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Research paper

A Comparative Study of Single-tooth and Multi-tooth Stator of 4S-8P Permanent Magnet FSM for Electric Bicycle Application

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Abstract

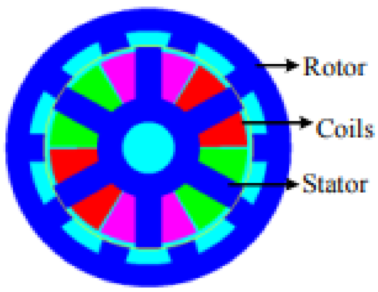
This paper present a comparative study of single-tooth and multi-tooth stator of 4S-8P permanent magnet Flux Switching Machine (FSM) for electric bicycle application. Detailed comparison of the performance characteristics of the machines are presented that include important issues such as average torque, volume of PM, back-EMF and speed performance. For a fair comparison, the valid stator slot and rotor combinations is same dimension and analyzed using finite element analysis, and the one among of the design has the best electromagnetic performance is selected. On the basis of the investigation, it can be concluded that the single-tooth design of proposed permanent magnet FSM for a single phase 4S-8P topology has presented higher torque performance compared to multi-tooth design. However, since design of single-tooth exhibits a higher back-EMF, Design optimization and improvement structural is ongoing to achieve the best performance.

Keywords: *Permanent Magnet; Electric Bicycles; Flux Switching Machines; Multi-tooth, Single-tooth.*

1. Introduction

Considerable attention have been devoted to develop more energy efficient and cost-saving traction machines for electric bicycles applications [1]-[4]. At present, switched reluctance motor (SRM) [1] [4], axial flux permanent magnet motor (AFPM) [10] and interior permanent magnet synchronous motor (IPMSM) [8-9] have be found in such applications. However, SRM is not desirable which is noisy in vibration so make this motor unattractive in this application. The latest research of Axial Flux Permanent Magnet (AFPM) motor prepared for electric bicycle applications is shown in Figure 1. These machine can deliver high torque to weight ratio, better efficiency, lower thermal and noise problems. However, there was an inherent weakness in the design and high manufacturing cost because of the high diameter of the size design motor and permanent magnet (PM). Recently, researchers and some industrial machine drive manufactures are showing interest in permanent magnet flux switching machine (FSM), due to their simple rotor structure, high torque performance and high efficiency.

Therefore, a new structure topology of 4Slot-8Pole Permanent Magnet Flux Switching Machine (FSM) for the electric bicycle applications is introduced and compared. The objective of this paper is to provide the performance characteristic comparisons of the single-tooth and multi-tooth 4S-8P permanent magnet FSM designs. For a fair comparison, both of the design topologies are designed to have same dimensions as possible to meet the specified physical and operational constraints. To achieve this objective, a design sensitivity analysis, principles of operation, torque characteristics and power of this new topology are studied by JMAG-Designer through a 2D-FEA. Permanent magnet motor size and volume is designed at 85mm and 2610mm^3, respectively.



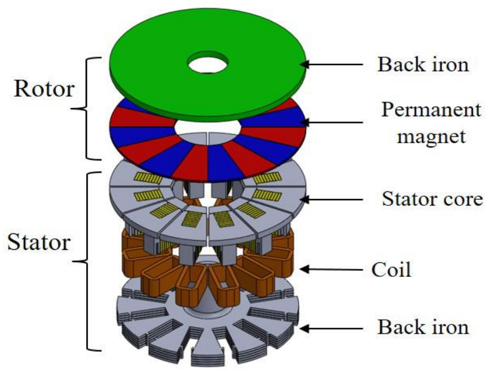


Fig. 1: Conventional Design of Electric Bicycle Design and Complete Structure of Single Phase Permanent Magnet FSM (a) Switched Reluctance Motor (SRM) (b) Axial Flux Permanent Magnet Motor (AFPM)

