Design of 2-phase Snail-cam type Switched Reluctance Motor

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Abstract —This paper deals with design and analysis of a 2-phase switched reluctance motor (SRM), which is the cooling fan motor of a refrigerator. Some design aspects should be treated for avoiding the dead zones that can lead to starting problem, and rotating in one-direction for the application. To solve these problems, the snail-cam type rotor pole and the asymmetric stator pole are investigated in the design process. The magnetic characteristics, flux linkage, inductance and static torque, have been calculated using 2D finite element method (FEM) coupled with circuit equations. The field solution and the analysis on electric circuit have been processed to give the description of the dynamic state performance of the prototype.

Key Words – asymmetric stator pole, fan motor, snail-cam type, SRM, dead zones.

I. INTRODUCTION

Recently, Brushless DC motor (BLDC) has been commonly used in household applications, but the higher cost of permanent magnet and the complexity of the controller are some of their disadvantages. These problems can increase the cost of productions. As compared with BLDC, however, SRM has many advantages such as solidity, low cost drive topology and economical efficiency due to simple construction[1]-[4]. These characteristics are competent to satisfy the demands for a part of household electric appliances.

This paper deals with design and analysis of a 2-phase SRM, which is the cooling fan motor of a refrigerator. The motor can coincide with the demanded characteristics of the small fan as 2W. However, some design aspects should be treated because a general 2-phase SRM has wide zero torque zones, i.e. dead zones, that can lead to starting problem[1][2], and rotates in bi-direction while the cooling fan requires the rotation in one-direction only. To solve these problems, the snail-cam type rotor poles and the asymmetric stator poles are investigated in the design process. These configurations are able to eliminate dead zones and to improve torque ripple. For selecting the optimum shapes of the poles, the dynamic state performances which are instantaneous phase current and torque, have been calculated and then, the average torque and efficiency are compared between each variable pole shape. It is presented for the prototype that a phase flux linkage, a phase inductance, instantaneous torque and a phase current calculated by using a hybrid method combining FEM with the voltage equation.

II.DES IGN MODEL

A 2-phase snail-cam type with asymmetric stator pole structure is designed as the fan motor for a refrigerator. It is a 4:2 motor which has 4-pole stator and 2-pole rotor. Fig 1 shows the configuration of the prototype at the moment when phase A is fully unaligned with one pair of rotor poles. This rotor position is criterion as 0° for a relative angle between stator and rotor poles in this paper. It has four stator poles and two rotor poles with single tooth per pole configuration. For each phase, a pair of concentrated winding is wound in series on the diagonally opposite stator poles. Fig 2 is the picture of the fabricated motor with the cooling fan and its drive.

