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Flux Switching Permanent Magnet Motor using Segmented Outer Rotor Structure for Electric Scooter

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Abstract

Flux switching motor is a type of electric machine that locates both flux source and armature windings on the stator leaving its rotor a simple piece of iron. This machine was developed by combining the toothed stator structure of induction machine and the toothed rotor structure of switched reluctance machine together. Furthermore, it has three types of flux sources which include permanent magnet. Conventionally, the toothed kind of rotor has dominated machines rotor design and has been known for high manufacturing cost and iron loss, resulting to low performance.This calls for worry and the need to overcome it and also reduce the manufacturing cost while securing high torque. This paper presents flux switching permanent magnet motor employing segmented outer rotor for high torque capability. 2D-FEA using JMAG to investigate the motor characteristics in terms of flux linkage, Induce back-emf, cogging torque, maximum average torque and efficiency. Finally, preliminary results and comparison revealed that motors employing segmented rotor are capable of higher torque than conventional toothed rotor.

Keywords: *flux switching motor, segmented rotor, outer rotor, permanent magnet, loss-free excitation*

1. Introduction

High cost of petroleum products used by internal combustion engine vehicles and harmful pollution coming out of it has posed major challenges to humanity in general [1]. Already, these incentives have attracted call for the elimination of internal combustion engine vehicles. Already, innovation and refinement have been made in electric motor technology in the area of improving its flux, torque density, power and efficiency for vehicle propulsion. Also, the refinements can be related to size of motor, shape of motor and flux source location. Now, electric motors are increasing in torque and in efficiency [2]. What this means is that for a start, the new motors use considerable less energy than traditional motors because; there is less heat loss energy.

Electric motor, which is an electromechanical device consisting of stator and rotor parts takes in an input electrical energy (voltage and current) and converts it into output mechanical energy (torque and speed) to enable work be accomplished in real time has brought technological breakthrough after the days of Michael Faraday who invented electric machine in 1820s [3]. In those early days, it was direct current (DC) machine only but afterwards, another type, alternating current (AC) machine was developed. Both DC and AC machines work on the principle of electromagnetism but their configurations are different from one and the other. DC machines have field windings on the stator and armature windings on the rotor. However, AC machine is further classified into synchronous machine (SM), induction machine (IM) and switched reluctance machines (SRM) respectively. Synchronous machines (SMs) have three types of sources such as permanent magnet (PM), field excitation (FE) or combination of (PMand FE). Permanent magnet synchronous motor (PMSM) has been successfully developed with the average torque capability of 110 Nm and power output of 6kW. However, this torque cannot sustain acceleration for long distance travel. Figure 1 illustrates the cross-sections of PMSM [4-5]. Furthermore, research and development continues in the area of design for improved torque and power to sustain acceleration vehicle.

Another motor type, flux switching motor (FSM), has a different construction with cooling system has a simple robust rotating rotor. FSM was introduced in 1956 [6] and has attracted significance attention in electric propulsion. Generally, FSM is designated into three

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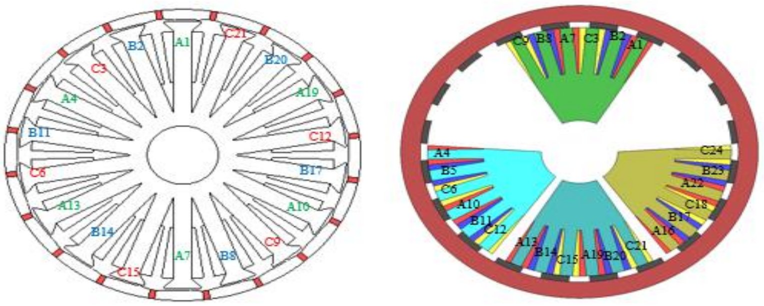
types such as flux switching motor with PM flux source (FSPMM), flux switching motor with FE field source (FEFSM) and hybrid flux switching motor with PM and FE sources respectively [7-9].

