Investigation on high-power-density design of small PM motors focusing on air gap configuration

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Abstract. This paper describes a case study of high-power-density design of small permanent magnet (PM) motors focusing on their air gap configurations. Two types of the PM motors, i.e., a radial air gap type and an axial air gap type, are comparatively discussed. Comparison between the two types has been conducted from the viewpoints of I-T characteristics, N-T characteristics, efficiency maps, torque ripple characteristics, and so forth. It has been clarified that the axial air gap type has significant advantages to achieve the high-power-density under some limited condition.

1. Introduction
Electrification of various equipment such as automobiles, industrial machines, home appliances, etc. is intensively promoted to improve the energy conversion efficiency and the control performance. Electrical motors play an important role for the electrification, and improvement of their efficiency and power density is an unavoidable issue to expand their application fields. Permanent magnet synchronous motors (PMSMs) have recently been employed instead of induction motors because of their higher efficiency and higher power density. In the case of pancake shaped motors, axial air gap PM motors have significant advantages for the improvement of the power density, compared with radial air gap PM motors.

In general, when the motors are designed to have a flat pancake proportion, higher-power-density design can be achieved because the rotor surface area generating the electromagnetic torque of the axial air gap PM motors is much larger than that of the radial air gap PM motors. In addition, the axial air gap PM motor can easily reduce the copper loss of the windings because of their higher space factor of the stator slots, which is another advantage over the radial air gap PM motor. In the paper, a comparative case study is conducted between a newly developed axial air gap PM motor and an existing benchmark radial air gap PM motor, where both motors are designed to have almost same current-to-torque (I-T) characteristics. A finite element method (FEM) based three-dimensional electromagnetic analyses are carried out to investigate the effectiveness of the axial air gap configuration for the downsizing of the motor.

2. Motor Design Conditions and Three-Dimensional Electromagnetic Analysis

2.1. Motor Design Conditions and Constraints
The following conditions are given in designing the motors:
(1) using same material PM and same volume PM,
(2) setting almost same winding resistance per phase,
(3) assuming the same space factor of the windings, and
(4) using the magnetic material of which iron loss is almost same. An electromagnetic analysis is conducted with JMAG-Designer 17.1™ to investigate how high the power density of the axial air gap PM motor can be achieved, compared with the radial air gap PM motor.

2.2. Overview of Designed Motors
Figure 1 shows overviews of the designed PM motors and their major dimensions. The radial air gap PM motor is a surface PM (SPM) type of which stator has concentrated windings. Supposing this radial air gap SPM motor as a benchmark, the axial air gap PM motor is designed so that the I-T characteristics of the both motors are identical as described later. The diameter of the axial air gap PM motor is adjusted to make its I-T characteristic equal to that of the radial air gap PM motor.

![Figure 1. Overview of designed motors.]

2.3. Motor Specifications and Materials Used in Motors
Table 1 indicates major specifications of the two motors. The air gap of the axial type is slightly wider than that of the radial type because it is rather difficult to maintain the air gap precisely in the manufacturing process and the attractive axial force in the air gap is remarkably strong.

| Table 1. Materials used in designed motors. | Radial gap motor | Axial gap motor |
|-------------------------------------------|-----------------|----------------|
| Stator core                               | 35JN440         | Somaloy 1000 SP |
| Rotor core                                | 35JN440         | SUS304         |
| Magnet                                    | MNF12E          | MNF12E          |
| Shaft                                     | S45C            | S45C            |

| Table 2. Specifications of designed motors. | Radial gap motor | Axial gap motor |
|-------------------------------------------|-----------------|----------------|
| Motor type                                | SPM motor       | SPM motor      |
| Outer diameter                            | Φ100 mm         | Φ120 mm        |
| Air gap distance                          | 0.637 mm        | 0.750 mm       |
| Slot combination                          | 12s8p           | 24s16p         |
| Coil space factor                         | 40 %            | 40 %           |
| Number of turns                           | 30 T/slot       | 26 T/slot      |
| Conductor diameter                        | Φ1.02 mm        | Φ1.03 mm       |
| Phase resistance                          | 0.364 Ω/phase   | 0.353 Ω/phase  |
| Coil connection                           | Star connection | Star connection |
| Current density (10A rms/phase)           | 6.14 A rms/mm²  | 6.02 A rms/mm² |
| $L_d$                                      | 2.01 mH         | 0.567 mH       |
| $L_q$                                      | 2.05 mH         | 0.585 mH       |
The slot combinations of the both motors are 2:3 based and the number of winding turns of the axial type is chosen 26 to achieve equal I-T characteristic to the radial type.

