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Electromagnetic Performance of Segmented Stator Flux Switching Permanent Magnet Motor

Muhammad Aiman Ahmad Syukri[1], Erwan Sulaiman[1]*, S. M. Naufal [1]

[1]Faculty of Electrical and Electronic Engineering,
Universiti Tun Hussein Onn Malaysia, Batu Pahat, 84600, MALAYSIA

*Corresponding Author Designation

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Abstract: This paper describes the electromagnetic performance of the segmental stator flux switching permanent magnet motor. Few designs of the electrical motor with segmental stator structure have been studied, such as flux switching motor (FSM) and flux switching permanent magnet (FSPM) motor to produce a design with unique characteristics. Those characteristics are to isolate each phase of winding or a group of winding to be more independent and without any medium interconnect between segments. The objective of this paper is to analyze the electromagnetic performance of segmental stator FSPM on the issue relating to the stator segmentation technique and compare the electromagnetic performance of conventional and segmental stator FSPM. The performance of the design using no load and load analyses is investigated by using 2-D finite element analysis (FEA) software develop by JMAG designer version 16.0. After summarizing and comparing the performance of all designs, the segmental FSPM motor has lower torque than the other two design models, which might accelerate the motor's speed. In terms of electromagnetic performance, the conventional FSPM motor outperforms the segmental FSPM motor with high torque of 215.16 Nm value than other designs and has a low output power to rotate the motor. In conclusion, the result is satisfactory as it achieves the objectives of comparison of electrical performance between the designs.

Keywords: Electrical Motor, Flux Switching Permanent Magnet, Segmental Stator

1. Introduction

Flux-switching permanent magnet (FSPM) machine is a kind of stator-typed permanent magnet machine, which is suitable for driving electric vehicles and hybrid electric vehicles because of their large power or torque density and high efficiency. Because of this, FSPM machines have been gaining interest over the last few decades. These are several advantages that FSPM provides including high torque density compared to other permanent magnet machines, favorable thermal management or simplicity of magnet heat dissipation due to the location of permanent magnets on the stator passive, low demagnetization possibility and hence robust rotor structure which is suitable for high-speed applications, etc. [1]. However, the bigger motor size limits its use in small spaces, as well as increases

**Corresponding author: erwan@uthm.edu.my*

manufacturing costs. Researchers are using the theory of flux switching to develop an electric machine that is primarily dependent on a permanent magnet, direct current excitation, or both, such as a flux switching motor, based on these advantages [2].

The segmented stator of the FSPM motor is comprised of discontinued sections or segments, resulting in segments. Furthermore, the stator construction is in a C-core form, with the two ends of each segmental stator occupying just half of the ‘C’ core shape stator [3]. The segmented stator design can be chosen depending on the kind of winding to make the winding process easier and to increase the slotted fill factor. The benefits of a segmental stator are fault tolerance in the stator winding, such as line-to-line, line-to-ground, and three-phase faults. The basic notion of the segmental stator FSPM is that it is made up of a discontinued section of the stator. The motor is expected to continue operating with lower torque if an electric fault occurs in one of the stator segments [4].

This paper focuses on the design structure of a flux-switching permanent magnet's segmental stator and conventional stator. Furthermore, it will focus on the issue and performance of the segmental stator which is electromagnetic performance in synchronous machines, as well as compare performance between the segmental stator and conventional stator.

2. Materials and Methods

2.1 Parameter Designs

The design of the segmental stator FSPM machine was utilized using JMAG-Designer software. The parameter specification of new designs is shown in Table 1. The data specification of the FSPM machine to analyze the electromagnetic performance in terms of magnetic flux linkage, the cogging torque analysis, phase back-EMF and electromagnetic torque analysis.