2. Initial Design Considerations

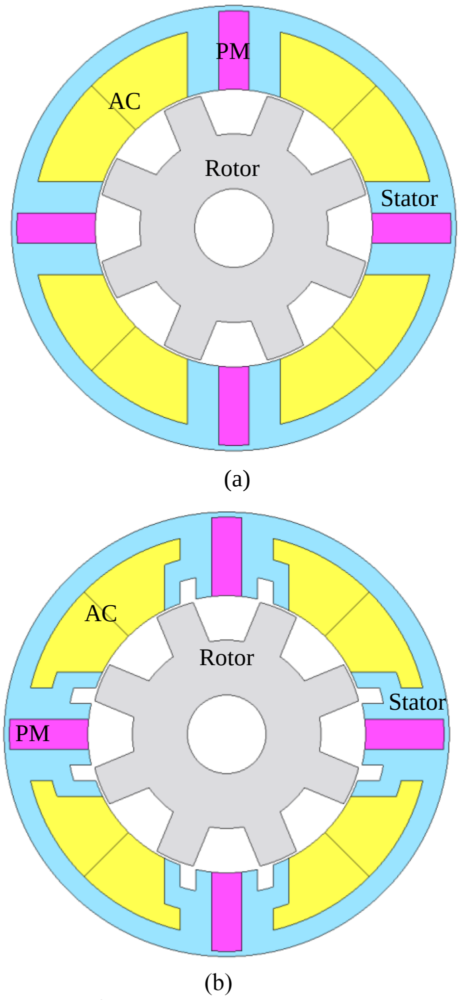


Fig. 2: Cross section of 4S-8P permanent magnet FSM design. (a) single-tooth 4S-8P, (b) multi-tooth 4S-8P

Regarding to this proposed design, the possible number of rotor pole and stator slot is defined by (1).

$$N_r = N_s\left(1 \pm \frac{k}{2q}\right) \tag{1}$$

Where Ns is the number of stator slots, Nr is the number of rotor poles, k is the natural number, entity having value 1, 2, 3 and q is the number of phases. For the suggested motor, q is 1 and Ns equal to 12. Even though the design is less slot and pole number, it can be examined as the perfect combination of slot-pole to avoid odd rotor pole number such as 10Slot-15Pole machine yielding unbalanced pulling force and also to take positive balance between rotor and stator pole width for minimizing inescapable torque pulsation.

Likewise, all armature phases use similar winding configurations and are embedded in the stator core to form the winding slot. In addition, PMs with the arrangement of other circumferential directions to each rotor tooth are used.

The initial radius of the rotor is selected according to the rotor radius of the general machine from about 60% to 70% of the total radius of the machine. The armature coil slot area is set to be rectangular shape with similar slot area as shown in Figure 1. It is clear that by rectangular coil shape, the design optimization can be carried out easily. Furthermore, the area of armature coil slot is less than the stator teeth area, so that all fluxes from armature coil are supposed to have acceptable space to flow in the stator yoke.

Since the volume of PM is limited to 2610mm3, the final machine is more reasonable to have less weight. But in comparison, much high performances to be obtained in terms of output torque and power. The type of PM material is Neomax35AH. While, the stator and rotor parts are made up of electrical steel coded 35A250 from JMAG designer. Accordingly, all armature use phases to embedded the analogous arrangements and winding in the stator core to form the winding slots. In addition, PMs with the arrangement of other circumferential directions to each rotor tooth are used.

Originally, the stator, rotor, permanent magnet, and armature coils of the machine are drawn by using Geometry Editor from JMAG-Designer ver. 14.0, published by the Japan Research Institute (JRI) to carry out the analytical study which is completed by 2D-Finite Element Analysis (FEA). The design restriction and the specifications of the proposed machine are shown in Table 1.

Table 1: Design parameter 4S-8P permanent magnet FSM

No.	Parameter	4S-8P Permanent Magnet-FSM
1	No. of phase	1
2	Number of stator pole	4
3	Number of rotor pole	8
4	Radius of inner Stator (mm)	26.5
5	Radius of outer Stator (mm)	42.5
6	Radius of outer Rotor (mm)	22
7	Radius of inner Rotor s(mm)	7.5
8	Width of Rotor tooth (mm)	7.5
9	Width of stator tooth (mm)	5.95
10	Height of stator pole (mm)	15
11	Height of rotor pole (mm)	8
12	Stack length of motor (mm)	20.3
13	length of air gap (mm)	0.25
14	Volume of PM (g)	80

3. Performance Analysis Based on 2D Finite Element Analysis

The performance correlation is accomplished in open circuit and closed circuit. The open circuit magnetic test incorporates flux linkage and distribution, induced voltages and cogging torque while closed circuit magnetic research consists of torque characteristic, torque power curve versus speed and efficiency analysis.

