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Construction and Characteristics of Single Phase Switched Reluctance Motor

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Abstract - The single phase switched reluctance motor (SRM) has many merits; simple structure and driving circuits, easy operation and speed control, and etc. This paper presents the torque characteristics of disk type single phase SRM by changing the salient pole lengths and pole arcs. The prototype single phase SRM has a three dimensional magnetic flux pattern because of its structure. That is, the radial and axial magnetic flux contributes to torque generation. Thus, 3D analysis is required for computation of its magnetic field. In this paper, 3D FEM is used for analyzing the magnetic flux distribution and magnetic co-energy.

Keywords: Single phase SRM, 3D FEM, salient pole, axial and radial direction flux

1. Introduction

The single phase SRM has all of the merits of the multi phase SRM; a simple and robust structure and economic operating driver, with the exception of a self-starting disability. In addition, because the single phase SRM's stator poles are excited simultaneously by one exciting winding, the driving circuit elements can be reduced. [1-4] Therefore, it is expected that single phase SRM will be suitable for special driving systems. [5, 6]

The energy density per volume is higher than the poly phase SRM, and the axial length may be shorter than that of any type motor. We manufactured the prototype single phase SRM for use in low speed fan motors and in places where it is narrow and hard to maintain. As such, we experimented on the characteristics of the prototype single phase SRM; speed and torque. [7, 8]

In this paper, we compare the characteristics of the single phase SRM and the poly phase SRM, and analyze the structural characteristics by the 3D FEM. In addition, we investigate the effect of the starting device using a permanent magnet and speed vs. torque.

2. Characteristics of the single phase SRM

2.1 Comparison of Single and 3 Phase SRM

Fig.1 shows the structure of a single phase SRM. The single phase SRM is composed of 6 pieces each of "ㄷ" shaped stator pole and "ㅓ" shaped rotor pole. While the stator has ring type winding, the salient pole type rotor has no winding. Table 1 depicts the difference between a 3 phase SRM and a single phase SRM.

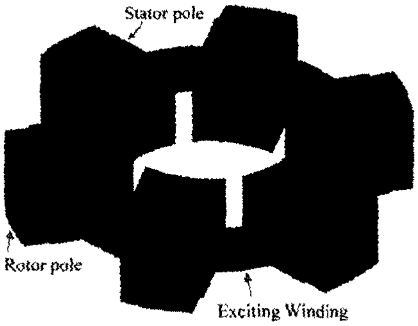

Fig. 1 Structure of Single Phase SRM

Table 1 Comparison of a single and 3 phase SRM

	Single phase SRM	3 phase SRM
Starting device	necessary	unnecessary
pole (stator/rotor)	6/6, 8/8	6/4, 8/6
driving circuit	1 or 2	3 or 6
exciting pole	all, simultaneously	exciting pole, only
flux direction	axial & radial	radial
energy density per unit vol.	large	little
control circuit	simple	complicated

2.2 Structural Characteristics of single phase SRM

Equ. (1) shows the torque developed in a single phase SRM. As the direction of the current has no relation with

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rotation direction, the magnitude and the direction of torque are determined by the variation of inductance.

$$T_e = \frac{1}{2} i^2 \frac{dL}{d\theta} \tag{1}$$

The inductance of the single phase SRM varies as shown in Fig. 2 in accordance with the stator and rotor's mutual positions in Fig. 3. Fig. 3 illustrates that positive direction torque is generated at θ_1~θ_2, where inductance increases, negative direction torque is generated at θ_3~θ_4, where inductance decreases. θ_0~θ_1, θ_2~θ_3 are dead zones because torque is not generated by inductance. Therefore, in order to initiate single phase SRM, the rotor and stator must be stopped at θ_1~θ_2 where positive torque is generated because inductance increases at initialization.

