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Design and Implementation of Axial-Type Switched Reluntance Motor

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Electric motors, finite-element methods, switched reluctance motor (SRM).

ABSTRACT
This paper presents the design of an axial-type switched reluctance motor (SRM) with the aim of improving the output torque characteristic. The axial-type structure has several advantages, including a large air-gap area due to the dependence on the radial length, whereas the air-gap area of the radial-type motor depends on the axial length. This advantage is expected to increase the inductance and the output torque. This study describe the design of an axial-type SRM and the fabrication of a prototype SRM using laminated iron sheet. The theoretical value of the design of the SRM with those obtained by experiments is compared.

Introduction

Switched Reluctance Motor (SRMs) has been attracting attention because of the increased cost of the Neodium magnet use in permanent-magnet synchronous motors (PMSMs). SRMs have several advantages over PMSMs, such as magnet-free construction and possible high-speed rotation because of its simple and strong structure constructed by the laminated steel plate. Owing to these advantages, SRMs have become an active research area, and its application to electric vehicles (EVs) and hybrid EVs, which require both high-torque and high-speed characteristics, is expected (Widmer & Mecrow, 2011). However, in comparison with PMSMs, it is difficult to achieve higher torque density with SRMs because of the magnet-free structure. It requires high current density or many turns to increase the torque. These lead to low efficiency or large machine volumes. Therefore, further research and investigations are required to increase the torque density.

With respect to the motor structure, two types of structures the radial type and the axial type can be used in the SRM. To increase the torque density, the axial-type structure is suitable because the structure can increase the air-gap area, which is dependent on the diameter of the machine, whereas the radial-type motor gap area is dependent on the machine length.

DESIGN METHODOLOGY

An SRM generates the torque by varying the magnetic core energy, which is caused by the rotor magnetic permeability variation into the air gap. The continuous output torque is obtained by changing the excitation phase when the inductance becomes a maximum value. Usually, the concentrated winding is used in the SRM, and the mutual inductance is negligible in comparison with self-inductance. Therefore, the theoretical output torque formula is shown in (1), where $\frac{dL}{d\theta}$ is the variation of the self-inductance, which is caused by the rotor magnetic permeance variation, and *i* is the instantaneous current, i.e.

$$T = \frac{\frac{1}{2}dL}{d\theta i^2} \quad - \quad - \quad - \quad - \quad - \qquad (1)$$

The inductance variation is decided by the difference between the maximum inductance and the minimum inductance. Consequently, an important parameter for increasing the output torque is the inductance difference. Figure 1 shows an over view of the proposed axial-type SRM, Figure 2 shows the definition of the design parameters. This paper describes the design of the three parameters the shape of the teeth, the rotor teeth axial length, and the back yoke thickness—using 3-DFEA because these parameters.

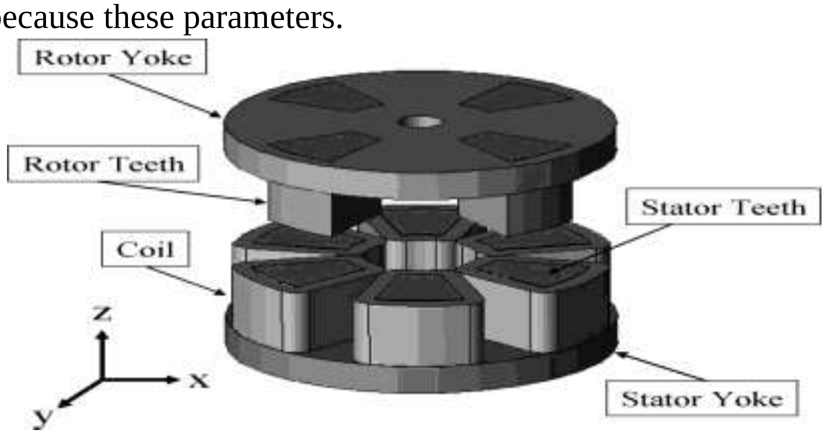

Figure 1: Overview of an Axial-Type SRM.