3.1 Flux linkage performance

The amplitude of PM generated magnetic flux linkage for single-tooth and multi-tooth design is achieved by rotating rotor at the speed of 500 r/min while armature current density is set at 0 A/mm^2. A comparison of the and multi-tooth 4S-8P for PM-FSM design is shown in Fig. 3. Result reveal that the flux linkage of single-tooth is at 0.48Wb which is much higher compared to design multi-tooth is at 0.25Wb. But all of these design still getting higher flux linkage performance compare to the conventional SRM at only 0.09Wb. The flux is multiplied on the grounds because the rotor pole height is lessening, indicating that the flux may take longer to complete a cycle. In addition, flux leakage and flux cancellations have been minimized, which also influences the magnitude of the flux link.

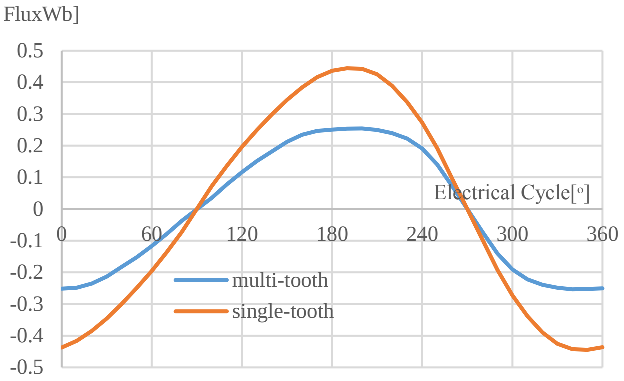


Fig. 3: Flux Linkage Analysis Performances

3.2 Back EMF Performance

Back electromagnetic force (EMF) is commonly referred to the voltage that arises in electric motors when there is relative movement between the motor armature and the magnetic field of the motor field magnets, or windings. Fig.4 shown that both PM-FSM design waveform shows a more favourable sinusoidal feature with amplitude of single-tooth approximately 173V compare to multi-tooth that only 97V. The voltages generated by PM-FSM design are higher than the conventional of AFPM which is at 12.9V because induced Electromagnetic Force (EMF) is directly proportional to the flux linkage. Since the amplitude of the magnetic flux is increased, the back EMF are also increased. In addition, high back EMF can be used for a regenerative braking system to charge the source.

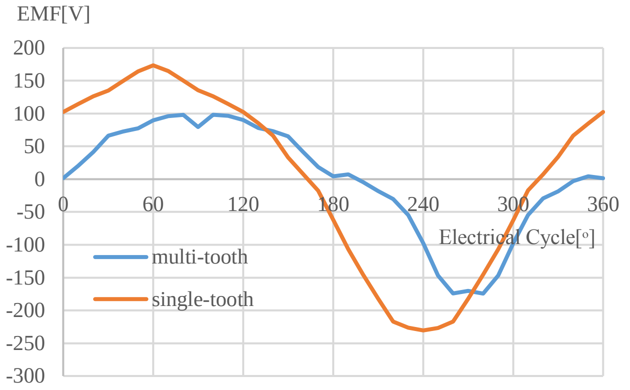


Fig. 4: Back Electromagnetic Force (EMF) Performances

3.3 Average Output Power and Torque at Various Armature Current Densities

Therefore, Fig.5 and Fig.6 proves the output torque waveforms gained on the basis of Finite Element Analysis (FEA) at maximum current density. The design of single-tooth permanent magnet FSM was found to be 3.4Nm compare to the multi-tooth design is at 2.9Nm. This situation has proven that the higher amount of armature current density, Ja, would be generated the higher torque. This is a big improvement on the PM-FSM with a robust rotor structure that allows much higher torque and is suitable for the use of electric bicycles.

