Influence of Various Tooth Shape Topology for Single-Phase Permanent Magnet Flux Switching Machine

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Abstract. Permanent magnet flux switching machine (PMFSM) has the advantages of solid design structure, high torque performances, and high efficiency. The method to increase performance and decrease the cost of the motor through a selection of numbers of slot and pole is a major issue that needs to be solved. Therefore, to further improve the electromagnetic torque, a novel 4-4S-8P multi-tooth, 4S-8P segmental-tooth and single-tooth PMFSM machine respectively is proposed based on the slot pole analysis performance. Hence, the performance is including the flux linkage, cogging torque, back-electromotive force (back-emf), output torque, and power performance. The results display that the various tooth shape topology have a large impact on the performance design. JMAG Designer version 14.3 under 2D finite element analysis (2D-FEA) are used to complete the analysis. The results show that the right combination of a single-tooth 4S-8P PMFSM structure is the best choice according to the high performance of torque analysis.

1. Introduction
The Flux Switching Machine (FSM) was started in the mid-1950s and first published [1]. Various new machines have become FSM topologies in a broad range of applications, from commercial vehicles to wind, wind and space, and has become popular lately. A new FSM motor are very easy to construct together by the power of an electronic controller. It requires only two semiconductor switches that drive power and has the potential for high volume, cost-efficient products. Furthermore, the flux switching has an electronically commutated brushless motor that has a much longer life offers highly accurate and more flexible torque and a higher speed at no additional cost [2]. FSM has a variable speed application that has been considered a possible candidate for any potential motor design because of their major improvements [3].

The PMFSM has a brief history and it is an unknown type of PM machines. There were resurrected research interests in PMFSM, certainly due to the number of anticipated benefits. Given that the dynamic parts, for example, the armature windings and the PM configured in the stator directly, but adequate cooling of the machine is easily associated. Moreover, additional advantages, like robust rotor structure, high torque, and flux densities, high performance and improve flux weakening ability are systematically analysed and monitored for different applications. Most recently, the design machines with multi-tooth, segmental and single-tooth design, have been investigated [2, 4, 5].

This analysis, to improve further the performance of motor, a proposed topology 4-4S-8P multi-tooth, 4S-8P for segmental and single-tooth PMFSM design respectively is proposed based on the slot pole analysis performance. Arranging of the paper analysis is being monitored. Formative process of
the various tooth shape topology is illustrated, and consequently, operation principle of various tooth shape is compared by 2-D finite-element analysis (2-D-FEA) in the second section. Subsequently, performance comparisons between all three design machines, in conditions of no-load for example, flux linkage and back-EMF performance, and in load performance such as an electromagnetic torque and power are performed in the section 3. Lastly, highlighted conclusions have been illustrated in the section 4.

2. Operation Principle of Various Tooth Shape Topology for Single-Phase Permanent Magnet Flux Switching Machine

Primary machine geometrical dimension is identical in the. Fig. 1. It displays the enlarged motor with the original size of the main machine parts including for example in the space between the rotor and stator, the rotor length and armature coil, and stator yoke diameter. This model, from a practical point of view, the stator diameter for all the three motors has been fixed at 85 mm. The requirements and characteristics of all three design of PMFSM are presented in the table 1. The cross-section of the multi-tooth, single-tooth and segmental-tooth design has been shown in Fig. 2. Eventually, the design was formed by using a JMAG Software Designer version 14.3.

![Figure 1. Main machine dimension of the proposed PMFSM](image)

| Item                  | PMFSM             |
|-----------------------|-------------------|
| phase                 | 1                 |
| Pole/slot             | 4S-8P             |
| Air gap (mm)          | 0.25              |
| Current density (mm²) | 3.5               |
| Stator Radius (mm)    | 42.5              |
| Rotor Radius (mm)     | 22                |
| Stack length (mm)     | 30                |
| Permanent magnet (g/slot) | 14             |
| Stator yoke (mm)      | 4.5               |
| DC Voltage (V)        | 36                |
Figure 2. The topology of the purpose design motor in PMFSM, a) Multi-tooth, b) Single-tooth, c) Segmental.