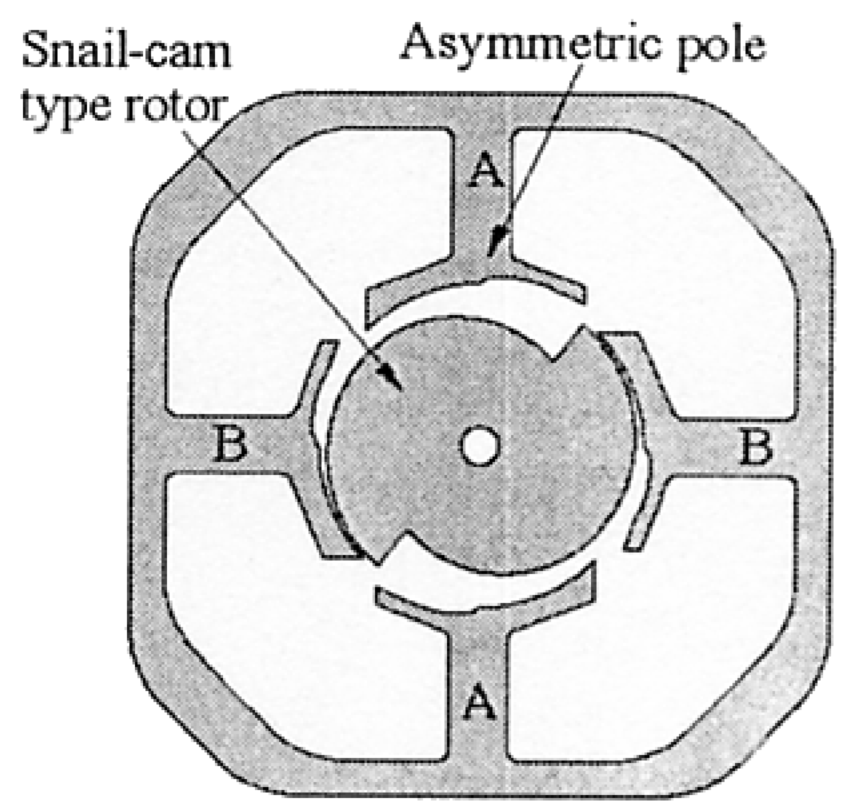


Fig. 1 Configuration of the prototype on the 2-phase 4:2 SRM

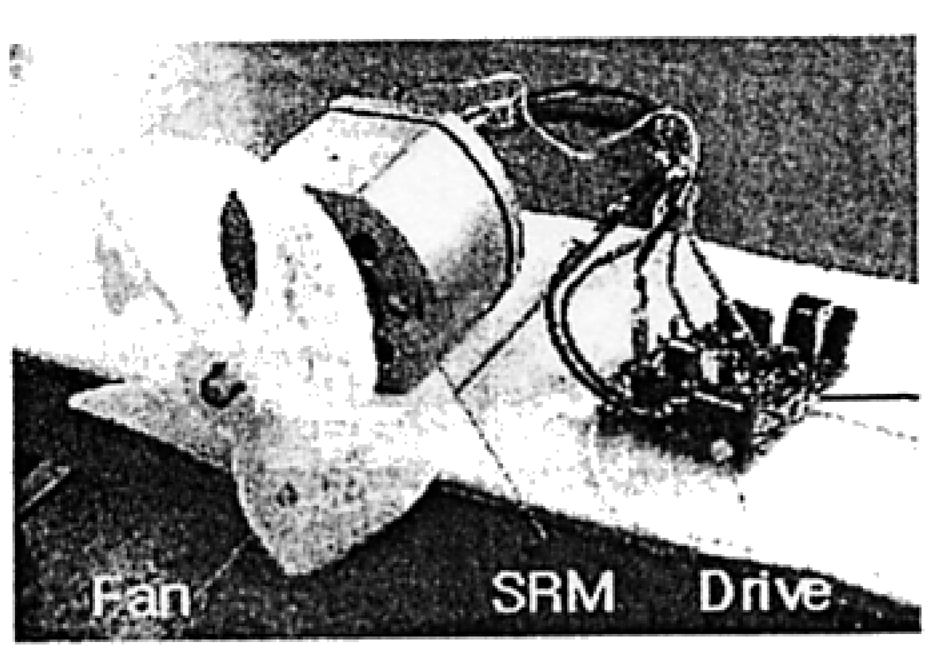


Fig. 2 Prototype with a cooling fan and its drive

III. DESIGN CONSIDERATIONS

A. Basic Design Theory

The selection of pole number and pole shape of the stator and rotor influences on the torque production capability, the self-starting capability, the core losses and even the cost. The lower number of phase and pole is better for household appliances because of the cost.

The 2-phase motor is desirable because of the savings in connections and transistors. In the case of an irregular 4:2 motor with a stepped air gap, the aligned inductance is slightly increased compared with that of the primitive 2-phase, but the unaligned inductance is also greater. Therefore, there may be no gain in inductance ratio of the unaligned inductance to aligned inductance compared with the primitive motor. However the dead zones near the unaligned position is reduced, as shown in Fig. 3. The effect of stepping the air gap is to extend the region of positive inductance variation such that at any rotor position there is a positive $dL/d\theta$ for either phase winding[1]. Therefore, it has better effect to use a uniformly tapered gap such as a snail-cam. For rotation in one direction, each phase can produce unidirectional torque over an angle greater than $\pi/2$, making $\rho_E > 1$ in one direction only. ρ_E is the ratio of the effective torque zone to the stroke angle[2]. Each inductance profile and dead zones are compared in Fig.3.

The stepped stator pole can help to extend the region of positive inductance variation and to improve torque characteristics as well as rotor pole shape. For deciding stator pole shape, the pole arc is selected in the first place. The selection of the pole arcs must be generally within the low half of the feasible triangle which expresses all possible combinations of pole arc. The following necessary constraints[3] should be met,

$$\min(\beta_s, \beta_r) > \frac{2\pi}{mN_r} = \varepsilon \quad and \quad \beta_s + \beta_r \le \frac{2\pi}{N_r} \qquad (1)$$

where $\beta_s$and $\beta_r$are the stator and the rotor pole arcs respectively. m is the number of phase and N_r is the number of rotor poles. ε is a stroke angle.

