Investigation the optimum performance of the surface-mounted PMSM under different magnetization patterns

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Abstract. This paper investigates the influence of different magnetization patterns on the performances of the surface-mounted permanent magnet synchronous machines (SMPMSMs). Three magnetization patterns are employed, which are radial, parallel, and ideal Halbach magnetizations. These magnetization patterns are applied to 9-slot/10-pole and 15-slot/4-pole permanent magnet (PM) machines. The PM machines are designed and simulated by using Opera 2D finite element. The performances of three PM motors, such as airgap flux density, phase back-EMF, and cogging torque, are evaluated under the influence of different magnetization patterns. The total harmonic distortion of phase back-EMF ($THD_v$) for the motors are investigated. The PM motors with ideal Halbach magnetization provide the lowest cogging torque and the lowest total harmonic distortion of phase back-EMF. Besides that, the optimum setting of the magnet pole-arc can reduce the total harmonic distortion of phase back-EMF and achieve lower cogging torque. The optimum magnet pole-arc produced by radial magnetization in 9-slot/10-pole motor is 24.8° mech., with cogging torque of 0.45 Nm, and $THD_v$ of 2.69 %.
Meanwhile, the optimum magnet pole-arc produced by parallel magnetization in 9-slot/10-pole motor is 26.0° mech., with cogging torque of 0.41 Nm, and $THD_v$ of 2.00 %.

1. Introduction
Permanent magnet synchronous machine (PMSM) is the high efficiency electrical machines that can greatly reduce the electrical energy consumption. Permanent magnets (PMs) are the materials where the magnetic field is generated within the material itself [1]. A permanent magnet is considered good when it has a high magnetic field with a low mass and stable against the influences of demagnetization [2], [3]. Permanent magnets are essential in electrical industries, especially in power generation and electric machines. The operation of turbines and generator needs permanent magnets to convert mechanical energy into electrical energy while electrical motors used permanent magnets to convert electrical energy to mechanical energy [4], [5]. The PM machines have the benefit of pre-excitation from the
magnets, which can increase the efficiency considerably and smaller in size as compare with the AC motor [6]. Using permanent magnets in machines also provide longer operating life span, higher rotational speed, and lower thermal resistance [7], [8].

Permanent magnet synchronous machine provides excitation field by a permanent magnet instead of a coil [9]. The terms of synchronous refer to the fact that rotor and magnetic field rotate with the same speed [10], [11]. This is because the PM machine generated through shaft mounted permanent magnet, and the currents are induced in the stationary armature [12]. Besides that, several rotor topologies of PM machines can be formed. These varieties are depending on the magnet shape and the rotor structure [13]. Most of the PM motors used PMs that are mounted on the rotor surface, but the PM configuration can also be inseted magnets, interior magnets, or buried magnets [14]. The effect of magnetization patterns on machine performances can be significant, i.e., the rotor magnetization has an important influence on the motor characteristics.

However, the surface-mounted permanent magnet synchronous machines (SMPMSMs) have several problems that need to be concerned, such as cogging torque, phase back-EMF and its total harmonic distortion \((THD_v)\), which are influenced by different magnetization patterns. High cogging torque results in speed ripples, which reduce the performance of the SMPMSM. Therefore, this paper investigates the influence of different magnetization patterns on the performances of the SMPMSMs. Three magnetization patterns are considered and applied, which are radial, parallel, and ideal Halbach magnetizations in overlapping and non-overlapping winding machines. Then, the optimum setting of magnet pole-arcs are determined to obtain a lower cogging torque and a lower \(THD_v\) with various magnetization patterns.

The organization of this paper is as follows. The motor design parameters for various PM machines are presented in Section II. Section III describes the finite element modeling and simulation of different PM motors. Section IV presents the predicted phase back-EMF and cogging torque of various PM machines influence by different magnetization patterns. The performances of PM machines are predicted with varying magnet pole-arcs under various magnetization patterns in Section V. Concluding remarks are presented in Section VI.

