Torque Performance Analysis of Three-Phase Permanent Magnet Flux Switching Motor in Out-runner Segmented Rotor for In-Wheel Propulsion

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***Abstract*—This paper presents torque performance of three-phase permanent magnet flux switching motor (PMFSM) in out-runner segmented rotor for vehicular propulsion. This is the first time permanent magnet flux source and rotor segment are being employed in FSM design. PMFSM is electric machine in which both armature winding and permanent magnet source are located on the stationary stator only. The rotor is simple piece of sheet steel lamination to contain speed operation. The operating principle of proposed motor employing segmented rotor being used to modulate the polarity of the flux linkage in the stationary stator is confirmed with clear benefits. The 2D Finite Element Analysis (FEA) utilized the JMAG Designer version 14 to investigate four motors performances of the same stator pole in terms of magnetic flux linkages, cogging torque, induced back-emf and average torque. Results shows that 24s-14p motor can gauge optimum average torque of 263.5Nm and has high performance for in-wheel propulsion for long distance travels compared with conventional PMSM.**

***Index Terms*—flux switching motor, out-runner segmented rotor, permanent magnet, radial magnetic direction, loss-free excitation, 2D-finite element analysis**

I. Introduction

Recently, a segmented rotor was used in flux switching machine (FSM) in which all active parts are located on the stator leaving the rotor without material to contain high speed and the performance in terms of torque is greatly improved [1]-[3]. It is very obvious that this configuration using segmented rotor and deployment of Permanent Magnet (PM) and armature windings on the stator provides gains for operating with bipolar flux in the magnetic circuit [4]-[5]. The segmented rotor is used to create bipolar flux linkages in the armature windings with also bipolar flux in the armature tooth for a single cycle of operation. An investigation into the design of PMFS motor in out-runner structure employing segmented rotor is described in this paper. This is necessitated with the reference for the application and specification associated with long distance travels. The design is concerned with securing very high torque without compromising other constraints needed for long distance travel such as weight of motor. In general, flux switching motor is developed by utilizing the advantages of permanent magnet synchronous machine (PMSM) and switched reluctance motor (SRM) [6], [7]. For the rotor rotation to go through poles of the motors under investigation, the flux linkage in the armature undergoes the period of revolution of each motor's pole [7]. Generally, rotor speed of FSM is as expressed in (1).

$$N_s = \frac{60f}{P} \tag{1}$$

where N_s rotor speed, f is frequency, P number of poles Also, electrical frequency is stated in (2).

$$f_e = N_r * f_m \tag{2}$$

where f_e is electrical frequency, N_r is number of rotor and f_m is mechanical frequency.

Flux switching machine (FSM) is categorized into three kinds namely, permanent magnet FSM, field excitation FSM and hybrid excitation FSM respectively. These three kinds are due to different means of flux source excitation. Examples of FSMs are illustrated in Fig. 1. In PMFSM, PM is the flux source, FEFSM utilizes field coil while HEFSM employs both PM and FE as main and secondary sources of excitation [8]-[12].

For three-phase machine employing segmented rotor with PM flux source, 24 stator is the minimum of teeth necessary for AC working for four set of windings as PM is placed alternately on 12 stator tip and armature winding on the remaining 12 stator slots [2]. For stator-rotor combination, it is desirable to have more number of stator teeth than rotor, so for the 24 stator pole number, feasible rotor pole numbers are 8, 10, 14 and 22poles.

Permanent magnet FS motors have attracted researchers' interest due its beneficial attributes of end short coils, short flux path and high torque density [13]-[15]. As it is at present, almost PMFSMs in published literatures have been in conventional toothed rotor without any attention considering segmented rotor which provides high torque for high application [16]. First of all, we will describe the operating principle of this motor employing out-runner segmented rotor and PM source of flux excitation and design it. The performance of the

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motor is examined in terms of magnetic flux linkages, cogging torque, induced back-emf and average torque.

