The Influenced of Different Magnetization Patterns on the Performance of the Semi-buried Permanent Magnet Synchronous Machine

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Abstract. The performance of semi-buried permanent magnet synchronous machines (SBPMSMs) by the influence of two magnetization patterns are presented in this paper. These magnetization patterns include radial and parallel, which applied into 9-slot/8-pole (9s/8p) and 6-slot/4-pole (6s/4p) SBPMSMs. Hence, to evaluate the machines performance, AutoCAD and Opera2D finite element software are used to model and predict the electromagnetic characteristic performance of SBPMSMs. Two PM machines are optimized i.e. flux density distribution, phase back-EMF, and cogging torque by two magnetization patterns. The phase back-EMF of the machines are computed into harmonic components to investigate the total harmonic distortion (THDv). It is found that the lowest THDv for both 9s/8p and 6s/4p motors are in parallel magnetization (PaM), which are 8.66% and 3.98%, respectively. However, the lowest cogging torque for 9s/8p is radial magnetization (RaM), which is 0.0101 Nm and for 6s/4p is 0.1730 Nm with parallel magnetization pattern. By comparing the result of the optimum magnet pole arc for both motors, the 6s/4p motors show the minimum cogging torque and harmonic distortions are 0.16 Nm and 1.63% in PaM patterns. As a result, optimum motor performances among these two motors are 6s/4p PM motors with PaM pattern.

1. Introduction

The material of permanent magnet (PM) can occur magnetic field in that area [1]. Permanent magnet synchronous machine (PMSMs) is very popular in industrial application because it gives a good interest in high performance and good efficiency in the electrical motor[2]. Also, PMSMs is another excellent option for a complete range of motion control applications. For example, the PMSMs are broadly used in robotics, device equipment, actuators, and are being considered in most applications, consisting of commercial drives and vehicular propulsion. There are several rotor topologies of PMSMs which
classified as surface-mounted, surface-inset, and interior design. In surface-mounted, the magnets are usually magnetized radially. The attachment of the magnet on the rotor surface gives the construction of the motor is simple and cheap. While surface-inset PM machine, the permanent magnet is radially magnetized and is inserted in the sunken space of the rotor. For the interior of the PM machine, the magnet is buried inside the rotor.

Several problems that need to overcome in SBPMSMs are cogging torque, phase back-EMF, and total harmonic distortion (\(THD_v\)). The minimization methods have been studied by the researcher on the influence of design parameters on cogging torque, such as proper tooth-tip design, skewing, and rotor shaping [3]. The researcher briefly investigated the effect of cogging torque on the PM machines when changing the pole-pitch of rotor magnet, where the cogging torque is produced by the interaction between rotor magnets and the tooth [4]. According to [5], the effect of cogging torque has appeared when the interaction between the permanent magnet and the slotted iron structure happens. So, the approach of stator skewing has been employed to reduce the cogging torque. Meanwhile, a phase back-EMF study that is influenced by the PM pole-pitch is carried out during the motor rotates [6]. On the other hand, \(THD_v\) is the harmonics contents of the phase back-EMF, which is further investigated when the magnet pole-arc is changing [7].

Whereas, the surface-inset PM machines can provide better protection against demagnetization, but many materials are needed. Meanwhile, interior design PM machines are good, but the flux density is low in the air-gap. However, the research on the semi-buried PM machines is still lacking. Therefore, this project focuses on semi-buried permanent magnet synchronous machines (SBPMSMs).

This paper is structured, followed by the specification PM machines in Section II. Section III are demonstrated the FEA modelling with the simulation of SBPMSMs. The FEA outcomes with phase-back EMF and cogging torque with RaM and PaM patterns are presented in Section IV. The performances of SBPMSMs are predicted with varying rotor pole span under various magnetization patterns in Section V. Concluding remarks are presented in Section VI.