2. Motor Design Parameters

An analytical calculation is used to obtain the motor dimension of surface–mounted PM synchronous motor with 9-slot/10-pole and 15-pole/4-pole for the non-overlapping and overlapping machines. The number of slot per pole, \(N_{opp}\), of the PM machines is obtained from (1). The motor dimensions are calculated in Table 1.

\[
N_{opp} = N_s/N_p
\]

Table 1. Motor dimensions.

| Parameters                        | 9-slot/10-pole | 15-slot/4-pole |
|----------------------------------|---------------|---------------|
| Magnet thickness, \(l_m\) (mm)   | 3.0           | 3.0           |
| Axial active length, \(l_a\) (mm)| 50            | 50.0          |
| Stator outer radius, \(R_{so}\) (mm)| 50         | 50.0          |
| Stator yoke thickness, \(W_{y}\) (mm)| 5.3       | 7.5           |
| Tooth body, \(W_{tb}\) (mm)      | 10.5          | 5.0           |
| Tooth-tip height, \(W_{tt}\) (mm)| 3.7           | 1.8           |
| Stator opening, \(W_{so}\) (mm)  | 2.5           | 2.5           |
| Stator bore radius, \(R_{sb}\) (mm)| 26.9        | 21.3          |
| Airgap thickness, \(l_g\) (mm)   | 1.0           | 1.0           |
| Magnet outer radius, \(R_m\) (mm)| 25.9          | 20.3          |
| Rotor outer radius, \(R_r\) (mm) | 22.9          | 17.3          |

The pole pitch, \(\theta_p\), and the slot pitch, \(\theta_s\), of the motor is calculated by using (2) and (3), respectively.

\[
\theta_p = 360^\circ/N_p
\]
The conductor number is selected according to the slot area of the motor. The number turns per coil, \( N_c \), of 9-slot/10-pole and 15-slot/4-pole are obtained by (4), where \( A_{cu} \) is the copper area and \( D_w \) is the wire diameter. The 9-slot/10-pole motor has 57 turns and 15-slot/10-pole has 43 turns.

The number turns per coil, \( N_c = \frac{360^\circ}{N_{scm}} \) (3)

The frequency of cogging torque, \( f_{ct} \), can be expressed as

\[
f_{ct} = \frac{360^\circ}{N_{scm}} \]

where \( N_{scm} \) is the smallest common multiple of slot and pole number. For 9-slot/10-pole, the \( N_{scm} \) is 90 whereas the \( N_{scm} \) for 15-slot/4-pole is 120. Hence, the frequency cogging torque is 20° elect. for 9-slot/10-pole motor and 6° elect. for the 15-slot/4-pole motor. The motors are running at synchronous speed. The synchronous speed, \( n_{syn} \), of 9-slot/10-pole and 15-slot/4-pole motors are expressed by

\[
n_{syn} = \frac{120f}{N_p} \]

(6)

The cogging torque and phase back-EMF are analyzed for every magnetization pattern. The cogging torque and phase back-EMF are compared among the different magnetization patterns in 9-slot/10-pole and 15-slot/4-pole motors.

3. Finite Element Modeling and Simulation

In this section, Opera 2D FEM is used to evaluate the motor performances, which are airgap flux density, phase back-EMF, and cogging torque for 9-slot/10-pole and 15-slot/4-pole PMSMs. The cross sectional area of the PM machines is illustrated in Figure 1.

**Figure 3** reveals the contour of magnetic flux density distribution across sectional area of 15-slot/4-pole PM motor during open-circuit condition with radial, parallel, and ideal Halbach magnetization patterns. From the observation of **Figure 3**, the magnetic flux distribution of 15-slot/4-pole motor does not have significant differences among three magnetization patterns. From **Figure 3**, the magnetic flux density occurs across the 15-slot/4-pole motor in radial, parallel, and ideal Halbach are 1.58 T, 1.57 T, and 1.61 T, respectively. Based on **Figure 3**, the highest magnetic flux density among different magnetization patterns is ideal Halbach magnetization; while the lowest flux density is parallel magnetization. At the same time, most of the magnetic flux density across the stator in the 15-slot/4-pole motor consist of four regions. To summarize, the highest magnetic flux density distribution of 9-slot/10-pole and 15-slot/4-pole motors is ideal Halbach magnetization pattern.