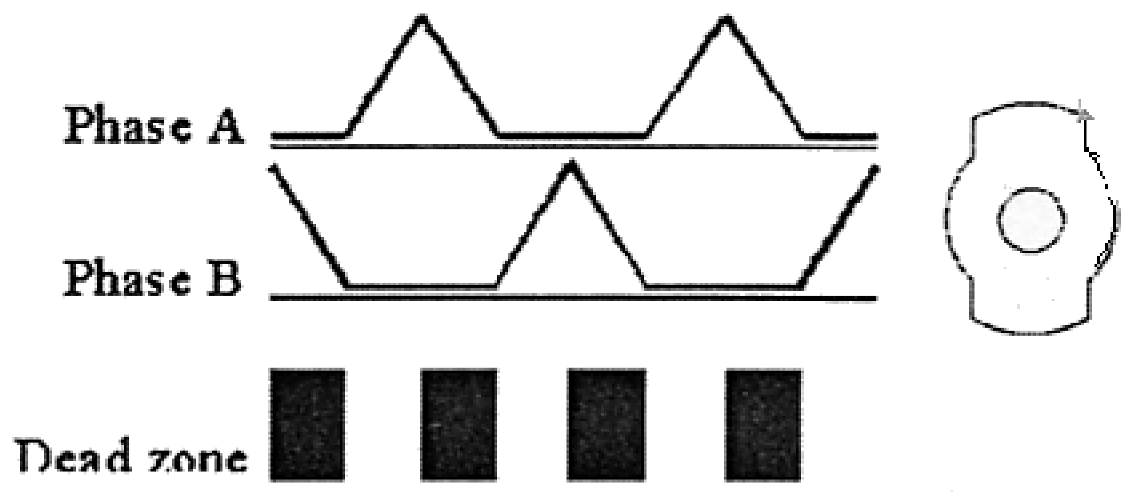
However, even the minimum angle of the stator pole arc in the equation (1) is unreasonable for 2-phase 4:2 motor because of raising leakage flux between stator poles. The angle of stator pole arc should be therefore smaller than the minimum angle.

In this paper, 6-type asymmetric shapes of stator pole are considered as Fig. 4 and Fig. 5. The pole shapes in Fig. 5 are the combination of segments in Fig. 4. The stator pole shape which satisfies the demands is decided from the analysis results by 2D FEM. The deterioration of torque characteristics induced by small stator pole arc can be compensated by the asymmetric stator pole shape.

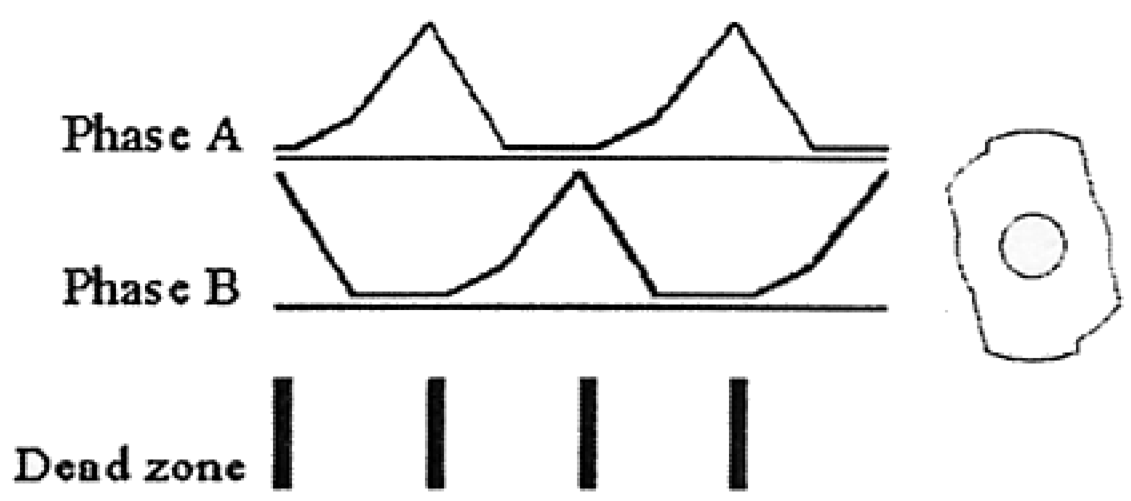
In the selection of air gap length, a smaller air gap is preferred if the mechanical tolerance allows. The air gap length of 0.3mm is selected for the prototype.

The back-yoke thickness of the stator and the rotor is selected to meet the necessary tradeoff, that is being large enough to ensure the peak flux pass both yokes without saturation and ensuring sufficient winding space.

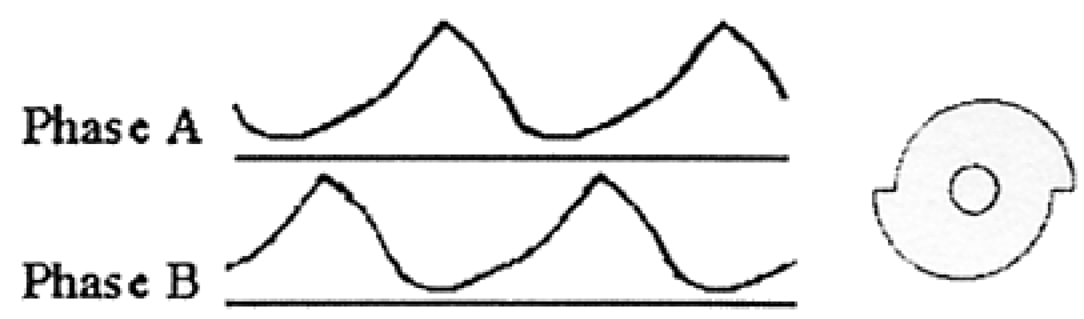
The other design parameters, width of stator pole, depth of rotor pole, diameter of rotor, number of winding and so on, can be calculated by the equations of reference[2]~[3]. And all of design parameters can be changed until the torque characteristics meet the demands by analyzing the results of 2D FEM analysis.