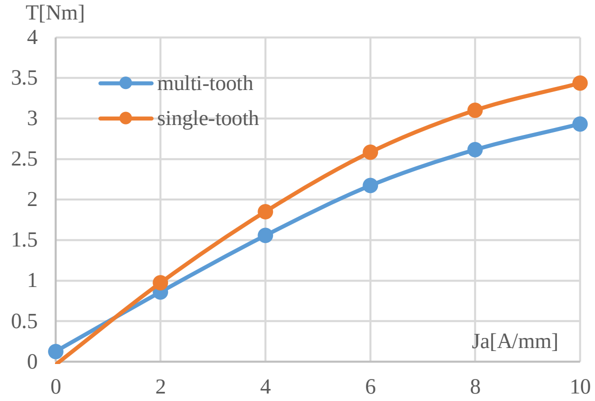


Fig. 5: Torque against armature current density, Ja

Meanwhile, resulting data for power performance of proposed single-tooth and multi-tooth design PM-FSM structure design has contributed the output power approximately gauged at 124W. According to the figure, the power increase from Ja of 2Arms/mm^2 and reached the maximum reading at Ja of 10Arms/mm2 but start declining thereafter until Ja of 10 Arms/mm2.

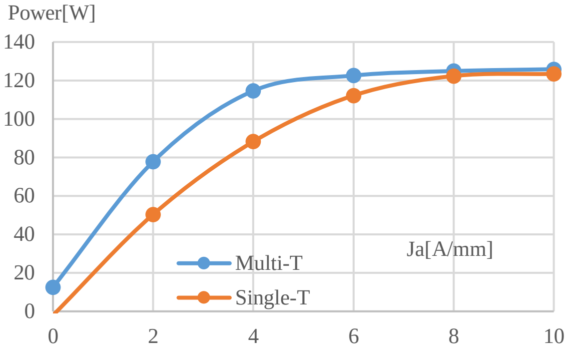


Fig. 6: Power against armature current density, Ja

3.4 Torque and Power versus Speed Characteristic

In the proposed PM-FSM design, the maximum output torque amplitude for single-tooth design is 3.4Nm at the base speed of 498rpm while the corresponding power is 220W as shown in Fig.7 and Fig.8. The torque increment is due to the increment of the number of turns. Then, selecting the optimal split ratio plays its role in improving the output torque. In addition, the output power of single-tooth design generate is 187W, which is slightly lower than the multi-tooth design with 2.9Nm torque and 490rpm speed performance. Therefore, by further refining and optimizing the design, it is foreseeable that the energy performance of the proposed machine can be improved under appropriate conditions.

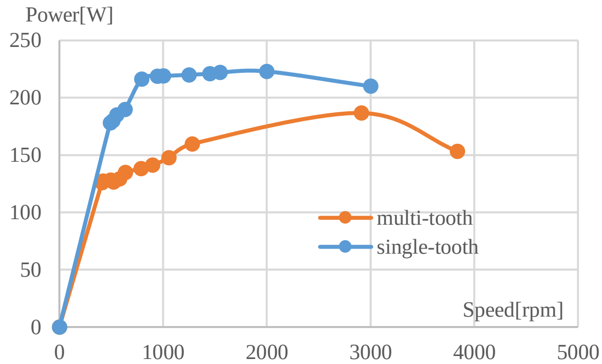


Fig. 7: Power versus speed characteristics

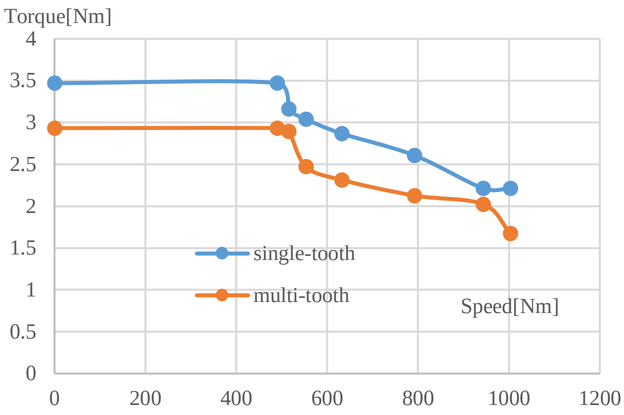


Fig. 8: Power versus speed characteristics

4. Conclusion

This paper has presented a quantitative comparison among these two different types of 4S-8P permanent magnet FSM topologies for electric bicycles applications. The summarized key observations include:

1) The multi-tooth core permanent magnet FSM has a minimum usage of PM and copper materials, hence a low manufacturing costs can be accomplished. However, design optimization must be performed to further increase torque performance.

2) The C-core single-tooth permanent magnet FSM has the highest torque performance. However the values are very close to the multi-tooth design. Also exhibits a largest value of back-EMF and cogging torque. Therefore, design modification must be performed to further reduce back-EMF and cogging torque performance.

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