**Figure 4** shows the radial component of magnetic flux density, \( B_r \), in the middle of airgap for 9-slot/10-pole and 15-slot/4-pole PM motors under influence of different magnetization patterns. From **Figure 4**, the highest magnitude of \( B_r \) among the PM motors is generated by ideal Halbach magnetization, followed by the radial magnetization, and the lowest magnitude of \( B_r \) is produced by

![Figure 1. Cross sectional area of the PM machines. (a) 9-slot/10-pole. (b) 15-slot/4-pole.](image-url)
4. Phase Back-EMF and Cogging Torque

Figure 5 shows the phase back-EMF of three PM motors for radial, parallel, and ideal Halbach magnetization patterns. For 9-slot/10-pole and 15-slot/4-pole motors with radial and parallel magnetizations demonstrated more trapezoidal waveform as compared with ideal Halbach magnetization. The trapezoidal waveform is mostly referred to brushless DC PM motor; while for the sinusoidal waveform is prone to brushless AC PM motor.

Based on Figure 5(a), the peak phase back-EMF of 9-slot/10-pole motor produced by radial, parallel, and ideal Halbach are increasing, i.e., 22.93 V, 24.27 V, and 26.94 V, respectively. This proves that the highest magnitude of phase back-EMF for the 9-slot/10-pole motor is ideal Halbach magnetization pattern and the lowest in the radial magnetization pattern. Meanwhile, Figure 5(b) reveals the peak phase back-EMF of the 15-slot/4-pole motor in radial, parallel, and ideal Halbach magnetizations are 54.59 V, 56.59 V, and 56.33 V, respectively.

The harmonics of the phase back-EMF for 9-slot/10-pole and 15-slot/4-pole motors are demonstrated in Figure 6. From Figure 6(a), the highest total harmonic distortion of phase back-EMF (THDv) for 9-slot/10-pole motor is 16.14 %, which is produced by radial magnetization; while the lowest THDv is 0.03 %, which is produced by ideal Halbach magnetization pattern. Meanwhile, in Figure 6(b), for 15-slot/4-pole, the highest THDv is 14.49 %, which is produced by radial magnetization pattern and the lowest THDv is 0.29 % for ideal Halbach magnetization pattern. According to Figure 6, it can be seen that the highest THDv among these motors is produced by radial magnetization pattern and the lowest THDv is produced by ideal Halbach magnetization pattern.

On the other hand, the interaction between the PMs and the stator slots of PMSM produces cogging torque. The frequency of cogging torque is obtained through the smallest common multiple, $N_{scm}$. For
Figure 6. The harmonics of the phase back-EMF under different magnetization patterns for the PM machines. (a) 9-slot/10-pole. (c) 15-slot/10-pole

Figure 7. The cogging torque of the PM motors with different magnetization patterns. (a) 9-slot/10-pole. (b) 15-slot/10-pole.

9-slot/10-pole motor, the $N_{scm} = 40$ and for the 15-slot/4-pole motor, $N_{scm} = 24$.

Figure 7 shows the cogging torque among 9-slot/10-pole and 15-slot/4-pole motors with radial, parallel and ideal Halbach magnetization patterns. Based on Figure 7(a), 9-slot/10-pole motor shows the highest cogging torque in parallel magnetization pattern, which is 0.859508 Nm and the lowest cogging torque is ideal Halbach magnetization pattern with 0.357893 Nm. By observing Figure 7(b), for 15-slot/4-pole motor, the highest cogging torque is produced by radial magnetization pattern, which is 0.062326 Nm, and the lowest cogging torque is 0.001905 Nm produced by ideal Halbach magnetization pattern. The peak cogging torque of the PM motors with different magnetization patterns is tabulated in Table 2. According to Table 2, it can be seen that the lowest peak cogging torque among the PM machines is produced by ideal Halbach magnetization pattern. This is because ideal Halbach has almost sinusoidal airgap field distribution, as shown in Figure 5.