(a) Regular motor



(b) Stepped-gap motor



(c) Snail-cam motor (No dead-zone)

Fig. 3 Inductance profile and dead-zone

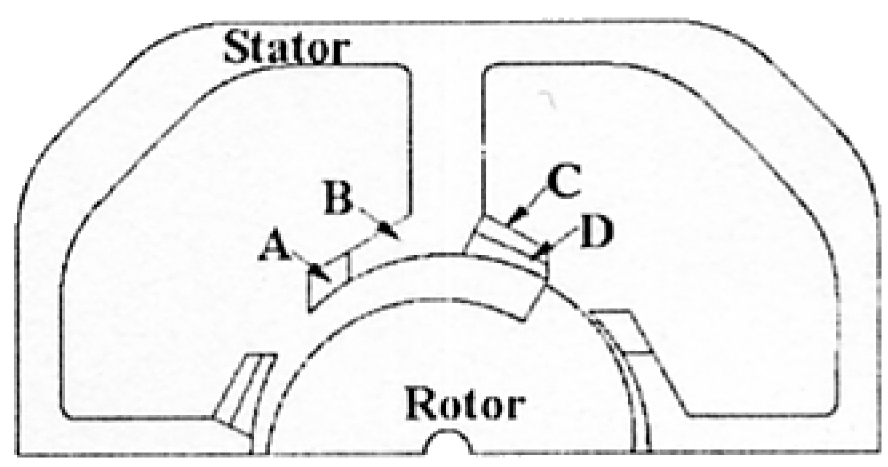
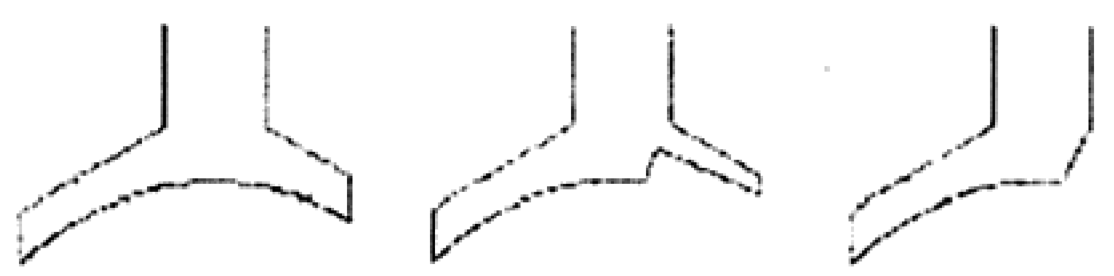


Fig. 4 Segment of a stator pole


(a) type M1(A+B+C+D) (b) type M2 (A+B+C) (c) type M3 (A+B)


(d) type M4(B+C+D) (e) type M5 (B+C) (f) type M6 (B)

Fig. 5 Details of asymmetric pole geometry

B. Field Computation Method

2D FEM is used to consider the nonlinear characteristics of the electric machine. When making assumption as quasi static field, displacement current can be neglected, and the equivalent magnetizing current density also can be neglected in this SRM model because it has no permanent magnet. Therefore, the electro-magnetic governing equation of SRM with field variable $\vec{A}$ is obtained by Maxwell's electromagnetic equation as follows:

$$\nabla\times(\frac{1}{\mu}\nabla\times\vec{A})=\vec{J}_0 \qquad (2)$$

where $\vec{J}_0$ is the applied current density, $\vec{A}$ is the magnetic vector potential and μ is the magnetic permeability.

C. Voltage Equation

The detail performance study of the prototype requires an analysis of its dynamic state performance. This includes the dynamic characteristics of phase current and torque, and the influence of some critical parameters on them. For the analysis of the dynamic characteristics, a voltage equation is coupled with equation (2) and then system matrix is obtained by time difference schemes. The voltage equation of one phase of SRM is as follows:

$$V_s=R_m i_m+L_m\frac{di_m}{dt}+E_m \qquad (3)$$

where V_s is the supply voltage, R_m is the winding resistance per phase, i_m is the phase current, L_m is leakage inductance of end-coil and E_m is back-electromotive force induced in the coil.

D. Calculation of Torque

The method of Maxwell stress tensor is used to calculate the static torque for the range of rotor position and phase excitation. Thus static torque is expressed as the following equation (4).

$$\vec{T}=\oint_s \vec{r}\times\vec{P}\,d\vec{S} \qquad (4)$$

where $\vec{r}$ is distance vector of a point to axis rotation.