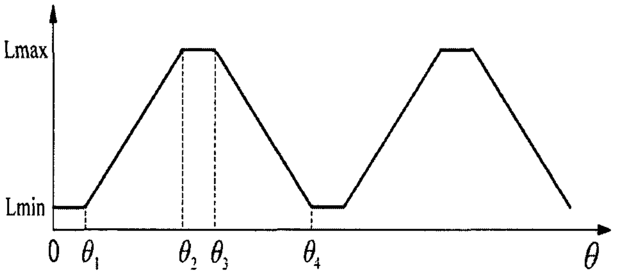


Fig. 2 Inductance of single phase SRM

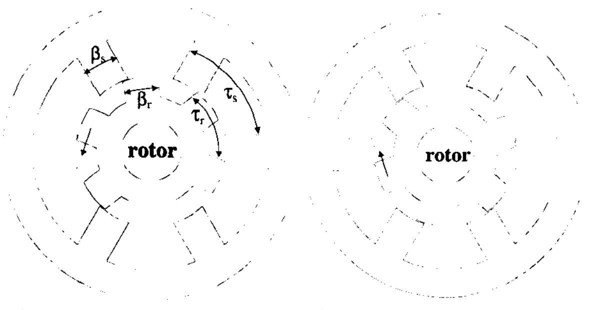


Fig. 3 Exchange of rotating direction by rotor position.

Furthermore, if a single phase SRM's 6 rotor poles are stopped at the position shown in Fig. 3(a), the rotating direction of the rotor will be counter-clockwise. Conversely, if the rotor hand is stopped at the position shown in Fig. 3(b), the rotating direction of the rotor will be clockwise. Therefore, the rotor poles must be stopped in the designated stator position. A starting device is necessary in order to select the rotating direction of the single phase SRM. Starting torque will not be obtained if the rotor is fixed at the aligned position between the stator pole and rotor pole, because both stator and rotor have the same number of poles. In this regard, the prototype of the single phase SRM is setup with a special starting device using a permanent magnet so that the rotor pole is halted at the self starting point shown in Fig. 3 when the input power is cut off.

2.3 Analysis by 3D FEM

Rotors have no electrical circuit, receiving electromagnetic force by the flux in the airgap. Flux distribution in the airgap is very complex in comparison with other types of motors with radial flux. Therefore, for analysis of the magnetic coenergy, it is more convenient and accurate to analyze by the FEM than by the equivalent circuits using electric parameters. As the majority of rotating electric machines are composed of radial flux, under the same assumptions they can be simply and quickly analyzed using 2 dimension FEM. However, we must analyze energy distribution using 3 dimensional FEM because our prototype single phase SRM uses radial and axial fluxes simultaneously, as indicated in Fig. 4.

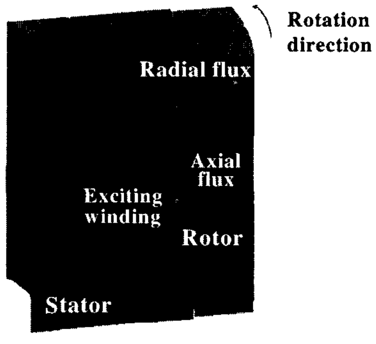
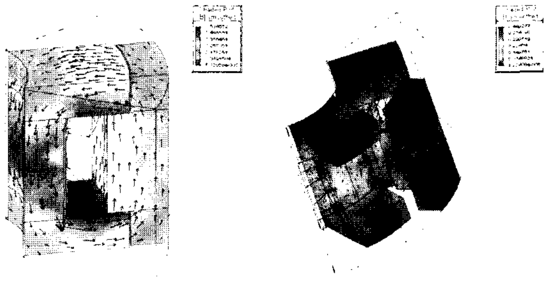


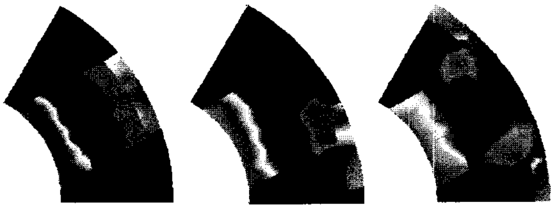
Fig. 4 A Single phase SRM pole

In this study we created a starting device using a permanent magnet and installed it in the appropriate location on the rotor.