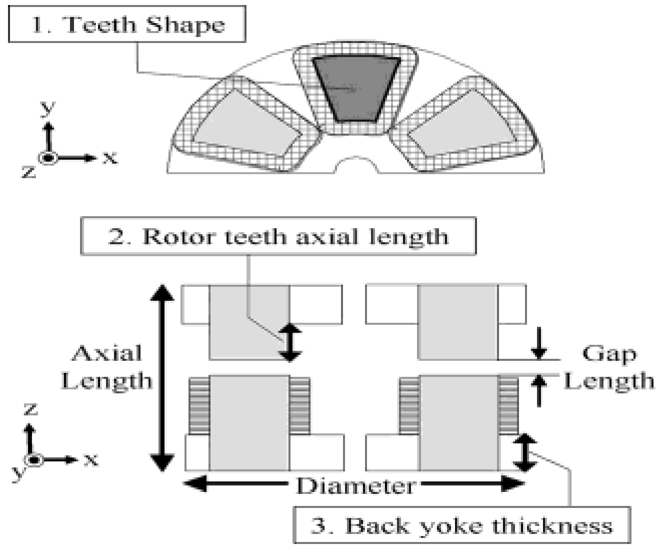

Figure 2: Definition of the parameters.

2.1 Design Specifications

Table 1 shows the design conditions. As shown in Table 1, the design condition determines the 6 slots/4 poles (6/4) combination because the 6/4 combination is the simplest structure in an SRM. The design specification used for the fabrication of the rotor and stator of the switched reluctance motor (SRM), are briefly summarized in table 2 and 3.

Table 1: Design specification

Diameter (mm)	140
Axial length (mm)	100 or less
Gap length (mm)	1.0
Pole number	4
Slot number	6
Number of turns (slot)	32
Peak current (A)	225

Table 2: Design specification of stator

Back yoke thickness	14mm
Stator teeth length	66mm
Number of turns on stator	70
Number of poles of stator	6
Number of bearing	1
Number of stack teeth in stator	110

Table 3: Design specification of rotor

Back yoke thickness	14mm
Rotor teeth length	32mm
Number of turns	None
Number of poles on rotor	4
Number of bearing	None
Number of stack teeth in rotor	52

Teeth Shape Design

Since the shapes of the teeth significantly affect the inductance difference, here, both conventional teeth shapes—rectangular and round—are selected, and each inductance is analyzed and compared.

Rotor Teeth Axial Length

At the position where the rotor teeth faces the stator teeth, the rotor teeth axial length does not affect the maximum inductance because the air-gap magnetic resistance is dominant, and the rotor teeth magnetic resistance is negligible. In contrast, at the position where the rotor teeth does not face the stator teeth, the rotor teeth axial length affects the minimum inductance because the major magnetic resistance is the air resistance between the stator teeth and the rotor yoke. Hence, the increasing rotor teeth axial length means decreasing the minimum inductance. However, the minimum inductance does not decrease in proportion to the rotor teeth axial length, indicating that it converges to a constant value. In addition, the increasing rotor teeth axial length is limited by the design condition, and the long rotor axial length makes the rotor oscillate because of the centrifugal force.

Back Yoke Thickness

The design of the back yoke thickness is important to avoid the magnetic saturation, which decreases the maximum inductance. Since the same amount of flux flows from the stator teeth to the back yoke, the back yoke cross-sectional area should be selected to correspond with the stator teeth surface area. In the case of the concentrated winding SRM, the linkage flux is divided in to two flux passes at the yoke part. Therefore, the back yoke cross-sectional area needs a surface area that is greater than 0.5 times that of the stator surface area.

Fabrication And Experiment Results

Figures 3,4 and 5 show the pictures of the fabricated machine. The teeth are constructed by the laminated steel plate that is parallel to the magnetic flux direction, and the target shape is

cut to reduce the eddy-current loss. In addition, the flat shape winding is used to improve the winding slot-fill factor.

Figure 3: Constructed Rotor of SRM.