Equation (4) is obtained by the surface integration of a stress tensor vector $\vec{P}$ over an air gap enclosing the rotor surface $\vec{S}$. Max well stress tensor is given by (5)[5].

$$\vec{P}=\frac{1}{\mu}(\vec{n}\cdot\vec{B})\vec{B}-\frac{1}{2\mu}\vec{B}^2\vec{n} \qquad (5)$$

where μ_0 is the permeability of free space, $\vec{n}$ is the normal vector to the surface $\vec{S}$, $\vec{B}$ is the magnetic flux density.

IV. DESIGN AND ANALYSIS RESULTS

The specifications of the prototype design are shown in table 1. The motor volume, outer diameter and stack length, is restricted by the space of system. And the supply voltage and dwell angle, which is between switch turn-on and off, are limited by its drive. The dwell angle is the same with the stroke angle because only one Hall IC as position sensor is used for cost reduction. It is the design object that the rated torque is obtained without dead zones at rated speed, satisfying the other constraints, and the motor has as high efficiency as possible.

In the rotor design, the snail-cam type rotor is considered to extend the region of positive inductance variation such that at any rotor position and to rotate in one direction only. The detail configuration such as the rotor diameter and the slot depth are decided using the analysis results by FEM and the rotor is shown in Fig. 6.

The switch turn-on and turn-off angles affect the instantaneous current and torque significantly and affect the dynamic state performance of SRM. In this paper, by controlling the only switch turn-on angle, the phase current and the torque can be regulated to the required value because the dwell angle of the prototype is constant. Fig. 7 and Fig. 8 show the effects of both asymmetric pole shapes and the switch turn-on angles on the average torque and efficiency, respectively. For a calculation of the efficiency, iron loss and mechanical loss are ignored in this paper and only the output power and copper loss have been considered.

According to the switch turn-on angle, the aspect of torque values is more changeable than that of efficiency. In the cases of the 6-type models, the more asymmetric shape a stator pole is, the higher average torque is. On the contrary, efficiency is lower when the stator pole has more asymmetric shape. Therefore the shape of stator pole is selected to meet the necessary tradeoff, and the result is shown in Fig. 6.

Table 1. Specifications on the prototype

Supply voltage	30	V
Rated speed	2600	rpm
Rated torque	77	gf-cm
Outer diameter	60	mm
Shaft diameter	3.17	mm
Stack length	11.5	mm
Stroke angle	90	°