The FSPMM has attracted so much interest due to its advantages of loss-free excitation and elimination of connections to external stationary electric circuits, thereby recording less copper loss. This motor has various factors including advances in magnetic material, and computer aided design tools [10-12]. With PM being the natural source of flux, various topologies have been designed for numerous allied purposes suchas automotive, lost cost appliance, aerospace. All these designs are with inner rotor structure respectively which are targeted for out-wheel application [13]. In the same mode, outer rotor FSPMM motors have been proposed for in-wheel [14]. Meanwhile, all the designs mentioned above have so far been in salient/toothed rotorwithout given consideration to segmented rotor [15].

In this paper, FSPMM employing segmented rotor is presented for in-wheel application. A research carried out recently showed that the use of segmented rotor ensured performance [16]. The use of segmented rotor in flux switching mechanism has the gain of operating with a bipolar flux in the magnetic circuit as bipolar flux linkage is achieved by the rotor from the armature winding.



(a) [4] (b) [5]

Figure 1. Three-phase permanent magnet synchronous motor (PMSM)
(a) Toothed stator (b) Segmented stator

2. Research Method

The motor design is conducted using the commercial finite element analysis (FEA) package, JMAG Software version 14.1 released by Japanese Research Institute. Both designs and machine dimensions with specifications are illustrated in Table 1.

Table 1. Design Specifications and Restriction

Descriptions	PMSM	PSPMM-SOR
No of phases	3	3
No of rotor poles	10	14
Diameter of motor (mm)	279.4	279.4
Air gap length (mm)	0.5	0.5
PM mass (kg)	1	1
Stack length (mm)	100	100
Stator shaft	30	30
DC-voltage inverter (V)	415	415
Inverter current (A_{rms})	360	360
Number of conductors	18	18
Armature slot area (mm^2)	432	432
Rated speed (rev/min)	1900	1900

The 2D - FEA package, used is the commercial JMAG-Software ver.14.0, released by Japan Research Institute (JRI). At first, the JMAG Geometry Editor is used to draw the rotor, rotor shaft, stator, armature coil and permanent magnet. This motor is uploaded on the JMAG Designer where materials, conditions, circuits and properties of the machine are set. The PM material used is NEOMAX-35AH whose residual flux density and coercive force at 20^{O}C are 1.2T and 932kA/m while the electrical steel 35H210 is used for rotor and stator body. Furthermore, the external rotor shaft is a non-ferromagnetic material of aluminium conductor. Coil arrangement test is examined to validate the working operating principle of FSPMM-SOR. Following it, is flux distribution and finally, flux distribution, torque characteristics and efficiency. Flow chart for design process is illustrated in Figure 2 and part of each of the parameters designed is illustrated in Figure 3.