Design specifications for dimensions of the motors and the workflow for 2D analysis are illustrated in the Fig. 3. The design specification and conditions for all the design motor should be similar. The project implementation has been divided into two phase which are the design and analyse the performance of PMFSM respectively. Geometry editor is applied to design all the motor part separately for example in the rotor, stator and armature coil whereas the simulation and setting of condition of the motor formed by utilizing the JMAG-Designer.

2.1. The Possible Combinations of Stator and Rotor Pole Number for Single-Phase Multi-tooth Design

In order to achieve high performance design, the best possible combination of the number of poles needs to be set [6]. Therefore, some relevant parameters are considered to propose the potential combination of the stator and rotor poles number [7]. This slot and poles combination can be identified using (1) and (2).

\[ N_s = k m \ (k=2, 4, 6\ldots) \]  

\[ N_r = N_s (2n-1) + 1 \]  

The number of stator and rotor poles will be the \( N_s \) and \( N_r \), respectively, while number of phases is \( m \). More generally, the number of rotor pole and slot pole especially for single phase should be even in order that the machine can be designed such that a phase winding comprises a coil that has a phase shift of 180 electrical degree among the coils.
2.2. *The Possible Combinations of Stator and Rotor Pole Number for Single-Phase Segmental-tooth and Single-tooth Design*

Preliminary, according to design of single-tooth and segmental PMFSM, the number of stator slot should be even multiple of phase numbers. In this aspect, the relationship between stator slot number, $N_s$ and rotor pole number, $N_r$ is [8];

$$N_r = N_s (1 \pm \frac{k}{2q})$$  \hspace{1cm} (3)

Therefore, the symbol of $(k)$ and $q$ is a natural entity with its value of 1,2,3 and by the number of phases respectively. Furthermore, the electric frequency $(f_e)$, of a proposed motor can be designated as (4).

$$f_e = N_r * f_m$$  \hspace{1cm} (4)
Consequently, $f_e$ and $f_m$ is the electric frequency and the mechanical rotation frequency. The current of armature coil ($I_a$) and number of turns ($N_a$) is determined through the (5) and (6), separately whereas considering diameter specification used for the copper is 0.56mm.

$$I_a = \frac{j_a S_a}{N_a} \sqrt{2} \quad (5)$$

$$N_a = \frac{\alpha S_a}{\pi (A_{copper})^2} \quad (6)$$

Subscripts ‘a’ indicates armature coil, $j_a$, $S_a$, and $A_{copper}$ are current density, slot area (mm²), and area of copper, respectively. Through the analysis, the appropriate electrical limit to the inverter is 240V DC bus voltage and 2.47 Arms for the maximum current of the inverter, while $j_a$ 10 Arms/mm² are set to correspond to the current density in the armature coil. Since the design of the multi-tooth structure is different, the slot area of 207.9mm² for multi-tooth design and 216.88mm² for the single-tooth and segmental-tooth, respectively. In addition, the particle volume is set at 14g maximum for each slot with using an irreversible NEOMAX-35AH material. In the meantime, for the stator and the rotor, an electromagnetic 35A250 type of steel is used. To ensure the flux flows uniformly without any leakage from the stator to rotor, the motor’s filling factor ($\alpha$) are set to 0.5. The power is found using equation (7), and that is proportional to the torque and speed analysis.

$$P = \frac{2\pi}{60} * T * S \quad (7)$$

3. Comparison of the Proposed Design

All the three design performance the comparison is done in the open and close circuit circumstances. The open circuit test includes flux linkage and induced voltages (back-emf) whereas close circuit analysis consists of torque at different armature current densities while torque and power at various speeds respectively.