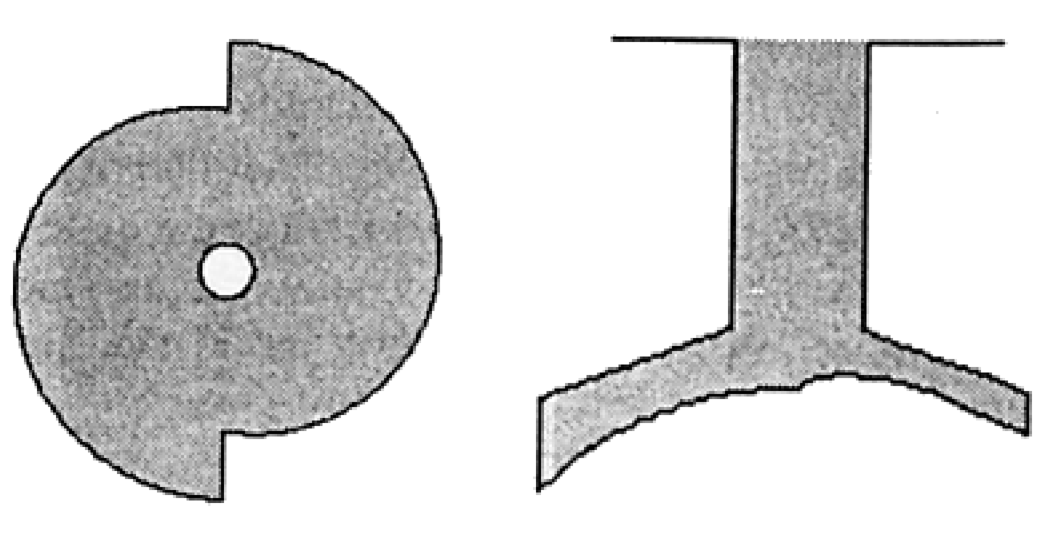


Fig. 6 Detail configurations of rotor and stator poles

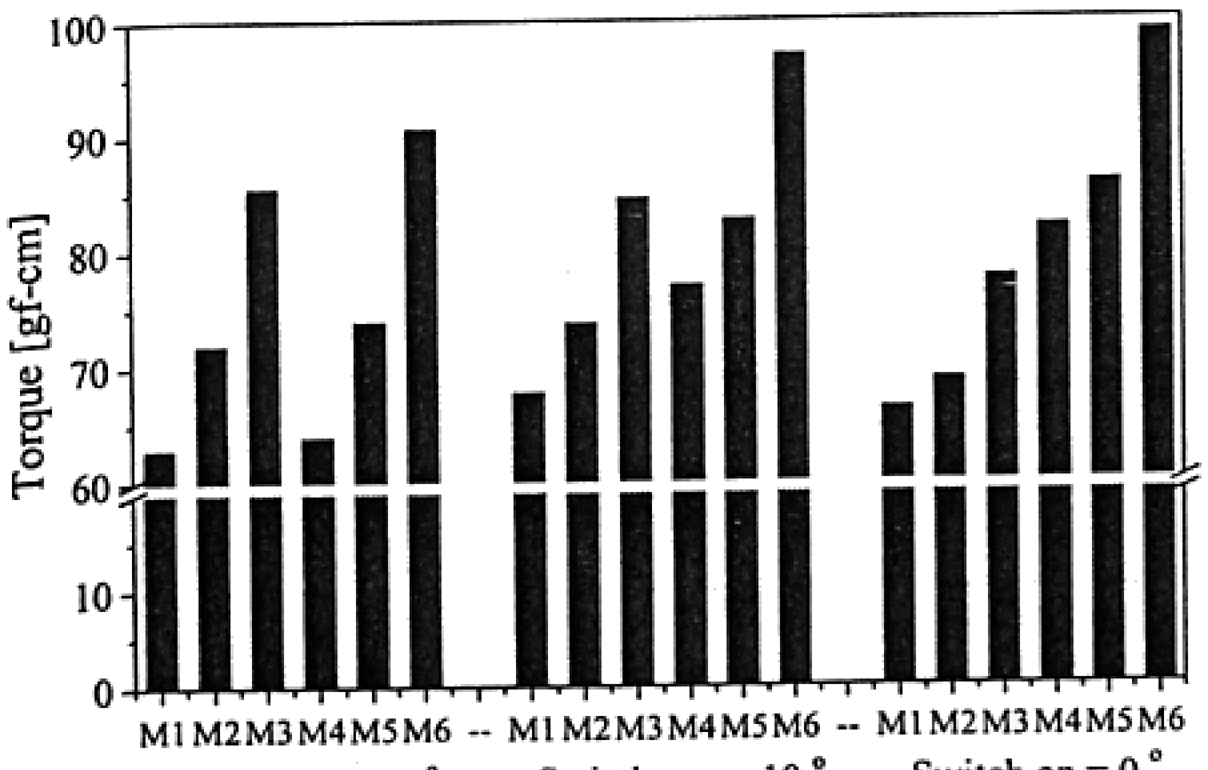


Fig. 7 The comparison of average torque according to switch turn-on angle and asymmetric pole shape