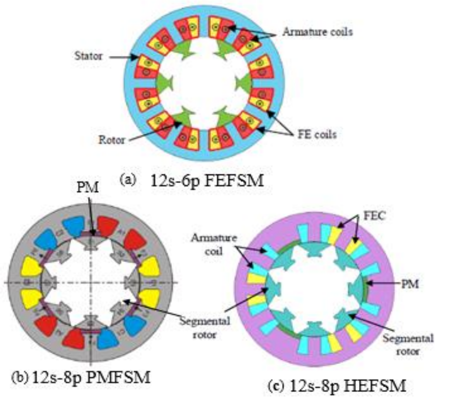

Fig. 1. Examples of FSMs in segmental (inner) rotor

II. Design Methodology

To identify a desirable motor topology in terms of promising high magnetic flux linkage for high torque and capability, four different motors are designed and investigated. In designing each motor which was carried out using JMAG - Geometry editor and later uploaded into Running Solver for simulation and analysis. The motor parts which include rotor, stator armature coil and PM are designed in the Geometry editor while setting in the materials, conditions circuit mesh setting are developed in the Designer. The material selected for the rotor and stator is electrical steel 35H210 while the PM is Neomax-35AH. Design flow chart is illustrated in Fig. 2. The four motors under investigation are 24s-8p, 24s-10p, 24s-14p and 24s-22p on 24 number stator pole teeth. Table 1 shows the specifications for motor design.

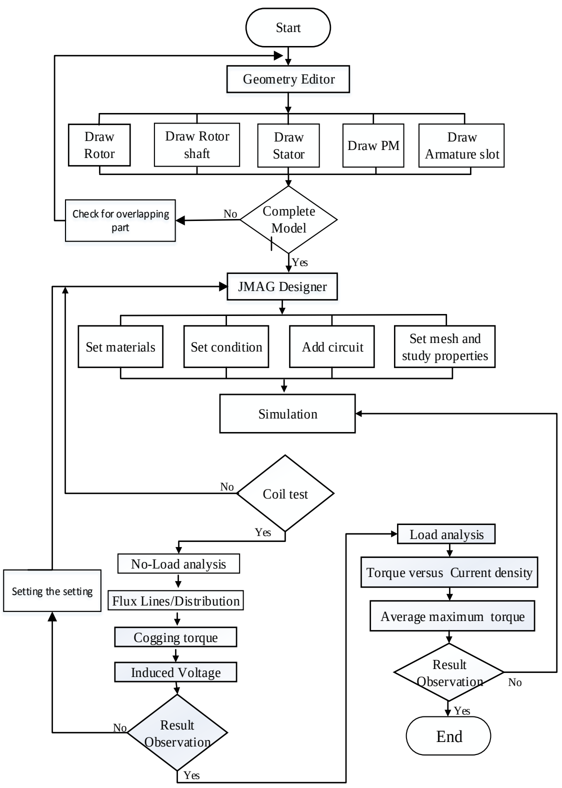

Fig. 2. Work flow chart of motor design in JMAG Geometry

Table I: Motor's Specifications and Restrictions

Descriptions	PMFSM
No of phase	3
No of rotor pole	8,10,14, 22
Rotor type	Segment
Stator type	Salient
Rotor pole length (mm)	20.50
Rotor outer radius (mm)	139.70
No of stator pole	24
Diameter of motor (mm)	279.40
PM mass (kg)	1
Stack length (mm)	100
Stator shaft (mm)	30
Air-gap length (mm)	0.5
DC-voltage inverter (V)	415
Inverter current (A_{rms})	360
Number of conductors	18
Armature slot area (mm^2)	432

