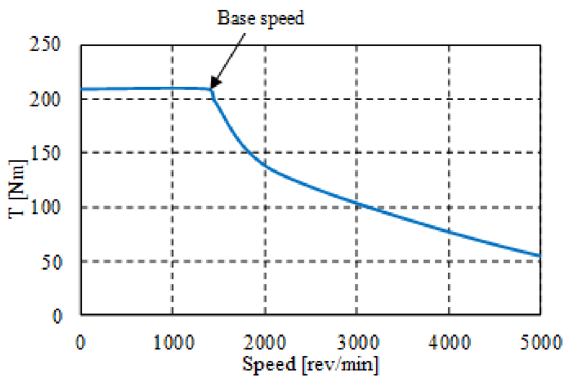

Figure 11. Torque versus speed characteristics of 24 slot-14 pole FSPM motor

4.3. Torque and Power against Speed Charactaeristics

Plot of torque and power against speed is shown in Figure 12. At the base speed of 1374 rev/min which is attained by the motor understudy generated output power of 28kW. And this promising performance is expected to improve with design improvement.

4.4. Motor Loss and Efficiency of the FSPM motor

The loss and efficiency of the motor understudy are calculated using finite element analysis considering iron losses in all the laminated steel cores and copper losses in the armature coils. Figure 13 highlights the chosen operating points from 1 through point 8 in all. They are considered at maximum torque, maximum power and frequency operating point within the operating region as specified. Detailed loss analysis is outlined in Figure 14. At high torque operating point 1, efficiency of the motor is 93.16% with the low copper loss under load condition. Meanwhile, at the highest speed at point 2, the efficiency is 94.35% under the lowest load condition. However, efficiency is highest at this point as a result of less copper loss and iron loss. For the remaining operating points of 3 to 8, under medium load condition, the motor achieves high efficiency rate. The losses at each operating point are outlined in Table 2.

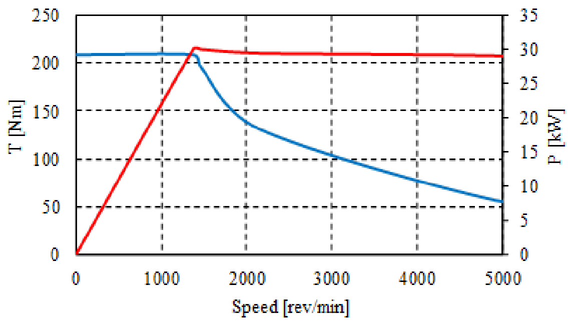

Figure 12. Torque and power versus speed of 24 slot-14 pole FSPM motor

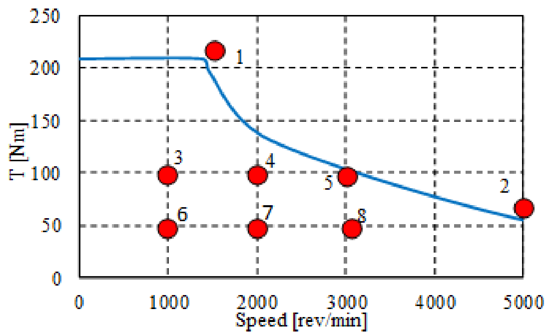

Figure 13. Specific operating points of 24slot-14pole FSPM motor

Table 2. The detailed loss analysis and motor efficiency

Point	P_{out} (W)	P_{iron} (W)	P_{copper} (W)	P_{total} (W)	Efficiency (%)
1	332328	414.114	16482.66	349224.8	93.16
2	196910	3969.002	457.8516	201336.9	94.35
3	100000	72.53145	2770.735	102843.3	94.42
4	200000	210.1237	2770.735	202980.9	95.18
5	300000	396.203	2770.735	303166.9	95.0
6	5000	54.87562	1354.508	51409.38	94.09
7	10000	158.4833	1354.508	101513	95.28
8	150000	293.2833	1354.508	151647.8	95.31

Average Efficiency 94.6%

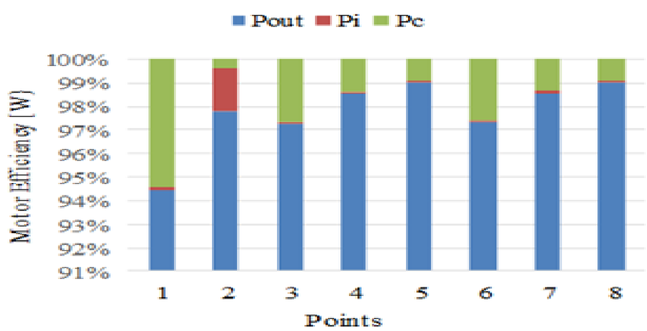

Figure 14. Loss and motor efficiency at frequent operating points of the motor

5. CONCLUSION

This paper has presented a novel design of 24slot-14pole FSPM motor employing segmented outer rotor for pure electric scooter propulsion using appropriate split ratio because it plays a vital role in enhancing high torque. JMAG Software version 14 is used in the design and simulation. Segmented rotor ensures low manufacturing cost, less material usage, fault tolerant and high performance, thus, the proposed motor is suitable for ESV propulsion for long distance travel. Based on 2D-FEA, the motor which is secured using an external rotor shaft achieved the torque of 209Nm and will further be improved in optimization.

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