Table 3. Motor dimensions.

|                      | Radial gap motor | Axial gap motor |
|----------------------|------------------|-----------------|
| Outer diameter       | 100 mm           | 120 mm          |
| Iron core axial length | 50 mm            | 33.8 mm         |
| Axial length         | 70 mm            | 33.8 mm         |
| Including coil ends  | 70 mm            | 33.8 mm         |
| Iron core volume     | 392 cm³          | 382 cm³         |
| Volume including coil ends | 550 cm³      | 382 cm³         |

Table 4. Estimated weights of components and whole motors.

|                      | Radial gap motor | Axial gap motor |
|----------------------|------------------|-----------------|
| Stator core          | 1117 g           | 868 g           |
| Rotor core           | 697 g            | 130 g           |
| Permanent magnet     | 223 g            | 223 g           |
| Shaft                | 122 g            | 80 g            |
| Windings             | 394 g            | 469 g           |
| Total                | 2554 g           | 1771 g          |

Because the space factors of the windings are identical, the winding resistance of each phase can be almost same by using the same diameter conductors. Therefore, the current densities of the windings are also approximately 6 A for both motors. The inductances are calculated from the electromagnetic analysis results, and it can be found that the inductances of the axial type are approximately quarter of those of the radial type because of the low-winding-turns and the wide air gap.

Table 2 shows materials used in each motor. Soft magnetic composite (SMC) (Somaloy 1000 SP: 220kW/m3) is employed as a stator core material in the axial air gap PM motor because its iron loss at 400 Hz and 1 T is relatively close to that of the electromagnetic steel plate used in the radial air gap PM motor (35JN440: 178 kW/m3). The rotor cores of the two motors are composed of the electromagnetic steel plates (35JN440) in the radial type and the stainless steel (SUS304) in the axial type, respectively. The axial air gap PM motor employs a non-magnetic material such as SUS304 in the rotor back yoke to prevent the eddy currents. However, a general metal material (S45C) is used for the shaft from a mechanical strength reason.

2.4. Proportions and Dimensions of Designed Motors

Table 3 shows major dimensions of the two motors. As described above, the outer diameter of the axial air gap PM motor is designed to be 20-% larger than that of the radial air gap PM motor in order to make the I-T characteristics equal. The motor axial length of the axial type can be reduced to approximately 68 % of the radial type, and can be reduced down to less than 50 % if the coil ends of the radial type are included. As can be found in the table, the iron core volumes their selves are almost same with each other, but the total volume of the axial type can significantly be reduced when the coil ends of the radial type are included in the motor volume. The volume of the motor cannot always be reduced if the axial air gap configuration is employed due to the limitation of the rotor diameter and its mechanical strength. However, the axial air gap approach is remarkably effective to improve the power density for small motors from 1 to 2-kW output power range.

Table 4 shows estimated weights of the components and the total of each motor. Every weight is calculated from the component volume and the specific gravity. The rotor weight of the axial type is much lower than that of the radial type, which implies that higher power rate is expected. As described previously, both of the motors have the same weight PMs on the rotor, but the total weights of the rotors are very different because of volume difference of the rotor cores. However, the weight of the windings
in the axial type is heavier because more slots are in the stator core, which makes the total amount of the conductors higher. The winding weight of the axial type is increased by 19%, compared with that of the radial type. All in all, however, overall weight of the axial type can be remarkably reduced by 31%; hence the axial air gap approach is efficient to improve the weight as well as the volume.

3. Operating Conditions And Operation Characteristics Of Design Motors

3.1. Operating Conditions

(1) No-Load electromotive force (e.m.f.)
The motors are operated at 3000 r/min with open windings, and no-load e.m.f. is observed at the motor terminals.

(2) I-T characteristics
Only the q-axis current is given to the motors, and phase angle advancing control is not applied to the motors when the I-T characteristic is examined. The current waveforms are sinusoidal of which effective value is from 0 to 10 A. The rotating speed is kept constant at 3000 r/min throughout the I-T characteristic test.

(3) Rotating speed and Torque (N-T) characteristics
The sinusoidal currents are given to the motors, where the maximum value is 10 A. No voltage drop caused in the inverter and the wire harness is not considered. The inverter DC-bus voltage is fixed at 100 V.

(4) Efficiency maps
The efficiency maps are obtained along with the N-T characteristics described above, so the every condition is exactly same as that of N-T characteristic test. Particularly, a conductor eddy current loss is not taken into account.

(5) Torque waveforms
The torque waveforms are observed under the same conditions as those of the I-T characteristics. In addition, the cogging torque waveforms are obtained by rotating the motors at 60 r/min.

3.2. No-Load Electromotive Force
Figure 2 shows e.m.f. waveforms of the two motors at no load condition. The e.m.f. amplitude of the radial type is approximately 60 V, while that of the axial type is 46 V.
The e.m.f. constant of the axial type is lower than that of the radial type, which contributes to the higher-speed operation. In addition, the e.m.f. waveform of axial type is very close to sinusoidal, compared with that of the radial type. Owing to the sinusoidal e.m.f., reduction of the torque ripple is expected by giving the sinusoidal currents to the motor unless the space harmonics of the concentrated winding stator affect the torque generation.

