Analytical Design Structure of New Segmental Stator Permanent Magnet Flux Switching Motor

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Abstract. Permanent Magnet Flux Switching Machines (PMFSM)s are among the most widely investigated types of electric motor because of high flux density compared to switch reluctance motor (SRM). The aim of the present work is to design a three phase 12Slot-14Pole segmental stator (SegSta) PMFSM and to investigate the flux linkage of U, V, W phase. In this study, 12S-14P SegSta PMFSM is investigated by using 2-D finite element analysis (FEA) software develop by J MAG designer ver 15.0. The geometry structure of the 12S-14P PMFSM design is 264 mm diameter and the permanent magnet total weight is approximately 2 kg. The results of the 2-D FEA simulation indicate that the open angle between each SegSta is 30 degree for uniformly flux distribution in each SegSta core. It is found that the amplitude difference for each U, V, W phase is approximately zero since at 30 degree the flux density is evenly distributed at stator core with concentrated winding. Overall, this paper contributes to the methodology for designing a segmental stator 12Slot-14Pole PMFSM.

1. Introduction
Evidence suggests that inherent tolerant and unique characteristic is among the most important factors of electric machine, specifically the alternating current (AC) machine. Generally, the type of AC machine design can be categorised into induction machine (IM), switched- reluctance machine (SRM) and permanent magnet (PM) based machine. Among these machines, IM have the advantages of low cost and simple motor controller which have been widely used in lightweight applications but have low torque and efficiency [1]. In contrast to IM, SRM have a major advantage against IM which is the independent concentrated phase winding but both IM and SRM have similarities of low torque performance. If no PM based machine is considered low torque performance because of only reluctance torque, therefore a PM based machine proven to have a high flux density and high torque output because of the PM as an magnetic torque[2]–[5].

As discussed before, a PM based machine can be group into interior PM machine (IPM), surface-mounted PM machine (SPM), PM flux switching machine (PMFSM) and hybrid- excitation flux switching machine (HEFSM) [6]–[11]. Design-wise, the PMs in the IPM are incorporated in the rotor structure, contrary to the commonly used surface-PM machine. It is thought to achieve higher efficiency and have been widely used in industrial and domestic appliances because of the system requiring high power density and high efficiency [12]–[14]. Moreover, IPM’s have a wide constant power speed range and this been associated with traction.
appliances such as electric vehicles [15], [16]. Another machine known as surface-mounted permanent magnet synchronous machine (SPMSM) is developed for industrial applications such as an auxiliary power unit, robotic arms, electrical tools due to high power rating appliance [17], [18]. Furthermore, there are several complicated PM shapes model in SPMSM such as skew, V-type skew, and X-type skew model in which proved that torque ripple and axial force is lower in V-type skew [19], [20].

Besides, recent years show that a permanent magnet flux switching machines (PMFSM) efficient development in drive system and FEA design software attract more researcher attention and special interest due to their high torque density, high efficiency and rigid rotor assembly [21]. In addition, PMFSM machines have indicate improvement in comparison to a synchronous machine in high speed range generator, due to compelling part to relief of PM demagnetization in high-speed operation [22]. Moreover, SFPM machine have been redesigned to obtain a sufficient torque density that are better than most doubly salient PM machines [23].

Thereby, by combining the unique independent slot of SRM and high magnetic flux from PMFSM would improve the reliability and fault tolerance of machine. This paper focus on the initial design methodology of segmental stator (SegSta) configuration of PMFSM to provide short-end winding, concentrated flux path and fault-tolerant [24], [25]. SegSta structure could isolate each phase winding or each group of winding to be independent and without any medium interconnect between each segmental stator. Figure 1 overview the segmental stator structure and conventional salient stator structure of PM based machine.

![Figure 1. Overview of segmental stator structure in PM based electric machine.](image)

2. Analytical design structure of 12S-14P SegSta PMFSM

In this section, the initial design methodology of the propose 12Slot-14Pole SegSta PMFSM will be analyse into three subsections, which is rotor, stator core and armature slot design methodology. The concept of the segmental stator core is made up of discontinued section or known as the segments. For each individual segment, there is a C-core stator shape where a PM is located between them and alternately arranged together with both end of each segments occupy a half C core shape stator. Therefore, flux produce from the PM have a shorter path and form a small loop at the C-core stator when the respective phase is excited. Besides, the degree of gap is a non-magnetic material or airgap.
2.1. Rotor design method

Figure 2 shows the parameters of salient rotor structure of the proposed SegSta PMFSM and the following equations are used in the process of designing rotor structure. Initially, sum of all stator teeth width, $W_s$, is equal to the sum of all rotor teeth width $W_r$.

$$W_r = W_s \quad (1)$$

Meanwhile, the outer radius of rotor, $R_{ro}$, is calculated as equation below:

$$R_{ro} = \left[70\% \times Stator_{ro}\right] - G_{air} \quad (2)$$

$$R_{ri} = 30 \text{ mm} \quad (3)$$

where the air gap distance, $G_{air}$, is 0.5 mm. Afterwards, inner radius of rotor is calculated as

$$R_{rip} = \left[\frac{R_{ro} - R_{ri}}{2}\right] + R_{ri} \quad (4)$$

Since the circumferential of rotor is as follow

$$L_{rotor\;outer} = 2\pi \times R_{or} = 580.57 \text{ mm} \quad (5)$$

Therefore, rotor pole width can be determining as equation (6):

$$R_{pw} = \frac{L_{rotor\;outer}}{\text{Number of rotor pole} \times 2} = 20.73 \text{ mm} \quad (6)$$

2.2. Stator core design method

Figure 3 illustrates the proposed segmental stator structure of PMFSM with the define parameters based on analytical method. From the figure, the dimension of stator outer radius, $S_{or}$, and the stator inner radius, $S_{ir}$, is limited to 132 mm and 92.9 mm. Then, the stator teeth width, $S_{tw}$, is defined to be

Figure 2. Salient rotor structure of SegSta 12S-14P PMFSM
equal with permanent magnet width, $PM_{width}$ which is 8.0 mm. In addition, the parameter of stator back radius, $S_{bir}$ is calculated and set to 124 mm. Meanwhile, the angle span between each segmental stator, $\theta_{seg}$ is define based on [26]. Figure 4 is the magnified view for single segmental stator with parameter.