Table 1: Parameter Specification of Conventional and Segmental FSPM

Parameter	Conventional FSPM	2 Segmental FSPM	4 Segmental FSPM
Rotor pole number	14	10	14
Stator outer radius	132mm	132mm	132mm
Rotor outer radius	92.4mm	92.4mm	92.4mm
Stack length	70mm	70mm	70mm
Air gap	0.5mm	0.5mm	0.5mm
PM weight	1kg	1kg	1kg
Armature turns	7 turns	7 turns	7 turns
Armature slot area	168mm2	168mm2	168mm2
Stator pole width	18.7mm	12.7mm	8.6mm
Rotor pole width	15mm	15mm	20mm

2.2 FSPM Designs

The Geometry Editor was used to design the models, which will then be imported into JMAG Designer for simulation using the appropriate parameters [1]. The motor part is separated into a few categories such as rotor, permanent magnet, stator and armature coil. Figure 1 shows the model designs of conventional FSPM, two segmental FSPM and four segmental FSPM.

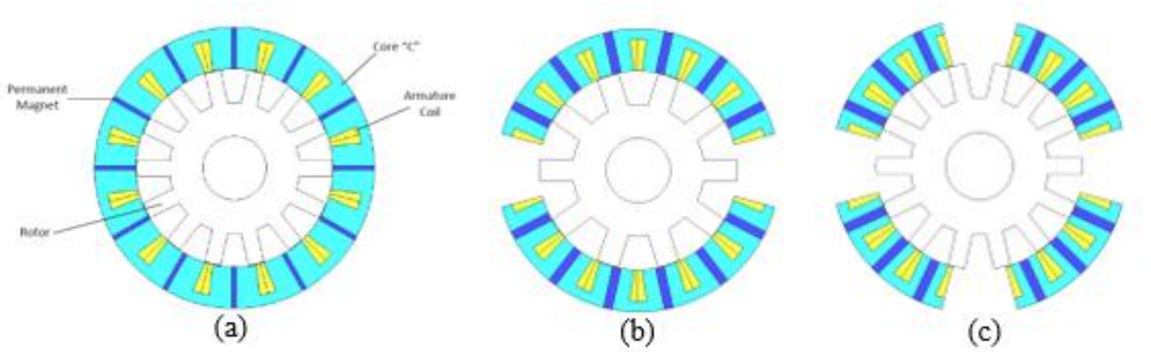

Figure 1: The model designs of (a) conventional, (b) two segmental and (c) four segmental FSPM

2.3 Project workflow

Figure 2 shows the workflow and process of no-load analysis and load analysis simulation by using JMAD Designer software. The process of no load analysis starts from 12 coil arrangement tests, 3 coil arrangement tests, UVW test and zero rotor position. After no load analysis is successfully simulated, the value of the input current of the armature coil is calculated and then inserted into the value on the 3-phase circuit. Then, the simulation of the study case was run to generate the result.