### Table 2. The peak cogging torque of the PM motors with different magnetization patterns.

| Motors          | RaM    | PaM    | IH         |
|-----------------|--------|--------|------------|
| 9-slot/10-pole  | 0.843005 | 0.859508 | 0.357983   |
| 15-slot/4-pole  | 0.062326 | 0.036070 | 0.001905   |

5. Magnet Pole-Arc

The magnet pole-arcs can affect the performances of PM machines, such as the phase back-EMF and the cogging torque. So, in this research, the magnet pole-arcs are varied from 24° mech. until 36° mech. in 9-slot/10-pole for SMPMSM in order to investigate the optimum magnet pole for obtaining the optimum setting between $THD_v$ and cogging torque with radial and parallel magnetization patterns. Figure 8 shows the phase back-EMF of 9-slot/10-pole motor with different magnet pole-arcs for radial and parallel magnetization patterns. Based on Figure 8, the phase back-EMF for 9-slot/10-pole PM motor with radial and parallel magnetization patterns for full pitch magnet are more trapezoidal and
Figure 8. The phase back-EMF of 9-slot/10-pole motor with different magnet pole-arcs and various magnetizations. (a) RaM. (b) PaM.

Figure 9. The cogging torque of 9-slot/10-pole motor for different magnet pole-arcs and various magnetizations. (a) RaM. (b) PaM.

Figure 10. The THD, and peak cogging torque versus magnet pole-arc for 9-slot/10-pole motor under various magnetizations. (a) RaM. (b) PaM.

become more sinusoids after reducing the magnet pole-arc. Figure 9 shows the cogging torque of 9-slot/10-pole motor for different magnet pole-arcs for radial and parallel magnetization patterns.

From Figure 9, smaller magnet pole-arc provides lower cogging torque in the 9-slot/10-pole motor with radial and parallel magnetization patterns. Figure 10 shows the THD, of phase back-EMF and the peak cogging torque when the magnet pole-arc is varied in 9-slot/10-pole motor. According to Figure 10(a), the optimum magnet pole-arc produced by radial magnetization is 24.8° mech., with cogging torque of 0.45 Nm, and \( THD \), of 2.69 %. Meanwhile, based on Figure 10(b), the optimum magnet pole-arc produced by parallel magnetization is 26.0° mech., with cogging torque of 0.41 Nm, and \( THD \) of 2.00 %.

6. Conclusion
As a conclusion, the analytical calculation of the 9-slot/10-pole and 15-slot/4/pole PM motors are performed. The performances of 9-slot/10 pole and 15-slot/4-pole PM motors are different based on
different magnetization patterns. The highest magnitude of the phase back-EMF produced by a 15-slot/4-pole motor is with parallel magnetization pattern, followed by the ideal Halbach and radial magnetization patterns. Motor with radial magnetization pattern in 9-slot/10-pole shows the highest total harmonic distortion while the lowest total harmonic distortion is produced by the ideal Halbach magnetization pattern of 15-slot/4-pole motor. Ideal Halbach magnetization pattern gives the lowest cogging torque followed by the parallel and radial magnetization patterns. Furthermore, the ascending trend of phase back-EMF is parallel, radial, and ideal Halbach magnetization patterns. Hence, the optimum motor performance of 9-slot/10-pole and 15-slot/4-pole SMPMSM is ideal Halbach magnetization pattern compares with radial and parallel magnetization pattern. Smaller magnet pole-arc provides lower cogging torque in the 9-slot/10-pole motor with radial and parallel magnetization patterns. The optimum magnet pole-arc produced by radial magnetization in 9-slot/10-pole motor is 24.8° mech., with cogging torque of 0.45 Nm, and \( THD_v \) of 2.69 %. Meanwhile, the optimum magnet pole-arc produced by parallel magnetization in 9-slot/10-pole motor is 26.0° mech., with cogging torque of 0.41 Nm, and \( THD_v \) of 2.00 %.

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