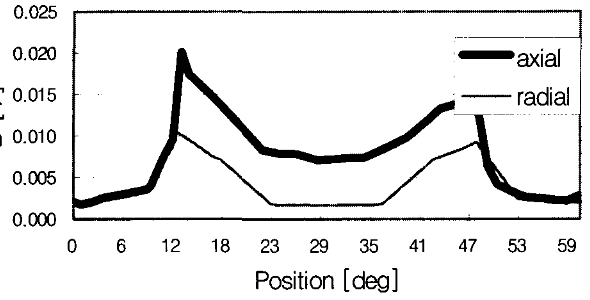
Fig. 5 shows the result of a 3D FEM analysis for the variation of fluxes on relative positions between a salient rotor pole and a stator pole, where it is evident that the axial flux is greater than the radial flux. Therefore, it is appropriate to install it in a narrow location because of the high energy efficiency per unit volume and shorter shaft length.



(a) 3 Dimension analysis



(b) Axial fluxes vs. position



(c) The distribution of axial and radial fluxes

Fig. 5 Analysis of one pole by 3D FEM

2.4 Characteristics of single phase SRM for pole arc and salient pole length

The single phase SRM's stator pole number, Ns, is the same as the rotor pole number, Nr. As such, the pole pitch angle is $\tau_s = \tau_r$. The possibility of starting, core loss, switching frequency, pole arc and salient pole length that affect variations of flux during rotation are very important design parameters. Equs. (2) and (3) are the preconditions for stator pole arc βs and rotor pole arc βr. Equ. (4) shows pole pitch angle τ.

$$(\beta_r + \beta_s) \le \frac{2\pi}{N_r} \tag{2}$$

$$\beta_s \le \frac{2\pi}{N_r} - \beta_r \tag{3}$$

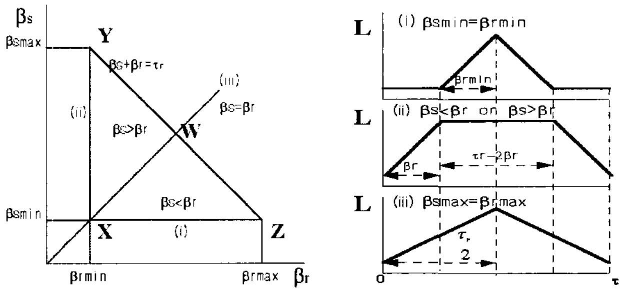
$$\tau_r = \frac{2\pi}{N_r} \tag{4}$$

Pole arcs βs and βr that satisfy Equ. (2) are determined by the triangular XYZ areas as shown in Fig. 6(a),(b) which indicate the inductance vs. the pole arcs βs and βr in the XYZ triangle.

If stator pole arc βs and rotor pole arc βr are both on point x, the variations of inductance have no dead zone as shown in Fig. 6(b)-(i). In order to change structures, pole arcs βs and βr are moved along XY and XZ from point X. A dead zone appears next, and the minimum inductance block disappears at points Y and Z. Fig. 6(b)-(ii) shows the variations of inductance.

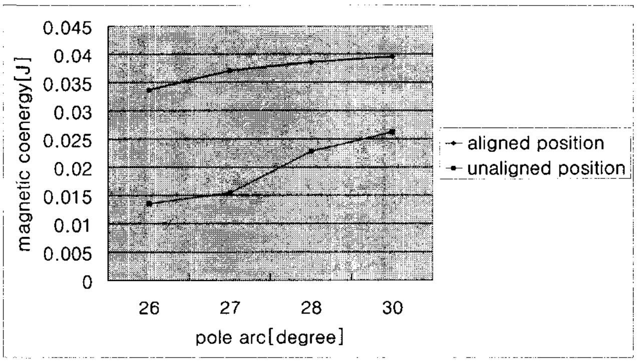
Stator arc βs is greatest at point Y, rotor arc βr is greatest at point Z, and βs and βr are equal at point W. Fig. 6(b)-(iii) shows the variations of inductance. Therefore, we can pick out the XWY area of βr < βs on the SRM design. [10]

In the design of a salient pole rotor, pole arc βr salient pole that affects on the magnitude of inductance at an unaligned position has to be considered simultaneously.