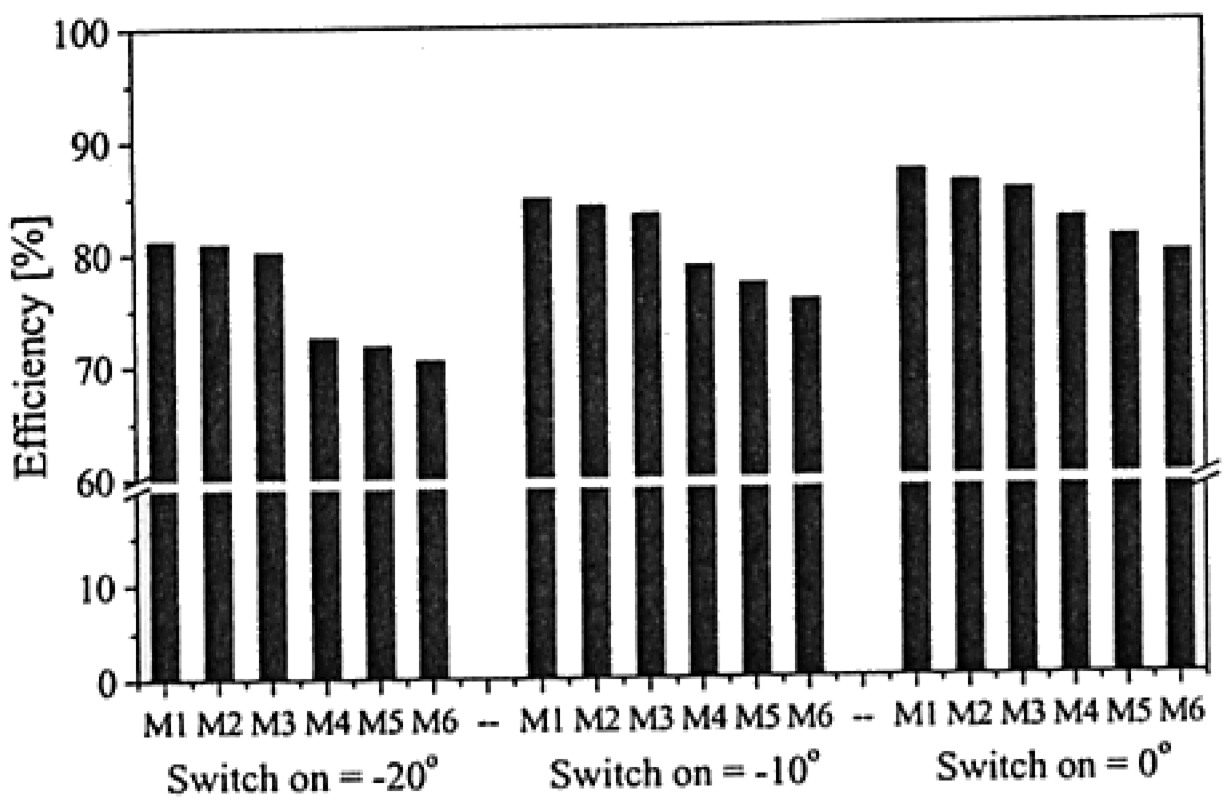


Fig. 8 The comparison of efficiency according to switch turn-on angle and asymmetric pole shape

Fig. 9 and Fig. 10 are the instantaneous torque of the prototype and the one phase current, respectively. In the torque profile, the dead zones have not appeared at all and the minimum value of torque has been high relatively. And the value of the average torque meets the demand level. Fig. 11 is the flux and inductance for one period of inductance profile.