2. Specification PM Machines

Basic machines sizing equations are used to obtain the machines dimensions for 9s/8p and 6s/4p SBPMSMs with non-overlapping machines. Initially, several parameters are set for 9s/8p and 6s/4p SBPMSMs to determine the machines dimensions equations, and the dimension is tabulated in Table 1. Then, the average flux density in the air-gap, \(B_g\), is calculated by

\[
B_g = \frac{B_r}{1 + \frac{\mu_r l_g}{l_m}}
\]

(1)

| Specification                  | 9s/8p | 6s/4p |
|-------------------------------|-------|-------|
| The thickness of magnet (mm)  | 3.0   | 3.0   |
| Active length (mm)            | 50.0  | 50.0  |
| The radius of the outer stator (mm) | 50.0 | 50.0 |
| Height of stator (mm)         | 5.2   | 9.0   |
| Height of tooth body (mm)     | 9.2   | 12.0  |
| Height of Tooth-tip (mm)      | 4.0   | 5.2   |
| Height of stator opening (mm) | 2.5   | 2.5   |
| The radius of stator bore (mm)| 26.9  | 23.5  |
| Length of air-gap (mm)        | 1.0   | 1.0   |
| The radius of outer magnet (mm)| 25.9 | 22.5 |
| The radius of outer rotor (mm)| 22.9  | 19.5  |

Where \(B_r\) is the remanence of a magnet is 1.2 T, \(\mu_r\) is the relative permeability of magnet is 1.05, \(l_g\) is
the thickness of the air-gap and $l_m$ is the thickness of the magnet. The optimum split ratio can be determined in

$$\frac{D_x}{D_y} = \frac{-b - \sqrt{b^2 - 4ac}}{2a}$$

(2)

The dimension of stator tooth needs to be determined for magnetic flux crossing in a sloth-pitch, so the total flux per stator tooth, $\phi_{sp}$

$$\phi_{sp} = B_s \times \left( \frac{2\pi R_s}{N_s} \right) l_a$$

(4)

Besides that, a portion of the fluxes from PMs enter the tooth-pole through tooth body width surface and crosses the tooth-tip height. After that, the total flux crossing the tooth-tips height, $\phi_x$, is expressed in (5)

$$\phi_x = \left[ \frac{2\pi R_s - W_{tb}}{2} \right] l_a$$

(5)

The total flux per pole-pitch, $\phi_{pp}$ produced by an arbitrary magnetic pole, for example, the South pole is separated into two paths where is passing through the rotor yoke area, Ary and going to North pole. So, the total flux per pole-pitch that crosses the magnet surface, $\phi_{pp}$ can be calculated in (6)

$$\phi_{pp} = B_p \left( \frac{2\pi R_{im}}{N_p} l_a \right)$$

(6)

3. Finite Element Modelling and Simulation

The outcome of this paper is evaluated by using Opera 2D FEM and presented in this section. The machines performance i.e. air-gap flux distribution, phase back-EMF, and cogging torque for 9s/8p and 6s/4p of SBPMSMs are discussed. The complete model of both SBPMSMs with the conductor number of stator coil is shown in Figure 1.

Figure 2 shown magnetic fluxes during the open-circuit test on 9s/8p under different magnetization patterns of SBPMSMs. Based on Figure 2, the most magnetic fluxes of 6s/4p for both magnetization patterns do not significantly differ. However, for magnetic fluxes for RaM and PaM pattern give 1.48T and 1.57T respectively. Figure 2 shows that the highest magnetic fluxes in 6s/4p machines with RaM and PaM patterns are weighted in the purplish region, the stator tooth body at 0º and 180º. Besides that, maximum of the magnetic flux density across the stator pole on the 6s/4p SBPMSMs is located between the east and west regions, as agreed with the magnetic fluxes potential shown in Figure 2.