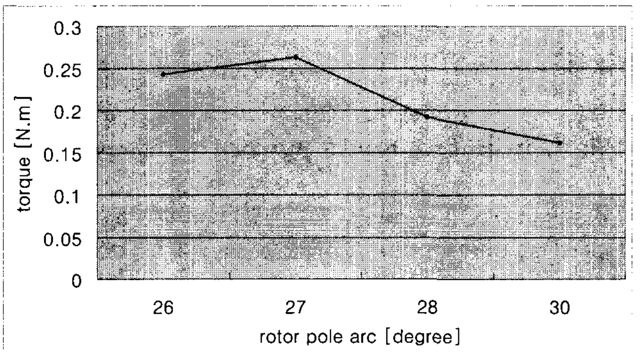


(a) Relation between pole arc of stator and rotor (b) Inductance vs.pole arc

Fig. 6 Pole arc of stator – rotor and inductance



(a) Distribution of magnetic coenergy

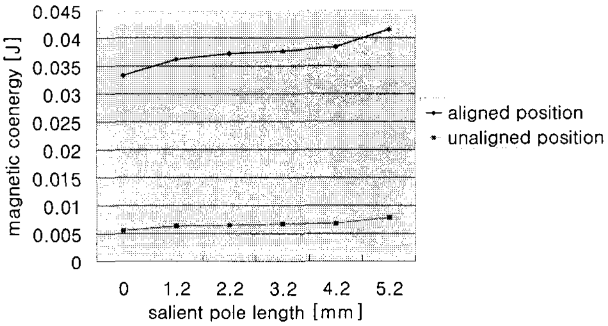


(b) Variations of torque

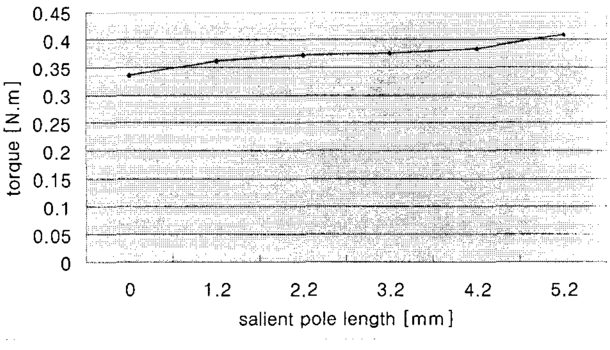
Fig. 7 Variations of magnetic coenergy and torque according to the pole arc magnitude

It is ideal for linkage flux to be 0 at the unaligned position, but torque diminishes when the pole arc length becomes close to half of the inductance variation period because the rotor pole and stator pole overlap at the unaligned position. Fig. 7 shows the magnetic coenergy according to the pole arc's magnitude and torque. It also demonstrates clearly that torques are diminished by raising the magnetic coenergy at the unaligned position when the rotor pole arc is βr=27°.

The length of pole arc and salient rotor pole can increase the inductance at the unaligned position. If the length of the rotor salient pole is long and not being narrow to radial direction, but the inductance becomes big because the stator pole and the rotor salient pole overlap at unaligned position, so the increment of inductance is small between unaligned position and aligned position. As a result, torques decrease. Therefore the salient pole length must be determined for the inductance between the aligned position and the unaligned position to be different enough in order to obtain a sufficient salient pole effect. In addition to that, the 'ㄷ' shape of the stator pole space required for winding must also be considered.



(a) Distributions of magnetic coenergy



(b) Variations of instant torque

Fig. 8 Variations of magnetic coenergy and instant torque according to the salient pole length.