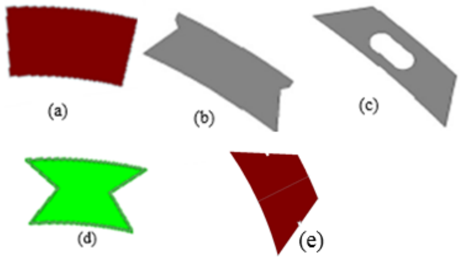

Fig. 3. Various rotor segments considered

A. *Design and Choice of Rotor Segment*

The choice of a rotor segment for the proposed PMFSM is necessary to reduce manufacturing cost, lowering iron loss while generating high flux linkage and high torque capability. It is on record that rotor segment exhibits good receptacle of magnetic 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]-[18]. For speed operation, external rotor shaft is useful for rotor retainment. Fig. 3 illustrates segmented shapes considered for outer rotor topology. Segment shapes in Fig. 3 (a)-(c) have been proposed and discussed in [16]. More so, design in (d) has a balanced dovetail base suitable for out wheel application. Meanwhile, previous designs have embraced external circuit connections and also lack retainment shaft. Therefore, this PMFSM understudy, adopts a new rotor segment design to contain retainment as shown in Fig. 3(e). Geometric design adopts the formula which ensures proper segment rotor angle and segment span as given in (3) and (3.1):

$$\text{Rotor angle, } \theta = \frac{360 \text{ x rotor radius (mm)}}{2\pi \text{ x inner rotor radius (mm)}} \quad (3)$$

$$\text{Segment span } \theta_s = \theta + x \quad (3.1)$$

where $1° \leq x \geq 3°$.

B. *Operating Principle of PMFSM in Out-Runner Segmented Rotor*

In Fig. 4 is shown the cross-sections of the four different motor configurations under investigation. In order to understand the principle of operation of segmented rotor PMFSM in out-runner, the rectilinear cell arrangement is presented in Fig. 5. The flux switching mechanism is explained using PM1 and armature coil. At the initial condition when stator tooth is in alignment with rotor S1, there is flux flow from PM1 into S1 in upward direction linking with S1 and back to the stator back iron as shown in Fig. 5 (a). However, in the second alignment, when segment rotor S1 begins to rotate in counter-clockwise direction, flux begins to flow from PM1 through S1 into the stator pole. Therefore, as S1 continues to rotate and at the third quadrant, there is switch of flux at the same S1 from PM1 to the downward direction as shown in Fig. 5 (b).

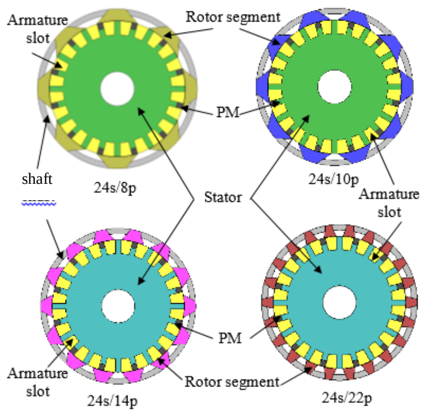

Fig. 4. Cross-sections of PMFSMs in out-runner rotor segments with external retainment shaft

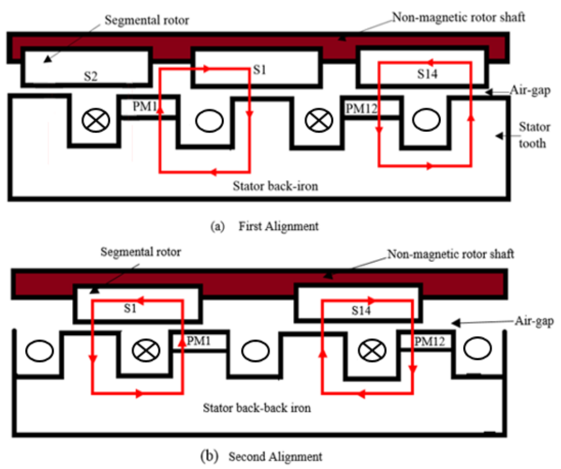

Fig. 5. Operating principle of out-runner PMFSM in rotor segment (a) First alignment, (b) Second alignment