Figure 3 shows the radial component of magnetic flux distribution, $B_r$, among RaM and PaM patterns on 9s/8p and 6s/4p SBPMSMs. Figure 3 (a) shows that the amplitude of $B_r$ produced by the SBPMSMs with RaM pattern is slightly bigger than that of the PaM pattern; however, the radial magnetic flux density produced by both magnetization patterns in the mid-air-gap is almost the same. Based on Figure 3 (b), $B_r$'s amplitude by the SBPMSMs with RaM is slightly bigger than that of the PaM pattern. The radial component of magnetic flux density with RaM is somewhat smaller than that of the PaM pattern. The effect of the slot opening on the radial component of magnetic flux density for 9s/8p machines is 100º, 140º, 180º, 200º, and 264º. Meanwhile, for 6s/4p motor, the PaM pattern can produce a more sinusoidal waveform of $B_r$; however, the RaM pattern can create a more trapezoidal waveform of $B_r$. Therefore, the amplitude of radial magnetic fluxes in the mid-air-gap of the SBPMSMs with RaM pattern is higher than that of the PaM pattern.
Figure 1. Complete model of the SBPMSMs with the conductor number of stator coil. (a) 9s/8p (b) 6s/4p.

Figure 2. Magnetic fluxes during open-circuit test on 6s/4p of SBPMSMs (a) Radial (b) Parallel

Figure 3. The $B_r$, at the mid-air-gap for SBPMSMs of RaM and PaM patterns. (a) 9s/8p. (b) 6s/4p

4. The Phase Back-EMF and Cogging Torque
Figure 4 displays phase back-EMF against the rotor position for SBPMSMs with two magnetization patterns, i.e., 9s/8p and 6s/4p SBPMSMs. By observing the figure aforementioned, these two SBPMSMs with RaM and PaM patterns indicates trapezoidal EMF. The trapezoidal EMF is suitable for brushless DC operation, while the sinusoidal EMF preferred for brushes AC operation. The amplitude-phase back-EMF of 9s/8p machines produced by RaM and PaM patterns is 28.11 V and 29.63 V are shown in
**Figure 4 (a).** The RaM pattern created by the SBPMSMs is almost the same as emf PaM pattern. This show good agreement with the $B_r$ in **Figure 3 (a).** Meanwhile, **Figure 4 (b) the amplitude of phase back-EMF for 6s/4p motor with RaM pattern is higher than that of the PaM pattern. So, this shows good agreement with the $B_r$ in **Figure 3 (b).** The 6s/4p motor displays that the peak phase back-EMF for RaM and PaM is 40.43 V and 41.20 V respectively.

The THD, for the phase back-EMF of 9s/8p and 6s/4p SBPMSMs are displayed in **Figure 5.** **Figure 5 (a) shows that the minimum value of THDv of 9s/8p is 8.66 % developed from PaM pattern while for RaM the value is 11.31%. Other than that, for **Figure 5 (b), the minimum THD, is 3.98% developed by PaM pattern while for RaM is 10.8%. Figure 5 shows that the minimum THD, between 9s/8p and 6s/4p are PaM patterns.

Interaction between the permanent magnets and the stator slots produces cogging torque. The uneven air gap permeance causes the magnets in the rotor to seek a position of minimum reluctance [8].

**Figure 4.** The phase back-EMF waveform of SBPMSMs of RaM and PaM patterns. (a) 9s/8p. (b) 6s/4p.

**Figure 5.** Percentage of harmonics to fundamental of phase back-EMF for SBPMSMs of RaM and PaM patterns. (a) 9s/8p. (b) 6s/4p

**Figure 6.** The cogging torque of the SBPMSMs of RaM and PaM patterns. (a) 9s/8p. (b) 6s/4p.

**Figure 6** present the cogging torque waveform among 9s/8p and 6s/4p motors in RaM and PaM patterns. Based on **Figure 6 (a),** the minimum cogging torque for 9s/8p is RaM pattern which is 0.010096 Nm, while the PaM pattern is 0.016489 Nm. **Figure 6 (b),** reveals the minimum cogging torque for 6s/4p is
PaM patterns which is 0.173002 Nm and for RaM is 0.275769 Nm. The minimum cogging torque between 9s/8p and 6s/4p motor are displayed in Table 2.

| Motors   | Magnetization pattern | Cogging Torque (Nm) |
|----------|-----------------------|---------------------|
| 9s/8p    | RaM                   | 0.0101              |
|          | PaM                   | 0.0165              |
| 6s/4p    | RaM                   | 0.2758              |
|          | PaM                   | 0.1730              |

5. Pole-Arc variation of PM

The ratio of pole-arc to pole-pitch is one of the influential factors that affect PM machines' performance [9], [10]. When the rotor pole span of 6s/4p with RaM and PaM decreases, the phase back-EMF, cogging torque, and THD of phase back-EMF are changes as shown in Figure 7 and Figure 8. As the rotor pole span is reduced from the full pitch of 44° mechanicals to 33° mechanicals, the phase back-EMF waveforms change from trapezoidal to more sinusoidal.