Fig. 8 illustrates the magnetic coenergy distribution and torque obtained by FEM according to the length of the salient pole. We can confirm that the difference of magnetic coenergy between the unaligned position and the aligned position increases if the salient pole becomes longer. We decided that salient pole length should be about 5[mm] in the model analysis, because the magnetic coenergy and torque increased at a salient pole length of 5.2[mm] in the experiment. [11]

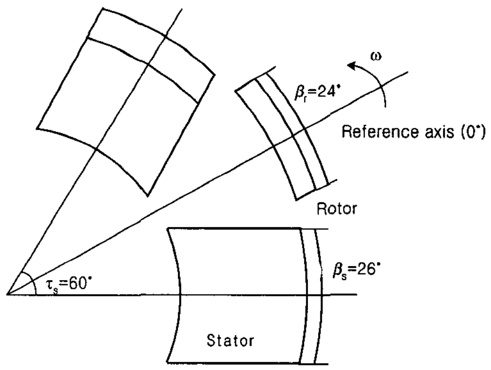
3. Driving Characteristics

3.1 Control method

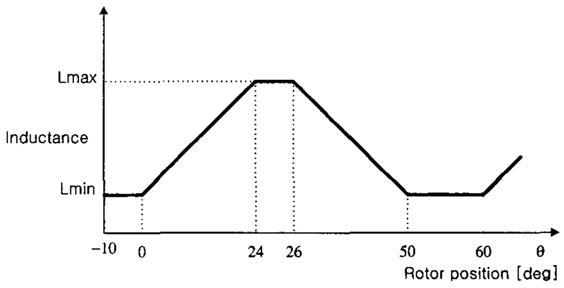
The driving methods of single phase SRM are divided into angle control and current control, and the current applying time and the shape become diverse according to speed and load. At the angle control point, which controls the current applying time and electric conducting time at the inductance period during high speed operation, the peak current is limited by anti-electromotive force in the rated speed and load. At this time, sufficient current must be made before the applying time in order to generate appropriate torque for load variation.

The current driving method has a low increase of anti-electromotive force and inductance. Although applied voltage is the same as that during high speed operation, low speed operation peak current is higher than that of high speed operation due to the high rate of the rising current. For that reason, this peak current is limited under the level of switching element's rated current, so the PWM and current control chopping must be used. Current applied to the motor is controlled by load and speed. [12]

3.2 Inductance wave of prototype SRM



(a) Rotor pole and stator pole



(b) Inductance wave

Fig. 9 Inductance waves of prototype single phase SRM

Fig. 9 shows the inductance variations by rotor position upon excitation of prototype SRM's stator. We determined the rotor and stator pole pitch angle to be $\tau_s = \tau_r = 60$, rotor pole arc to be $\beta r=24°$ and stator pole arc to be $\beta s=26°$ as in Fig. 9(a). If the overlap position of rotor pole arc and stator pole arc is 0°, the ideal inductance waves of prototype SRM will be as shown in Fig. 9(b).

3.3 Design and fabrication of driving circuit

We designed and fabricated a single phase SRM driving circuit that has a simpler structure and more variable control performance than the conventional motor of Fig. 10. We used an absolute encoder with a resolution of 360°/8192 to control the exciting period, and used DSP to generate the control signal that turns on/off IGBT at the desired position by comparing the position signal detected by the encoder.

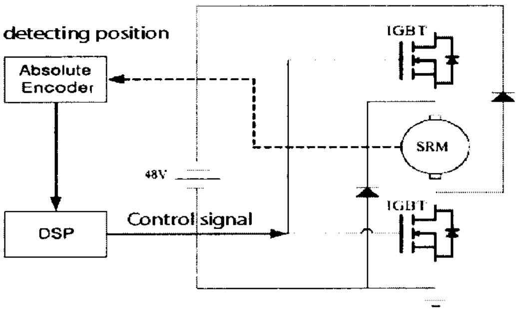


Fig. 10 Driving circuit

3.4 Driving characteristics

We studied the driving characteristic using the angle control method that can control the application time of steady voltage and electric conduction time. As shown in Fig. 9(b), the inductance wave can control exciting periods from -5° to 25°. However, the driving characteristics were measured from -3° to 22° taking into consideration exciting current rising time and residual current. Fig. 11 shows the variation speed measured with prototype SRM in the event that the exciting range was adjusted and with/without the permanent magnetic starting unit.