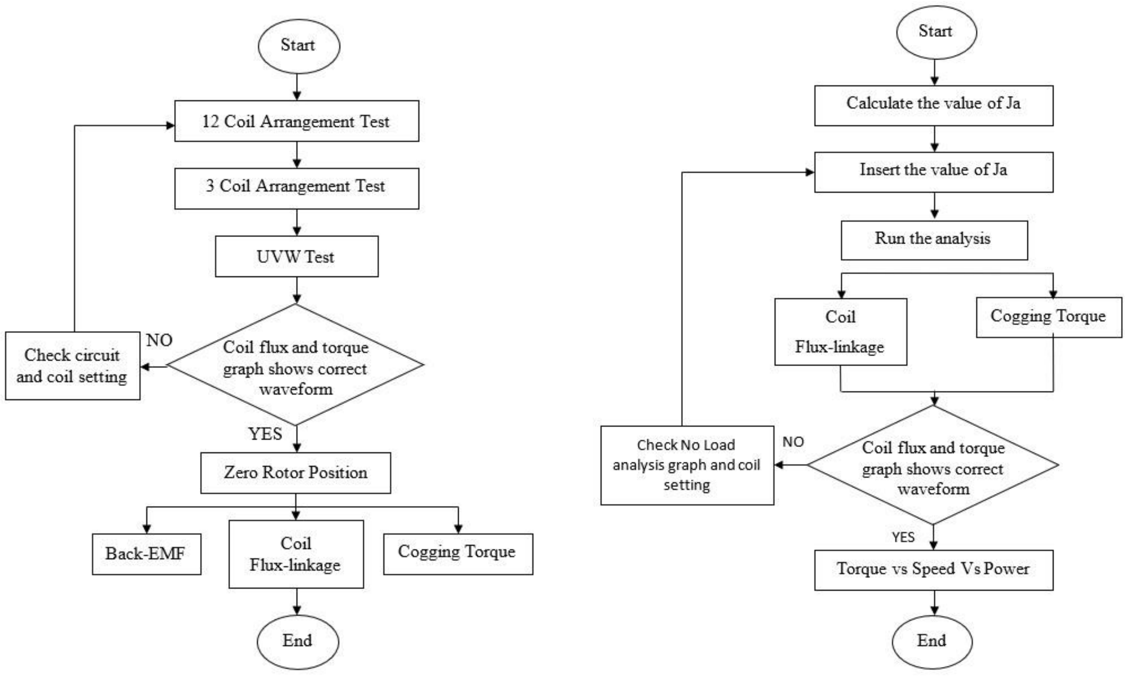

Figure 2: Process of (a) No load analysis and (b) load analysis in JMAG Designer

3. Results and Discussion

3.1 Coil Test and Zero Rotor Position

To verify the positioning of the armature coil and the principles of the proposed FSPM, a coil arrangement test was performed on each coil. The primary goal of this procedure is to identify the same pattern flux linkage that each coil produces. The armature coil with the same pattern then is combined together to create U, V and W flux. The position x-axis at 60°, 180° and 300° of the cosine waveforms is the maximum value of flux-linkage in zero position for U, V and W coil respectively. Based on this result, the position of waveform U is centered between waveform V and W. Figure 3 shows the zero-rotor position waveform for conventional, two-segmental and four-segmental FSPM.