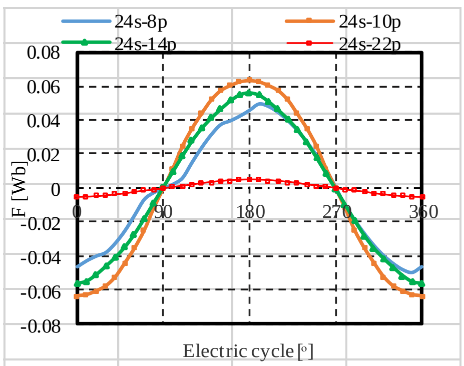

Fig. 6. U phase flux linkage of the designed PMFSMs

III. Performance Analysis

A. Open Circuit Condition: Magnetic Flux Linkage

Provision of high flux linkage presents initial good factor for good high torque motor whether it would lead to low torque or high torque. It is not all the time that high flux amplitude leads to high torque under load condition. In Fig. 6, the magnetic flux amplitude of the four motors under investigation are presented. Smooth sinusoidal waveform provides the benefit of being a suitable motor. It is seen that the amplitude of U-phase flux profile of 24s-10p gauged the highest amplitude followed by 24s-14p. Furthermore, 24s-8p is the third with harmonics while 24s-22p secured the lowest flux amplitude.

B. Open Circuit Condition: Cogging Torque

Cogging torque of each of the motors, all operating at 1900rpm are provided in Fig. 7. A cursory look at them, 24s-8p has the highest cogging torque of 75Nm peak to peak, and high cogging torque is not suitable for motor operation as it causes vibration and unnecessary noise. The configurations of 24s-10p secured the second position while 24s-8p and 24s-22p have low cogging torques. However, 24s-14p has more sinusoidal waveform to make it more favorable. Therefore, 24s-14p configuration has secured favourable sinusoidal waveform for smooth operation for the proposed motor.

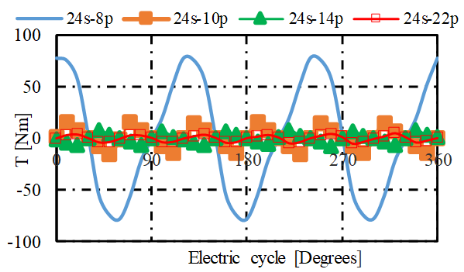

Fig. 7. Cogging torques of the designed PMFSMs

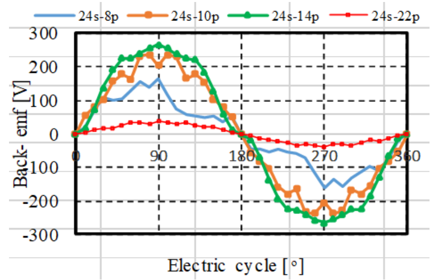

Fig. 8. Induced back-emf of PMFSMs at 1900rpm

C. Open Circuit Condition: Back-emf

At no-load condition such as zero current density of J_a 0 A/mm^2, the back-emf of each motor, the voltages induced by the PM and armature coil at the speed of 1900rev/min is presented in Fig. 8. The purpose is to identify which motor has the lowest induced back-emf and lower than the applied to work in a safe region. In the plot, it is observed that 24s-8p produced induced voltage of 150V which is not sinusoidal waveform. Again, it is laced with gross harmonic distortion. The 24s-10p provided almost 250V with sinusoidal waveform also characterized with harmonics. However, 24s-22p has the lowest back-emf of 40V and lastly, 24s-14p provided the highest back-emf of 260V but lower than the applied voltage having the best sinusoidal waveform with less harmonics. Therefore 24s-14p has exhibited sinusoidal waveform and this gives it advantage to perform better after further refinement to provide protection in case of unclear system fault [19].