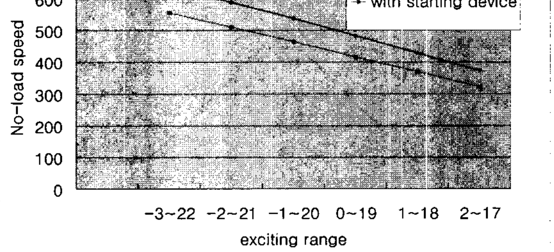


Fig. 11 Speed variations vs. exciting range and with/without starting unit

We confirmed that the permanent magnetic starting unit inserted under the rotor of prototype SRM caused torques and speeds to reduce by working on the load during operation as illustrated in Fig. 11. Fig. 13 shows the torque characteristics when the exciting current seen in Fig. 12 was applied at the range of 2° ~ 17°. [13]

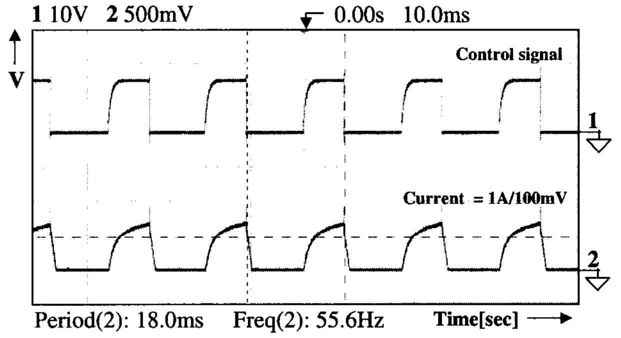


Fig. 12 Currents applied to single phase SRM

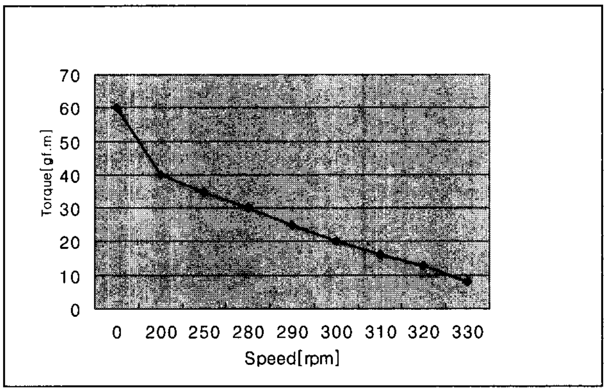


Fig. 13 Characteristic curve of torque

5. Conclusion

We designed and fabricated a prototype single phase SRM and its driver, which is appropriate for an inferior circumstance with short axis. We analyzed the distribution of flux density and magnetic coenergy at aligned and unaligned positions by 3D FEM, so as to confirm how the lengths of salient pole and the magnitude of pole arc affect torque. From prototype SRM experiments, we could certify a basic analysis as to why the salient pole length is limited and why the rotor pole arc is smaller than the stator's to restrain inductances rising at the unaligned position. A permanent magnetic starting unit was inserted under the rotor disk of the prototype SRM to obtain starting torque and to determine rotation direction affects on the driving characteristics if the speed becomes faster. For merchandising of the single phase SRM, salient pole lengths, pole arc magnitude and distributions of magnetic flux density need to be analyzed for optimal design parameters. In addition, a starting device is needed that does not affect on operation characteristic.

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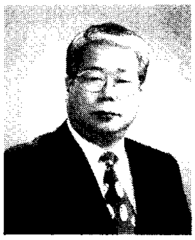

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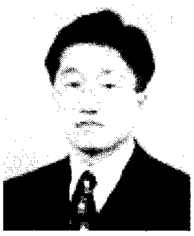

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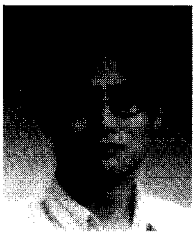

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