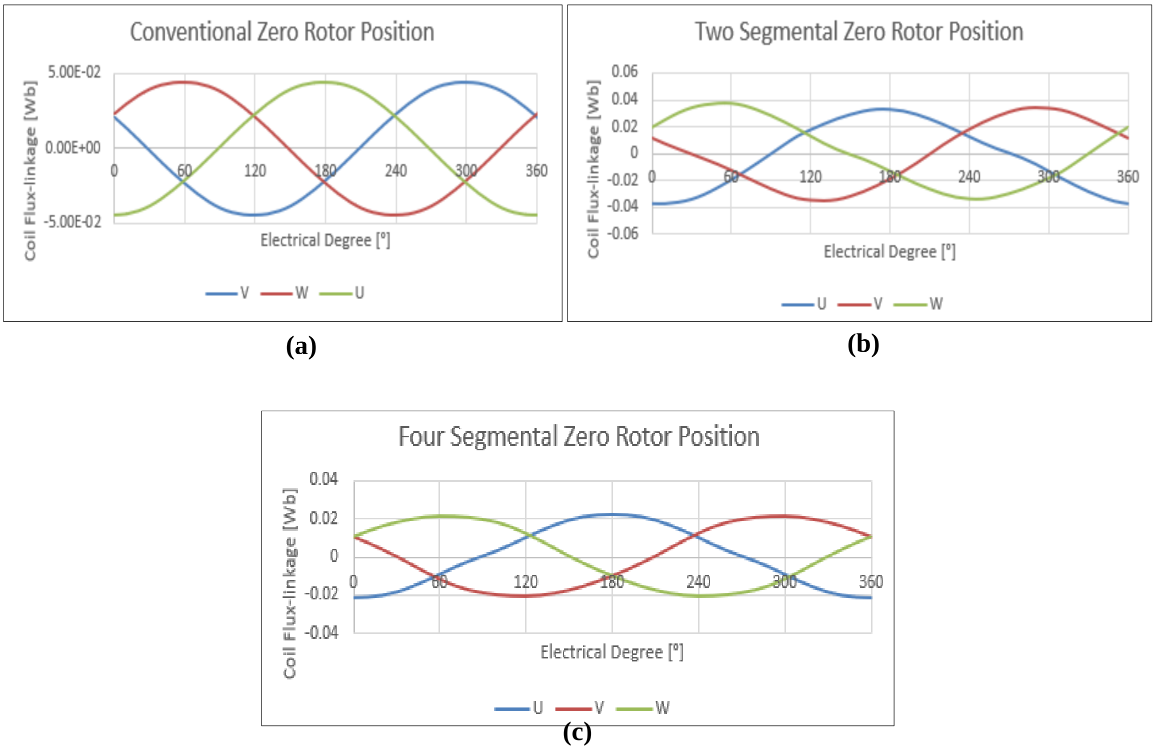

Figure 3: Zero rotor position waveform for (a) conventional, (b) two segmental and (c) four segmental FSPM

3.2 Cogging Torque

Figure 4 shows a combination of the cogging torque of all designs. Based on the result, the highest cogging torque is found in two segmental FSPM motor designs. While the lowest cogging torque value is conventional FSPM motor design. The cogging torque is known to be influenced by the speed of the motor. That means the speed of the motor will become slower if the motor has high cogging torque. From the result, the two segmental FSPM motor design has the highest cogging torque among these three designs. It can be concluded that the result of two segmental FSPMs has the highest cogging torque.

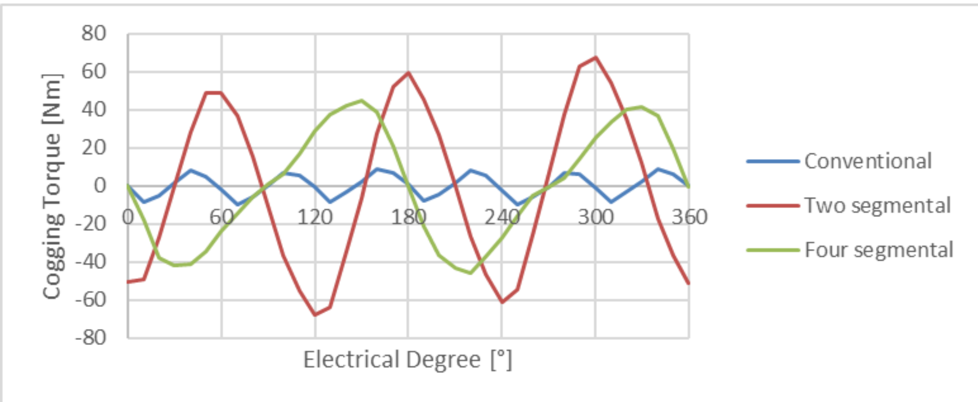

Figure 4: Combination of the cogging torque of all designs

3.3 Back-EMF

The back electromotive force of Back EMF is the system in the coil of an electric motor that opposes the current flowing through the coil during the armature rotation. For the harmonic amplitude, the conventional FSPM has lower total harmonic distortion (THD) while two segmental FSPMs have high

THD among all designs. THD is a measurement of the harmonic distortion present in a signal and is defined as the ratio of the sum of the powers of all harmonic components to the power of the fundamental frequency. The effect of back-EMF on these motor designs reduces the current flowing through the coils of the motor. It can be concluded that the result of two segmental FSPMs has the highest THD among all designs, which produces a forward field that adds to the high torque separately.

3.4 Armature Coil Flux Linkage at Various Armature Coil Densities

In order to analyze the flux characteristic, the armature coil flux linkage against various currents of the armature coil, I_A is plotted. The current of the armature coil is 5, 10, 15, 20, 25 and 30 in unit A_{rms}/mm^2. Figure 5 shows the graph plotted maximum flux-U for all designs. It is approximately 90% of the flux flow from the permanent magnet (PM) in the C core stator and the rest of the flux flows concentrated at the rotor periphery due to flux strengthening and leads to a higher torque. Based on the result, the highest maximum flux-U at armature current density of 30 A_{rms}/mm^2 is conventional FSPM among those designs with the value of 0.078Wb followed by four segmental FSPM with 0.057Wb and a lower value is two segmental FSPM with value 0.046Wb. It can be concluded that the conventional FSPM has a high flux linkage that causes to lead a higher torque.