Figure 4: Back York, shaft, and Stator Teeth with winding

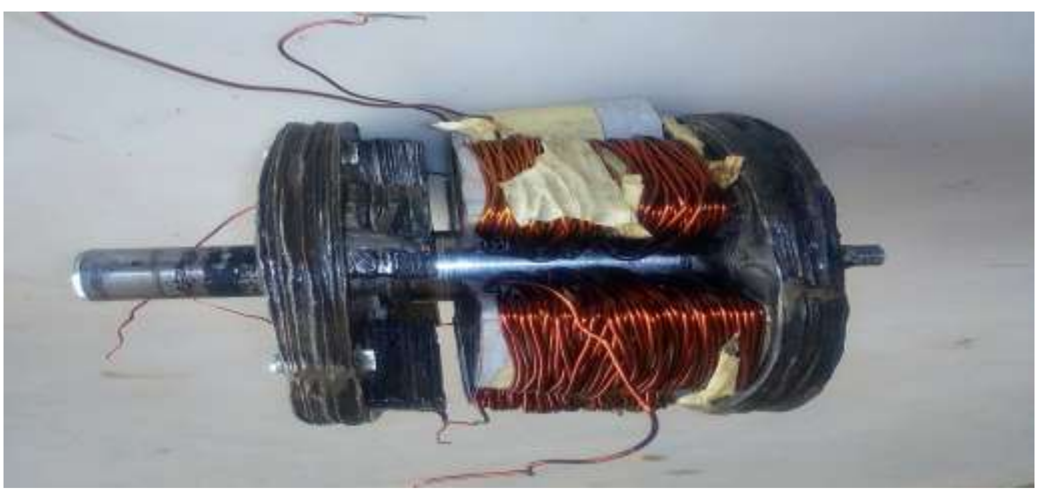

Figure 5: Back York, shaft, and Stator Teeth with winding

Experiment Condition

Fig. 6 shows the drive circuit construction. According to Fig 6, the experiment drive system is constructed using two three-phase inverters, where the positive inverter uses only the upper side arm, whereas the negative inverter uses only the lower side arm.

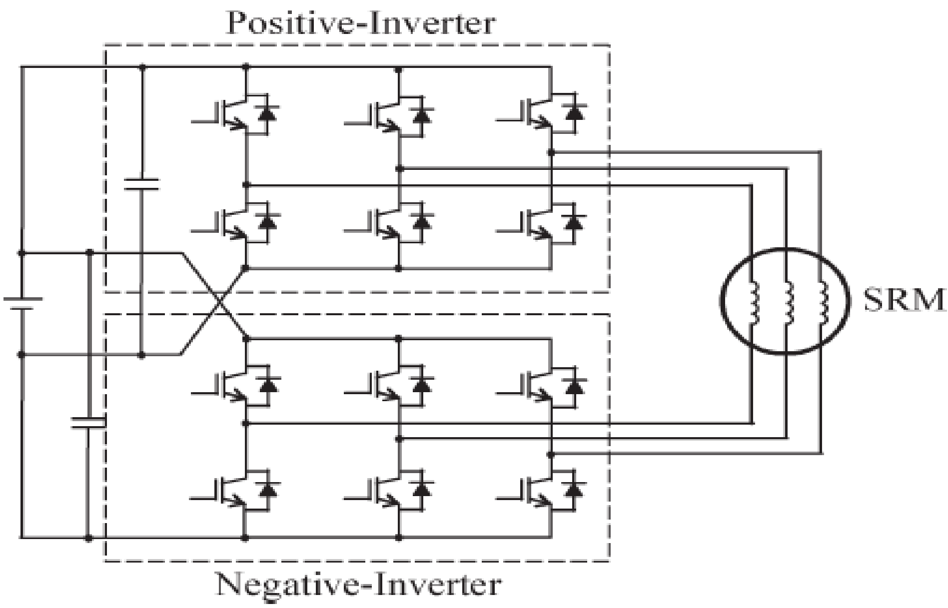

Figure 6: Motor drive circuit

Torque–Current Characteristic

The load test is confirmed by measuring the average torque at each current condition. The current is added between the excitation phase period 120◦ of the electrical angle. The input current is controlled by the hysteresis current control because the hysteresis current control is easy to implement, the response is fast, and it is insensitive to variations in the parameters (Petrus , Pop, Martis , Gyselinck ,and Iancu V ,2010) and (Bilgin, Emadi, and Krishnamurthy,2012)Fig. 8 shows the current waveform when the output torque is 4.9 N ・ m.