Since $S_{OR} = 132$ mm, air gap = 0.5 mm then

$$S_{lr} = 70\% \times S_{or} = 92.9 \text{ mm}$$ (7)

$$S_{sh} = S_{or} - S_{lr} = 39.1 \text{ mm}$$ (8)

Assume that the $PM_{length} = S_{sh} = S_{or} - S_{lr}$, then

$$PM_{width} = \frac{PM_{mass}}{\text{Stack length} \times (S_{or} - S_{lr}) \times \text{Number}_{PM} \times \text{Density}_{PM}}$$ (9)

$$L_{stator\_outer} = 2\pi \times S_{or} = 829.4 \text{ mm}$$ (10)

$$L_{stator\_inner} = 2\pi \times S_{lr} = 583.7 \text{ mm}$$ (11)

Since opening angle of segmental stator, OA = 30° = $\theta_{seg}$ and total of $\theta_{seg} = 120^\circ$, then

$$L_{seg\_so} = \frac{1}{3} \times L_{so} = 276.5 \text{ mm}$$ (12)

$$L_{seg\_si} = \frac{1}{3} \times L_{si} = 194.3 \text{ mm}$$ (13)

Assume stator pole width $S_{tw} = PM_{width} = 8$ mm and $S_{bil} = S_{tw}$, then

$$Slot_{lw} = \frac{L_{si} - L_{seg\_si} - 12PM_{length} - 24Stator_{tw}}{2(\text{Number of slot}=12)}$$ (14)
2.3. Stator core design method

Since the area of armature slot $S_A$ can be estimated by considering the general equation of a trapezoidal area as follow:

$$S_A = \frac{1}{2} (b_1 + b_2) \times h$$

(16)

where $b_1$ is the length of inner slot area, $b_2$ is the length of outer slot area and $h$ is the height of the slot area as follows:

$$b_1 = Slot_{tw}$$

(17)

$$L_{Sbir} = 2\pi \times S_{bir} = 779.11 \text{ mm}$$

(18)

$$L_{segsbi} = \frac{1}{3} \times L_{Sbir} = 259.70 \text{ mm}$$

(19)

$$b_2 = \frac{L_{Sbir} - S_{tw}N_s}{2N_s}$$

(20)

$$h = S_{bir} - S_{ir}$$

(21)

Substituting Equations (17), (20) and (21) into (16) yields

$$S_A = (S_{bir} - S_{ir}) \times (Slot_{tw} + \frac{L_{Sbir} - S_{tw}N_s}{2N_s})$$

(22)

With $W_A$ are considered as the armature, areas of $S_A$ can be simplified as follows:

$$S_A = [S_{bir} - S_{ir}] W_A$$

(23)

Therefore, the complete initial design of three phase SegSta 12S-14P PMFSM with segmental stator model is illustrated in figure 5, while the design parameters are listed in Table 1.

| Table 1. Design parameters of three phase 12Slot-14Pole SegSta PMFSM. |
|---------------------------------------------------------------|
| Parameters              | Dimensions |
| Number of phases       | 3          |
| No. of slots           | 12         |
| No. of poles           | 14         |
| Stator outer radius (mm), $S_{or}$ | 132   |
| Stator inner radius (mm), $S_{ir}$ | 92.9  |
| Stator back inner width (mm), $S_{bir}$ | 124  |
| Stator tooth width (mm), $S_{tw}$ | 8      |
| Rotor outer radius (mm), $R_{oro}$ | 92.4  |
| Rotor inner radius (mm), $R_{ori}$ | 30     |
| Rotor tooth width (mm), $R_{pw}$ | 11.8   |
| Open Angle, $\theta$ (°) | 30      |
| Rotor shaft radius (mm) | 15      |
| Air gap space, $G_{air}$ (mm) | 0.5    |
3. Results and Discussion

In order to validate the operating principle of the proposed design based on U-phase, V-phase, and W-phase, 2-D finite element analysis (FEA) has been performed to analyse the electromagnetic behavior. Moreover, it is significant to analyse the magnetic flux linkage and flux characteristic of the propose design since it determine the output performance of the electric motor. From figure 6, it is clearly demonstrated that the 120° phase difference between U-phase, V-phase and W-phase at zero rotor position despite the stator core is independent and segmental. The amplitude of flux linkage is 0.025 Wb at 180° for U-phase, at 60° for W-phase and at 300° for V-phase.

![Figure 5. Model of 12Slot-14Pole SegSta PMFSM](image)

![Figure 6. Flux linkage of U, V, W phase.](image)
4. Conclusion

This study set out to evaluate a new method of designing an initial design of SegSta 12Slot-14Pole PMFSM and the proposed fault-tolerant design structure has been studied and presented. The flux linkage of the proposed design showed that the segmental stator is the new fault-tolerant design able to give a uniform three phase sinusoidal waveform which is the fundamental of electrical machine.

5. References

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