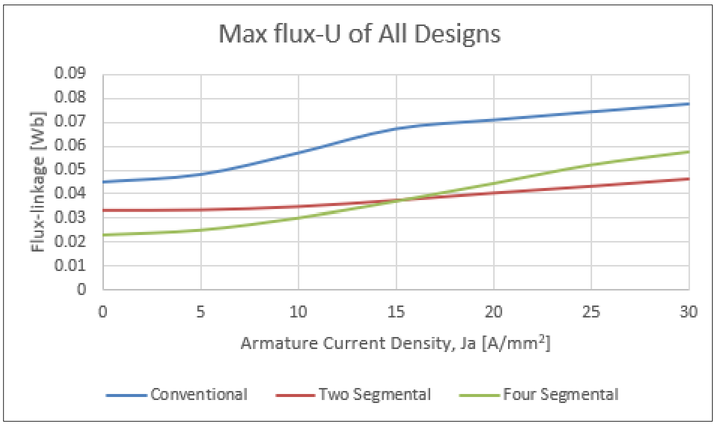

Figure 5: Comparison of Maximum Flux-U for all designs

3.5 Average Torque vs. Various Armature Current Density, J_a

The average torque vs. various armature current density, J_a is testing by injecting the various armature current density from 5 to 30 A_{rms}/mm^2 in order to analyze the pattern behaviors of average torque. The result simulation of conventional FSPM, two segmental and four segmental are shown in Figure 6. From the result, the average torque is increased as a higher value of armature current density is injected. Based on the result, the highest average torque at armature current density of 30 A_{rms}/mm^2 is conventional FSPM among those designs with a value of 213.85Nm followed by two segmental FSPM with 181.33Nm and a lower value is four segmental FSPM with value 161.83Nm. It can be concluded that the electromagnetic average torque of conventional FSPM has the highest torque which may affect the work performance. It also represents that the motor can handle to generate a certain amount of power to rotate the motor on its axis.

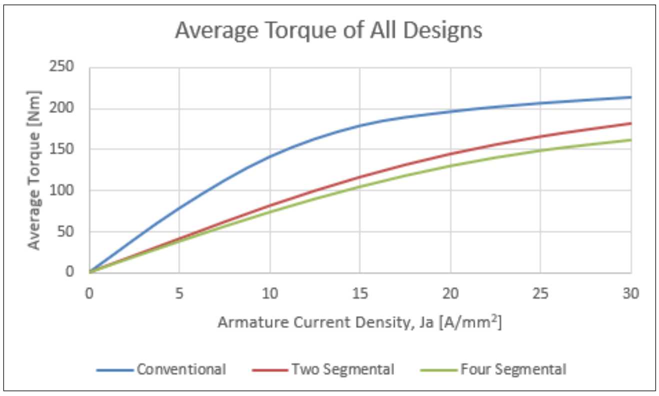

Figure 6: Comparison of Average Torque for all designs

3.6 Torque and Power vs. Speed

Figures 7, 8 and 9 show the torque and power versus speed characteristics of all FSPM designs. The value of torque and power is taken from the data simulation of average torque at various armature current densities of 5 to 30 A_{rms}/mm^2 and phase degrees of 0 to 80 degrees. It is found from Figure 7 that the speed of 4447.52 rpm is the highest torque of a conventional FSPM motor at a value of 215.16 Nm which the highest output power at 115.6kW. There is a drop in output power up to 23.28% at the speed of 27735.17 rpm with a value of 88.27kW. As in Figure 8, the highest torque of two segmental FSPM motors is 182.44 Nm at the speed of 8563.39 rpm. The highest output power is 202.54kW at the speed of 18032.48 rpm and begins to drop to 112.23kW at the speed of 49081.66 rpm which is about a 44.59% drop. Meanwhile from Figure 9, the highest torque of four segmental FSPM motors is 162.72 Nm at the speed of 6682.09 rpm. The output power at the highest is 135.69 kW at the speed of 31391.71 rpm and output power gradually decreases about 8.55% at a value of 124.09 kW at the speed of 80230.99 rpm.