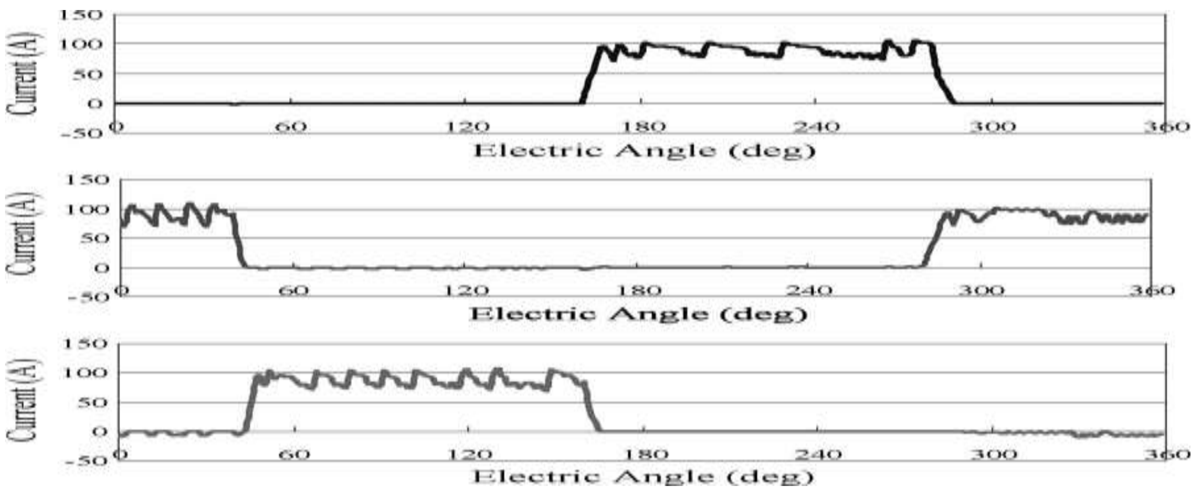

Figure 7. Input current waveform.

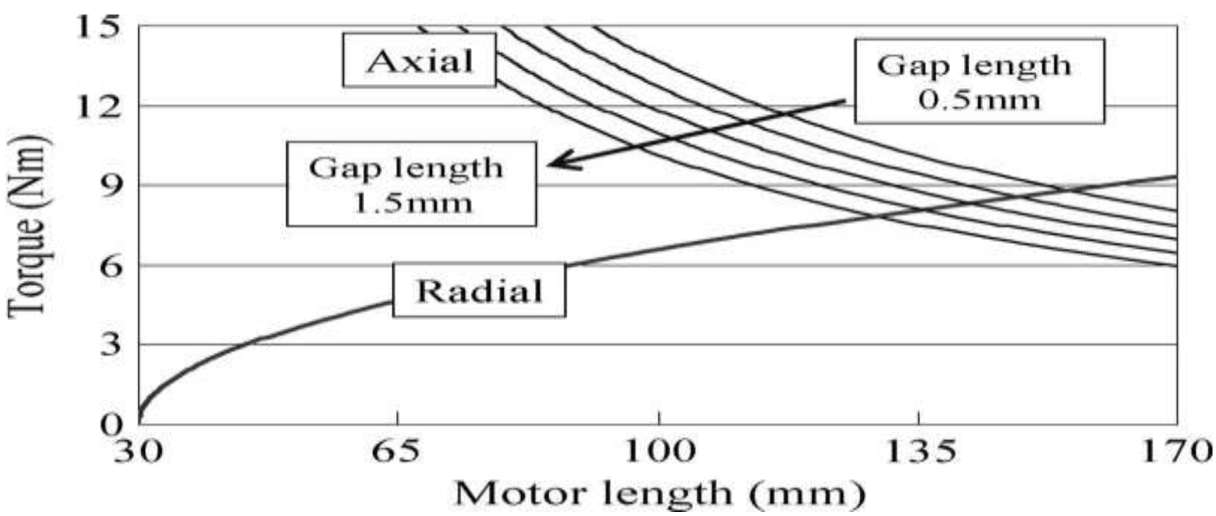

Fig. 8. Output torque calculation result depended on the gap length at each motor length.

Figure 8 shows the output torque characteristics of both the axial-type SRM and the radial-type SRM, where the horizontal and vertical axes represent the motor length and the output torque, respectively. According to Figure 8, if the axial-type SRM gap length is shorter than 0.5 mm, the axial-type SRM can have the torque that is two times that of the radial-type SRM. However, it is difficult to make a narrow air-gap axial-type machine because of the large electromagnetic force in the axial direction, which generates rotor distortion (Shibamoto, Nakamura ,Goto, and Ichinokura ,2012). For these reasons, the design condition of the tested model has a gap length of 1.0 mm. In Figure 8, when the axial length is 100 mm, even if the air-gap length is 1.5 mm, the axial-type SRM can achieve higher torque than the radial-type SRM with a 0.3-mm air gap.

Conclusion

This paper has designed and fabricated an axial-type SRM that aimed at improving the output torque density . First, the method to design the parameters—the shape of the teeth, the rotor teeth, axial length, and the back yoke thickness—was considered. Second, the inductance and the torque–current characteristics were measured and compared. In the motor design, the axial-type SRM was designed with a gap length of 1.0 mm, whereas the gap length of the radial type SRM is 0.3 mm because the axial-type SRM has a large electromagnetic force in the axial direction, which generates rotor distortion and makes small gap lengths difficult. However, although the gap length is three times larger, the axial-type SRM can realize higher torque than the radial-type SRM.

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