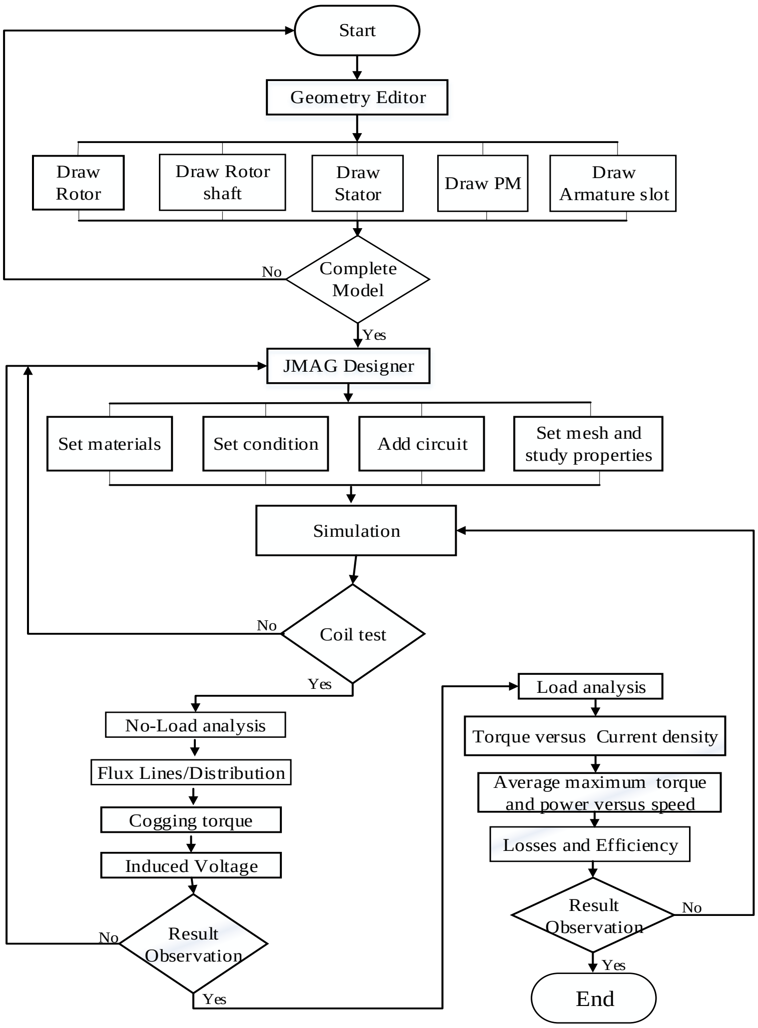


Figure 2. Flow chart of design and performance investigation

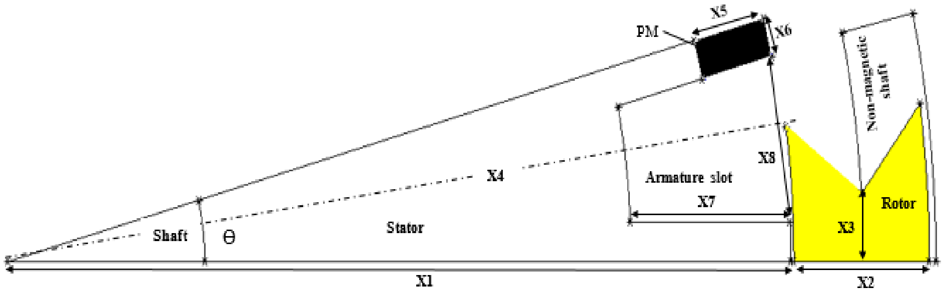


Figure 3. Design parameters of FSPMM-SOR

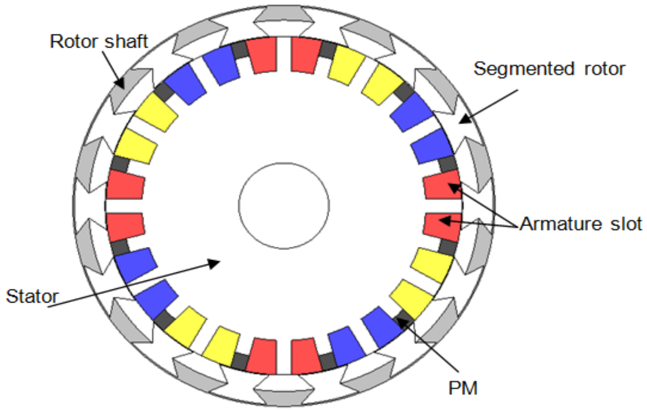


Figure 4. Cross-sections of 24S-14P FSPMM-SOR

2.1 Design of Choice of Rotor

Already some segmented rotor geometries are considered for the proposed motor as illustrated in Figure 5. The shape in (a) shows an earliest circumferential extending pole applied in inner rotor synchronous reluctance machine [17,18]. Though circumferential extending pole is ideal in terms of performance in inner rotor configuration, it needs notable modifications for outer rotor application. However, to retain these segments, for speed operation, design provision is necessary so that non-magnetic material is used to secure them without adding excessive load to affect motor’s performance. The modification led to dovetail structure in part (b) and the transerving design in part (c) [19]. While the dovetail segment is applied in the FSM as compromise, it lacks the mechanical strength to be used for any application. To overcome it, this proposed segment geometry provides a feature so that the segmented rotors will be properly secured using an external rotor shaft without compromising motor’s performance. To achieve this, the geometry follows relationship that exists between length of an arc and segment of a circle using the convention given in Equation 1.

$$\text{Segment span: } \theta = \frac{180 \text{ x rotor tooth width radius (mm)}}{\pi \text{ x inner rotor radius (mm)}} \quad (1)$$