D. Effect of Rotor Pole Length of the Motors

As observed in the plot induced emf waveforms of the motors in Fig. 8, it is seen that motors are all laced with distortion in various orders. At the same rotor pole length of the motors, 24s-14p achieved the lowest odd harmonics orders of 5, 7, 11, 13 and 17 as shown in Fig. 9. Therefore, further design improvement will be carried out to lower and also obtain smooth sinusoidal waveforms.

E. Closed Circuit: Torque against Current Density

The torque output of the PMFSM understudy are examined at various armature current density which varied from 0A/mm^2 to 30A/mm^2 and the capability of each is plotted as shown in Fig. 10. Comparing these motors, 24s-22p achieved the lowest torque of 69Nm. This is followed by 24s-8p with 190Nm. On its part, 24s-10p secured 196Nm while 24s-14p gauged the highest torque of 263.5Nm.

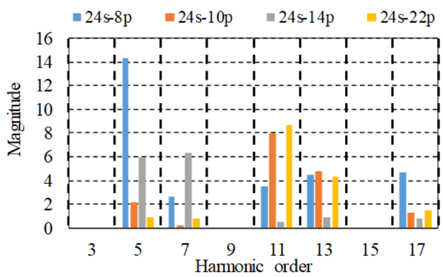

Fig. 9. Magnitude of harmonics with different disorder

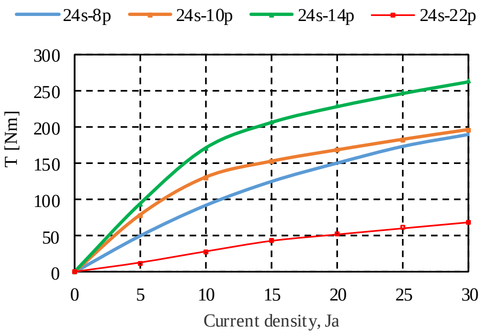

Fig. 10. Torque versus current density of the PMFSMs

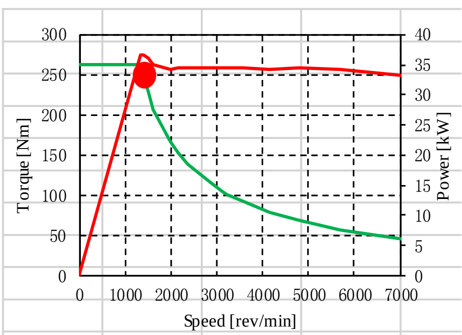

Fig. 11. Torque and power against speed characteristics

F. Closed Circuit: Torque and Power Against Speed

Having secured the highest output torque, graph of torque and power against speed characteristics of 24s-14p is plotted in Fig 11. It is seen clearly that at the base speed of 1330.82 rev/min, the PMFSM generated average torque of 263.5Nm as circled with red color. More so, at this torque, the corresponding power is 35kW. Torque is represented with the solid green color while power is represented with solid red color.

IV. Performance Analysis

This paper has presented three-phase permanent magnet flux switching motor capable of high torque for in-wheel application. Four motors were designed and compared as to select the topology which provided the highest output torque for high performance. Operating principle of flux switching motor employing out-runner segmented rotor was highlighted. A derived equation was employed to determine initial segment span to allow maximum flux to flow through the segment. JMAG Software version 14 was used to design and analyze electromagnetic performances of the motors in terms of cogging torque, induced-emf and output torque. Of the four motors, 24s-14p gauged favorable high magnetic flux, lowest cogging torque highest average torque of 263.5Nm. The proposed flux switching motor has been designed utilizing permanent magnet flux source placed on stator tip using outer segmented rotor and performance is compared with exterior PMSM which used round rotor with PM of 2kg mass and achieved torque output of 110 Nm and power of 6kW. The proposed motor utilized PM 1kg mass and achieved torque of 263.5Nm and constant power of 35 kW. With this excellent performance, the motor is ideal for in-wheel vehicle propulsion.

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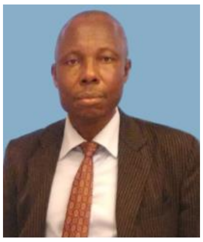

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