3.3. I-T Characteristics
Figure 3 shows the I-T characteristics of both motors. As can be seen in the figure, the I-T characteristics of the two motors are identical and are linear to the motor current, which implies that magnetic saturation is not occurred in the motors.

3.4. N-T characteristics
Figure 4 shows the N-T characteristics of both motors, where the axial air gap PM motor is capable to rotate in the higher-speed range whereas the torque constant operation region is almost same. As described above, the axial type is capable to operate in the higher-speed range owing to less e.m.f.

3.5. Efficiency Maps
Efficiency maps are indicated in Figure 5 and Figure 6. The axial type has a larger region where higher efficiency is obtained. However, this large high-efficiency area may slightly be degraded by the conductor eddy current that has not been considered in the analysis. This conductor eddy current loss may be caused because of the fully open slot configuration is introduced to the axial type. It should be noted that there is a highest efficiency area over 95 % in the efficiency map of the axial type.
Figures 7 and 8 shows iron-loss maps, and Figs. 9 and 10 shows copper-loss maps, respectively. The range of the iron-loss variation is from 0 to 10 W, but the copper-losses increase to 100 W in the N-T characteristics; hence both of the motors can be regarded as copper machines. The magnetic materials used in the stator cores, i.e., 35JN440 and Somaloy 1000 SP, play an important role to reduce the iron-losses. In other words, the copper-losses must be suppressed to achieve higher efficiency in these motors. The copper-losses can be reduced by increasing the space factor of the windings, e.g., using flat square windings, or by enlarging the slot area.

3.6. Torque Waveforms
Figure 11 shows the torque waveforms of the two motors in the steady state. Both of the motors generate the same average torque, but the torque ripples of the axial type and the radial type are 19.5 % and 14.5 %, respectively.

As illustrated in Figure 1 the double stators of the axial type are skewed, so the torque ripple can effectively suppressed, compared with the radial type. It is considered that the torque ripples are caused by the fifth and the seventh components of the space harmonics, which is mainly generated by the concentrated winding configuration.

Figure 12 shows an enlarged one period of the cogging torque waveforms. The peak to peak values of the cogging torque waveforms are 0.42 Nm for the radial type and 0.45 Nm for the axial type, respectively. Compared with the rated average torque, the cogging torque is small enough for many kinds of applications. The torque ripple is varied with the average torque value as shown in Figure 13.
The torque ripple ratio is almost inverse proportional to the average torque for both motors. It is confirmed that the axial type is slightly superior to the radial type in the higher torque region.

4. CONCLUSION
The paper has described a case study of a motor design, where the two types of the motors have been designed, i.e., a radial air gap PM motor and an axial air gap PM motor. Under the same conditions, e.g., the same amount of the PM, the same space factor of the windings, the similar iron-loss property material, and the same winding resistance, it has been found that the axial air gap PM motor can reduce the motor volume (including the coil ends) by 30 % and the motor weight by 30 %, respectively. From another point of view, the axial length of the axial type can be reduced to almost half of the radial type although the diameter is increased by 20 %. In general, the axial air gap PM motor is very suitable for the pan-cake design of the motor because the center space of the double stators can be utilized for the mechanism such as a bearing. In the investigation described in the paper, both motors have employed the same amount of ferrite PMs, but the motor size can further be reduced by taking advantage of Nd bonded PM instead of the ferrite. As a result, overall performance of the axial air gap PM motor has been found to be superior to that of the radial air gap PM motor. However, it is indispensable to enhance the mechanical strength of the axial type rotor because the attractive force between the stator teeth and the rotor PM poles is significantly strong regardless of the thin rotor structure. In addition, reduction of the torque ripple is another problem to be solved, which is the future work of this study.

References
[1] H.Kamiyama, T.Noguchi, A.Hattori, Y.Yamada, S.Yokoyama, (2017), “Development of High-Torque Density Pancake Motor for Automotive Applications”, IEEJ Annual National Conference
[2] K.Takishima, K.Sakai, (2019), "Starting Characteristics of Axial and Radial Type Ultra-Lightweight Motors Based on Magnetic Resonance Coupling", IEEJ J. Industry Applications, vol. 8, no. 3, pp. 471-479.
[3] S. Morimoto, Y. Asano, T. Kosaka, and Y. Enomoto, (2014), “Recent Technical Trands in PMSM”, in Proc. IPEC-2014, pp.1997-2003
[4] J.A. Tapia, F. Leonardi, and T.A. Lipo, (2003), “Consequent-pole Permanent- Magnet Machine with Extended Field-Weakening Capability”, IEEE Trans. on IA., Vol. 39, No. 39, pp. 1704-1709.
[5] M.Aoyama, T.Noguchi, (2015), "Preliminary Experimental Verification of Self-Excited Wound-Field Synchronous Reactive Power for Robust Maximum Torque Per Ampere Control", IJIT2015.