Where θ = is the segment span angle

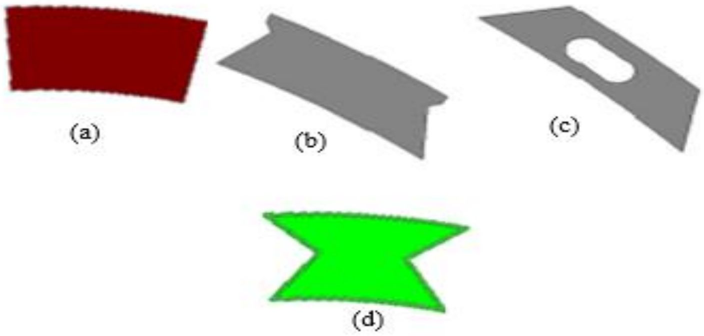


Figure 5. Segmented Rotors under Consideration

3. Results and Analysis

This section explained the results of research and at the same time, given the comprehensive discussion. Results are being presented in figures, graphs that make the reader to follow through the process. The discussions are made in the following sub-chapters.

3.1. Coil Arrangement Test (No-Load condition)

Coil arrangement tests must be carried to set the position of each armature coil phase and also confirm the operating principle of FSPMM-SOR. To certify this, this coil arrangement is performed separately on each armature. As the PM is placed alternate radial magnetizing direction with armature stator tooth winding. It is observed that the coils are being defined in arrangement with three-phase winding system. Figure 6 illustrates the three each flux linkage as U, V and W. Furthermore, the operating system of FSPMM-SOR is also achieved.

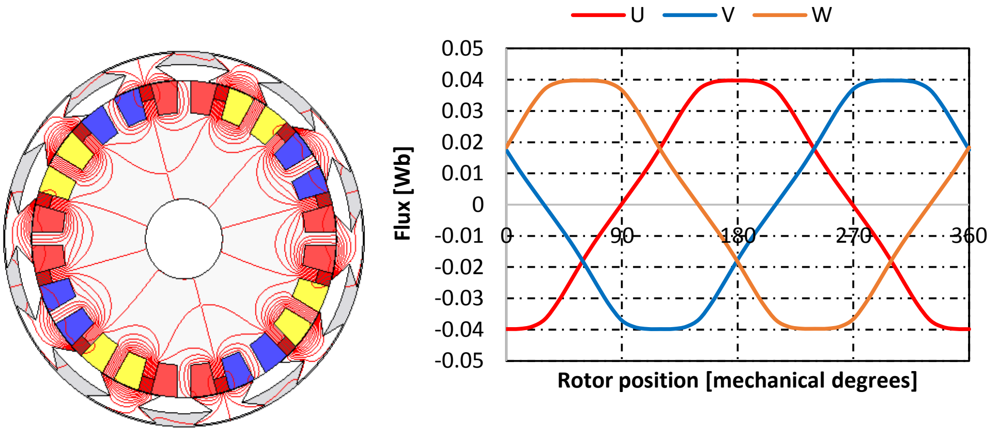


Figure 6. Three-Phase PSPMM-SOR

3.2. Induced Back-Emf (No-Load Condition)

Under no-load condition, plot of the induced back-emf generated with the PM flux source at the speed of 1900rev/min is shown in Figure 7. It recorded induced emf of 215 V and it is less than the applied voltage. This value is acceptable since it is lower than the applied voltageand as such, will protect the system in case of any disorder. However, this value will hopefully reduce during design improvement.