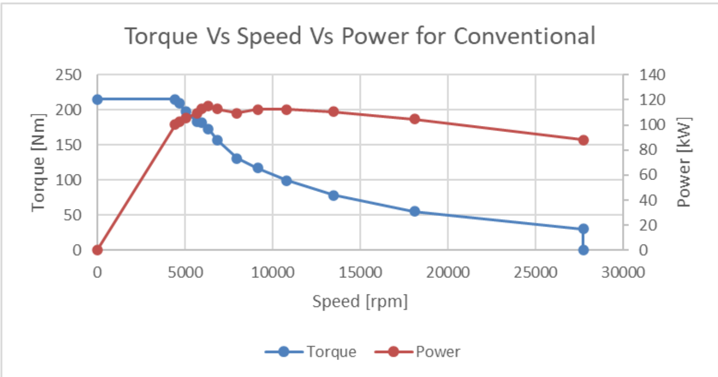

Figure 7: Torque and Power vs. Speed for conventional FSPM

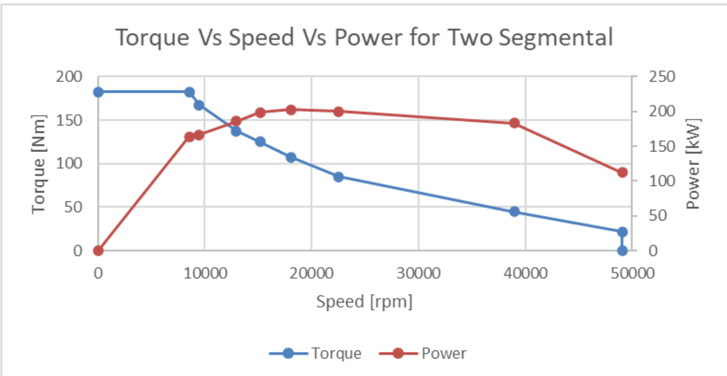

Figure 8: Torque and Power vs. Speed for two segmental FSPM

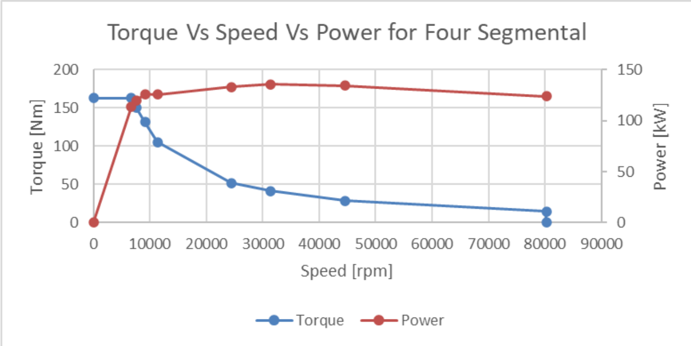

Figure 9: Torque and Power vs. Speed for four segmental FSPM

Based on all the results, it can be concluded that the conventional FSPM has the highest torque and it can affect the load that a motor can support while still producing the necessary amount of power to rotate the motor. When torque is highest, the ability to perform work. The output power of all designs will drop when the FSPM motor is operated beyond the base speed region due to iron loss.

4. Conclusion

In the conclusion, this paper is successful to propose the model design of segmental stator FSPM and compare the electromagnetic performance of all designed FSPM motors. The working principles of all three designs with various segmental is observed and verified by successful design and coil test analyses, as well as performance testing under no load and load conditions. Based on the presented results, it can be concluded that the conventional motor has the highest torque of than other two design models which can cause the speed of the motor to become slower. The segmental FSPM motor has more advantages than the conventional FSPM motor in terms of electromagnetic performance and flexibility. The meaning of flexibility here is when one segment is broken or error, the other segment will cover up. Overall, it can be concluded that the conventional FSPM has the highest torque with a value of 215.16 Nm than other designs for greater acceleration in motor and generate the lower output power to rotate the engine on its axis with the percentage of reducing output power which is 23.28%.

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