3.1. Magnetic Flux Characteristics

Before observing the flux linkage performance, the coil arrangement test is analysed on each armature coil separately in order to verify that the principle operation of the PMFSM and to set the position of each phase of the armature coil. By set a rotating rotor at speed of 500 r/min and zero armature current, the magnetic flux linkage is generated by magnitude of PM.

![Figure 4. Flux linkage at armature coils.](image)
Consequently, Fig. 4 shown the flux linkage for multi-tooth, single-tooth, and segmental-tooth design and findings showed that single-tooth design has the largest flux linkage which it is 0.45Wb supported by multi-tooth design with 0.25Wb. The lowest flux of approximately at 0.05Wb is produced by segmental-tooth design. Initially, flux distortion occurred due to the higher back-emf. The higher back-emf will encourage higher flux distortion. However, the future optimization method analysis can perform a balance magnetic flux.

3.2. Back EMF Characteristics
Results achieved of back-EMF are presented in the Fig. 5. From all the three design, waveform of back-EMF is distorted, and that is occurred due to the higher flux linkage performance. The voltages generated by the design of single-tooth are higher in comparison to other design motor roughly at 163V. In general, the back-emf flux is linearly in performance of flux linkage analysis. When the magnitude of the flux linkage increases, the back-emf is will also increase. Furthermore, higher back-emf may be used for regenerative braking systems for charging source. Moreover, voltage from back-emf is even smaller than the voltage applied to the motor that makes it easy to ensure protection due to some faults [9].

![Figure 5. Back-emf at no load performance.](image)

3.3. Load Performance
As a final analysis of load performance, armature current density is set at the maximum current condition. Hence, Fig.6 and Fig.7 proved the result of the torque and power output performance at minimum current density, namely Ja 0 Arms² to maximum current density, which is Ja 10 Arms². It proved that the maximum torque and power performance is coming from the single-tooth design motor with approximately 4.1Nm and 166W, accordingly followed by multi-tooth and segmental-tooth design.
Figure 6. Simulation power at load performance.

However, the increment of power for segmental-tooth design is seem not to be linear may be the cause of the iron and copper losses occur. Meanwhile the design of single-tooth and multi-tooth appears to produce a high torque linear value when zero current density at Ja 0 and slightly increase with high current value at Ja 10. Thus, plot in linear demonstrates that design has ability to achieve very high torque value with increase the current density. A multi-tooth design has been found that 75W of power and 2.1Nm torque performance respectively, compare to the segmental-tooth at 46W and 0.7Nm power and torque performance respectively. This condition revealed that the high value of flux linkage, will develop greater torque performance. It remains, the overall effect on the proposed designs are visualized in Table 2.

Figure 7. Simulation torque at load performance.

Table 2. Comparison Performance of Various Tooth Shape Topology

| Item            | Unit | Multi-tooth | Single-tooth | Segmental-tooth |
|-----------------|------|-------------|--------------|-----------------|
| Flux linkage    | Wb   | 0.25        | 0.45         | 0.04            |
| Torque          | Nm   | 2.16        | 4.14         | 0.70            |
| Power           | W    | 75.64       | 165.55       | 46.34           |
| Speed           | Nm   | 333.70      | 381.00       | 626.50          |
| Torque ripple   | Nm   | 4.48        | 2.13         | 13.8            |
4. Conclusions
In the present paper, the impact of various tooth shape topology for single-phase permanent magnet flux switching machine has been presented. Three topologies, multi-tooth, single-tooth and segmental-tooth with concentrated windings were examined and compared. To identify the best design among them, especially in terms of flux, torque and power, no load and load test have been carried out. Builds on the 2-D FEA, the single-tooth design has been selected for the future analysis due to the highest torque of 4.1Nm, the largest flux linkage of 0.45Wb, and power of 166W. Furthermore, the voltage of back-emf for this design was considered proportionate and prevalent in motor design due to high performance of flux linkage.

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