Figure 8 reveals cogging torque of 6s/4p motor for various rotor pole span with RaM and PaM patterns. Based on Table 3, the rotor pole span 36° mechanical and 42° mechanical have lower cogging torque among the pole-arc, which are 0.138477 Nm and 0.156057 Nm, respectively. The cogging torque experienced by 44° mechanicals is the highest for RaM patterns while for PaM is 33° mechanical when the rotor pole span is varied. Hence, by reducing the rotor pole span to a certain mechanical degree, the machines' cogging torque can be reduced effectively.

![Figure 7](image1)

(a) Rotor position (elect.deg.)

(b) Rotor position (elect.deg.)

**Figure 7.** The phase back-EMF of 6s/4p machines with particular rotor pole span and different magnetizations. (a) Radial. (b) Parallel.
**Figure 8.** Cogging torque of 6s/4p motor for particular rotor pole span and various magnetizations. (a) Radial. (b) Parallel.

![Image of cogging torque graph](image)

**Figure 9.** The $THD_v$ and peak cogging torque versus rotor pole span for 6s/4p motor with different magnetizations. (a) Radial. (b) Parallel.

![Image of THD and cogging torque graph](image)

| Motors  | Pole-arc (mech.) | Amplitude Cogging Torque (Nm) | $THD_v$ (%) |
|---------|------------------|-------------------------------|-------------|
| 6s/4p   | 44°              | 0.275761                      | 8.1498      |
|         | 42°              | 0.254445                      | 5.6664      |
|         | 39°              | 0.206267                      | 1.9472      |
|         | 36°              | 0.138477                      | 6.8447      |
|         | 33°              | 0.191744                      | 12.1373     |
| 6s/4p   | 44°              | 0.172991                      | 2.5692      |
| (PaM)   | 42°              | 0.156057                      | 1.6265      |
|         | 39°              | 0.167766                      | 6.0944      |
|         | 36°              | 0.179011                      | 10.711      |
|         | 33°              | 0.250226                      | 14.0002     |

**Table 3.** Cogging Torque and $THD_v$ for particular rotor pole span.

**Figure 9** shows the $THD_v$ phase back-EMF and the peak cogging torque when the rotor pole span is varied in 6s/4p machines. The optimum rotor pole span for RaM patterns is 19.4° mechanical, with cogging torque is 0.02 Nm, and $THD_v$ is 7.67% shown in **Figure 9 (a)**. Other than that, the optimum rotor pole span in PaM pattern is 15.9° mechanical, with cogging torque is 0.02 Nm, and $THD_v$ is 4.76% displayed in **Figure 9 (b)**.

6. Conclusion

Magnetic fluxes, phase back-EMF and cogging torque are the output from OPERA 2D of SBPMSMs with RaM and PaM patterns. The predicted output performances of both 9s/8p and 6s/4p machines are summarized. PaM patterns give the maximum amplitude of phase back-EMF of 6s/4p while the minimum amplitude is RaM patterns. The maximum $THD_v$ for 9s/8p is RaM patterns, while the minimum $THD_v$ for 6s/4p is RaM patterns. The minimum cogging torque is RaM patterns. Thus, PaM patterns show an optimum machines performance of 9s/8p and 6s/4p SBPMSMs compare with RaM patterns.
patterns. Apart from that, THDv and cogging torque of SBPMSMs can be reduced by using suitable semi-buried rotor pole span. From the result, the performance of the optimum machine of SBPMSMs is 6s/4p with parallel magnetization pattern. This is because 6s/4p motor used less magnet material compared with others, hence the lower cost is needed to build this SBPMSMs.

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7. References

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