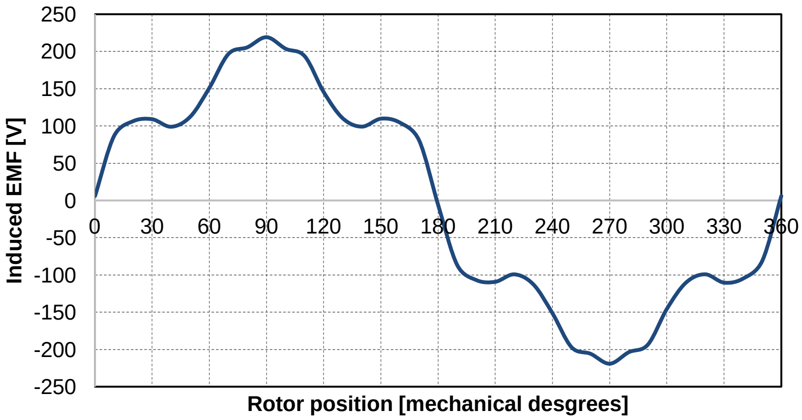


Figure 7. Induced back-emf

3.3. Cogging Torque Analysis

To ensure that the proposed motor did not vibrate during operation, cogging torque analysis is conducted of which the torque profile is 8.4 Nm peak- to-peak as illustrated in Figure This value is quite small and thus, the motor is save from vibration and noise. Furthermore, design refinement will reduce this value.

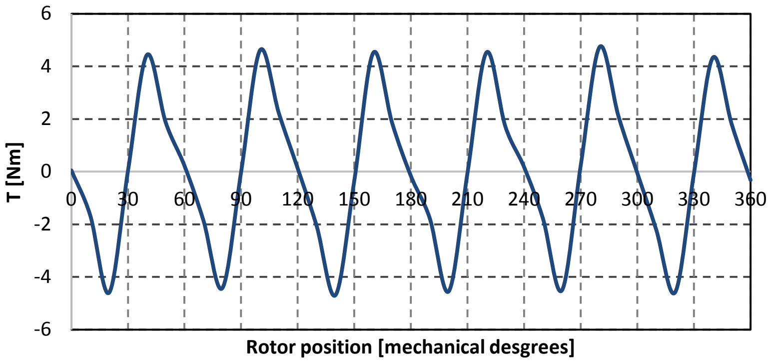


Figure 8. Cogging Torque

3.4 Torque and Power versus Speed Characteristics (Load Condition)

Another characteristic for through examination is torque and power versus speed in which at load condition, at the maximum armature current density of J_a= 30A/mm^2 is supplied to the motor. It isseen that at the base speed of 1374 rev/min,the proposed motor achieved thetorque and power of 209Nm and 30kW.This is quite good with the initial design. Figure 9 illustrates the torque and power versus speed performance of the motor. However, with the power is constant throughout the entire speed operating region. Therefore, this promising torque capability shows likelihood to improve further with design optimisation.

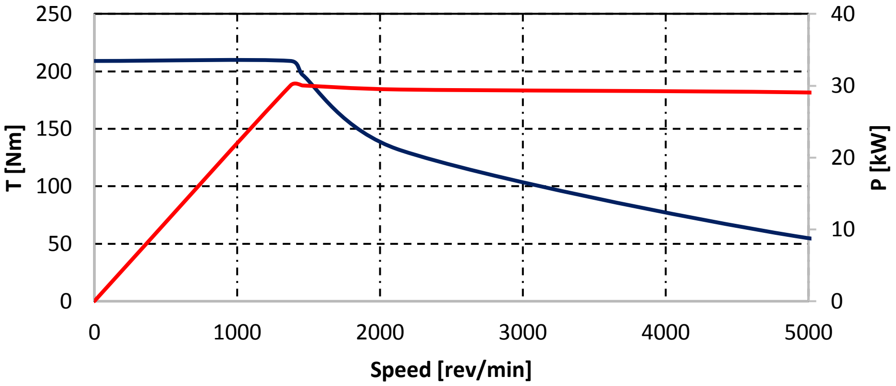


Figure 9. Torque and Power versus Speed Charcateristics

3.5. Motor Loss and Efficiency

To further ascertain the performance of the proposed motor**, i**ron loss analysis was carried. At the end, the efficiency was calculated using finite element analysis. The losses recorded by the motor was not very significant. This is one ofthe gains of segmented rotor employing alternate stator tooth armature winding. Figure 10 highlights the chosen operating points from 1through point 8 in all. They are considered at maximum torque, maximum speed and frequency operating point within the operating region as specified. At high torque operating point 1, iron loss is highest the highest speed as shown in Figure 11 while the copper is highest at the maximum current density as shown in Figure 12. Meanwhile, every other point recorded minimal losses which on the average is negligible. Therefore, efficiency of the motor is 94.45% with the low copper loss under load condition. The highest speed of 5000rre/min at point 2, the efficiency is 97.02% under the minimum load condition. 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’s efficiency rate as much as 94% to 98%.Detailed result of lossanalysis with efficiency Pout, is outlined in Figure 13.