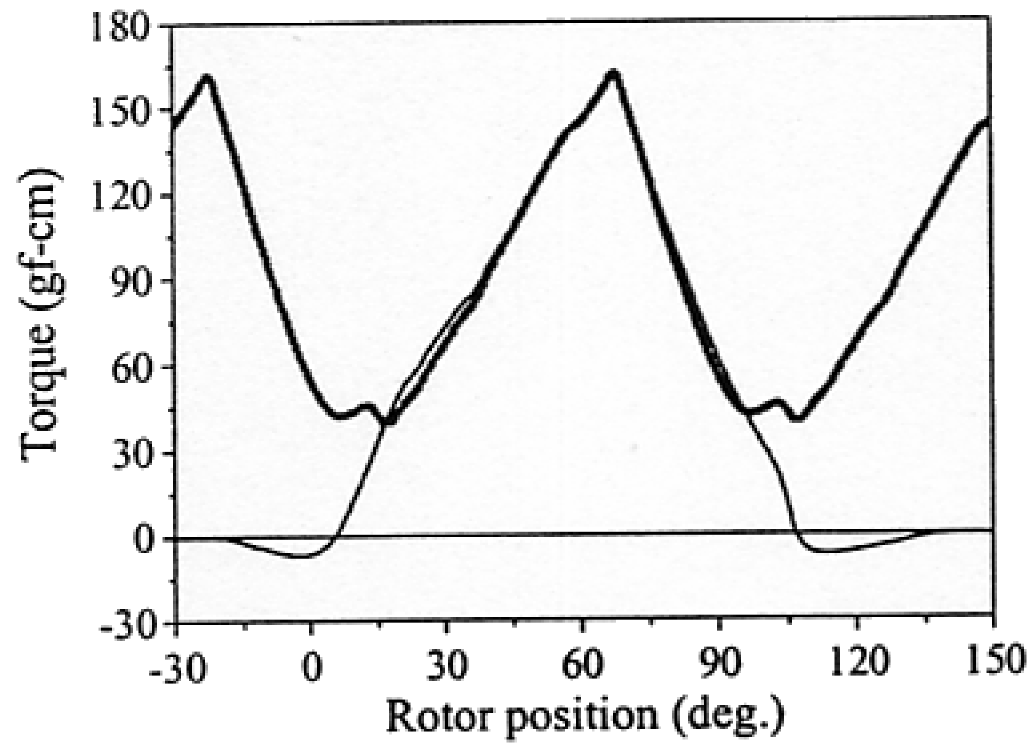


Fig. 9 Instantaneous torque of the prototype

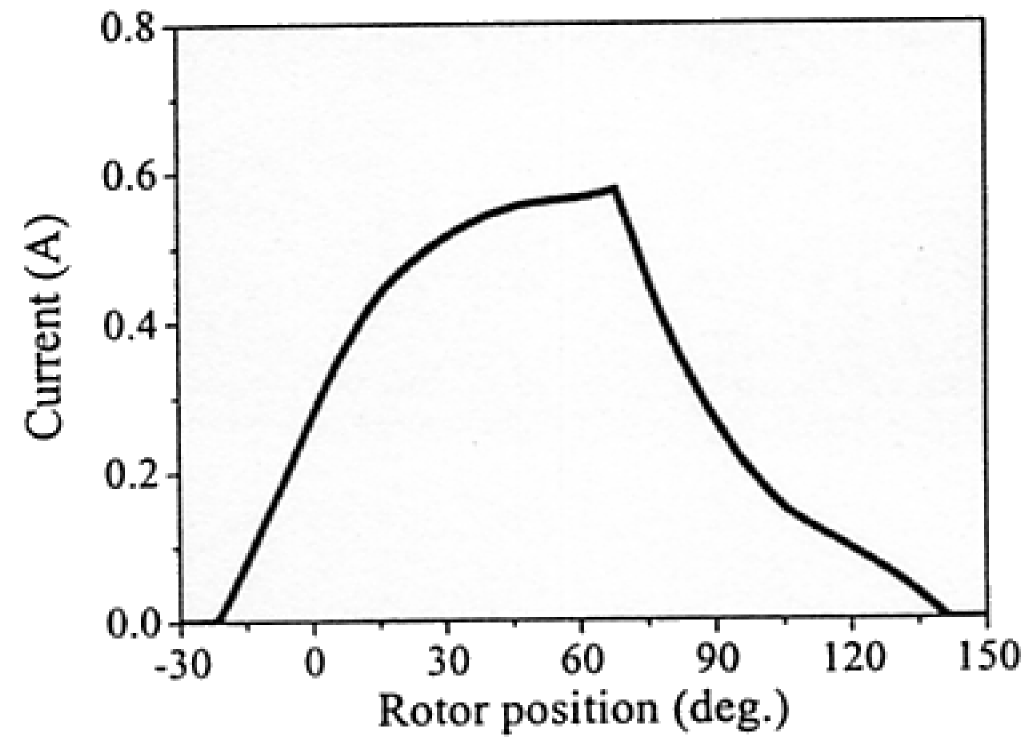


Fig. 10 One phase current of the prototype

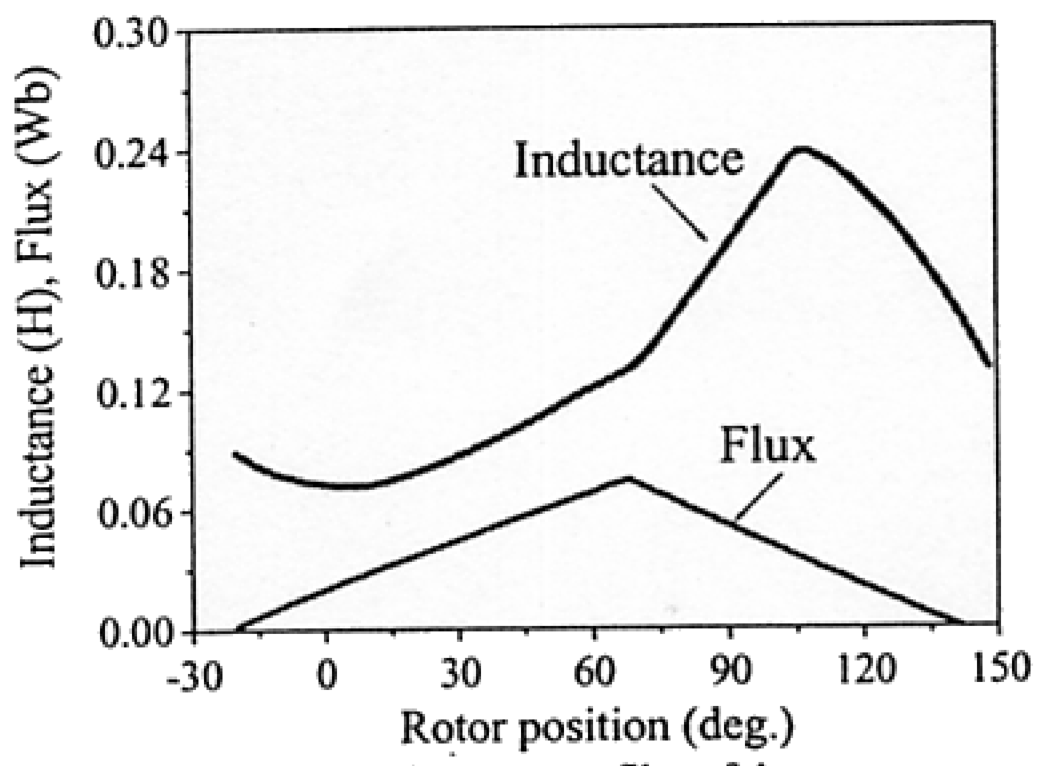


Fig. 11 Flux and inductance profiles of the prototype

V. CONCLUSIONS

This paper demonstrates the effect of pole shapes on torque characteristics for 2-phase SRM design. Its results show that snail-cam type rotor and asymmetric stator poles make it possible to remove the dead zones, to suppress torque ripple and even to increase value of average torque. These facts are helpful to design the shape of each pole or to predict the performance of 2-phase SRM. Research for the optimal shape of pole, comparison with experimental result should be future work.

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