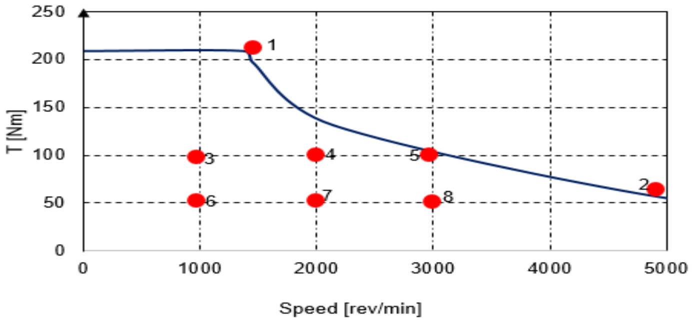


Figure. 10 Specific operating points for iron loss analysis

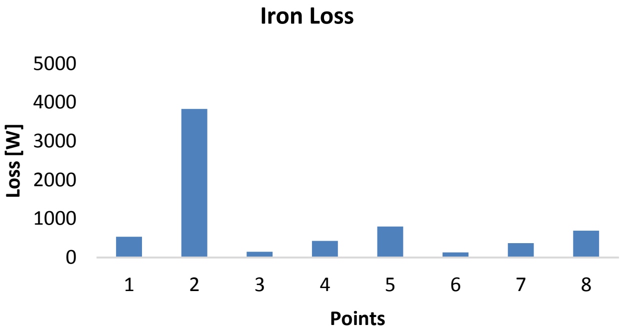


Figure 11. Iron loss at different operating points

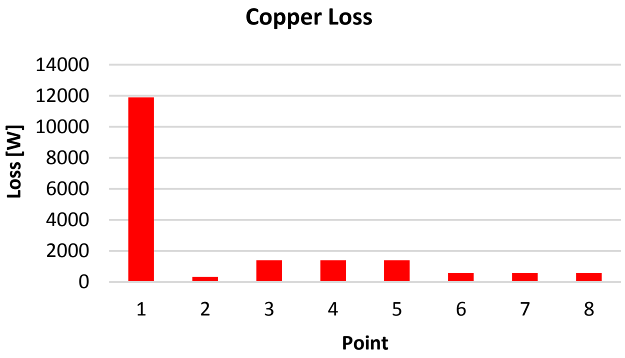


Figure 12. Copper loss at different operating points

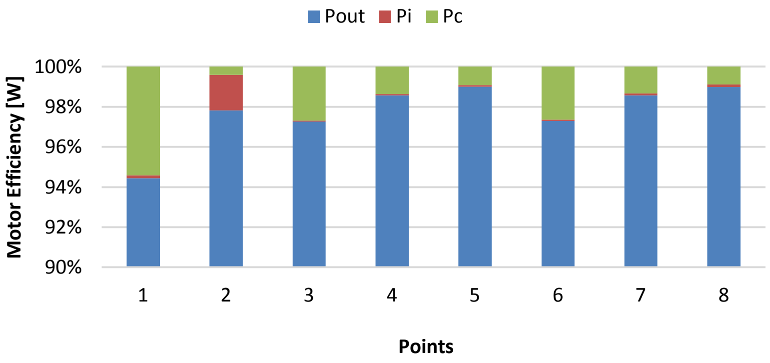


Figure 13. Losses and motor efficiency at frequent operating points

4. Conclusion

This paper has designed and presented the performances of flux switching permanent magnet motor employing segmented outer rotor for In-wheel drive application. It consisted of 24 stator slots-14 segmented rotor pole with 1kg mass of PM alternately in placed on stator tip with single toot windings. The 2D-FEA was by JMAG to examine its characteristicssuch as flux linkage, induced back-emf, cogging torque, average torque and efficiency. The result of performance revealed that there are more gains using segmented rotor in terms of manufacturing cost, high torquecapability and sustainable high efficiency.

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